RESIN CONNECTORS IN TIMBER

VALENTINA DI MARIA

A thesis submitted in partial fulfilment of the requirements of

Nottingham Trent University for the degree of Doctor of Philosophy

February 2017

ABSTRACT

The use of Glued In Rod joints for wooden constructions is an efficient technology to connect and design members in new timber structures and to rehabilitate the damaged structural elements of historical buildings. The major issue concerning the use of adhesive anchors in timber is the lack of a standard regulation in the current Eurocode 5 for timber structures. Due to the gap in knowledge of this specific topic in engineering structural design, designers' choices are still supported by test analysis which enables knowledge, and the prediction, of the structural behaviour of Glued In Rod joints.

Over the last 30 years, research studies have suggested diverse and contradictory procedures for the prediction of the withdrawal capacity of adhesive anchors in timber whose application led to the relay of inconsistent information about the use of Glued In Rods in the timber engineering field.

The presented research work is aimed at clarifying the contradictory nature amongst existing design rules and at proposing a correct design procedure to assess the load bearing capacity of adhesive anchors in timber, whilst also taking into consideration the high product-dependency which Glued In Rod connections are characterised by. Moreover, the thesis investigates the development of new prototypes of resin connectors in timber through the identification of innovative technical solutions in order to achieve an improved structural performance of the studied adhesive joints.

An extensive experimental program has been carried out on 'traditional' and new prototypes of adhesive anchors in timber, identified respectively by smooth-cylindrical and rough-threaded internal boreholes in which 8 mm steel rods have been glued by the use of low and high viscosity epoxy resins. The tensile performance of more than 100 samples of single adhesive anchors made from solid timber and glulam has been tested by pull-compression tests in confined test regimes, in both cold states and at elevated temperatures.

Experimental findings suggest that in cold states and in restrictive manufacturing conditions, the adoption of the new prototype of Glued In Rods, characterised by the presence of a threaded and rough internal bonding surface, can simultaneously provide an increase of up to 12% in the withdrawal capacity and a decrease in the joint's cost, due to a significant reduction (30-40%) in the use of epoxy resins when compared to 'traditional' Glued In Rods. Conversely, a change in the internal borehole's shape does not affect the thermal performance of the connections, highlighting that the structural performance of a Glued In Rod joint at elevated temperatures is

highly dependent on the thermal properties (Heat Deflection Temperature) of the resin used to assemble the connection.

Regarding the design of the withdrawal capacity of Glued In Rods, a critical literature review revealed that previous design equations all stemmed from research studies based on the application of different methods and investigative methodologies for both the manufacturing and the testing phases; hence, they cannot be used to produce general statements on the structural behaviour of Glued In Rods. The thesis filled the gap in knowledge about the design of adhesive anchors in timber by proposing a simple and innovative design process mainly composed of two phases: the identification of a specific bond strength parameter which has to be determined by standard experiments and provided by adhesive manufactures, and the presentation of a mathematical equation which allows the calculation of the withdrawal capacity of a single adhesive anchor in timber by knowing the aforementioned bond strength parameter and joint's geometrical features.

This research thesis provides critical information about all the stages that the process of using Glued In Rod connections involves (manufacturing, testing, installation and design) identifying priority actions to be undertaken for the implementation of European technical guidelines and design methods for the use of adhesive anchors in the timber engineering field.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

List of Figures

List of Tables

LIST OF SYMBOLS

E_1, E_2 Young's moduli of adherends

t_1, t_2 thickness of adherends

b width of lap joint

l bond length of lap joint

d, t_3 glueline thickness

G glueline shear modulus

γ shear strain

$\varepsilon_1, \varepsilon_2$ normal strain of adherends

σ normal stress

σ_f normal strength

τ shear stress

τ_f shear strength

τ_m mean shear stress

τ_{max} maximum shear stress

δ slip

δ_s, δ_n shear and normal deformation

$\delta_{s,f}$ shear slip at failure

P normal load

P_{max} maximum load capacity of lap joint

ρ joint factor

f_v shear strength of lap joint

G_f fracture energy

ω joint brittleness ratio

N, P tensile strength of adhesive anchor

R resultant force

τ_0 uniform bond stress

d, d_h hole diameter

d_r rod diameter

h, l glued length of adhesive anchor

φ correction factor

$\tau_{steel-adhesive}$ shear stress at steel-adhesive interface

$\tau_{adhesive-adherend}$ shear stress at adhesive-adherend interface

E, A_{steel} modulus of elasticity, tensile stress area of steel

G, t shear modulus, glueline thickness of adhesive

w axial displacement of adhesive anchor

$E_{steel}, E_{adhesive}$ steel, adhesive energy

ε axial strain in adhesive anchor

λ' parameter for adhesive anchor

σ_x normal stress in x direction

τ_x shear stress in x direction

a half rod diameter

R half hole diameter

ε_x steel bar extension

E_s modulus of elasticity of steel

G_{glue} shear modulus of grout

E_{wood}, A_{wood} modulus of elasticity, area of wood

E_{rod}, A_{rod} modulus of elasticity, area of steel rod

F_{max} maximum load capacity of adhesive anchor

N_m medium load capacity

d displacement

d_m, d_{av} average displacement

d_{net} net displacement

$d_{net,av}$ average net displacement

$\tau_{adhesive-wood}$ shear stress at adhesive-wood interface

$\tau_{adhesive-wood,av}$, $\tau_{adhesive-wood,m}$ average shear stress at adhesive-wood interface

$\tau_{steel-adhesive,av}$ average shear stress at steel-adhesive interface

N_{adh} load at point of loss adhesion

T_g glass transition temperature

T_{deep}, $T_{shallow}$ temperature recorded by deep, shallow thermocouples

T_{av} average temperature

τ_u ultimate shear stress

$\tau_{u,m}$ average ultimate shear stress

$\tau_{\max Cook}$ maximum shear stress according to Cook's theory

$\tau_{\max,\mathrm{m}\,Cook}$ average maximum shear stress according to Cook's theory

$\tau_{0\,Cook}$ shear stress at z=0 according to Cook's theory

$\tau_{0,\mathrm{m}\,Cook}$ average shear stress at z=0 according to Cook's theory

$\tau_{\mathrm{average}\,Cook}$ average shear stress according to Cook's theory

LIST OF ABBREVIATIONS

GIR	Glued In Rod
POLA	Point Of Loss Adhesion
EC5	Eurocode 5
GIROD	Glued In ROD program
LVL	Laminated Veneer Lumber
GLULAM	Glued Laminated Timber
GL24	Glulam structural grade
C16, D18	Softwood, Hardwood structural grade
R60	fire resistance of 60 minutes
MC	Moisture Content
HDT	Heat Deflection Temperature
ASTM	American Society for Testing and Materials
CYL	Cylindrical
THR	Threaded
DF	Douglas Fir
M8	8mm steel rod
EX 1:1, EX1	two-component epoxy resin
EX 3:1, EX3	two-component epoxy resin
DMTA	Dynamic Mechanical Thermal Analysis
DSC	Differential Scanning Calorimeter
CV	Coefficient of Variation

ACKNOWLEDGMENTS

The adhesive material used in this research work was exclusively and entirely provided by the 2K Polymer Systems Limited company, based in Alfreton (UK). The constant support, shown throughout all stages of this research project, is gratefully acknowledged.

‘I really do not know how many times I dreamt of writing the acknowledgments of my PhD thesis; I knew that writing this paragraph would have corresponded to the end of my research work.

This special moment has come and I am extremely proud of myself.

I would have never reached this point without the constant support of several people and for this reason I am very keen to thank them.

First of all, my director of study **Anton Ianakiev,** thanks for being an important landmark during the years of my PhD. You guided me through this long and tough academic journey day by day holding my hand, smiling and providing technical insights. I will never thank you enough for being a great supervisor and for giving me the possibility of becoming the researcher I am.

Rob Evans for his feedback on my research work. You taught me how to be a good lecturer during our lab classes and I will never forget your valuable and constructive advice.

Christine McCall, my super funny, passionate, awesome and knowledgeable English teacher who was the first person who believed in my skills and abilities.

Thanks to **all NTU’s technicians** (Judith, little Dave, Dave, James, Jules) for the time spent with me in laboratory and for being always so kind and professional.

Christina for being such a true friend, a special person who has been the most beautiful discovery of this experience in the UK. I feel so lucky to have you in my life!

Ugne for having been the perfect flatmate making me feel “at home” even though I was 2000 km away from Italy.

Silvia for supporting each other during our PhD courses.

Eva for believing in my choices and being proud of my achievements.

Giamila for having encouraged me every single day in Nottingham.

My family, who have always believed in my ambitions supporting the choices I made even though they could have been painful. Vi voglio un mondo di bene!

My sister Elena, a woman who has always been a great example of femininity, courage, strength and kindness and whose words are able to warm up my heart and protect my mind from every single thing that can happen in this world.

Finally, I need to save these last lines for a special man who loved me unconditionally even when the most difficult moments of this PhD journey made me behave as a crazy woman. Thanks to **my sweet love Mario** who supported me all the way by looking into my eyes and by transmitting all the positive energy needed to complete this significant path of my life.’

Thank again to all of you!

DECLARATION

- The author declares that parts of the research work presented in this thesis were published in advance in a journal paper and in two conference proceedings. The author is the sole responsible for the ideas, samples' preparation, data collection, data critical analysis included in the aforementioned papers, written under the supervision of Dr Anton Ianakiev.

Journal papers
DI MARIA, V., IANAKIEV, A. (2015). 'Adhesive Connections in Timber: A Comparison between Rough and Smooth Wood Bonding Surfaces', World Academy of Science, Engineering and Technology, International Science Index 99, *International Journal of Chemical, Nuclear, Materials and Metallurgical Engineering*, 9(3), 395 - 401.
Conference proceedings
DI MARIA, V., IANAKIEV, A. (2015). 'Adhesive Connections in Timber: A Comparison between Rough and Smooth Wood Bonding Surfaces'. *In ICWACT 2015 : 17th International Conference on Wood Adhesives, Chemistry and Technology* . Miami, USA, 9-10 March. Miami: WASET. International Science Index 13 (3) IV, 616-622.
DI MARIA, V., IANAKIEV, A. (2014). 'Resin connectors in timber' Poster presented at the Inaugural College of Art, Design and Built Environment Doctoral Conference, Nottingham Trent University, 9-10 Jun 2014.

- A formal academic collaboration program between Nottingham Trent University (UK) and the Politecnico of Milan (IT) led to the development of an experimental campaign conducted on adhesive anchors in timber at elevated temperatures. Nottingham Trent University provided materials and samples' preparations while the Politecnico of Milan offered its technical facilities for testing and data collections, under the supervision of Dr Giovanni Muciaccia.

1. INTRODUCTION AND RESEARCH DESIGN

1.1 DEFINITION OF GLUED IN BOLT CONNECTIONS

"Timber is an eco-friendly building material and currently timber structures represent one of the most typical examples of sustainable construction.

The technological evolution in timber engineering has led to the presence of different connection systems for wooden constructions (Otero Chans et al. 2008) which nowadays allow designers to select the most appropriate connection in terms of structural performance, manufacturing features and cost for any application (Piazza et al. 2005).

Carpentry joints, made by the workability of wood surfaces in contact, and traditional mechanical joints, such as screws, bolts, nuts, aluminium angle brackets and perforated plates are the most common connection systems used in wooden structures (Otero Chans et al. 2010b).

In some applications these traditional joints become complex, aesthetically displeasing and do not correspond to the original design calculations. Therefore, taking into account that the majority of design efforts are usually spent on joints, as they are a critical part of the whole structure's design, timber engineering needs improvements and renovations in fastening systems.

Glued In Rod joints (Fig. 1-1) can be the answer to this issue (Yeboah et al. 2012).

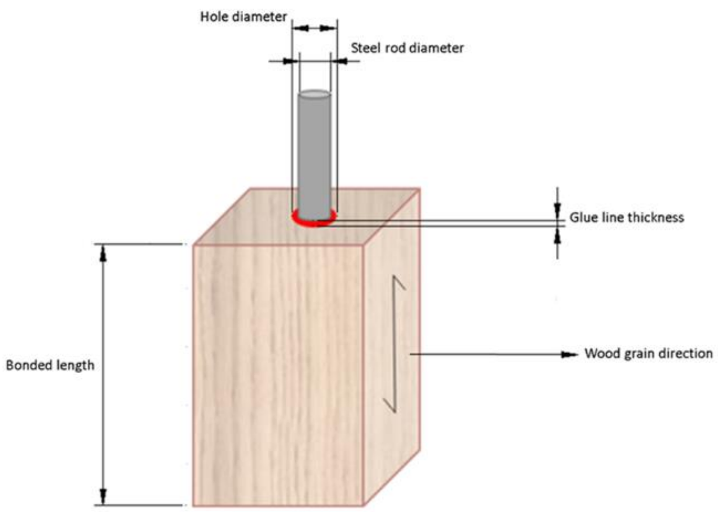


Fig. 1-1: Glued In Rod joint (Di Maria and Ianakiev 2015)

Glued in bolts are new adhesive joints composed of timber, steel rods or fibre reinforced polymers and glue (e.g. epoxy resin). Steel bars are embedded into adhesive-filled holes in wooden elements (Yeboah et al. 2012). Commonly the adhesive is injected using cartridge systems, the predrilled holes are wider than the diameters of the bars (Bengtsson et al. 2000) and the distance between the steel and timber corresponds to the glue line thickness.

If properly designed, this connection system is characterised by ductile behaviour and high stiffness values, without showing the presence of an initial settlement phase. Other benefits include a total invisibility of the joint which improves its aesthetic quality (Gubana 2008) and a competitive production cost (Harvey and Ansell 2000) considering its overall characteristics.

Compared to traditional connectors, in glued in bolts the stress is distributed along all the bonded length preventing stress concentration points near anchor bolts of mechanical joints. This joint also provides good protection from fire and corrosion of the embedded steel elements (Gubana 2008). Nevertheless, the strict quality control ensuring the correct manufacture of the joints during test analysis and in situ remains one of the critical issues for this type of adhesive connection (TRADA 2000)" (Di Maria and Ianakiev 2015).

1.1.1 Parameters affecting the Mechanical Behaviour of GIR

The design principle which makes a Glued In Rod connection work efficiently takes into consideration the fact that the connection has to be designed in order to be subjected to normal forces in the direction of the steel bar (Gehri n.d.). For this reason the main parameter which has to be studied to verify the connection's performance is its withdrawal capacity.

Currently in the civil engineering field the use of adhesives which are able to transfer loads between members of a structure is well-known and frequently adopted especially in concrete; however, their use in timber is still considered as a 'hybrid' fastening technology.

In an adhesive anchor the mechanism used to transfer load is through the creation of a strong bond which has to be generated by the adhesive between its adherends. In this particular case, the resin has to create a chemical and mechanical interlocking between steel and timber. The shear strength distribution which takes place in an adhesive anchor is subjected to a tension load equivalent to N. The joint's strength is developed due to the creation of internal shear forces (τ) which are distributed along the joint's embedded length and whose total sum is the resultant force ($R=\Sigma\ \tau$) which corresponds to the original tension force N (Cortis and Rossi 2011).

Hence, the withdrawal force is opposed by internal resistant forces which are located along the bonding areas and for this reason by changing some of the joint properties (geometrical and material) the maximum bond strength changes since it is proportional to the hole surface (Cortis and Rossi 2011).

Several parameters can influence the pull-out strength of a Glued In Rod connection. The numerous combinations of these different factors lead to a difficult design of the joint which should be carefully studied before any real applications in situ in order to obtain a connection which can successfully respond to the design's requirements (Steiger et al. 2015).

1.2 APPLICATIONS OF GLUED IN RODS

1.2.1 Connections for timber structures

The structural performance of a joint highly depends on how the joint is designed for a specific application. However, Glued In Rods in timber have been frequently classified as rigid or semi-rigid connections.

Adhesive connections in timber can be adopted to create:

- timber to timber connection: joint continuity system (beam joints)
- timber to steel connection: corner joint (moment-resisting joints), support joints (column-foundation joint)
- strengthening connection.

A timber to timber connection involves the manufacture of the connection in a construction site where an adhesive "drilled-in anchor" (Eligehausen et al. 2006a) is installed in timber beams. These types of connections are frequently used for structural rehabilitation and conservation of historical wood structures (e.g. churches, houses, roofs) (LegnoDOC 2003), especially for restoring defective parts of old timber beams (Piazza et al. 2005), usually damaged by severe long-term wood moisture variations (Cavalli et al. 2014).

In particular, wood hygroscopic variations and the presence of biotic attacks highly affect the physical and structural integrity of beam-ends in old timber structures. In the past, several methods have been applied to repair "decayed beam ends" in historic timber buildings which all involve the replacement of the damaged part of the timber beam with a new timber section (Pizzo and Schober 2008).

In this specific case, the new section is connected to the original part of the timber beam by using resin connectors. The use of this rehabilitation system allows the restoration of both structural and aesthetic functions of ancient timber structures in situ (Pizzo and Schober 2008).

On the contrary, in a timber to steel connection, a Glued In Rod joint is usually pre-manufactured in factory and consequently installed in situ by connecting the joint's steel bars to other steel elements by traditional steel fasteners (Piazza et al. 2005).

"Rigid corner joints such as 'in glulam plane grid structures' (Piazza et al. 1998 in Del Senno et al. 2004) or 'in moment-resistant corner joints of portal frames' (Buchanan et al. 1996 in Del Senno et al. 2004) could be used where there is an intersection between structural members" (Di Maria and Ianakiev 2015) and when it is needed to "transfer a moment around the knee joint" (STA 2015). A column to foundation connection is an additional relevant design solution for Glued In Rods due to the great force transferability of this joint. However, the presence of a timber to steel connection is essential in the design of this latter connection to prevent the wooden element from being in direct contact with a possible concrete foundation in order to prevent the joint from having durability issues (Piazza et al. 2005).

"Furthermore, adhesive joints could have a crack prevention function in areas where the stress has a perpendicular direction to the wood grain such as 'apex zones of curved beams' (LegnoDOC 2003)" (Di Maria and Ianakiev 2015) or in zones which are characterised by the presence of high shear stresses (Steiger et al. 2015).

1.2.2 Glued In Rods in new timber structures

One of the first real applications of Glued In Rod was developed by Hilmer Riberholt: the first researcher who investigated and successfully used Glued In Rod connections for wooden blades in a wind turbine in Nibe, Denmark in 1986.

Nowadays the application of resin connectors is increasing in the recent timber construction field; a bridge in the Netherlands and a leisure centre in the UK are typical examples of new constructions in which Glued In Rods have been successfully installed.

However, it is critical to underline that all worldwide timber constructions which have been built by using Glued In Rod connections resulted in being expensive structures. In fact, they all needed to be experimentally tested in laboratory before being correctly designed and successively safely installed in situ due to a total absence of standardised rules for the design of adhesive anchors in timber (STA 2015) in both cold and fire conditions.

1.3 STATEMENT OF THE PROBLEM

"The main issue for the glued in bolt connection system is the lack of standard regulation in this specific structural design sector (TRADA 2000). Despite progress in the field, the European

Standard, EN 1995 Eurocode 5 (EC5) for the structural design of timber, currently does not provide established technical rules for Glued In Rod connections. Furthermore, none of the current regulations establishes classes of strength for the adhesive that should be used for adhesive anchor in timber (Piazza el al. 2005).

Hence, resin connectors have been in use since the 1980s without a precise design method. Designers' choices have been supported by national standards (e.g. German DIN 1052; Italian CNR 2007) and by destructive test analysis of joints that enables knowledge and prediction of the resistance capacity of the joint.

Numerous studies and several experimental activities have been carried out in recent and past years leading unfortunately to imprecise information about Glued In Rods in timber, suggesting various design equations and contradictory conclusions (Otero Chans et al. 2008)" (Di Maria and Ianakiev 2015).

Especially because of the recent products' evolution in both chemical and timber engineering fields, more information and further experimental tests are required to gain a proper knowledge of this 'product-dependent' adhesive connection and to define a standardisation process for the design and application of this connection system.

1.3.1 Previous research studies

In the last 30 years, more than 100 researchers dealt with adhesive anchors in timber. In order to clearly present the numerous past studies, it is possible to classify these research projects in two distinctive categories. The first class of investigations (Fig. 1-2) was aimed at conducting parametric analyses in order to analyse how specific factors (material properties, geometrical parameters, type of load), could affect the structural performance of the connection. In particular, within this class of studies critical technical contributions regarding the influence of timber density, glue rheology and joint geometry were provided respectively by Otero Chans et al. (2010a), Bernasconi (2001) and Estevez Cimadevila et al. (2013).

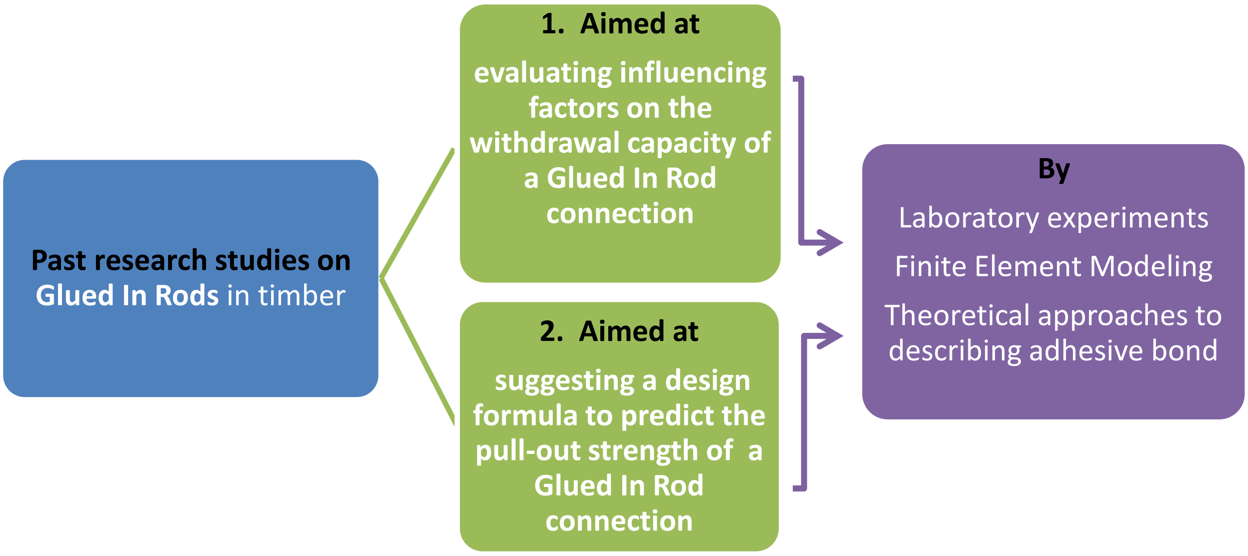


Fig. 1-2: chart for past research studies about Glued In Rods in timber

The second class of previous studies (Fig. 1-2) was aimed at studying and predicting the pull-out behaviour of adhesive anchors in timber through the suggestions of design equations whose formulation was obtained through the conduction of laboratory experiments, analytical studies and the use of theoretical approaches, presented in detailed in Chapter 2, to describing the behaviour of an adhesive joint.

All the design formulas presented in the past are carefully described in Chapter 3 of this thesis, which includes the critical description of all the methodologies used to obtain diverse mathematical equations which were identified as alternative methods to predict the withdrawal capacity of an adhesive anchor in timber.

1.4 Research Aims and Objectives

The research work is aimed at

- identifying and evaluating critical parameters to be included in a design equation to assess the withdrawal resistance of Glued In Rod joints in timber structures
- providing technical guidelines for the standardisation process of Glued In Rods including installation, testing and design methods for the structural use of adhesive connections in the timber engineering field in cold condition and at elevated temperatures.

The objectives of this research are to

- examine the existing design formulas suggested by several past research studies in order to identify the main reasons which cause their contradictory nature
- study well-known theoretical approaches used to describe the behaviour of adhesive bond to evaluate their possible application in adhesive anchor in timber
- propose and analyse in laboratory innovative solutions to assemble new prototypes of glued in bolt joints in order to achieve an improved structural performance in cold conditions and at elevated temperatures.

1.5 ANTICIPATED ORIGINAL CONTRIBUTION TO KNOWLEDGE

Despite the presence of many research studies on Glued In Rod joints in timber, there is no relevant research aimed at resolving the contradictory findings drawn by past experimental activities. Addressing this crucial issue represents a primary objective of this research thesis. Furthermore, the adoption of an effective method of predicting the structural behaviour of adhesive connections combined with the study of the joint's material performances by laboratory experimentations will help to fill the gap in knowledge regarding the standard design and use of adhesive connections in the field of timber engineering.

The originality of the presented research work is also shown by the solutions adopted to improve the connections' performance in the experimental stage: an innovative preparation of timber bonding surfaces characterised by specific geometrical properties and the use of epoxy resins with different chemical compositions which have never been tested for timber structural applications.

In particular, the scope of this research work is to gain critical information about all the stages that the process of using a Glued In Rod connection involves (manual manufacturing, testing, installation and design) by performing experiments under controlled laboratory conditions.

The conduction of experimental investigations in factory and in universities' laboratories leads to the characterisation of the short-term withdrawal performance of adhesive anchors in timber and the identification of critical product-dependent parameters.

The outcomes of this research will originally contribute to identifying technical guidelines for the development of a standardisation process for Glued In Rods to be included in building codes.

Hence, the presence of standard regulations for Glued In Rod connectors will support engineers and designers in safely design adhesive anchors in timber structures.

The study of the performance of multiple Glued In Rods connection systems and the analysis of their installation between sections of new or existing timber structures are beyond the scope of this research work. The applicability of complex connection systems made of adhesive anchors on the building site should be taken into consideration only after :

- gaining full knowledge on the short and long-term mechanical properties of single adhesive anchors in timber
- establishing standard procedures for the structural design of Glued In Rods.

Therefore, the presented research study will not seek to provide examples of different configuration of joints made of Glued In Rods for in situ timber constructions.

In spite of the fact that possible applications have been suggested by several researchers as presented in paragraph 1.2, the installation of Glued In Rods in timber structures on site has not been fully explored yet due to the lack of standard regulation which hinders the use of adhesive anchors in the timber engineering field.

1.6 SIGNIFICANCE OF THE RESEARCH

The research findings will provide technical guidelines for all the stages that the process of using Glued In Rod connections involves: installation, testing and design methods. The research will likely be of interest to designers and engineers in becoming knowledgeable about the topic of adhesive connections in timber.

1.7 RESEARCH METHODOLOGY

The theoretical framework adopted for the development of this research project is mainly composed of four different phases (Fig. 1-16).

1.7.1 Initial study on 'Resin connectors in timber'

This preliminary phase is aimed at gaining knowledge of adhesive timber connections and the materials which adhesive joints are made of: wood, resin and steel. It is important to study the properties of the materials in terms of their natural, chemical and mechanical features to better understand the mechanical behaviour of Glued In Rod joints. In order to develop a good understanding of adhesive connections, previous research studies are analysed to identify the most common applications in real and experimental cases.

This first research phase also involves the identification of the positive and negative aspects of the use of adhesive connections in timber structures. The conclusions drawn from past research studies tend to highlight the presence of several benefits in using resin connectors in timber frame; however the main issue related to these innovative connections is the lack of a standard design regulation. For this reason, the role which this relevant issue has in the design process is carefully addressed in this preliminary study.

1.7.2 Literature review

The critical evaluation of past experimental research studies is an essential part of the second phase of this theoretical framework. An extensive and comprehensive literature review leads to having an overview of the theoretical and analytical design approaches adopted in past research work to describe the mechanical behaviour of Glued In Rod joints. The attention is focussed, in particular, on the contradictory conclusions of previous research findings. Although more than 18 design equations have been suggested in past research projects to predict the pull-out capacity of glued in bar connections, none of them has been identified as a correct design equation for the possible implementation into the European standards regulation.

A comparative approach is used to analyse the proposed calculation equations. The comparison aims to seek the main differences in terms of variables and theoretical approaches used to formulate the existing design rules. Subsequently, the explanation of the conflict amongst the results obtained from different past studies (Dominowski 1980) represents the most important objective of the second phase of this methodological research approach.

Consequently, the results collected from the comparative study are reanalysed to draw an analogy between the suggested design recommendations for timber adhesive connections and the existing technical approvals (ETAG 001) for the design of bonded anchors in concrete. The latter analysis is aimed at identifying whether theoretical approaches/design methods used for adhesive anchors in concrete could be repurposed to be partially applied in the study of the design process of bonded anchors in timber.

1.7.3 Data collection

The experimental phase, which is based on the manufacturing and testing process of more than 100 samples of Glued In Rods, is the central part of the research process (Fig. 1-17). It is mainly developed using a quantitative approach which follows a rigid procedure structure (Kumar 2014: 14-15). The typical steps of the scientific method are followed to gather data and find empirical evidence (Mastin 2008) of the relationships amongst the main critical parameters that affect the mechanical behaviour of Glued In Rod joints.

1.7.3.1 Experimental hypothesis

In this specific research study, the experimental design starts with the definition of the test hypothesis: the ductile behaviour of the studied resin connections when they are subjected to tension by an axial pull-out force.

1.7.3.1.1 Pull-out strength condition

The test configuration chosen in this research thesis to study the withdrawal capacity of samples of Glued In Rod connections in laboratory conditions is the pull-compression configuration. Despite Tlustochowicz et al. (2011) defined the pull-compression test as a testing method which can hardly represent the real behaviour of the joint in real applications due to the presence of distributive compression stresses created by the test set up, the pull-compression configuration is within all the possible types of test configurations for Glued In Rods a testing solution which is able to correctly assess the axial loaded behaviour of the joint in an economical way (Yeboah et al. 2012). In fact, it is characterised by the use of testing samples with small dimensions and reduced amount of steel.

In particular the tests developed in this research thesis are mainly carried out on samples of adhesive connections made of one steel bar because in a parametric analysis on Glued In Rods the study of single adhesive anchors can better identify the main relationships amongst critical parameters (Steiger et al. 2004). All tests are conducted on samples of adhesive anchors in timber glued parallel to the wood grain to take advantage of the high strength properties by which timber is characterised in this specific wood-grain direction.

Moreover, the geometric properties of the steel plate, used during the pull-out tests to induce compression, are selected in analogy with the existing regulation for adhesive anchors in concrete (EOTA 2006) presenting around the steel anchor an uncompressed circular area whose diameter is equal to 1.5 - 2 times the hole diameter (d_h) dimension (Fig. 1-3).

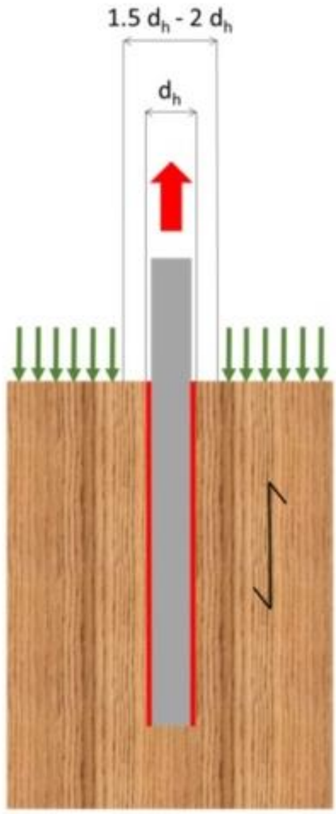


Fig. 1-3: pull-compression test's details of experimental research tests conducted in this research thesis: the connection presents around the steel anchor an uncompressed circular area whose diameter is equal to 1.5 - 2 times the hole diameter (d_h).

1.7.3.1.2 Failure Criteria

Gathering information about all the possible failure modes recorded by previous research studies (Serrano et al. 2008 , Tlustochowicz et al. 2011, Steiger et al. 2015), it is possible to classify the failure mode of Glued In Rods in 3 main categories:

1. adhesive failure
2. timber failure
3. steel failure.

The first failure mode occurs when the joint fails at the adhesive-adherend surfaces or within the adhesive which is commonly named as cohesive failure of the resin. The second failure mode involves the brittle failure of the joint in its wooden parts. Usually this failure mode takes place because of a wrong design of the connection for testing purposes.

Thirdly, the failure which happens through the yielding of the steel bar of the connection is classified as 'steel failure' and it is a ductile failure mode. Hence, this failure is identified as the safest and preferable failure mode for an adhesive anchor in a timber structures in order to prevent the joint from presenting brittle failures which usually characterise wooden elements.

1.7.3.2 Identify variables

Subsequently, the definition of which variables are taken into consideration during the laboratory activity represents the starting point of the data collection phase.

The most important geometric parameters determining the mechanical performance of adhesive connections in timber are: steel bar diameter, rod direction in relation to the wood grain, number and spacing of rods, bond line thickness, bonded length and hole diameter (Tlostochowicz et al. 2011, LegnoDOC 2003).

Since the study of all the geometric parameters could lead to having excess variables, producing different results from the experiments that would not be comparable, the study is particularly focused on the followed parameters:

- hole shape and bonding surface properties (smooth, rough)
- bond line thickness
- bonded length.

1.7.3.3 Identify test materials

After choosing the variables to be measured in the experiments (Fellow and Liu 2008: 3-32), a further selection regards the materials to be used to assemble the adhesive connection. Epoxy resins, stainless steel bars and different timber species and typologies (solid and glulam) have been selected for this research thesis. Regarding the solid wooden samples, the two different timber species which have been chosen as substrate for adhesive anchors are Oak, the most common hardwood species that historical churches and buildings are made of, and Douglas Fir, one of the most used softwoods for construction.

A TESTO 606-2 pin-moisture meter (Fig. 1-4) is used to assess the moisture content values of all timber samples, tension and compression tests are conducted by an INSTRON 3367 machine on wooden samples (Fig. 1-5 and Fig. 1-6) to characterise the material in different grain direction (parallel and perpendicular to the wood grain: Fig. 1-7) and furthermore a visual analysis by using a 300X usb-microscope (Fig. 1-9) is undertaken to highlight different wood’s anatomical properties.

Fig. 1-4: TESTO 606-2 pin-moisture meter for timber and building materials

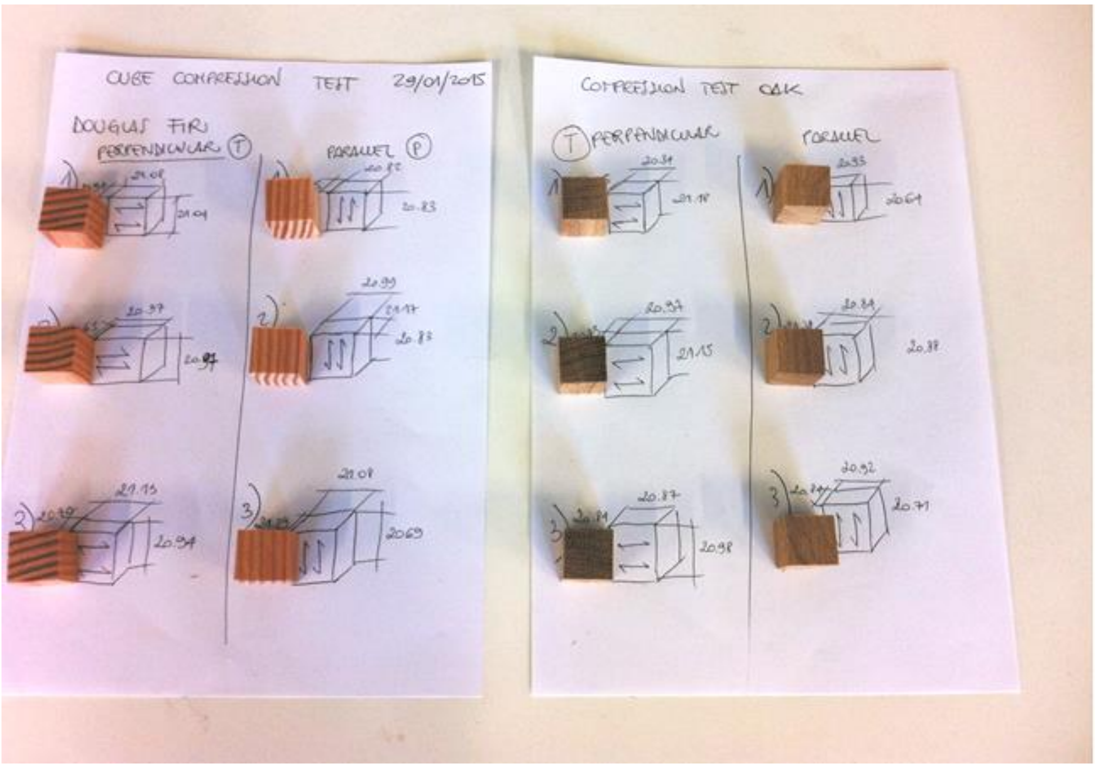


Fig. 1-5: timber samples (Douglas Fir [left]; European White Oak [right]) for compression tests according to BS 373:1957 (dimensions of cubes: 20x20x20 mm)

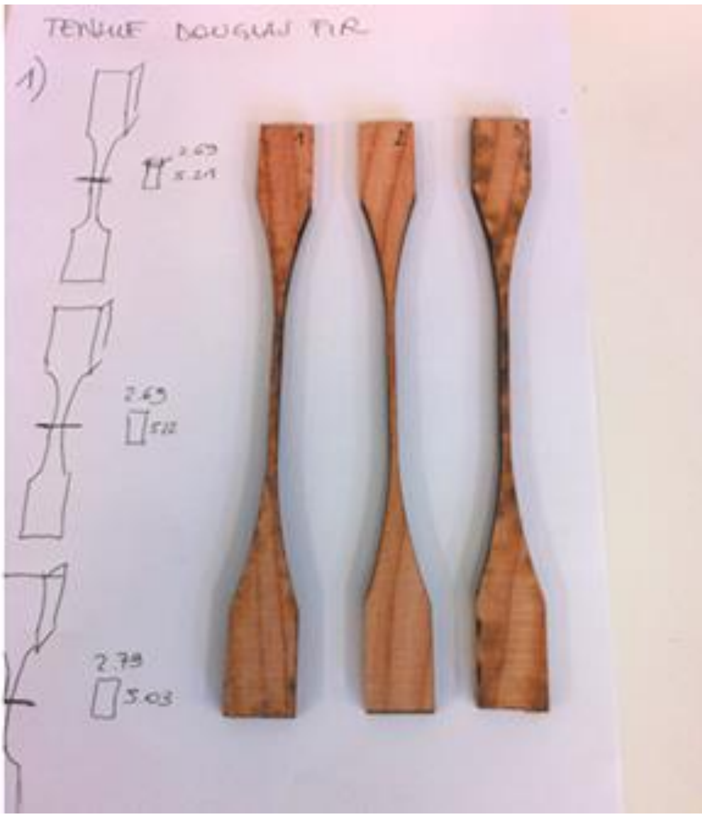


Fig. 1-6: timber samples (Douglas Fir) for tension tests (lengh:15 cm, minimum cross section:3x5 mm)

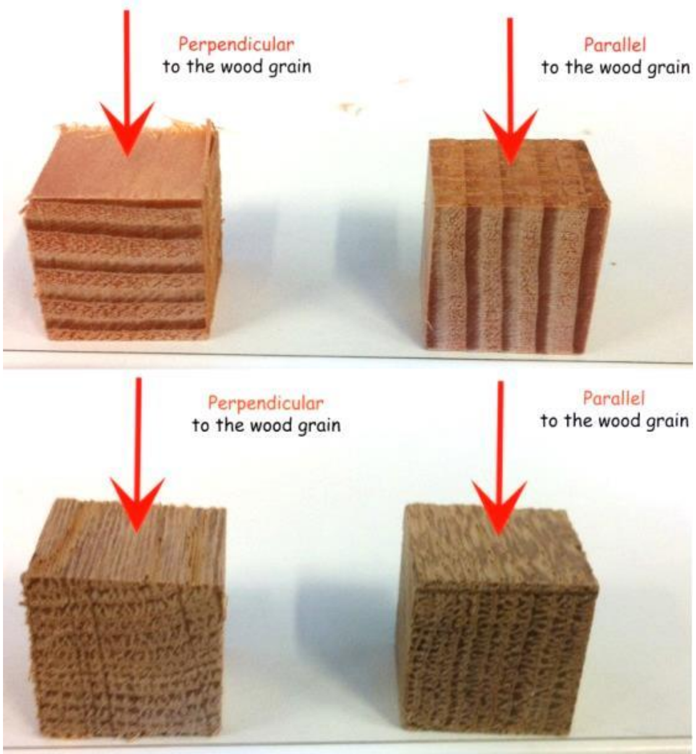


Fig. 1-7: timber samples (Douglas Fir [top]; European White Oak [bottom]) to be tested in compression parallel (right) and perpendicular (left) to the wood grain direction (dimensions of cubes: 20x20x20 mm)

Bi-component epoxy adhesives have been chosen as they are more suitable for timber application, especially for in site work (Custodio et al. 2012), due to their molecular configuration which does not change over the course of time (CenciLegno 2008). This factor could enhance the joint's durability. Threaded stainless steel bars (Fig. 1-8) with high tensile strength have also been selected for this experimental activity, to study the bond between resin and timber and to allow the failure to occur at the adhesive-adherend interface. In real applications, using bars with lower steel grades would lead to having the failure in the steel bar and therefore a ductile failure mode of the glued in bolt joint (Estevez Cimadevila et al. 2013).

The interaction between timber and adhesive is studied through the manufacturing and testing process of lap joints which are further monitored by the use of a thermal camera FLIR B200 (Fig. 1-10) to deeply understand the bond process during and after the adhesive curing process.
Moreover, the idea of using threaded steel bars rather than corrugated or plastic rods is based on previous research findings. In fact, according to Otero Chans et al. (2010a), threaded rod surfaces do not require any treatment before being in contact with adhesives because the load transmission in this specific case between steel and resin is mechanical, "going from one thread to the next". This research thesis does not take into account the idea of replacing steel rods with FRP (Fibre Reinforced Polymer) bars, design solution fully investigated by Yeboah et al. in 2012 and by Adam et al. in 2016, because the use of FRP would not guarantee a ductile failure mode of the joint (Steiger et al. 2015) and would significantly increase the cost of the whole connection.

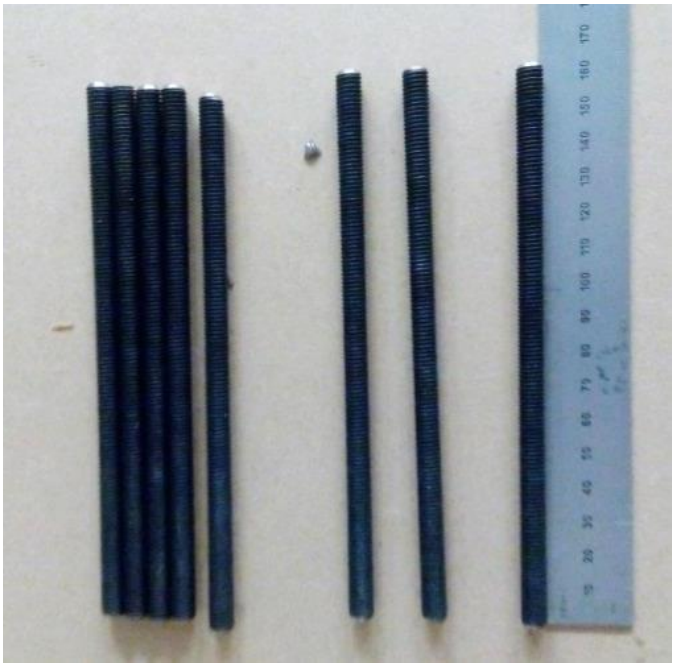


Fig. 1-8: cut steel bars (length: 160 mm)

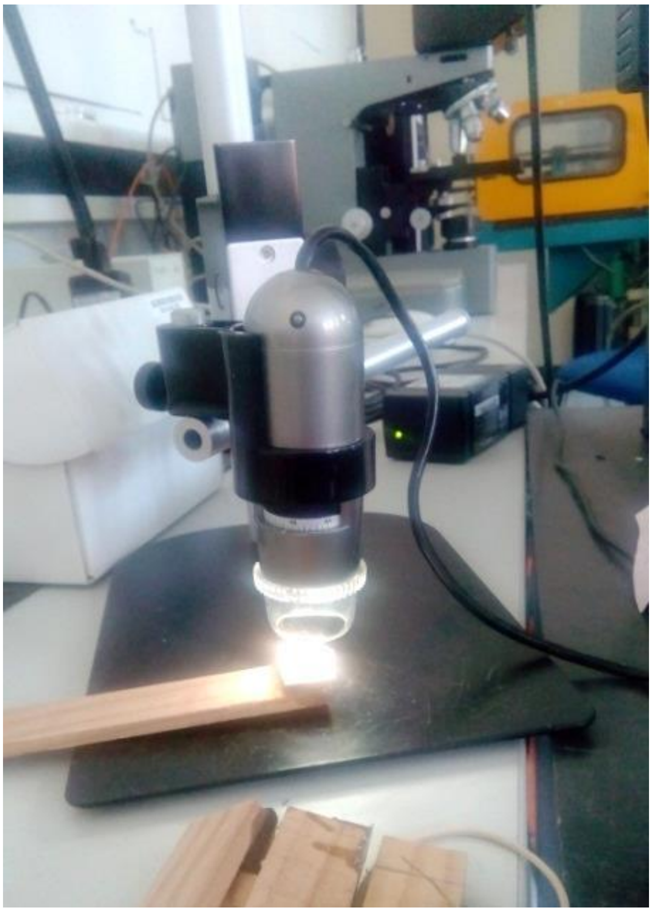


Fig. 1-9: 300X usb-microscope

Fig. 1-10: FLIR B200 thermal imaging camera

1.7.3.4 Design the experimental pilot study

The design of the experimental phase starts with the identification of a pilot study. 24 'traditional' samples of Glued In Rod joints are cast by using a two-component 1:1 ratio pure epoxy (provided and manufactured by the 2K Polymer Systems company based in Alfreton, UK) to glue stainless steel bars into pre-drilled holes, characterised by smooth and cylindrical internal surfaces, in Douglas Fir timber samples.

Through an intensive lab activity, the 'traditional' samples of glued in rod joints are tested using a direct tensile testing machine for pull-out loading test. The testing is performed in confined conditions in a pull-compression test regime.

The aim of the pilot study is to validate the effectiveness of the testing machine (Von Diether n.d.) and to provide a first set of test results of the pull-out capacity of adhesive joints, characterised by different glue line thicknesses and bonded lengths. The main outcomes are reported in Lilleyman's master thesis (2013).

1.7.3.5 Design a new prototype of adhesive anchors in timber

The idea of improving the performance of the connection is based, in this research work, on the adoption of manufacturing techniques aimed at enhancing either the bond quality and the mechanical interlocking at the epoxy-wood contact surface.

The design of a 'traditional' Glued In Rod joint, identified by a cylindrical and smooth internal surface, is modified by the use of a specific drill bit, into a new prototype of adhesive anchor characterised by an internal borehole with a rough and threaded surface. Instead of undertaking exclusively research experiments on 'traditional' glued in rods, identified with a smooth cylindrical borehole, to evaluate their structural performance when subjected to different manufacturing and testing conditions, this research thesis studies and compares the structural performance of new prototypes of adhesive anchors in timber.

Through the analyses of the conclusions drawn by few research studies which investigated how the properties at the contact surface could affect the bond quality and the pull-out capacity of adhesive connections, it is possible to comprehend that a modification in the hole shape of an adhesive anchor in timber can significantly increase its withdrawal capacity (Estevez Cimadevila et al. 2013; Martin et al. 2013) and that the roughness property of a bonding surface plays a crucial role in achieving good bonding conditions (Eistetter 1999, Deng 1997, Gurit n.d.).

By changing only one variable related to the bonded length and by keeping all other parameters which characterise a Glued In Rod connection constant, it can be assumed that an increase in the glued length would not produce a proportional improvement in the pull-out strength of an adhesive anchor; hence, the strategy adopted to create a new adhesive connection (Fig. 1-11) is developed by seeking a new joint's design. The aim is to reduce the joint's cost production by optimising the use of epoxy resin and by adopting easy-to-use tools to manufacture the connection in order to propose a feasible and competitive product on the civil engineering market.

For this reason in this research study, the simultaneous change in the hole shape and in the superficial properties of the internal wooden surface (surface texture) is introduced in the joint design in order to investigate whether the structural performance of an adhesive anchor in timber can be positively affected by these modifications.

Particularly, during the manufacturing phase of the new adhesive joint prototype, an innovative technique is adopted by the use of specific drill bits to create threads in the wooden substrate along the joint embedment length.

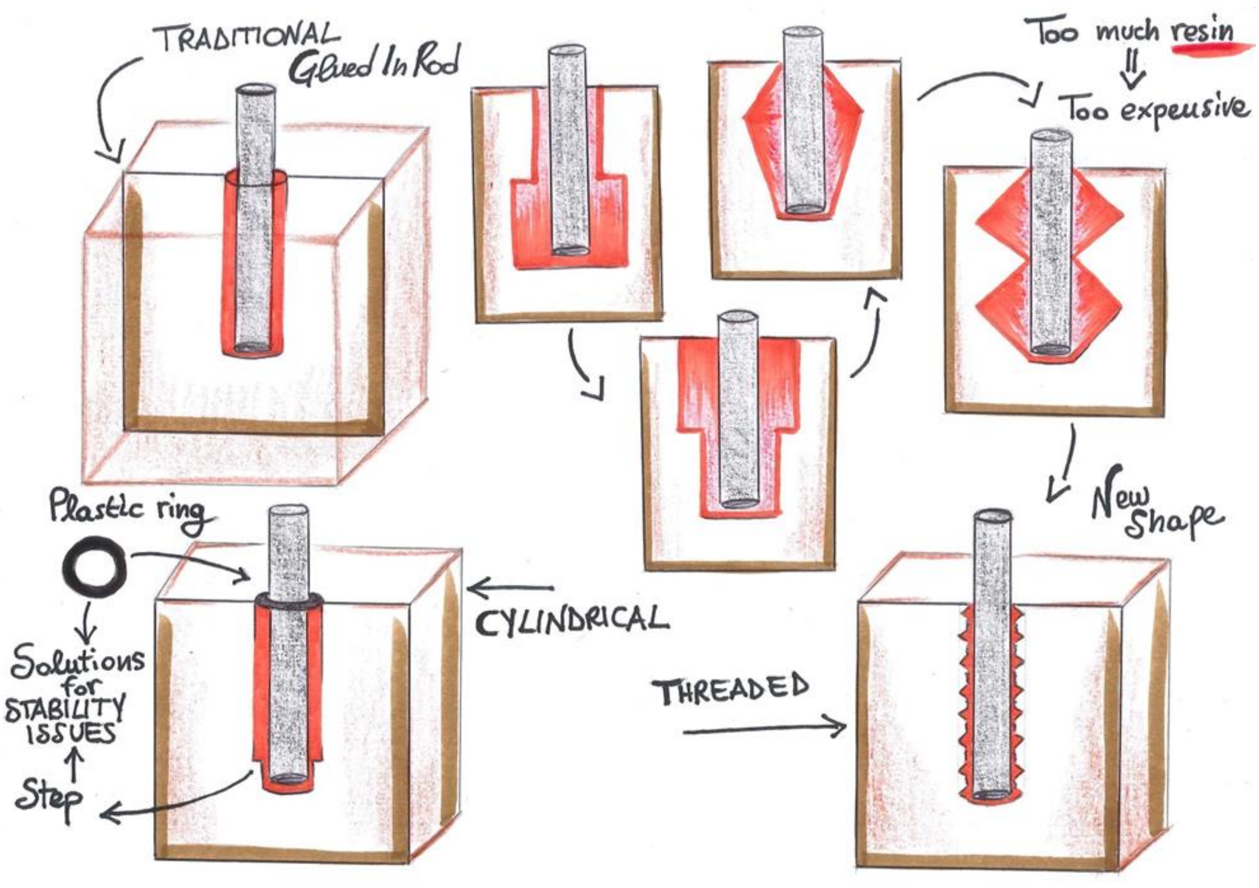


Fig. 1-11: sketch of joints development

The creation of an internal threaded and rough surface into the bore hole of the new joint prototype increases the contact surface and, therefore, the possibility for the adhesive of having a larger contact area in which better penetrate and develop not only a chemical bonding but also a mechanical adhesion (Piazza et al. 2005), provided in both materials (steel and timber) by the presence of threaded bonding surfaces. Hence, the new joint prototype is able to transfer load either by shape and by adhesion.

1.7.3.6 Conduct the experiments

The key experimental part is aimed at studying the relationships amongst parameters which can affect the pull-out capacity of glued in bars.

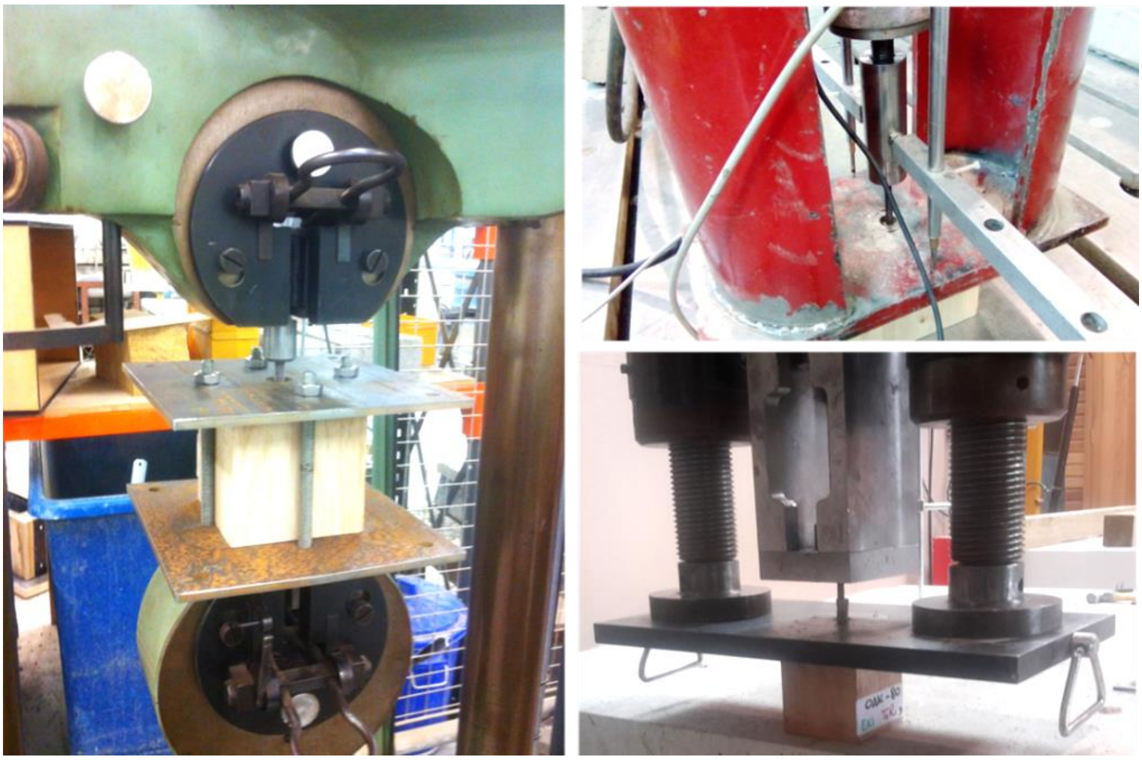


Fig. 1-12: Avery Denison 6158 universal testing machine (left) and fatigue testing machines [load cell: 100 kN: right]

This stage of the experimental activity includes the developing and the evaluation of new prototypes of glued in rod joints and the comparison of their pull out resistance capacity to 'traditional' Glued In Rod joints by the use of fatigue testing machines (Fig. 1-12).

The main innovative ideas on which this study is focused in order to optimise the joint mechanical performance are:

- the use of two-component epoxy resins with different viscosity values (Fig. 1-13)

Fig. 1-13: cartridges of epoxy resins: EX 1:1 (left) and EX 3:1 (right)

- the preparation of wooden bonding surfaces with specific geometrical properties through the use of specific wood working tools which make the joint prototype feasible for in situ applications.

Changing some critical features of the joint may lead to having a better bonding condition and improved pull-out behaviour of the adhesive connection in real applications.

Through laboratory activities, a statistically significant number of the joint's prototypes are assembled and tested by pull-out tests in order to assess their short-term tensile performances in cold conditions and at elevated temperatures (Fig. 1-17). All cold-state experiments presented in this research thesis have been carried out at the Nottingham Trent University's (NTU) laboratory and at 2K Polymer System company's facilities. On the contrary, the laboratory experimentation about the performance of adhesive anchors in timber subjected to elevated temperature has been performed at Politecnico di Milano in Italy, thanks to an academic collaboration.

In this latter set of experiments, samples of adhesive anchors in timber are heated up in a sophisticated electric furnace (Fig. 1-14) in controlled temperature and loading conditions.

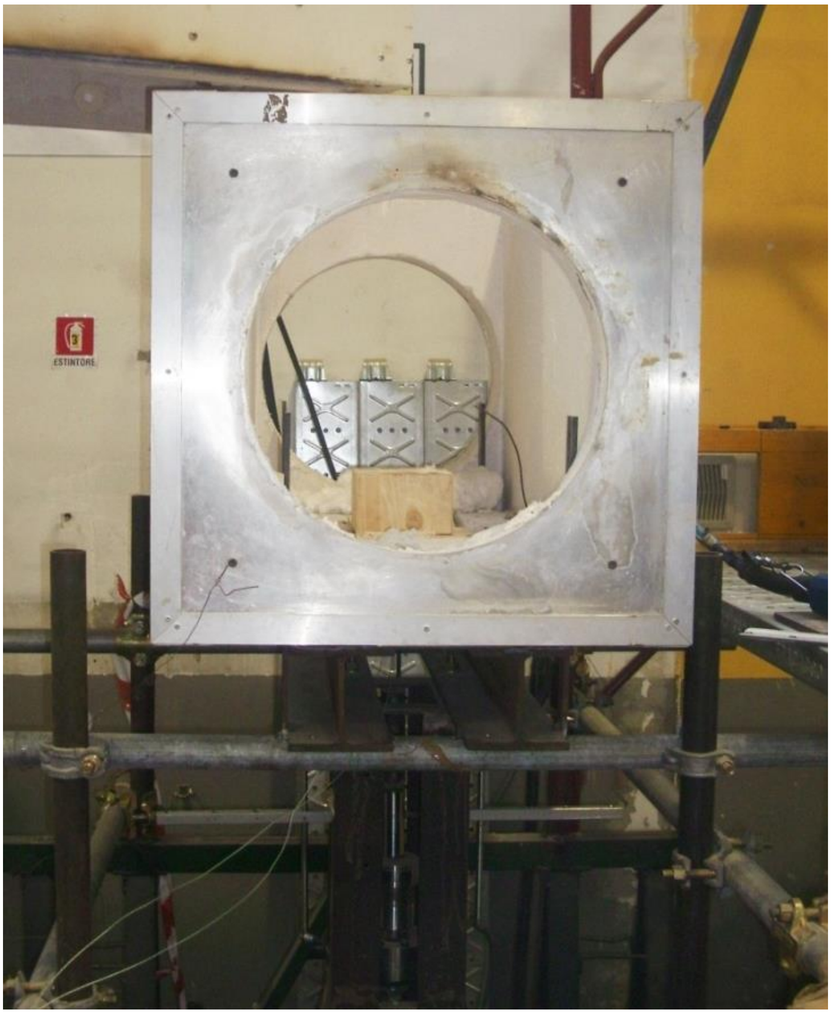


Fig. 1-14: electric furnace for tests at elevated temperatures

After concluding the laboratory experimentation, the test results are analysed to verify their compatibility with the initial experimental test hypothesis: it is evaluated whether it is possible to achieve the ductile structural behaviour of the studied adhesive connections.

1.7.4 Data analysis and Research outcomes

The final stage of this theoretical framework is the analysis and discussion of the data collected during the previous phase. In this conclusive phase the use of a specific graphic method called POLA (Point Of Loss Adhesion) assumes a key role in the analysis of the data obtained by the experimental tests. POLA method has been extrapolated from current regulations on adhesive anchors in concrete (ETAG 001-5) and its application has been translated for the first time in this research thesis into the study of Glued In Rods allowing a correct determination of the maximum pull-out loading capacity ($N_{adhesion}$) for each tested sample.

In addition, a triangulation method is used to correlate and combine the experimental results with the outcomes drawn by the use of past calculation methods and the theoretical approaches used to describe the behaviour of adhesive connections.

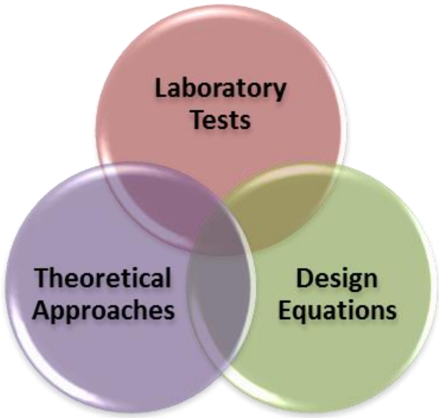


Fig. 1-15: triangulation method

The use of this triangulation method (Fig. 1-15) allows the identification of a correct design equation and the suggestion of technical guidelines which represents an original contribution to knowledge on the problems linked to the standardised design process of Glued In Rod joints in cold conditions and at elevated temperatures.

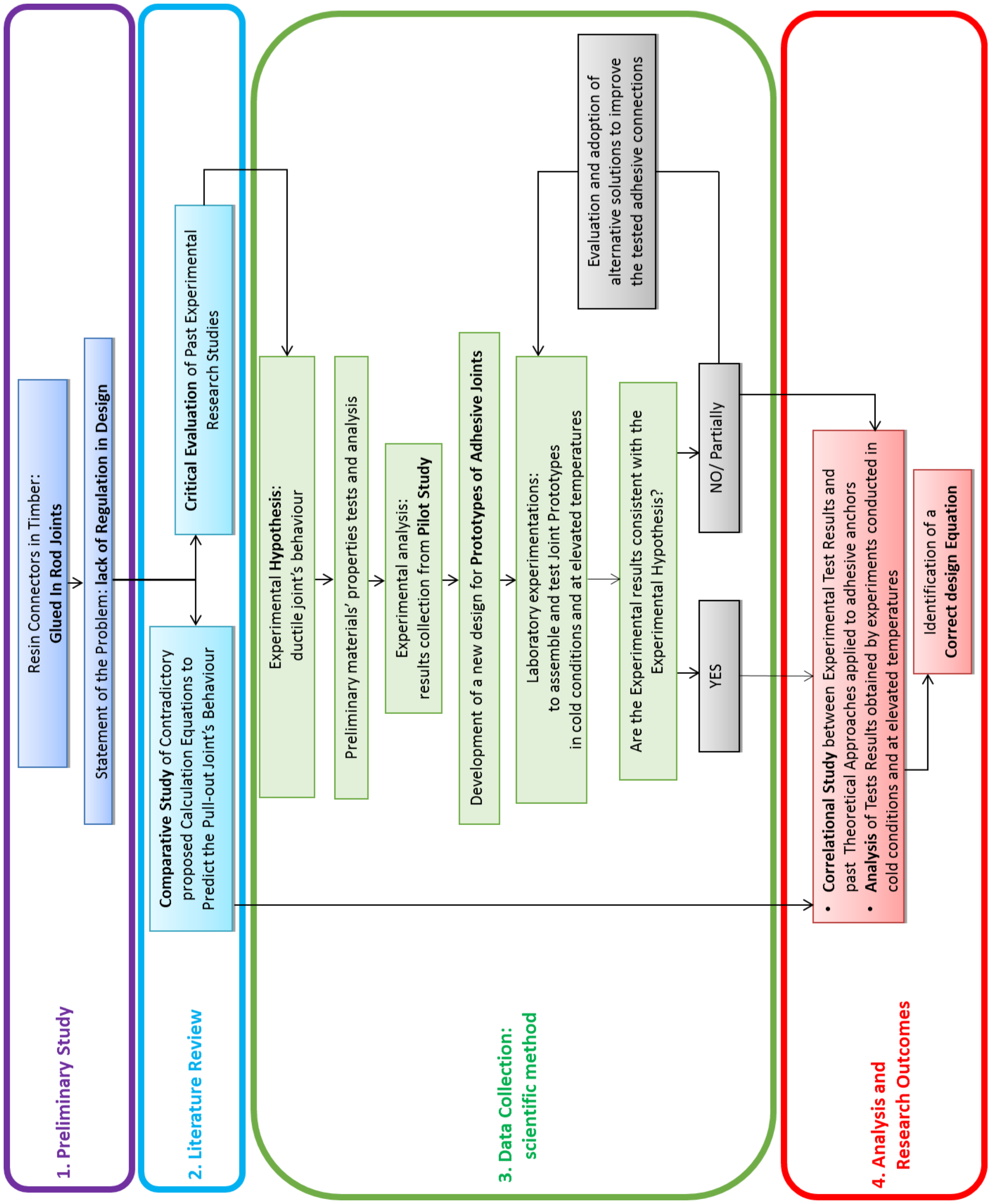


Fig. 1-16: methodology chart

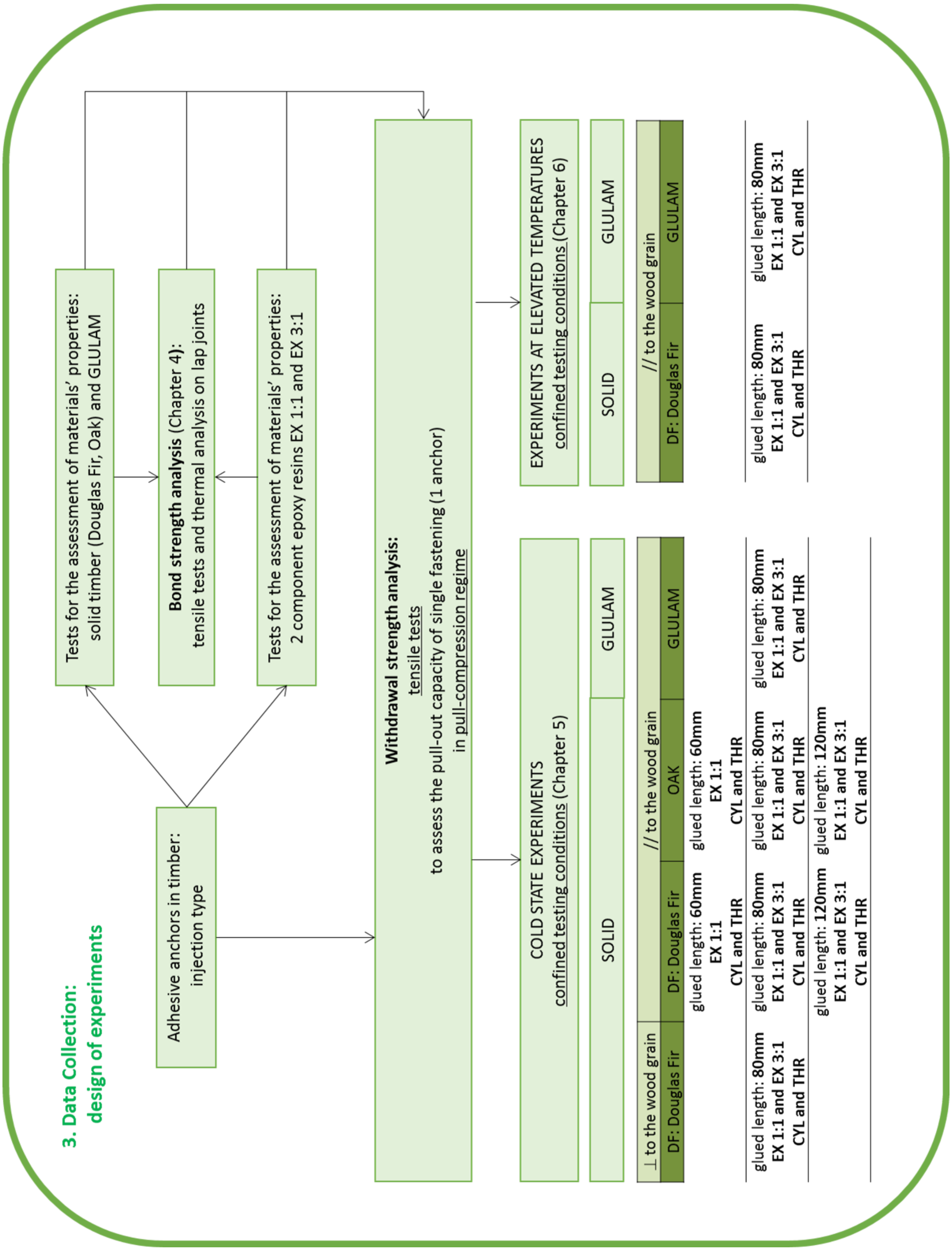


Fig. 1-17: design of experiments conducted on samples of adhesive connections (epoxy resins: EX 1:1 and EX 3:1; internal borehole shape: cylindrical (CYL) and threaded (THR))

2. THEORETICAL APPROACHES TO DESCRIBING AN ADHESIVE BOND

2.1 INTRODUCTION

The behaviour of adhesive joints is affected by the geometrical features and mechanical parameters of adherends and adhesives, which in this research study are identified respectively by timber and epoxy resins.

The understanding of the mechanical behaviour of Glued In Rod connections plays a significant role in the identification of a correct design approach (Valoroso 2007). In particular, the study of the stress distribution along the glue line provides essential information about the complex interaction amongst the three different materials a Glued In Rod joint is made of: timber, epoxy and steel.

The approaches used to study the bond of an adhesive connection in past research studies can be classified in two main categories:

1. numerical analysis through the use of the finite element modelling method
2. analytical analysis based on mathematical formulations in closed-form solutions (Valoroso 2007; Tomasi in Piazza et al. 2005: 228).

This chapter of the thesis is aimed at exploring in detail the latter category and therefore, at analysing the most popular theoretical approaches used to study the mechanical behaviour of adhesive anchors.

2.2 INTERNAL STRESS DISTRIBUTION: THE VOLKERSEN'S THEORY

Volkersen was the first researcher who developed in 1938 (Aicher 2003) a theory to analyse the stress distribution along an adhesive bonding layer (Gindl-Altmutter et al. 2012).

Gaining a good knowledge on the Volkersen theory for "single lap joint" (Tlustochowicz et al. 2011) leads to a deep understanding of the mechanical behaviour of Glued In Rod connections (Aicher 2003).

The Volkersen's theory is based on strong assumptions in order to simplify the theoretical approach:

- the adherends are subjected only to an axial normal tension, without taking into account problems related to eccentricity and consequently bending effects

- the adhesive can only present shear stress deformation; hence its axial deformation is not taken into consideration
- the adherend can only present normal deformation (Piazza et al. 2005), without taking into account the shear deformation
- the adhesive and the adherend are supposed to be isotropic and have a linear and elastic material behaviour (Aicher 2003).

The application of the normal forces induces in the adherends of the lap joint normal deformations, having a linear trend with a maximum value where the force is applied and a minimum value equal to zero at the end of each adherend. The difference of ε_1 and ε_2 along the glue line generates “a variation of the shear strain and, consequently of shear stress” (Aicher 2003). In fact, at both adherends ends there are significant differences in normal deformations, identifying areas in which the shear stress and strain assume high values. In particular for the case of single lap joint characterised by adherends with different normal stiffnesses and dimensions, the maximum value of the shear stress and strain “is located at the end of the stiffer adherend” (Aicher 2003).

A further simplification can be done considering the case of infinitive stiffness of adherends and therefore a uniform distribution of the shear stress along the bonding line.

Taking into consideration that the shear strain can be expressed in relationship to the difference of the normal deformations of the two adherends, the shear stress can be calculated through the following mathematical steps, extrapolated from “Structural adhesive joints including glued in bolt” written by Aicher in 2003.

$$\gamma = \gamma_0 + \frac{1}{d}\left(\int_{-l/2}^{x} \varepsilon_1(x)dx - \int_{-l/2}^{x} \varepsilon_2(x)dx\right)$$

$$\varepsilon_1(x) = \mathrm{f}\,[\tau_1(x)] = \frac{1}{E_1 t_1}\int_{-l/2}^{x} \tau_1(x)dx \qquad \tau = \gamma G$$

$$\varepsilon_2(x) = \mathrm{f}\,[\tau_2(x)] = \frac{1}{E_2 t_2 b}\,[P - b\int_{-l/2}^{x} \tau_2(x)dx\,] \quad \tau = \gamma G$$

$$\frac{d^2\gamma}{d\,x^2} - K^2\gamma = 0$$

$$K^2 = \frac{G}{E_1 t_1 t_3}\,(1+\alpha) \qquad \alpha = \frac{E_1 t_1 b}{E_2 t_2 b}$$

Internal shear stress distribution along the joint length:

$$\tau(x) = \tau_m \frac{\rho}{2}\left[\frac{\cosh\left(\frac{\rho x}{l}\right)}{\sinh\left(\frac{\rho}{2}\right)} - \frac{(1-\alpha)}{(1+\alpha)}\frac{\sinh\left(\frac{\rho x}{l}\right)}{\cosh\left(\frac{\rho}{2}\right)}\right] \qquad \tau_m = P/lb$$

$$Joint\ Factor \quad \rho = Kl = \sqrt{\frac{l^2 G}{E_1 t_1 t_3}\,(1+\alpha)}$$

for $x = {}^{l}/_{2}$

$$\frac{\tau_{max}}{\tau_m} = \frac{\rho}{2}\left[\coth\frac{\rho}{2} + \frac{(1-\alpha)}{(1+\alpha)}\tanh\frac{\rho}{2}\right]$$

$$\frac{\tau_{max}}{\tau_m} = \frac{\rho}{2}\left[\coth\frac{\rho}{2}\right] \quad for \quad \alpha = 1$$

Considering $\alpha = 1$, it means taking into account a lap joint made of adherends characterised by equal dimensions and properties ($E_1 = E_2$) and ($t_1 = t_2$).

In order to identify the limit value to which τ_{max} tends:

$$\frac{\tau_{max}}{\tau_m} = \frac{\rho}{2}\left[\coth\frac{\rho}{2}\right] \quad for \quad \rho \to \infty \quad \frac{\tau_{max}}{\tau_m} = \frac{\rho}{1+\alpha}$$

$$\frac{\tau_{max}}{\tau_m} = \frac{\rho}{2} = \sqrt{\frac{l^2 G}{2E_1 t_1 t_3}} \quad for \quad \alpha = 1$$

The maximum shear stress value in the bonding layer at both adherends ends is:

$$\tau_{max} = \frac{\rho}{2}\left[\coth\frac{\rho}{2}\right]\frac{P_{max}}{bl}$$

It is possible to calculate P_{max}, using the following formula,

$$P_{max} = \frac{2bl\,\tau_{max}\tanh\frac{\rho}{2}}{\rho} = 2\,b\,\tau_{max}\left[\tanh\sqrt{\frac{l^2 G}{2E_1 t_1 t_3}}\right]\sqrt{\frac{E_1 t_1 t_3}{2G}}$$

and identify a P^*_{max} value for $\rho \geq 5$,limit condition in which τ_{max} "does not decrease any more" (Aicher 2003):

$$P^*_{max} = \tau_{max}\, b \sqrt{\frac{2E_1 t_1 t_3}{G}} \qquad for \qquad \rho \to \infty \;\; and \;\; \alpha = 1$$

$$Global\ shear\ strength \qquad f_v = \frac{P^*_{max}}{bl} \qquad for \qquad \rho \to \infty \;\; and \;\; \alpha = 1$$

The Volkersen's joint factor and consequently all the geometrical parameters included in its definition such as glued length, axial stiffness of adherends, shear stiffness of adhesive, glue line and adherends thicknesses, affect the adhesive joint strength. However, the limit condition P^*_{max} identifies the point beyond which the withdrawal capacity of the joint does not increase enhancing the bond length, confirming that a limitless linear relationship between connection strength and glued length does not exist. Furthermore, it is particularly interesting to note that the global shear strength of the connection gradually decreases with an increase in the glued length.

In particular from the analysis of Volkersen's formulations interesting conclusive statements that can be made.

Regarding

$$\frac{\tau_{max}}{\tau_m} = \frac{\rho}{2} = \sqrt{\frac{l^2 G}{2E_1 t_1 t_3}} \qquad for \qquad \alpha = 1$$

- τ_{max} does not depend on the joint length but only on the glued length
- The choice of using an adhesive with a high shear stiffness would increase τ_{max} for $\alpha = 1$ (Stoeckel et al. 2013).

In relationship to

$$P_{max} = \frac{2bl\,\tau_{max} \tanh\frac{\rho}{2}}{\rho} = 2\, b\, \tau_{max} \left[\tanh \sqrt{\frac{l^2 G}{2E_1 t_1 t_3}}\right] \sqrt{\frac{E_1 t_1 t_3}{2G}}$$

it can be observed through the analysis of the formula for P_{max} that an increase in the glue line thickness results in an increase in the pull-out capacity of the lap joint. However, this statement could not be proven by any experimental work, confirming a no direct proportionality between lap joint strength and the volume of adhesive used to assemble it (Piazza et al. 2005).

In conclusion it can be stated that Volkersen's study is an exhaustive approach to study adhesive connection because it includes the analysis of all the main geometrical parameters and mechanical properties of adherends and adhesive, describing a stress distribution along the bond line characterised by two peaks at each adherends ends. Nonetheless, considering the assumptions on which the theory is based is fundamental to conducting detailed analyses.

Applying this theory to a lap joint made of wooden adherends, would not consider that wood is an orthotropic material and its shear stiffness is commonly lower than the shear modulus of adhesives. Hence, these simplifications would not allow the study of the real mechanical behaviour of a wooden lap joint (Piazza et al. 2005).

Moreover, one of the most negative aspects of Volkersen's theory is that it does not take into consideration the peeling stresses which could be induced perpendicular to the bonding line, inside the glue and at the interface with wood by the bending effect resulting from the eccentricity of the forces P applied (Piazza et al. 2005, Spaggiari 2010, Valoroso 2007).

However, according to Tomasi (Piazza et al. 2005) the Volkersen's theory can be applied to Glued In Rod connections. Particularly the shear strength along the bond line could be assessed by Volkersen's formula, developing an axial symmetric analysis of a radial section of the adhesive joint, considered as a solid of revolution (Piazza et al. 2005)

2.3 LINEAR ELASTIC FRACTURE MECHANISM (LEFM)

A study such as the one developed by Volkersen in 1938, based on the analysis of maximum stresses and strains in adhesive joints in linear elastic conditions would not be able to correctly represent the complexity of modes in which the joint could fail. In fact in reality, the failure mode of adhesive connections often involves processes whose most accurate analysis would be carried out by using principles of fracture mechanics (Valoroso 2007).

For this reason many researchers started adopting approaches based on fracture and damage mechanics to predict the strength of adhesive joints (Aicher 2003) and study how the presence of internal cracks or defects could have affected their structural behaviours.

Specifically, the use of the Linear Elastic Fracture Mechanism (LEFM) had been identified as particularly applicable to glued joints in timber because of the likely presence of brittle behaviours either in the adhesive material or in wood elements (Aicher 2003). One of the most common approaches to studying the fracture mechanism of materials with linear elastic behaviour (LEFM) is based on the Griffith's theory which affirms through energetic considerations that, during a crack propagation, the development of a brittle fracture in a material occurs whether the material releases an amount of stored energy bigger than the work needed to extend the crack (Cailotto 2013).

2.4 NonLinear Fracture Mechanism (NLFM)

The Non-Linear Fracture Mechanism is based on the extent that the total energy of fracture can be expressed as the sum of two contributions: a fracture energy related to pure shear and the energy of fracture due to pure tension. The "fracture energy represents the energy required to bring a fixed unit area to complete separation" (Gustafsson 1987); however in this specific case the damaged area, in which the fracture would occur, corresponds to the contact surface between adherend and adhesive (Ascione 2008). Therefore, NLFM applied to Glued In Rods considers both the stress analysis of the adhesive bond and the study of the energy fracture (Steiger et al. 2015).

$$G_{fracture} = G_f = G_{f,1} + G_{f,2}$$

$$G_{f,1} = \int_0^\infty \sigma \, d\delta_n \qquad G_{f,2} = \int_0^\infty \tau \, d\delta_s$$

2.5 Gustafsson's Theory

Gustafsson in 1987 was the first researcher who combined the main concepts of a non-linear fracture mechanism to the theory suggested by Volkersen in 1938. He created a new theory, which is well-known with the name of "Generalised Volkersen Theory", where he applied to NLFM's main concepts the assumptions of the Volkersen's theory, considering that adherends and adhesive are subjected respectively only to normal and shear forces.

In fact, in order to respect Volkersen's assumptions, Gustafsson tried to analyse the strength of a bonding line only through the assessment of the part of the energy fracture related to pure shear at the adhesive interface: the shear fracture energy, identified by the area under the curve $\tau - \delta$ (shear stress-shear slip). It is important to note that the stress-shear slip curve is identified by a non-linear relationship (Steiger et al. 2015).

Gustafsson simplified the study of the complex constitutive relationship of the bond line through a classification of normalised curves $\tau - \delta$. Graphs had been selected to represent four different typical trends of shear stresses against deformations in adhesive. Each normalised curve is made of 2 segments, the ascending part describes the pre-fracture phase before reaching the peak value of the shear stress; contrarily, the second part identifies the post-fracture phase where the softening process of the material develops (Gustafsson 1987, Aicher 2003).

Gustafsson (1987) introduced a normalised "constitutive law of the bond line" in order to analyse and study the above presented shear stress-deformation curves.

$$\frac{\tau}{\tau_f} = S\left[\frac{\delta_s}{G_{f,2}/\tau_f}\right]$$

The presented constitutive law expresses the normalised shear stress in relationship to the shear slip, the shear fracture energy and a factor S which takes into consideration the geometrical features of the curve $\tau - \delta$ (Gustafsson 1987).

In particular, in order to be consistent with Volkersen's theory assumptions, Gustafsson (1987) expressed the normalised pull-out strength of a lap joint as a function of the shear fracture energy.

$$\frac{P_{max}}{\tau_f\, b\, l} = \frac{1+\alpha}{\overline{\omega}} \frac{\sinh \overline{\omega}}{(\cosh \overline{\omega} + \alpha)}$$

P_{max} = maximum pull-out force

τ_f = shear strength

α = Volkersen's parameter = $\frac{E_1 t_1 b}{E_2 t_2 b}$ $\alpha = 1$ if adherends have same dimensions and axial stiffness

$l_g = \frac{l^2}{t_1}$ $l_m = \frac{E_1 G_f}{\tau_f^2}$

$\overline{\omega} = \sqrt{\frac{l^2 \tau_f^2}{t_1 E_1 G_f}} = \sqrt{\frac{l_g}{l_m}}$ for $\alpha = 1$

Considering the specific scenario in which a lap joint, characterised by having "a fully developed fracture region" (Gustafsson 1987) very small compared to the total glued length, it is possible to express its maximum pull-out capacity according to LEFM and Griffith's theory with the formula below (Gustafsson 1987):

$$P_{max} = 2\, b \sqrt{t_1 E_1 G_f}$$

In fact, in a case in which it is possible to idealise a linear constitutive relation at the bonding layer the fracture energy can be written equal to the area of the triangle beneath the $\tau - \delta$ line.

$$G_f = \frac{1}{2}\,\tau_f \delta_{s,f}$$

According to the definition of the shear modulus $G = \frac{\tau}{\gamma} = \frac{\tau}{\left(\delta/t_3\right)} = \frac{\tau t_3}{\delta}$ $\quad \delta = \tau t_3/G$

Therefore, substituting the shear fracture energy G_f, expressed as function of the shear modulus G, in the P_{max} formula, it is possible to obtain the limit value P^*_{max}(valid for $\alpha = 1$) presented in Volkersen's studies (Aicher 2003).

$$G_f = \frac{1}{2}\,\tau_f \frac{\tau_f t_3}{G} = \frac{{\tau_f}^2 t_3}{2G}$$

$$\frac{G}{t_3} = \frac{{\tau_f}^2}{2G_f}$$

$$P^*_{max} = \tau_{max}\, b \sqrt{\frac{2E_1 t_1 t_3}{G}}$$

Hence, it is interesting to note that the adoption of a different analytical approach based on some of the most relevant fracture mechanism principles (NLFM, LEFM: Griffith's theory), allowed Gustafsson to obtain results in terms of prediction of the pull-out joint capacity consistent with the outcomes presented by Volkersen in 1938. Furthermore, both theories highlight the importance of the definition of specific parameters to fully understand the stress analysis of an adhesive bond. This latter aspect had been carefully explored by Gustafsson who introduced the extent of the "bond line shear brittleness", parameter useful to identify and establish the brittle or ductile nature of an adhesive in a glued connection (Aicher 2003) which is expressed as the ratio between the shear strength and the shear fracture energy, defined by Gustafsson and Serrano (2000) as the "bond layer material properties":

$$bond\ line\ shear\ brittleness = \frac{\tau_f^2}{G_f}$$

$$\omega = joint\ brittleness\ ratio = \frac{l^2 \tau_f^2}{t_1 E_1 G_f} \quad when\ \alpha = 1$$

He also defines a joint brittleness in order to be able to classify joints with high (fragile behaviour) and low brittleness (ductile behaviour) (Aicher 2003).

2.6 BOND STRESS MODEL FOR ADHESIVE ANCHOR IN CONCRETE AND RELATIVE ANALOGIES WITH GLUED IN RODS IN TIMBER

The common approach adopted in past research analyses to understand the mechanical behaviour of resin connectors in timber was identified by the study of the stress distribution at the interface between adherend and adhesive. In particular the stress analysis was often carried out through the application of the Volkersen's theory to study the stress distribution along an adhesive bonding layer (Gindl-Altmutter et al. 2012) in lap joints, as presented in the previous paragraphs.

The main intent was, in fact, to find a correlation between the stress distribution at the contact surface between adherend-adhesive in a lap joint and at the interface between wood and resin in a connection made of a steel bar glued in a timber element, when both joints were subjected to normal tensions.

However, although this approach leads to a correct understanding of the stress phenomena which take place in an adhesive bond in wooden elements, it limits the study of the mechanical behaviour of Glued In Rods because it does not take into consideration the mechanism of load transfer at the steel-resin interface.

Therefore, a correct interpretation of the mechanical behaviour of glued in bolts should involve, not only the study of the timber-resin contact surface, but the complete investigation of the mechanisms which take place amongst the three materials the joint is made of: steel, glue and timber. For this reason, it would be particularly interesting drawing analogies between Glued In Rods in timber and a type of adhesive joint whose understanding is nowadays completely gained: adhesive anchors in concrete.

Recently, specific knowledge of the behaviour of adhesive anchors in concrete has been deeply acquired and their structural design has been regulated by standard design codes.

Despite the fact that timber and concrete are construction materials with extremely different engineering properties, it can be stated that the behaviour of the joint materials at the interfaces between steel-adhesive and adhesive-timber can be studied by analogies with the bond stress distributions of an adhesive anchor in concrete. The main difference would not be identified at the steel-adhesive contact surface, whether similar materials are selected, but at the interface between glue and concrete.

In order to gain a full understanding of adhesive connections in timber, it would be useful to utilise some information extracted from previous studies of bonded anchors in concrete regarding the theoretical approaches presented to describe the internal load transfer mechanism.

2.6.1 Cook's studies regarding stress distribution in adhesive anchors

One of the studies particularly relevant in this field was conducted by Cook in 1993; his research work included a proposal of a bond stress model to describe the load transfer mechanism along the glued length in an adhesive anchor in concrete which takes place through "mechanical interlock" between steel and adhesive and by "adhesion and/or microinterlock" between adhesive and adherend substrate (Eligehausen et al. 2006b).

2.6.1.1 Cook's Uniform model for adhesive anchors

The simplest model to predict the stress distribution establishes the presence of a uniform and constant value of shear stress along the joint embedment length. The anchor capacity is defined as function of the glued length, the hole diameter and the shear stress at the failure load. Despite the fact that in this formula Cook introduced the hole diameter variable in order to take into account the contact surface between glue and adherend substrate, the equation simplifies the real load transfer mechanism existing amongst steel, adhesive and adherend (Cook et al. 1993). However, in subsequent Cook's studies the uniform stress formula was defined as the best model to predict the load bearing capacity of adhesive anchors with short glued lengths ($40\sqrt{d}$) (Cook et al. 1993, Eligehausen et al. 2006a). In particular in 1998 he edited the following formula swapping the hole diameter with the rod diameter because the use of the steel bar diameter in the equation allowed most frequently the correct prediction of the results obtained by several tension loading tests in adhesive anchors in concrete (Cook et al. 1998).

Moreover, Cook defined the shear stress at the steel-adhesive interface as a "product-specific" parameter which has to be determined by specific tests taking into account the adhesive typology, the base material condition (dry, wet, material temperature) and the hole preparation method (Eligehausen et al. 2006a). The formula also included a correction factor (φ) which considered the effect that a material substrate with different mechanical properties can have on the joint strength (Cook et al. 1998).

I. $$P = \tau_{adhesive-adherend}\, \pi\, d_h l$$

II. $$P = \tau_{steel-adhesive}\, \pi\, d_r\, l\, \varphi$$

2.6.1.2 *Cook's Elastic model for adhesive anchors*

The elastic model presented by Cook et al. in 1991 considers the "compatibility of displacement"(w) at the steel-adhesive and at the adhesive-adherend substrate and it is based on important energy consideration.

In this paragraph the words 'base material' or 'anchor substrate' identify the material in which the steel element is glued, therefore it corresponds to concrete when Cook's studies are referenced and to wood, in the case in which the theoretical stress models invented for concrete anchors could be applied to evaluating the behaviour of adhesive connections in timber.

According to Cook et al. (1991), the anchor system energy is defined as the sum of the internal strain energy, considering both steel and adhesive energy contributions, and the external work done by the load applied to the adhesive anchor (Cook et al. 1991; Cook 1993; Cook et al. 1993).

$$E = E_{internal} + E_{external}$$

$$E_{internal} = E_{steel} + E_{adhesive} = \frac{1}{2}\int_0^l \int_{A_{steel}} \sigma\varepsilon \, dA \, dz + \frac{1}{2}\int_0^l \int_{A_{adhesive}} \tau\gamma \, dA \, dz$$

$$E_{external} = -P\, w(l)$$

Considering the following expressions:

$$\int_{A_{steel}} dA = A \qquad \varepsilon = w$$

$$\int_{A_{adhesive}} dA \sim \pi dt \qquad \gamma = \frac{\delta}{t} = \frac{w}{t} \qquad \tau = \gamma G = \frac{w}{t} G$$

The anchor energy can be defined as:

$$E = E_{internal} + E_{external} = \left[\frac{1}{2}\int_0^l EA\, w^2 \, dz + \frac{1}{2}\int_0^l \frac{\pi dG}{t} w^2 dz\right] - P\, w(l)$$

and by solving the following differential equation it is possible to assess the anchor capacity:

$$w'' - \left[\frac{G\pi d}{tEA}\right] w = 0 \qquad \lambda^2 = \left[\frac{G\pi d}{tEA}\right]$$

$$w(z) = \frac{P}{EA\lambda}\frac{\cosh \lambda z}{\sinh \lambda l}$$

$$P = \tau_{max} \frac{\pi d}{\lambda} \tanh \lambda l$$

If λ is replaced by λ', factor independent of the hole diameter, it can be expressed by:

$$P = \frac{\pi \, \tau_{max} d^{1.5}}{\lambda'} \; \tanh \frac{\lambda' l}{\sqrt{d}}$$

Cook introduced a key concept regarding the assessment of “basic bond properties” in order to characterise the anchor system made of anchor substrate, adhesive and steel element (Cook 1993).

The main parameter, included in the formula of the anchor capacity, which defines the characteristics of the bonding layer is λ'. It is possible to assess λ' by the formula below and it is dependent on the axial stiffness of the steel rod (E) and on the stiffness of the adhesive anchor k (Cook et al. 1991). The latter parameter is identified by the ratio of the axial load with the anchor displacement; therefore, it corresponds to the slope of the curve in the load-displacement graph (Cook 1993). For this reason λ' is a parameter experimentally determined and it characterises the complex mechanical interaction among the anchor materials.

$$k = \frac{AE\lambda'}{\sqrt{d}} \; \tanh \frac{\lambda' l}{\sqrt{d}} \qquad k = \frac{P}{w(l)}$$

where $w(l) =$ displacement measured at the joint top surface; $d = \; d_{hole}$

The maximum shear stress can be calculated by the following formula, knowing the anchor withdrawal capacity and the parameter λ':

$$\tau_{max} = \frac{P\lambda'}{\pi d^{1.5}} \; \frac{1}{\tanh \frac{\lambda' l}{\sqrt{d}}}$$

Cook et al. in 1993 clarified that the τ_{max} in case of short glued length tends to be equal to τ_0, due to the fact that:

$$\tanh x \rightarrow x \quad for\ small\ values\ of\ x \qquad hence, \tau_{max} = \frac{P\lambda'}{\pi d\sqrt{d}} \frac{\sqrt{d}}{\lambda' l} = \frac{P}{\pi dl} = \tau_0$$

In this specific case obtaining P values by tests and working out the value of τ_0, λ' can be assessed “by a least-squares fit between the data points and the curve” drawn using the anchor capacity formula (Cook et al. 1993).

In Cook's studies λ' values were found extremely variable in relationship to the type of adhesive used to assemble the anchor but no largely dependent on the rod diameter size. For this reason, Cook in 1991 stated that the parameter λ', principally characterised the adhesive material and suggested that each type of glue should be classified by specific λ' values.

Nonetheless, it is important to note that Cook performed several tests choosing an adherend substrate (concrete) of a specific strength class for all the joints manufactured for the tests. Hence, in the scenario in which the capacity of anchors made of different substrate materials (timber, rock, etc.) is studied, the parameter λ' would change in relationship to both type of adhesive and substrate used for the connection.

Therefore, the identification of numerical factors such as λ' for the study of adhesive anchors is extremely important because they collect in one parameter very critical information of the whole anchor system connection.

In particular, if Cook's model was applied to resin connections in timber, λ' would be a reliable indicator of the mechanical features of the steel-adhesive and adhesive-timber interfaces and it would allow a comparison amongst joints made of different adhesive types (epoxy resin, polyurethane glue) and timber species (softwood, hardwood, glulam).

2.6.1.2.1 Similarities with Volkersen's theory

A further analysis of Cook's stress model leads to noting that the anchor capacity formulation suggested by Cook appears similar to Volkersen's expression; the main difference regards the fact that Volkersen's theory refers to a rectangular bonding area which characterises a lap joint and, diversely the cylindrical surface considered by Cook clearly represents the bonding interface between the adhesive and the base material in a glued in bolt connection.

In spite of the considerations made about the analysis of different bonding areas, both theories are based on the compatibility of the displacement at adhesive-adherend interface and they both include in their formulations the adhesive shear modulus (G). In Volkersen's equation, the steel material is correctly not included as the theory is based on the study of a simple lap joint which is not made of steel elements, but the formulation includes the modulus of elasticity of wood. On the contrary in Cook's formulation the hyperbolic formula is defined by the modulus of elasticity of steel, whereas the adherend substrate properties are indirectly taken into consideration only by the parameter λ'.

2.6.2 Farmer's studies regarding stress distribution in adhesive anchors

Farmer is one of the first researchers who investigated and compared the stress distribution in adhesive anchors made of different base materials such as "concrete, limestone and chalk". In 1975 he suggested a stress model based on the concept that the force which generates shear stresses in the connection is equal and opposite to the tensile force applied to the steel threaded rod.

In detail, Farmer (1975) considered only the mechanical properties of steel and adhesive at their contact surface, neglecting the base material characteristics.

$$\pi a^2 \delta\sigma_x = -2\pi a \tau_x \delta x$$

$$\tau_x = \frac{\varepsilon_x}{(R-a)} G_{glue}$$

$$\frac{d^2\varepsilon_x}{d\,x^2} - \lambda^2 \varepsilon_x = 0 \qquad where \qquad \lambda^2 = \frac{2\,G_{glue}}{E_s a\,(R-a)}$$

$$\varepsilon_x = \frac{\sigma}{E_s \lambda} e^{-\lambda x}$$

$$\tau_x = \frac{1}{2}\,a\lambda\sigma e^{-\lambda x}$$

$$when\; x = 0\; mm\; (at\; the\; top\; joint\; surface) \qquad \tau_{max} = \frac{1}{2}\,a\lambda\sigma$$

As it is possible to note the formula above expresses that the shear stress distribution along the joint embedded length decreases from the joint top surface to the end of the glued steel rod following an exponential decay. Despite the fact that this model confirmed a non-linear trend of the shear stress along the bonding layer, as subsequently assumed also by Cook in his elastic stress model for adhesive anchors, the equation did not allow the correct prediction of the shear stress values assessed by experiments. In particular through its application it was not possible to identify the difference in the shear stress values obtained from adhesive anchors made of different substrates.

This imprecise prediction is mainly due to fact that Farmer's stress model is based on a relevant assumption which defines that for "relatively thin [R - a= 0.4a]" glue line thicknesses the shear stress at the adhesive-material base interface can be well represented by the shear stress at the steel-adhesive contact surface (Farmer 1975).

For this reason the model is developed only through the analysis of the load transfer process at the steel-adhesive interface without considering the contact surface between adhesive and adherend substrate. In fact, the theoretical formula does not include any parameter related to the base material.

In the scenario in which this stress model was applied to Glued In Rods in timber, it can be stated that it would not be able to accurately represent the complex load transfer mechanism of the whole anchor system, especially at the adhesive-timber contact area.

However, the main aspect which should be discussed about Farmer's studies regards the significant difference he obtained in the experimental values of shear stress for adhesive anchors identified by identical steel and adhesive properties but made of different base materials. This aspect highlights how critical the role of the material base is in the general performance of adhesive anchors and how a low-quality substrate can negatively affect the connection strength.

2.7 SUMMARY

Chapter 2 provides a detailed overview of all the theoretical approaches used in past research studies to describe adhesive bonds and, in particular, to analyse the stress distribution at the adherend-adhesive interface in a Glued In Rod connection.

Critical information contained in Chapter 2 enables full understanding of the design formulas described in detail in Chapter 3. For example, by acquiring good knowledge of the "Generalised Volkersen Theory" it is possible to fully comprehend the development of the calculation method suggested in the European research project "GIROD-Glued In RODs for timber structures" to predict the withdrawal behaviour of adhesive anchors in timber.

Furthermore, this part of research work aims to explore theoretical approaches to interpreting the overall mechanical behaviour of glued in bolts in timber. In fact, the study presented in Chapter 2 analyses not only the stress distribution at the timber-resin contact surface but also the load transfer mechanisms amongst the three materials the joint is made of (steel-glue-timber).

For this reason, this chapter contains an original analogy drawn between adhesive anchors in concrete and Glued In Rods in timber. Theoretical approaches used for adhesive anchors in concrete are fully analysed and interpreted to be repurposed for the study of the bonding process in a Glued In Rod connection in timber.

Conclusions reached from this study highlight that theories based on analytical analysis and applied to adhesive anchors in concrete can be translated to adhesive connections in timber, only if adequate consideration and modification would be made to take into consideration the different mechanical properties which timber and concrete are characterised by.

Nevertheless, the new exploration of the applicability of theoretical studies used for adhesive anchors in concrete substrates to Glued In Rods in timber offers a different and novel approach to analysing the mechanical behaviour of resin connectors in timber.

3. CURRENT AND CONTRADICTORY DESIGN RULES

3.1 INTRODUCTION

Chapter 3 presents, in chronological order, the design formulas which had been suggested in past research studies to predict the pull-out behaviour of Glued In Rods connections. The content of this chapter is focused on the critical analysis of the most popular mathematical models and it is mainly aimed at identifying which test method, materials and methodologies had been adopted by previous authors to enable the formulation of design rules.

3.2 EXISTING DESIGN RULES

The pioneer of the development of a design code for Glued In Rod connections was the researcher Hilmer Riberholt who in 1988 presented the first mathematical equation to predict the "load-carrying capacity of glued in steel bolts" (Riberholt 1988). After his studies and practical applications of Glued In Rods, many other scientists and research work around the world, particularly in New Zealand, Russia and Canada, tried to address the problem related to the lack of standard design regulation for adhesive connections in timber.

In 1997 in the Part 2: Bridges of the Pre-Standard European Norms (prEN 1955) for the first time a formula to predict the pull-out behaviour of glued in rod connections was proposed. The choice of allocating the formula into the EC5 section related to the design of bridge structures was not made for technical reasons but only because the Part 1 of prEN 1995 had already been completed when the proposal of the formula was suggested (Steiger et al. 2015).

Many of the researchers who adopted the design procedure included in the prEN 1995 agreed with the presence of a serious problem related with the use of the suggested formula: it was not able to correctly predict the load-bearing capacity of GIR. Furthermore, in many cases the results obtained from some experimental tests were more conservative than the ones obtained through the use of the proposed formula (Tlustochowicz et al. 2011). It was clearly confirmed that the formula proposed in the prEN 1995 did not represent a safe engineering approach for the design of Glued In Rods.

A further analysis was needed to address this critical issue and for this reason a 3 year European project started in 1998 called GIROD-Glued In ROD. It was specifically focused on the full comprehension of the mechanical behaviour of Glued In Rod joints and on finding a design method for their structural use.

The intense study and experimental tests carried out by GIROD ended in 2002 with the finding of a calculation method for GIR. The discovered formula was immediately implemented in the final draft of prEN 1995 Part 2: Bridges Annex C in 2003 to predict the withdrawal strength of bonded connections (Steiger et al. 2015).

In 2003, the meeting of the Technical Committee 250 in charge of the structural Eurocodes (CEN/TC250) of CEN (European committee for standardization) held in the Netherlands (Delft) reached the final verdict for the implementation of the design formula for GIR into the prEN 1995. Due to the fact that the suggested design method did not include sufficient information (Stepinac 2012), the formula was defined inadequate and unsuitable for its inclusion into the European Norms of the design of timber structures and the Annex C was completely withdrawn (Steiger et al. 2015, Tlustochowicz et al. 2011).

After this remarkable event, many other researchers and research groups worked, explored and provided several experimental design equations to predict the pull out behaviour of adhesive anchor in timber but without reaching a universal design formula.

The European Cooperation in Science and Technology (COST) ran several actions regarding timber technologies:

1. COST Action E13: wood adhesion and glued products (1998-2002)
2. COST Action E34: bonding of timber (2004-2008)
3. COST Action FP1004: enhance mechanical properties of timber, engineered wood products and timber structures (2011-2015)
4. COST Action FP1101: assessment, reinforcement and monitoring of timber structures (2011-2015).

In these COST research actions finding a design calculation method for Glued In Rod connections only represented one of the innumerable tasks which the projects were aimed at.

Another European project which involved the analysis of adhesive connection in timber was called LICONS- Low Intrusion Conservation Systems for timber structures. It started in 2002 and ended in 2005 without relevant conclusion regarding the design of Glued In Rod connections.

The issue related to the lack of a correct design regulation for GIR is included in the program of the working group CEN/TC250/SC5, still representing a critical topic to be investigated (Stepinac 2012).

Currently, many different authors who have taken part of some COST actions and short term scientific missions such as Stepinac, Tomasi, Serrano, Rajcic attempt to summarise and draw conclusions from the developed work on Glued In Rod connections. However, despite the presence of further information regarding the mechanical behaviour of GIR, it seems that a design rule suitable for the implementation into the actual Eurocode 5 does not exist and it will likely not be included in the "next version of EC5, due in 2020" (STA 2015).

The following list presents in chronological order some of the most relevant authors who suggested in past research studies formulas to predict the pull-out capacity of Glued In Rods:

- 1988 Riberholt
- 1990 Buchanan and Townsend
- 1990s Deng
- 1990s German research
- 1990s Russian standards
- 1992 Swedish guidelines
- 1993 Kangas
- 1997 Eurocode 5 EC5 1995-1-1/proposal for part 2
- 1999 Aicher
- 1999 French rules
- 1998-2001 GIROD
- 2000 Kangas
- 2001 Eurocode 5 EC5 1995-2 Annex C final draft
- 2001 Bernasconi (characteristic values)
- 2001-2002 Feligioni and Lavisci - IRL/CNR (Ductile-Brittle)
- 2003 Eurocode 5 EC5 1995-2
- 2004 German design code DIN 1052:2004-08
- 2007 Steiger, Widmann and Gehri (mean values)
- 2007 New Zealand Design Guide (design method excel)
- 2007 IStructE and TRADA
- 2008 Rossignon and Espion
- 2008 German design code DIN 1052:2008-12
- 2010 CNR DT 206/2007
- 2013 Otero Chans
- 2015 Aicher CEN/TC 193

3.2.1 Riberholt

The first researcher who performed experimental tests on glued bolts into glulam elements which were aimed at identifying a design procedure for GIR connections was Hilmer Riberholt (Wiktor 1994).

In the report presented by Riberholt during the 21st meeting of CIB (International Council for Building research) held in Vancouver, Canada, in September 1988 there are listed formulas to predict the "characteristic load-carrying capacity" of glued bolts in different loaded conditions. These mathematical formulations came from the results of previous studied conducted by Riberholt between 1986 and 1988.

He proposed mathematical equation to study the withdrawal capacity of either lateral and axially loaded bolts in timber elements with bolts glued parallel or perpendicular to the wood grain.

3.2.1.1 Riberholt's experiments

A deep study on Glued In Rods was carried out by Riberholt between 1977 and 1988. In particular, in 1986 he conducted important experiments on glued bolt connection whose analysis led him to discovering important information about the design and the production of these structural connections.

The knowledge acquired through this investigation represented his first step towards the formulation of the design equations proposed during the CIB meetings held during September 1986 and 1988.

The production procedure followed by Riberholt (1986) in this specific laboratory experimentation involved the use of timber samples made of spruce glulam (L40), 20mm threaded rods and 2-component glues.

The preparation of the bonding surface between the rod and the adhesives played an important role in the sample manufacturing phase. A specific chemical process was used to clean and prepare the threaded rods in order to provide a good bonding with the adhesive. For this reason, before the gluing phase the steel rods were wetted with a chemical substance, called thrichlorethan (Riberholt 1986).

Obtaining a good bonding surface between steel and glue is certainly one of the most highlighted concerns that Riberholt presented in its studies. He specified that oversize holes can be drilled only in case of a perfect bonding of the glue with the steel rod. Contrarily, if the glue does not strongly bond to the bar he recommended that the glue line thickness should not exceed 0.5mm, otherwise the pull-out capacity of the joint would be decreased (Riberholt 1986).

For the experiments conducted in his investigation in 1986, he chose to drill a hole that was 1 mm bigger than the steel rod diameter (21mm), considering a glue line thickness of 0.5mm sufficient for a good pull-out performance.

This injection technique was applied by drilling two additional holes into the timber element. The holes are in direct connection with the main borehole where the steel rod has to be placed; the “injection hole” is needed to insert the adhesive and the “airing hole” to allow the resin to flow out once the gluing process was completed (Riberholt 1986).

This destructive method, used to glue the steel bars into the wooden samples, includes also the use of a paste to seal the bar insertion and prevent glue leaks defining this specific gluing technique as applicable to any joint’s orientation (Riberholt 1986).

Although this gluing procedure was described by Riberholt (1986) as a good and economic solution, it is notable that it involves the manufacturing of several little details during the production process which make the gluing procedure not very fast and easily reproducible. Moreover, the two holes drilled to simplify the gluing process may cause a permanent damage to the homogeneity of the timber samples. This minor changes into the wooden part of the joint could affect its mechanical behaviour, especially in the area close to the wood edge usually subjected to stress concentrations.

A pull-pull test was performed to verify the withdrawal capacity of the connections characterised by having a 20mm threaded rod, glued parallel to the wood grain, in each sample’s end.

The connection between the sample and the testing machine was made by a “spherical bush” for load transfer. A specific test setting was chosen to measure the pull-out displacements. In more detail, a thin plate was screwed into an end of each sample and was connected to two extensometers whose tips were placed on a small support firmly attached to the steel rod.

The apparatus suggested by Riberholt to assess the displacements involves the insertion of screws and the presence of a partial confinement due to the thin plate placed on the wooden end of the sample. Both parts of this apparatus may result in elements which could affect the general withdrawal behaviour of the connection during a tensile test.

All tests were performed in unconfined conditions. However, Riberholt did not state in his experimental report in which boundary conditions the experiments were carried out.

The pull-out strength of more than 50 glued connections with singular rod was tested using a hydraulic testing machine. Consequently, the test results were studied through “an entirely empirical approach" (Cook at al. 1998): multiple regression analyses. With the help of a statistical analysis software, he developed mathematical formulas for the prediction of the maximum withdrawal strength of adhesive connections in glulam.

The regression formulas suggested by Riberholt in 1986 took into consideration the use of two different types of glues: polyurethane and araldites; they were based on mathematical relationships, within the main parameters (density, glued length, hole diameter), characterised by high values of coefficients of correlation (R^2) in the multiple regression analyses.

$$F = -9.4 + 0.834\,\rho\, d_h \sqrt{l_g}$$ [kN] for rods glued by Polyurethan glues

$$F = 3.5 + 0.237\, d_h \sqrt{l_g}$$ [kN] for rods glued by Araldites glues

F = withdrawal force [kN]

ρ = timber specific density (0.42 is the value of the specific density used in this specific case for Glulam L40)

d_h = hole diameter [mm]

l_g = glued length [mm]

In a graph plotted by Riberholt (1986) in his report on page 22, it is possible to visualise the difference between the results in terms of pull-out strengths obtained by the laboratory experiments and the values estimated using the suggested design expressions. In particular, the graph clearly shows how the withdrawal capacity of the connections changes in relationship with different glued lengths.

The graph is related only to tests results obtained from samples made by Polyurethan glue, defined by Riberholt as the most suitable glue for injections into Glued In Rods. Most of the samples were characterised by a 60x60 mm cross section and a distance from edge equals to 1.5 times the rod diameter (1.5d). The edge distance of 1.5d was subsequently identified as the minimum distance needed between the rod and the sample's edge to avoid splitting failure mode in wood (Riberholt 1986). However, in case the stress exceeds the characteristic tension strength of the selected timber it is necessary an increase in the sample's cross section (Riberholt 1986).

For this reason a bigger cross section (100x100 mm) for joints with a glued length of 500mm was chosen, after noting that a tension failure in timber sample 60x60 mm glued for 400mm had occurred.

This proves the influence that the sample geometry has on the withdrawal performance of the joints and how important selecting the right distance edge is in order to assess the real withdrawal strength of the connection during the test.

Regarding the values estimated through the use of the suggested mathematical expression, it is possible to note that the formulas enable the prediction of the experimental pull-out values for glued length of 200 and 300mm. However, it is clearly visible that the formula overestimates the joint withdrawal behaviour for bigger glued lengths. In fact, it provides values higher than the experimental outcomes for 500mm (Riberholt 1986). The experimental result of samples glued for 400mm, with an average pull-out force of 109.1 kN, were likely not included in the graph due to the failure of the timber section for splitting which prevented the joint's withdrawal strength from being correctly assessed.

Furthermore, it is possible to observe that the experimental results obtained from samples with a glued length of 500mm, differently from the rest of the samples, had been manufactured with a thicker glue line thickness (hole diameter= 22mm). This change might have enhanced their pull-out capacity. Therefore, it is possible to highlight how, for this specific glued length, the formula imprecisely predicts the experimental results, taking into account that if the joints had had a glue line of 0.5 mm the samples might have been characterised by withdrawal strengths lower than the values plotted into the aforementioned graph.

3.2.1.1.1 Riberholts' main conclusive statements

- Araldites glues have a brittle behaviour compared to Polyurethane adhesive
- an edge distance of 1.5 times the rod diameter is enough to test the full pull-out strength of the connection, if the wooden cross section is designed to prevent tensile failure in the timber element
- enhancing the glued length means increasing the joint's ductility (Riberholt 1986).

3.2.1.2 Riberholt's design equation

Riberholt (1988) introduced in the proposal for CIB code specific formulas for different scenarios which include the study of the withdrawal strength of singular or multiple rods glued in timber using "brittle glues" and "non-brittle glues". He defined Resorcinol and Araldites adhesives as glues characterised by brittle behaviour and 2-component Polyurethane as glues with "non-brittle" behaviour (Riberholt 1988). This statement is based on conclusions drawn from the laboratory experiments carried out in 1986, where the use of Araldites glues led to a brittle failure mode of Glued In Rods during various tensile tests.

However, the statement which defines Resorcinol and Polyurethane as brittle and non-brittle glues respectively was argued by Serrano et al. (2008) in a COST Action report where it is stated that the rheology of adhesives does not depend only on the chemical properties of glues.

The first equation suggested by Riberholt (1988) to assess the withdrawal capacity of axially loaded rods into timber was obtained by regression analyses to study the relationship amongst four parameters which characterise a GIR connection: hole diameter, glued length, timber relative density. The withdrawal parameters represented the regression coefficients, whose values change in relationship with the type of adhesive used in the connection (Riberholt 1988).

These formulas were used to estimate the tensile capacity of some adhesive connections tested in past experiments; the discrepancy obtained between the test results and the estimated strengths made Riberholt modify the original withdrawal parameters' values. In fact, the final version of his formulas presented new withdrawal parameters and defined two different equations for the condition where the glued length was higher or lower than 200mm (Riberholt 1988).

In the final comments presented into the CIB code for the formulas application, Riberholt clarified that the characteristic density of timber should be inserted in the equations rather than the dimensionless relative density to calculate the characteristic withdrawal capacity of the connections. The application of the latter correction causes an inconsistency in the units of measurement in the equations formulated to provide a final resistance capacity expressed in Newton. This comment has been interpreted by some authors who started using in the formula the characteristic density of wood, expressed in Kg/m^3, and swapping the original characteristic withdrawal parameter into dimensionless factors, obtained by dividing the original parameter by 1000. However, it is clearly likely that this problem stems from a lack of information about the fact that the density should have been expressed in g/cm^3.

Riberholt's formulas (1988) do not take into consideration either the mechanical properties of the adhesives and the amount of glue utilised to manufacture the connection. Furthermore tests results analysed by the Danish author did not show any difference in the withdrawal capacity for bolts installed parallel or perpendicular to the wood grain. For this reason he probably did not provide any information in the formula regarding the direction of the rod in relation to the wood grain for the case of samples axially loaded.

However, many other research studies have found relevant differences, in terms of pull-out resistance, in considering the application of GIR in a direction which can be parallel or perpendicular to the wood grain. Authors such as Steiger et al. (2004) and Bernasconi (2001) had stated that the performance of the connection and the internal shear stress distribution at the bonding layer considerably change in relationship with rods glued in different direction to the timber grain.

a. $F = f_{ws}\,\rho\, d\,\sqrt{l_g}$ for $l_g \geq 200$ mm [N]

b. $F = f_{wl}\,\rho\, d\, l_g$ for $l_g < 200$ mm [N]

F = withdrawal force [N]

f_{ws} = withdrawal parameter for case a. It is equal to 520 [N/mm$^{1.5}$] for 'brittle' glues (Resorcinol, Araldites) or to 650 [N/mm$^{1.5}$] for 'non-brittle' glues (2 component Polyurethan)

f_{wl} = withdrawal parameter for case b. It is equal to 37 [N/mm^2] for 'brittle' glues (Resorcinol, Araldites) or to 46 [N/mm^2] for 'non-brittle' glues (2 component Polyurethan)

ρ = timber relative density

d = maximum value between hole diameter and external diameter of the rod [mm]

l_g = glued length [mm]

It is clearly notable that the design method suggested by Riberholt in the CIB code is strongly correlated with specific experiments. The formulas depend on the analysis of the results of tests performed only on timber samples made of similar density, moisture content and species. Therefore, the equations to predict the pull-out capacity can be hardly generalised and difficultly applied for timber connections made by different materials.

3.2.2 Buchanan and Townsend

In 1990 Buchanan and Townsend carried out experiments to assess the axial pull-out capacity of Glued In Rod connections parallel to the wood grain. Araldites based adhesives (Deng 1997) were used to glue deformed reinforcing dowels with 12 mm and 20 mm diameters into glulam samples, selecting different glue line thicknesses (2 and 5 mm) and glued lengths of 200mm and 300mm.

Despite the fact that Townsend during this experimental program analysed also the tensile capacity of few samples of adhesive connections made of threaded rods (Deng 1997), it is critical to highlight that the formula is related only to adhesive connections in timber made of steel reinforcing bars.

$F = 9.2\, d_r\, l_g\, (r_d)^2\, (r_e)^{0.5}$ [N] for l_g<200mm when d_r =12mm

$$F = 9.2\, d_r\ l_g\, (r_d)^2\, (r_e)^{0.5}\ [N]\ \text{ for } l_g\text{<300mm when } d_r = 20\text{mm}$$

F = withdrawal force [N]

d_r = rod diameter [mm]

d_h = hole diameter [mm]

d_e = edge distance from rod centreline [mm]

l_g = glued length [mm]

$$r_d = {}^{d_h}/_{d_r}$$

$$r_e = {}^{d_e}/_{d_r}$$

The validity of the equation, proposed to predict the pull out behaviour of Glued In Rod connections, was assessed by comparison with experimental results (LegnoDOC 2003). The formulas above have a strong correlation with the sample's geometry as they take into consideration the distance from the rod centreline to the sample edge. Additionally, they include the ratio between the hole diameter and the rod diameter which represents an important information about the glue line thickness.

However, the presented mathematical equation is not related to the wood density and it is valid only for specific rod diameters and glued lengths.

The bond between steel and glue is highly affected by the geometry of the contact surface.

For this reason, because of the presence of bonding surfaces with specific geometrical properties, it is important not to generalise this formula to the prediction of the behaviour of adhesive connections made of threaded rods.

Nevertheless, it is interesting to report that in the study conducted by Townsend in 1990, the tensile experimental results of samples made of threaded rods had a tensile performance higher than the specimens glued with reinforcement dowels. In fact, the threads in the bars enhance the contact surface between the steel and the epoxy, providing a stronger bond (Deng 1997). However, Townsend could not suggest any formula for adhesive anchors in timber made of threaded rods, in this specific case study, due to the study of a limited number of samples (Deng 1997).

3.2.3 Deng

In New Zealand Deng published in 1997 a research report where he presented the results of a significant number of tests to assess the “Strength of Epoxy Bonded Steel Connections in Glue laminated Timber”.

The methodology used by Deng to develop his experimental work finds similarities with Riberholt’s previous studies in terms of samples preparation and pull-out test setting. In fact, he applied an analogous invasive technique, which involves the drilling of auxiliary holes to glue the steel element glulam samples parallel to the wood grain direction. Furthermore, he tested the axial pull-out strength using a pull-pull test configuration. Deng’s test set up is similar to the one proposed by Riberholt in 1986.

Conversely, the originality of Deng’s work is represented by the choice of adopting a particular method to design his experiments on Glued In Rods called “Random Factorial design”. Specifically, this method involves the opportunity to study simultaneously “different experimental conditions” (PennState n.d.). In the first part of this specific study, several experimental combinations were tested through the analysis of 7 factors, each of those characterised by 2 different values (Deng 1997):

- bar diameter (16mm and 24mm)
- glued length (which varied from 5 to 10 times the bar diameter)
- wood condition (wet and dry)
- bar type (threaded and deformed)
- edge distance (which varied from 1.5 to 2.25 times the bar diameter)
- epoxy type (bought from different manufacturers)
- hole diameter (which varied from 1.15 to 1.4 times the bar diameter)

  (Deng 1997).

3.2.3.1 Deng’s design equation

The maximum tensile load had been recorded for each axial withdrawal test and the experimental results related to specific groups of factors were gathered and compared to find mathematical relationships amongst them. Through the calculation of the ratio of average loads obtained in different scenarios it was possible to correlate the main parameters and develop the following formula:

$$\mathrm{F} = 85.4\ k_b\ k_e\ k_m l_g^{\ 0.86} d_r^{\ 0.76}\ (d_h/d_r)^{0.5}\ (d_e/d_r)^{0.5} \qquad \text{for } (16 \le d_r \le 24)$$

$$\text{for } (5d_r \le l_g \le 15d_r)$$

for $(1.15d_r \leq d_h \leq 1.4d_r)$

for $(1.5d_r \leq d_e \leq 3d_r)$

F = withdrawal force [N]

k_b = bar type factor

k_e = epoxy factor

k_m = moisture factor

l_g = glued length [mm]

d_r = rod diameter [mm]

d_h = hole diameter [mm]

d_e = edge distance from rod centreline [mm]

Deng can be defined as the first researcher who presented a detailed empirical formulation for the withdrawal capacity of an adhesive connection including all the main parameters which could affect the pull-out strength of an adhesive connection in timber.

The factorial framework, applied to design his experiments, allowed Deng to understand which factor could have had a major impact on the performance of the connection. For example, in his thesis (Deng 1997) he defined the bar diameter, the glued length and wood moisture as the most relevant factors.

The glulam timber was classified in 2 different ways based on the moisture content (MC) assessed before and after the test execution: dry wood (MC<18%, k_m moisture factor=1) and wet wood (MC>25%,k_m moisture factor=0.75). In particular Deng (1997) expressed concern about the moisture content investigation; he emphasised the importance of keeping monitored the variation of moisture inside the wooden sample, not only during the investigative phase but also in real applications due to the effect that the environmental condition could have on the connection strength.

It is interesting to note that Deng's design equation includes a specific coefficient (k_b = bar type factor) to take into consideration whether the joint is assembled using steel threaded rods or reinforcing rods. Specifically, k_b is equal to 1 in case of threaded bars and to 0.79 for deformed rods. These values confirm that the use of deformed reinforcing rods would cause a weaker connection between the steel and the epoxy leading to a decrease in the withdrawal capacity of the joint. Therefore, Deng with his experiments proved what had been already observed by Townsend in 1990 regarding the difference in the performance of Glued In Rods characterised by different bar types.

Despite the fact that Deng (1997) introduced, for the first time, a formula that could be applied to predicting the pull-out strength of adhesive connections with different features, the suggested design equation is excessively related to the materials chosen for those specific experiments.

For example, the epoxy coefficient k_e, is identified by 3 different values which refer to 3 epoxy types (K-80, k_e = 1; West system, k_e = 0.86; Araldite 2005, k_e = 1.17). Unfortunately, in this specific study, the classification was not based on the chemical composition of the adhesive as it had been done by Riberholt during his experiments in 1986 with Polyurethan and Araldites glues but it was only based on the manufacturer nomenclature. For this reason, nowadays, in case Deng's design model was used to assess the strength of a glued in rod connection, it would be rather difficult to identify k_e and find a right correspondence between a new epoxy resin on the market and the one selected by Deng almost 20 years ago.

Furthermore, the presence of many boundary conditions on the parameters l_g, d_r , d_h and d_e , makes Deng's formula valid only in restrictive design conditions.

It can be noted that on one hand, the use of a factorial system allowed Deng to study many different conditions and find several relationship amongst all factors during the laboratory experimentation; on the other hand the factorial method did not permit the analysis of the variability of the test experiments because every single combination of geometrical features was tested only once. It is reasonable to state that one-replication test is not a suitable test method due to the high variability in results that usually wooden adhesive connections present in laboratory experiments.

In fact, the concept of testing by single repetitions does not take into consideration the complexity of the interaction amongst steel, wood and epoxy which not always leads to having joints with identical mechanical properties. In reality, the manufacturing process of Glued In Rods frequently involves the presence of minimal imperfections in the joint, such as bubble airs during the gluing process or, for example, a steel bar not correctly centred in the borehole; both of these situations could likely affect the performance of the joint. Therefore, a minimum number of 3 samples is strictly needed to gain realistic results about the behaviour of these connections in laboratory regime.

In Deng's experiments (1997) it is also possible to observe that most of the samples during his experimental activity failed by splitting of the wood sample which commonly indicates an incorrect design of the sample cross section.

For this reason he probably performed further experiments in which the effect of an extra "transverse reinforcement" (Deng 1997) on the general joint strength was tested. The reinforced samples resulted in being stronger than the no-reinforced ones, enabling the assessment of the real strength of the connection. This study underlines the crucial importance of the test boundary conditions on the final test results. Thus, it can be stated that the test set-up has a great influence on determining the correct performance of the connection.

3.2.4 German research – Mohler and Aicher

According to Tlustochowicz (2011), the German research regarding Glued In Rod connections started in 1987 and continued for several years leading to different design equations.

For example the following design model was presented by German authors in 1997 (Mohler and Aicher in Tlostochowicz 2011) and it includes a value called $f_{v,mean}$, defined as the 'anchorage strength', that is strictly connected to specific rod diameters.

$$\mathrm{F} = \pi\, d_r l_g f_{v,mean} \text{ for } l_g \leq 20\, d_r$$

F = withdrawal force [N]

l_g = glued length [mm]

d_r = rod diameter [mm]

$f_{v,mean}$= anchorage strength = 5 [N/mm^2] for $d_r \leq 24$

$f_{v,mean}$= anchorage strength = 5 – 0.2668 $(d_r - 24)$ [N/mm^2] for $24 < d_r \leq 30$

3.2.5 German research - Gerold

In 1992 the German researcher Gerold expressed the withdrawal capacity of adhesive connections in glulam as function of the rod diameter, glued length, wood density and the shear strength, specifically renamed in this case as "bond strength". The latter design parameter is influenced by λ which represents the ratio between the glued length and the rod diameter, defined for the first time with the name of "rod slenderness" (Otero Chans et al. 2010c).

In this specific research work it is possible to observe some analogies between Riberholt's studies and Gerold's analyses on Glued In Rods.

In fact, Gerold related his design model to a characteristic timber density of 380 kg/m^3, confirming what had been highlighted by Riberholt six years before regarding the importance of taking into consideration the influence of the timber density on the axial resistance of the joint. He also utilised the same adhesive classification that Riberholt had adopted in his studies, expressing a different bond strength in relationship to the use of different adhesive types (Polyurethan and Epoxy glues), respectively identified with the abbreviations PUR and EPX (Tlostochowicz et al. 2011).

$$\mathrm{F} = \pi\, d_r l_g \left(\frac{\rho}{\rho_k}\right)^c f_{v,mean}$$

F = withdrawal force [N]

l_g = glued length [mm]

d_r = rod diameter [mm]

ρ_k = characteristic wood density = 380 [kg/m^3]

ρ = wood density [kg/m^3]

$f_{v,mean}$= mean bond strength = $f_v\ (1 - k_s\ \lambda) k_d$ [N/mm^2]

λ = rod slenderness = $\frac{l_g}{d_r}$

k_d = 1 for metric threaded rods

for PUR glue:

f_v= anchorage strength = 7.5 [N/mm^2]

k_s = 0.019

c = 1

for EXP glue:

f_v= anchorage strength = 12.6 [N/mm^2]

k_s = 0.042

c = 0.55

3.2.6 Russian standards

Turkovsky during the 22nd meeting of the International council for building research studies and documentation (CIB) held in Berlin in 1989 presented a formula to assess the pull-out strength of glued in bars in glulam used for "transversal or inclined local reinforcements". In fact, Turkovsky (1989) in his work reported that the safest application for adhesive connections in glulam occurs exclusively when the steel element is glued in a direction which is perpendicular or inclined of 45° to the wood grain.

He also affirmed that gluing steel reinforcing bars perpendicular to the wood grain would allow the manufacture of a joint which can be connected more easily to other structural elements in diverse locations, not only at the end of a wooden beam (Turkovsky 1989).

The Russian author was the first researcher who suggested a design equation which specifically refers to the application of bars glued in glulam perpendicularly to the wood grain direction.

$$F = R_{sh}\, \pi\, (d_r + 0.005) l_{g*} k_1 k_2$$

F = withdrawal force [N]

l_g = glued length [mm]

l_{g*} [1]= l_g – 30mm [mm]

d_r = rod diameter [mm]

R_{sh}= design shearing strength of wood across grain = 4 [N/mm^2]

$k_1 = 1 - 0.01\frac{l_g}{d_r}$ = coefficient of irregular stress distribution along the bar

$k_2 = 1\ in\ case\ of\ single\ bar\ connection =$ coefficient of irregular stress distribution in multiple bars connection

It is possible to note that the following formula includes R_{sh} which is the shear strength of wood "across the grain" which is expressed as a standard value but it should be changed in relationship to the variability of the timber species utilised to assemble the connection. Furthermore, it is interesting to note that the author took into consideration possible gluing defects during the assembly process through a reduction of the glued length of 30mm.

[1] In the original description lg* is expressed in [m] but it is likely a mistake made by the original author in the original report.

In particular, he based his research on a study of connections made of 14-24mm steel reinforcement bar and glued with “epoxy adhesive with milled sand or cement as filler” and characterised by a 3-5mm glue line thickness (Turkovsky 1989).

Inclined Glued In Rods were also used by Turkovsky (1989) to assemble “V-shaped anchors” whose geometrical configuration would prevent the reinforcement from having structural problems closely related to the moisture of wood. In fact, differently to what happens in longitudinal application, the load bearing capacity of the joint is improved because of a lower concentration of forces around the wooden layers close to the bond line (Turkovsky 1989).

Although the author did not present any negative aspect in using inclined Glued In Rods, it would be interesting to underline that the insertion of a rod into a diagonal hole filled by resin in wood may cause difficulties in obtaining a connection with a uniform and constant glue line thickness due to gravity.

3.2.7 Swedish guidelines

The formula suggested into the Swedish guidelines to design Glued In Rods appears similar to the equation previously presented and introduced in 1997 by Mohler and Aicher (Tlustochowicz et al. 2011). The formula can be applied only to design the withdrawal strength of connection where the moisture content of timber is less than 20%. Otherwise, for installation in structure identified with higher value of moisture content the pull-out capacity calculated by the following equation should be decreased by 10% (Tlustochowicz et al. 2011).

$$\mathrm{F} = \pi\, d_r l_g f_{v,3}$$

F = withdrawal force [N]

l_g = glued length [mm]

d_r = rod diameter [mm]

$f_{v,3}$= anchorage strength = 3.4 [N/mm^2] for $\frac{l_g}{d_r} \leq 10$

$f_{v,3}$= anchorage strength = 3.9 – 0.05 $\frac{l_g}{d_r}$ [N/mm^2] for $10 < \frac{l_g}{d_r} \leq 20$

3.2.8 Kangas

Kangas in 1993 examined in depth what had been studied in 1989 by Turkovsky about V-shaped connections and developed new experiments whose outcomes led him to presenting a formula to express the withdrawal capacity of adhesive joint in glued laminated timber, characterised by a timber density of 450 kg/m^3. 20mm reinforcing steel bars were glued by using different types of resin (Polyutheran and Epoxy) into predrilled borehole, set at different angles to the wood grain orientation (from 30° to 90°), in glulam elements. It is interesting to note that in this research work the installation of rods glued parallel to the wood grain, being characterised by an angle of 0°, was not taken into consideration (Kangas 1993).

In the following mathematical expression the withdrawal strength of the connection and hole diameter are linearly dependent; in fact, the "anchorage capacity" is calculated considering the external bonding surface, precisely the contact area between timber and adhesive; although Kangas (1993) studied the behaviour of joints with rods oriented in different directions into timber beams, the analysis of his formulation reveals that the mean anchorage strength of the joint is not affected by the angle between the rod and the grain direction. He also imposed restrictions on the gluing thickness, establishing that the diameter of the borehole should not exceed 1.25 times the rod diameter (Kangas 1993).

$$\mathrm{F} = \pi\, d_h l_g f_{v,mean} \quad \text{for} \quad d_h \leq 1.25 d_r$$

F = withdrawal force [N]

l_g = glued length [mm]

d_h = hole diameter [mm]

d_r = rod diameter [mm]

$f_{v,mean}$= mean anchorage strength = $7(1-0.01\frac{l_g}{d_r})$ [N/mm^2]

Further studies conducted in 2000, led Kangas to modifying the mean anchorage strength in relationship to the definition of the shear strength suggested in the design proposal for the Eurocode 5 in 1997.

The new anchorage capacity was defines as follow (Kangas 2000):

$$F_k = \pi\, d_h l_g f_k \quad \text{for} \quad d_h \leq 1.25 d_r$$

F_k = characteristic withdrawal force [N]

f_k = characteristic shear anchorage strength = $11\ {d_h}^{-0.2}\ \frac{\rho_k}{400}$ [N/mm^2]

ρ_k = characteristic wood density [kg/m^3]

3.2.9 Eurocode 5

The following design equation was included in 1997 in the Part 2: Bridges of the Pre-Standard European Norms (prEN 1955) and it was described valid for the use of either steel threaded rods or deformed reinforcing bars to assemble adhesive connections in glulam (LegnoDOC 2003).

$$F_k = \pi\, d_{equ} l_g f_{v,k} \quad \text{for} \quad l_{g,min} = \max\,[0.4 d_r^{\,2};\ 8\, d_r]$$

F_k = characteristic withdrawal force [N]

l_g = glued length [mm]

d_h = hole diameter [mm]

d_r = rod diameter = $d_{nominal}$ for threaded rods [mm]; $1.1\ d_{nominal}$ for deformed reinforcing bars [mm]

d_{equ} = equivalent diameter = min[d_h , 1.25d_r] [mm]

ρ_k = characteristic wood density [kg/m^3]

$f_{v,k}$= characteristic shear strength = $1.2 \times 10^{-3} (d_{equ})^{-0.2} \rho_k^{\,1.5}$ [N/mm^2]

Regarding the validity of the formula in relationship to the influence of the rod orientation on the connection strength, in this specific case the design model was defined valid for either parallel, perpendicular or inclined installation of the steel element to the wood grain direction (LegnoDOC 2003).

This formula presented some negative aspects. Principally it does not specify any information regarding the adhesive which should be adopted; secondly it does not consider that the withdrawal strength is highly influenced by the quality of the bond and therefore by the type and quantity of the glue. From the following graph (Fig. 3-1) it is possible to observe how the limitation imposed on the equivalent diameter (min[d_h , 1.25d_r]) does not consider the quantity of adhesive used in the connection and consequently the relative effect that the glue line thickness could have on the general pull-out behaviour of the joint. The influence of a hole diameter bigger than 1.25d_r is not considered and furthermore for small rod diameters (8-14mm) only very thin adhesive bonding layers (1mm) are taken into account.

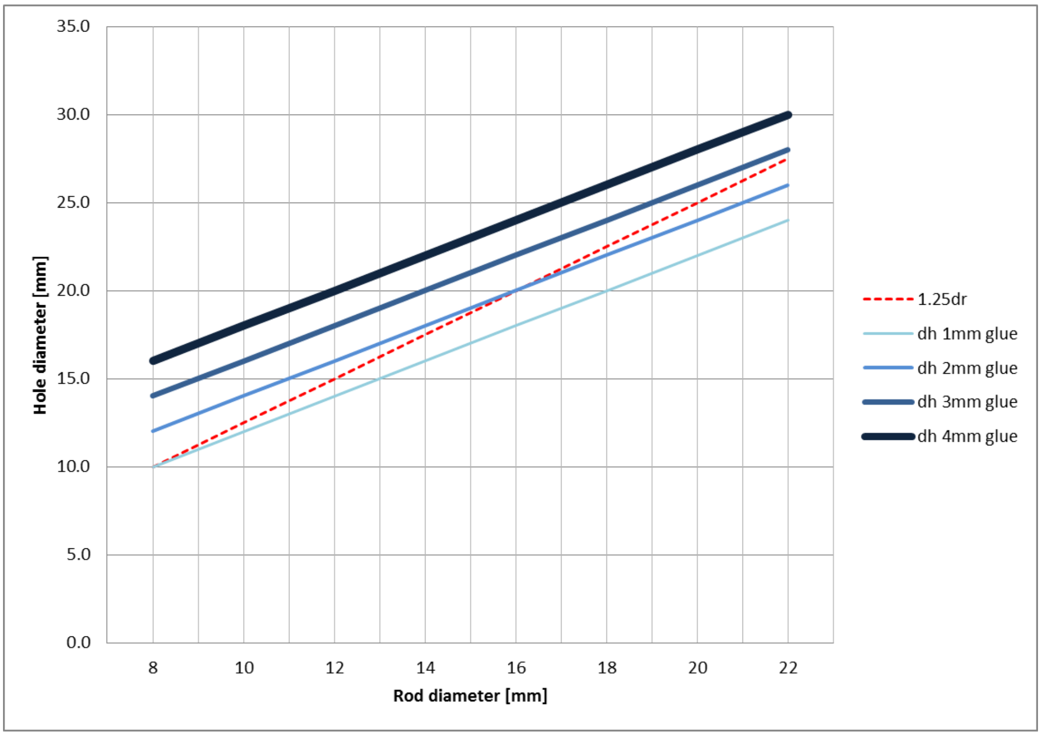


Fig. 3-1: relationships amongst equivalent diameter, hole diameter and rod diameter

It is well known by previous research (Serrano in Tlustochowicz et al. 2011) that the formula overestimates the withdrawal capacity of adhesive joints for long glued in lengths; in fact, it is possible to note that an enhancement of the glued length corresponds in an increasing in the pull out capacity of the joint. Therefore, because of the linear relationship between the adhesive length and the axial force it was proved by several authors that the experimental outcomes obtained in laboratory were not predictable by the use of the suggested design model. The formula was not included in the final version of the EC5 because it represented an unsafe approach for the design of glued in rods (Tlustochowicz et al. 2011).

However, in 2001 the aforementioned design equation had been revised in order to reconsider the introduction of a design equation in the Eurocode 5. The formula had been modified by introducing a new shear strength expression which was function of the parameter α, the angle identified between the direction of the wood fibre and the orientation of the steel rod in the timber sample. This modification highlights how the direction (parallel $\alpha = 0°$, perpendicular $\alpha = 90°$ or inclined to the wood grain) in which the steel rod is installed into the timber element can affect the final withdrawal strength of the connection.

$$f_{v,k} \quad \rightarrow \quad f_{v,\alpha,k} = \frac{f_{v,90,k}}{\sin^2\alpha + 1.5\cos^2\alpha}$$

$$where \qquad f_{v,90,k} = 1.2 \times 10^{-3} (d_{equ})^{-0.2} \rho_k{}^{1.5}$$

3.2.10 Aicher

The study conducted by Parida et al. (2013) regarding the performance of multiple Glued In Rods, included an interesting comparison between experimental and theoretical outcomes. The prediction of the pull-out strength of adhesive connections was calculated by using Aicher's design model (Aicher in Parida et al. 2013 :1469) which had been defined as one of the most appropriate formulas to obtain reliable information about structural behaviour of joints made of steel rods glued by polyurethane and epoxy resins in timber elements (Parida et al. 2013).

$$\mathrm{F} = \pi \, d_h l_g f_{v,mean}$$

F = withdrawal force [N]

l_g = glued length [mm]

d_h = hole diameter [mm]

d_r = rod diameter [mm]

λ = rod slenderness = $\frac{l_g}{d_r}$

ρ = wood density [kg/m^3]

$f_{v,mean}$= mean shear strength = min [8; 129 $d_r{}^{-0.52} \lambda^{-0.62} \left(\frac{\rho}{480}\right)^{0.45}$] [N/mm^2]

It is interesting to note that the shear strength is dependent on the geometrical properties of the joint; however factors related to the properties of the resin used to assemble the connection are not taken into account.

3.2.11 French Rules

French guidelines were published in 1999 in an exhaustive report entitled " Assemblages bois: tiges ou goujons colles de grandes dimensiones" where important information about the technical specifications for Glued In Rods was provided (Faye and Le Magorou et al. 2004)

The French guide included also the following design equation to assess the axial withdrawal capacity of adhesive connections in glulam, parallel to grain.

$$F_k = 85 \, d_r \sqrt{(l_g - 1.5 d_r)} \, f_{v,k} \quad \text{for } l_g > 17.5 d_r$$

F_k = characteristic withdrawal force [N]

l_g = glued length [mm]

d_r = rod diameter [mm]

$f_{v,k}$= characteristic shear strength of wood = 2.7 [N/mm^2]

3.2.12 GIROD

The European research project “GIROD- Glued In RODs for timber structures” was developed from 1998 to 2001 by the collaboration amongst several European research institutes from the UK, Germany and Sweden (Bengtsson 2002)

One of the main objectives of this wide project, focused on the study of the mechanical behaviour of adhesive connections in timber structures, was to establish a mathematical design formula to predict the strength of Glued In Rods. Specifically, it was requested to suggest a simple mathematical equation based on “theoretical and physical” considerations in order to identify a safe design approach for adhesive joints in timber (Bengtsson 2002).

The methodology adopted to develop a design formula during the GIROD research program appeared completely new and different from what had been previously applied in past research studies. Design formulas were usually numerical expressions obtained by the analysis of relationships amongst variables in specific tests; therefore, it can be affirmed that previous design equations were all experimentally determined. In a different way, during the GIROD program the design equation was developed through an analytical approach used by Gustafsson in 1987 to describe the internal stress distribution along a bonding layer in a lap joint taking into account non-linear fracture mechanisms (Johansson et al. 1995). The Gustafsson’s theory called “Generalised Volkersen Theory” is explained and presented in detail in Chapter 2. In 1995 it is possible to find in literature the first application of Gustafsson’s model to Glued In Rod connections where the main properties of the wooden adherends in Gustafsson’s formula related to lap joints were replaced by the characteristics of the materials which a glued in bolt connection is composed of (Johansson et al. 1995). Hence, it is critical to note that the definition of the bonding area had been changed from rectangular, which identified the bonding layer in a lap joint, with a cylindrical shape to enable the correct application of the formula to Glued In Rods.

$$\frac{F_{max}}{\tau_f\, b\, l} = \frac{1+\alpha}{\overline{\omega}} \frac{\sinh \overline{\omega}}{(\cosh \overline{\omega} + \alpha)} \qquad where\ \overline{\omega} = \sqrt{\frac{1+\alpha}{2}} \sqrt{\frac{l^2 \tau_f^2}{t_1 E_1 G_f}} \quad \alpha = \frac{E_1 A_1}{E_2 A_2}$$

By substituting $b\, l \rightarrow d_r\, \pi l_g$ $\quad E_1 A_1 \rightarrow E_{wood} A_{wood}$ $\quad E_2 A_2 \rightarrow E_{rod} A_{rod}$ (Johansson et al, 1995),

$$\frac{F_{max}}{\tau_f\, d_r\, \pi l_g} = \frac{1+\alpha}{\overline{\omega}} \frac{\sinh \overline{\omega}}{(\cosh \overline{\omega} + \alpha)} \qquad where\ \overline{\omega} = \sqrt{\frac{1+\alpha}{2}} \sqrt{\frac{{l_g}^2 \tau_f^2\, d_r\, \pi}{E_{wood} A_{wood} G_f}} \quad \alpha = \frac{E_{wood} A_{wood}}{E_{rod} A_{rod}}$$

which had been rewritten during the GIROD research work as (Bengtsson 2002):

$$\frac{F_{max}}{d_r\, \pi l_g} = \tau_f \frac{\tanh \overline{\omega}}{\overline{\omega}} \qquad where\ \overline{\omega} = \sqrt{\frac{l_{geo}}{l_m}}$$

$$l_{geo} = \frac{d_r\, \pi {l_g}^2}{2} \left(\frac{1}{A_{rod}} + \frac{E_{rod}}{E_{wood} A_{wood}} \right) \qquad l_m = \frac{E_{rod} G_f}{\tau_f^2}$$

According to Gustafsson and Serrano (2000), the “bond layer material properties”, τ_f and G_f, could be experimentally assessed by a specific test which allows a detailed analysis of the fracture mechanism at the bonding surfaces. The “bond line fracture test” is a small-scale analysis of the mechanical behaviour of a Glued In Rod made of a small wood specimen in which a steel rod with a diameter of 16mm is glued maintaining a constant adhesive thickness of 0.5mm.

The test result is a complete shear stress-deformation curve from which it is possible to determine the parameter τ_f (shear strength) and G_f (fracture energy). According to Gustafsson and Serrano (2000) only the second part of the $\tau - \delta$ curve should be taken into consideration to work out the correct shear fracture energy G_f. This would exclude the first elastic part and examine only the peak and post-peak parts of the graph which respectively identify the point in which the fracture mechanism at the bonding layer occurs (Gustafsson and Serrano 2000) and the phase where the gradual dissipation of the fracture energy “during progressive damage” takes place (Aicher 2003: 337).

Several experiments were performed during the GIROD European project which help to establish the validity of the design formula for adhesive connection composed of steel threaded rods glued, choosing a glue line thickness of 0.5mm (Bainbridge and Mettem 1999), parallel to the wood grain of glulam elements and tested in pull-compression regime. However, regarding the set up used to verify the withdrawal strength of the connection, the formula had been defined applicable also to predict the test results obtained by the pull-pull loading conditions (Bengtsson 2002) although the prediction would underestimate the joint strength.

Furthermore amongst the 3 different types of glues tested (EPX: epoxy, PRF: phenol resorcinol formaldehyde, PUR: 2-component polyurethan), epoxy resins “achieved good adhesion to the timber, attained sufficient shear strength to maintain integrity across the adhesive and provided anchorage to the rod through combined adhesion and mechanical interlock". Therefore, EPX glues met all the requirements needed for specific applications in resin connectors in timber structures (Bainbridge and Mettem 1999).

In addition, the test results obtained by samples glued using epoxy resins resulted in being safely predictable by GIROD's design formula (Bengtsson 2002).

Despite the GIROD program had been successfully concluded with the proposal of a design equation which combines theoretical and experimental principles, the validity of the formula was assessed only for restrictive cases which involved the use of specific materials and test conditions. Furthermore, the influence of timber density and moisture content on the load bearing capacity was neglected.

3.2.13 Eurocode 5 (2003)

The last suggestion for an implementation in the Eurocode 5 of a design rule for Glued In Rods was made in 2003 (Connolly and Mettem 2003). The interesting research outcomes of the European research project GIROD were implemented and used to formulate a new mathematical expression for the prediction of the axial pull-out resistance of bonded in rods joints.

$$F_k = \min \left[f_{y,k}\, A_{rod}\ ;\ \pi\, d_{eq} l_g\, f_k\, \frac{\tanh \bar{\omega}}{\bar{\omega}} \right]$$

for $l_{g,min}$ = max [$0.4 d_r{}^2$; 8 d_r] and $\frac{l_g}{d_r} < 18$ (Stepinac et al. 2013a)

F_k = characteristic withdrawal force [N]

$f_{y,k}$ = steel characteristic yield strength [N/mm^2]

A_{rod} = effective rod cross section area [mm^2]

l_g = glued length [mm]

d_h = hole diameter [mm]

d_r = rod diameter = $\begin{cases} d_{nominal} & \text{for threaded rods [mm]} \\ 1.1\, d_{nominal} & \text{for deformed reinforcing bars [mm]} \end{cases}$

d_{equ} = equivalent diameter = min[d_h , 1.25d_r] [mm]

f_k = 5.5 [N/mm^2]

$\overline{\omega} = \frac{0.016\ l_g}{\sqrt{d_r}}$

It is easy to observe that the formula was directly extrapolated from GIROD's research work but it is possible to note that it had been extremely simplified. Although the parameter $\overline{\omega}$ was still function of few geometrical properties of the joint, it did not have any relationship with the shear fracture energy G_f, parameter which characterises the load transfer mechanism at the bonding layer.

The shear strength at the bonding line suggested in the draft version of EC5 in 2003 was in the new formula identified by a standard number 5.5 [MPa] without specifying in which scenario the use of that standard shear strength value would have been a correct value to predict the connection strength.

In fact, no reference was made to wood density, to the direction of the rod in respect to the wood grain and no information was provided regarding the type of adhesive which should have been used to assemble the connection.

All these missing critical details might have contributed to defining the proposed equation as an inadequate design formula which "did not meet the actual status of research" (Steiger et al. 2015) about the design of Glued In Rod connections, during the meeting of the technical committee 250 (CEN/TC250) of CEN in 2003.

3.2.14 Bernasconi

In 2001 Bernasconi performed several tests to analyse Glued In Rods made of different combinations of "wood species, glue material and rod profile" (Benasconi 2001). The research was mainly aimed at identifying whether modifications in the joint geometry and properties, such as different embedded lengths, timber densities, timber species and hole diameters could have affected the bond strength of the connection when subjected to axial load. The conclusion drawn from laboratory tests, allowed Bernasconi (2001) to suggest a design equation which is strictly correlated to the specific products and pull-out testing conditions used in his research work.

The formula is based on a critical assumption which determines the presence of a uniform shear stress at the bonding layer, exclusively when the steel bar is glued in a direction which is perpendicular to the wood grain in spruce glued laminated timber. In fact, he specified that gluing the bar following a direction which is parallel to the timber grain would lead to a no-uniform shear stress distribution along the glued length (Benasconi 2001), statement lately confirmed in 2004 by Steiger et al.

$$F = \pi\, d_h l_g f_{v,k}$$

F = withdrawal force [N]

l_g = glued length [mm]

d_h = hole diameter [mm]

$f_{v,k}$= characteristic shear strength of wood [N/mm^2]= $25\, d_h{}^{-0.5}$

The characteristic shear strength according to Bernasconi (2001) is only dependent on the size of the hole diameter and therefore, on the glue line thickness. In other words the shear bond decreases when there is an increase in the hole diameter dimension. This aspect had been confirmed by test results obtained from his experiments, where he tested the pull-out resistance of samples of glued in threaded rods/steel reinforcement bars by 'pull-pile foundation' (Tlustochowicz et al. 2011) test regimes. His test results also revealed that changes in shear strength caused by a variation of the glued length can be neglected.

It is important to highlight that Bernasconi's design equation is only valid for adhesive connections made of spruce glulam timber; although he performed further experiments with samples assembled with beech glulam timber he could not establish the validity of his shear strength expression for other timber species.

However, he stated that the only characteristic which can strongly affect the bond stress is the wood species. In fact, he reported that tests performed on beech glued in rods resulted in presenting higher shear stress values than connections made of spruce glulam (Bernasconi 2001).

The latter consideration represents a significant aspect revealing the importance of the anchor substrate in the pull-out performance of the joint; however, the report did not provide complete information about the mechanical properties of the spruce and beech glulam used; in fact, no reference was made to the strength classes of the tested glued laminated timber, which nowadays should be identified in compliance with the BS EN14080-2013.

3.2.15 Feligioni CNR

The key concept of the excellent research program carried out by Feligioni et al. (2003) found its key concept in two words: 'glue rheology'. The mechanical properties of epoxy resins and the quantity of glued, expressed in volume [mm^3], used to assemble the joints during the laboratory experimentation were identified as critical parameters to be analysed for a correct study of the withdrawal capacity of Glued In Rod connections. For this reason the design formula suggested in the draft version of the Eurocode 5 in 1997 was modified in order to include experimentally determined factors to take into consideration the rheology of epoxy resins. It is in fact important to underline that this study was exclusively focused on the study of a specific type of adhesive: epoxy glues.

$$\mathrm{F} = \pi \, l_g \left[f_{v,k} d_{equ} + k \, e \, (\, d_r + e) \right]$$

F = withdrawal force [N]

l_g = glued length [mm]

d_h = hole diameter [mm]

ρ_k = characteristic wood density [kg/m^3]

$f_{v,k}$= characteristic shear strength = $1.2 \times 10^{-3} (d_{equ})^{-0.2} \rho_k{}^{1.5}$ [N/mm^2]

e = glue line thickness [mm]

d_r = rod diameter [mm]

d_{equ} = equivalent diameter = min[d_h , 1.25d_r] [mm]

k = glue strength parameter. It is equal to 0.086 for brittle epoxy and to 1.213 for ductile epoxy.

It can be stated that previous authors who dealt with the use of resins for Glued In Rods suggested a classification method for adhesives based on chemical compositions, as Riberholt proposed in 1988 categorising as “brittle” all Resorcinol and Araldites resins (Epoxy glues). This way to classify the adhesive material does not consider that a single type of glue could be further split into subcategories. In fact, according to Feligioni et al. (2003) epoxy resins can both present brittle and ductile behaviours, therefore the class of ‘epoxy-based’ resins would not identify glues with identical mechanical properties. This is in line with what Serrano stated in 2008 (Serrano et al. 2008) which confirmed that “the adhesive rheology may be adjusted within a wide range, independently of the chemical nature of the resin used”.

The main aspect which has to be highlighted about Feligioni’s design rule is the conditions in which this formula was considered valid. Principally, the design equation is exclusively related to a specific species of solid timber (spruce) and not to glued laminated timber, although the authors did not mention in the technical paper the reason why this material substrate was adopted and which direction was followed to glue the steel bars (parallel or perpendicular to the wood grain). However, from the analysis of some of the pictures presented in the report of Feligioni et al. (2003), it is possible to deduct that threaded rods were glued parallel to the wood grain.

Secondly the samples had been prepared following a very particular procedure which cannot be compared with the common manufacturing procedures used by previous researchers. A pull-compression test was chosen to assess the axial load capacity of the joint, clarifying that this type of confined tests shows minimal differences in test results when compared with test outcomes obtained by a pull-pull test regime (Feligioni et al. 2003).

This statement is in contrast with what had been proved by Bengtsson et al. in 2000 where different test configuration produced different results for Glued In Rods in glulam. The pull-out test performed in confined conditions revealed that the samples glued by ductile epoxy resins resulted in having the highest pull-out strength values.

Nonetheless, on one hand it seems that the use of ductile epoxy can increase the withdrawal capacity of the joint, on the other hand the results obtained by some durability tests on the connection, performed after 60 days from the joint production date, proved that glued in bars made of ductile epoxy tend to lose their global strength over time. This effect might be due to the development of the curing process which allows the resin to become stiffer (Feligioni et al. 2003). Contrarily, samples with brittle epoxy maintains a constant strength which would represent an optimal characteristic for a safe adhesive connection in timber.

It can be concluded that this study confirmed that the best failure mode which should be obtained in laboratory conditions to study the connection is the failure which occurs at the adhesive-wood interface which proves a good bond along the joint embedded length as previously pointed out by Bernasconi (2001).

3.2.16 Steiger, Gehri and Widmann

The research work conducted by Steiger at al. (2004) approached the study of the behaviour of axially loaded Glued In Rods through laboratory tests trying to identify the influence which specific parameters such as timber density, anchorage length and hole diameter have on the connection strength. Although this methodology had already been adopted in past studies, Steiger's approach found its unicity in a comparative analysis of experimental results in which samples of adhesive anchors in spruce glulam were characterised by steel bars glued parallel or perpendicular to the grain direction.

The analysis led to defining the rod-grain direction as one of the most important feature which characterises an adhesive joint in timber affirming that "timber [glulam] subjected to [axial] stresses parallel or perpendicular to the grain exhibits completely different behaviour" (Steiger et al. 2004); moreover, it was discovered that the modification of some aforementioned parameters in the joint geometry can affect the joint behaviour in a different way whether the steel rod of the connection is glued parallel or perpendicular to the wood grain. For example, it was stated that a change in the wood density would have a major influence on the axial strength of samples with parallel rod-grain direction (Steiger et al. 2004).

The results outcomes revealed that connections composed of rods glued in glulam perform better if installed perpendicular to the wood grain (Steiger et al. 2004).

However, this statement could be questionable because different pull-out test configurations had been used during the laboratory experimentation to test the adhesive joints. Specifically, the axial strength was tested by pull-pull tests for samples glued parallel to the wood grain and pull compression (pull-pile foundation) test for the samples glued perpendicular to the wood grain. These two test configurations are rather different and can produce results which may not be strictly comparable.

Nonetheless, the major negative aspect of this interesting research study concerned the authors' choice of studying only a specific type of Glued In Rod connections which was well-known in Switzerland with the name of "GSA system" (Tlustochowicz et al. 2011).

The GSA connection is characterised by a steel rod with very specific geometrical features glued by epoxy-type adhesive with a glue line thickness which varies in size along the joint embedded length. The first part of the rod has a smaller cross section in order to address the stress at the bottom of the connection and, at the same time, avoid stress concentrations which usually take place at the top part of the connection.

The analysis of test results acquired from GSA samples and the relative understanding of the relationships amongst the main parameters led to the proposal of the following equation to define the internal distribution of the nominal shear stress at the bonding layer (Steiger et al. 2004).

$$f_{v,0,mean} = k\, \lambda_h^{-\frac{1}{3}} \left(\frac{\rho_K}{480}\right)^{\frac{1}{2}}$$

$f_{v,0,mean}$= nominal shear strength

k = experimental parameter = 16

λ_h = rod slenderness (expressed by d_h instead of d_r) = $\frac{l_g}{d_h}$

ρ_k = characteristic wood density [kg/m^3]

This formula had been revised in 2007 and included in the general formula suggested to predict the withdrawal strength of adhesive anchors in timber (Tlustochowicz et al. 2011).

$$\mathrm{F} = \pi\, d_h l_g f_{v,mean}$$

F = withdrawal force [N]

l_g = glued length [mm]

d_h = hole diameter [mm]

d_r = rod diameter [mm]

$f_{v,mean}$= mean shear strength = 7.8 $\left(\frac{\lambda_h}{10}\right)^{-\frac{1}{3}} \left(\frac{\rho_K}{480}\right)^{0.6}$

This design equation is a clear example of a design formula for Glued In Rods which had been experimentally determined by tests conducted on a particular type of glued in rods. For this reason this design rule, more than others design equations presented in this chapter, should not be generalised and applied to the design of other adhesive connections if they do not comply with the following restrictions:

- GSA typology of adhesive connection identified by specific steel rods with a length of the 'restricted section' l_v = $5\,d_r$ and glued parallel to the glulam grain by epoxy-based adhesive
- $7.5 < \lambda_h < 12.5$
- $12 < d_r < 20$
- Spruce glulam $350 < \rho_k < 500$
- The shear strength along the joint length can be assumed uniform only for applications where rod is parallel to the wood grain.

3.2.17 New Zealand code

In 2007 the following design rule was included in the "New Zealand design guide – NZW14085 SC" (Stepinac et al. 2013a):

$$F = 6.73\, k_b\, k_e\, k_m \left(\frac{l_g}{d_r}\right)^{0.86} (d_r/20)^{1.62}\, (d_h/d_r)^{0.5}\, (d_e/d_r)^{0.5} \quad \text{for } (12 \le d_r \le 24)$$

for ($5d_r \le l_g \le 15d_r$)

for ($1.15d_r \le d_h \le 1.4d_r$)

for ($2.5d_r < d_e$)

F = withdrawal force [N]

k_b = bar type factor

k_e = epoxy factor =
- 1 for West System and K-80 adhesive
- 1.2 for Araldite 2005 adhesive

k_m = moisture factor=
- 1 if moisture content <15%
- 0.8 if 15%<moisture content <22%)

l_g = glued length [mm]

d_r = rod diameter [mm]

d_h = hole diameter [mm]

d_e = edge distance from rod centreline [mm]

It is interesting to note many similarities between this formulation and the design rule suggested by Deng in 1997. For this reason it can be assumed that the suggestion of the presented formula had been obtained from conclusions drawn by Deng (1997) thanks to his experimental work. Furthermore, it is important to highlight the product-dependent characteristic of the equation which limits its application to many cases in which all the restrictions are not respected.

3.2.18 Italian regulation CNR-DT 206/2007

The Italian technical document CNR-DT 206/2007 provides detailed information regarding the design of Glued In Rods made either from solid timber or glued laminated timber and identified by specific glue line thicknesses according to the adhesive manufacturer's instructions (CNR 2007).

It is interesting to note that the regulation takes into consideration 3 different failure modes which can occur when Glued In Rods are subjected to axial tension; furthermore specifications are given to predict the withdrawal strength of the connections, respectively for rods glued at 0° and α° respect to the wood grain direction.

Specifically for Glued In Rods parallel to the wood grain the Italian regulation suggests the equations below (CNR 2007):

$$F_d = \text{withdrawal force [N]} = \min \begin{cases} f_y A_{res} & \text{for rod tension failure} \\ \pi\, d_{eq} l_g f_{v,k} & \text{for shear failure at adhesive-timber interface} \\ f_t A_{eff} & \text{for total or partial tension failure in timber} \end{cases}$$

F_d = design withdrawal force [N]

f_y = steel rod yielding strength [N/ mm^2]

A_{res} = resistant steel rod cross-section [mm^2]

f_t = timber tensile strength parallel to the wood grain [N/ mm^2]

A_{eff} = effective timber failure area [mm^2]

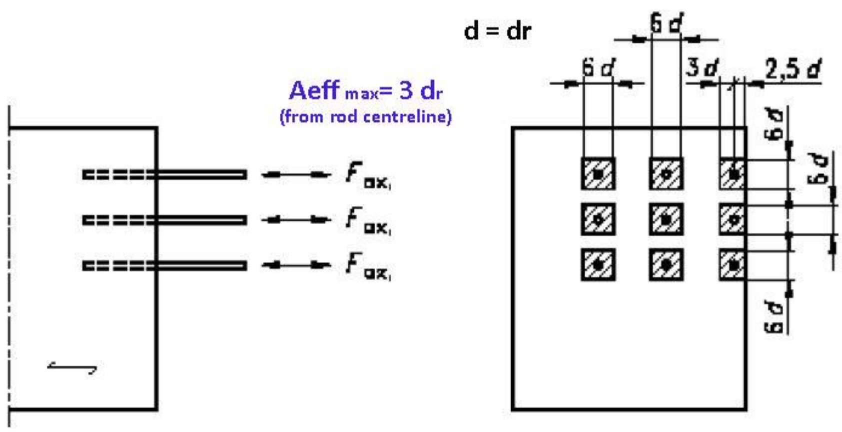


Fig. 3-2: effective timber are for glued in rod parallel to the wood grain (CNR 2007)

l_g = glued length [mm]

d_r = rod diameter [mm]

d_h = hole diameter [mm]

d_{eq} = equivalent diameter = min [d_h ; 1.10 d_r] [mm]

$$f_{v,k,\parallel} = \text{characteristic bond shear strength [N/mm}^2\text{]} = \begin{cases} 5.25-0.005 l_g \text{ if } 250 \le l_g \le 500 \\ 4 \text{ if } l_g \le 250 \\ 3.5-0.0015 l_g \text{ if } 500 \le l_g \le 1000 \end{cases}$$

In case of adhesive joints with rods glued perpendicular to the timber grain direction, the characteristic bond shear strength should be modified applying the following formula (CNR 2007):

$$f_{v,k,\perp} = f_{v,k,\parallel} \, [1.5 \, sin^2 \, \alpha + cos^2 \, \alpha]$$

where α = angle between rod-wood grain direction

3.2.19 IStructE and TRADA

The "Manual for the design of timber building structures to Eurocode 5" (IStructE and TRADA 2007) written by a collaboration between the Institution of Structural Engineers and TRADA reported that for a correct design of adhesive connections, composed of steel rods glued parallel or perpendicular to the wood grain direction into solid wood or glulam timber, subjected to axial load the following conditions should be verify:

$$F_k = f_{\,short} \, \rho_k \, d_{eff} \, l_g \quad \text{for } l_g < 200$$

$$F_k = f_{\,long} \, \rho_k \, d_{eff} \sqrt{l_g} \quad \text{for } l_g \ge 200$$

F_k = characteristic withdrawal force [N]

l_g = glued length [mm]

ρ_k = characteristic wood density [kg/m^3]

d_r = rod diameter [mm]

d_{eff} = effective diameter = max [d_h ; d_r] and < 1.25 d_r [mm]

f_{long} = withdrawal parameter equal to 0.520 for 'brittle' adhesives (Epoxy resins, PRF, etc.) or to 0.650 for 'non-brittle' glues (2 part Polyurethan, etc.)

f_{short} = withdrawal parameter equal to 0.037 for 'brittle' glues (Epoxy resins, PRF, etc.) or to 0.046 for 'non-brittle' glues (2 part Polyurethan, etc.)

It is possible to establish a strong connection of these formulations with the equations suggested by Riberholt in 1988 after having performed several tensile tests on Glued In Rod specimens. For this reason it can be deducted that the design code presented by the Institution of Structural Engineers and TRADA is still inextricably linked with specific empirical outcomes which can be hardly generalised to other case studies and in which the adhesive rheology is incorrectly related only to the chemical nomenclature of adhesives.

3.2.20 Rossignon and Epsion

The two empirical design equations presented by Rossignon and Epsion in 2008 are the summary of a laboratory activity aimed at studying the pull-out behaviour of 60 samples of glued in rods made of spruce glulam GL24, epoxy resin and steel threaded rods. The tests were conducted through pull-pull tests and the samples were characterised by a glue line thickness of 4 mm and a parallel rod-grain direction (Rossignon and Epsion 2008).

$$\mathrm{F} = \left[-0.15\,\lambda_h{}^2 + 9.2\,\lambda_h\right]\left(\frac{d_r}{16}\right)^{1.5}$$

F = withdrawal force [kN]

d_r = rod diameter [mm]

l_g = glued length [mm]

d_h = hole diameter [mm]

λ_h = rod slenderness (expressed by d_h instead of d_r) = $\frac{l_g}{d_h}$

$$F_k = 0.76 \left\{ \left[-0.15\,\lambda_h{}^2 + 9.2\,\lambda_h\right] \left(\frac{d_r}{16}\right)^{1.5} \right\}$$

F_k = characteristic withdrawal force [kN]

In this specific case, the design formula is function exclusively of the joint geometric parameters (rod diameter, hole diameter and glued length) without considering the main mechanical parameters (adhesive rheology, timber axial stiffness, density, moisture content, etc.) of the materials the joint is made of.

It is interesting to report that the most recorded failure mode during these tests was the timber splitting along the glued length of the sample, even though a considerable distance form edges was taken into account. Nevertheless, it has to be remarked that a standard edge distance to prevent timber form splitting is still not known due to the lack of a standard regulation for glued in rods.

This aspect supports Riberholt's statement (Riberholt 1986) which declared how the dimensions of the timber sample play a crucial role in the withdrawal performance of the connection.

However, the authors stated that the splitting of the timber samples was mainly due to either imperfections during the joint manufacturing process or bending moments induced by wrong forces alignment during the pull-out tests (Rossignon and Epsion 2008).

3.2.21 DIN 1052:2004-08 and DIN 1052:2008-12

In the German design codes the following design model is reported (Stepinac et al. 2013a, Tlustochowicz et al. 2011):

$$F = \pi\, d_r l_g f_{v,kd} \qquad \text{for } (6 \le d_r \le 30)$$

for ($l_{g,min}$ = max [$0.5 d_r{}^2$; $10 d_r$])

F = withdrawal force [N]

l_g = glued length [mm]

d_r = rod diameter [mm]

$$f_{v,kd} = \text{bond shear strength [N/mm}^2\text{]} = \begin{cases} 5.25\text{-}0.005 l_g & \text{if } 250 \leq l_g \leq 500 \\ 4 & \text{if } l_g \leq 250 \\ 3.5\text{-}0.0015 l_g & \text{if } 500 \leq l_g \leq 1000 \end{cases}$$

It is possible to observe that the shear strength at the bonding layer is inversely proportional to the glued length, as experimentally confirmed by several research activities conducted by Aicher in 1997 (Piazza et al. 2005) and Othero Chans et al. in 2010c.

3.2.22 Otero Chans

Otero Chans et al. in 2013 explored the differences in the pull-out behaviours of Glued In Rods made of different timber species and in particular they focused their attention on how the withdrawal strength of the connection changes in relationship to the wood species and consequently to the wood density. As confirmed in past research work by Bernasconi in 2001, the use of Glued In Rod specimens manufactured using timber elements with different mechanical properties can affect the joint performance.

This specific case study was a pioneering research work conducted by Otero Chans et al. since 2007 which was mainly aimed at studying the load bearing capacity of adhesive anchors through pull-out tests, performed in pull-pull configuration, on specimens made of threaded rods glued by 1 mm of epoxy resin into holes predrilled in different typology of wooden substrates:

- Glulam from softwood: the most common substrate material used to study Glued In Rod connections (STA 2015)
- Glulam from hardwood
- Solid timber

For the first time a design model was proposed specifically to predict the behaviour of Glued In Rods made of solid timber whose withdrawal capacity is expressed in the following design formula as a function of the characteristic shear strength of timber and of the no uniform shear stress distribution at the adhesive-wood interface, determined by Finite Element analyses which displayed an internal shear stress distribution along the glued length in accordance with the Volkersen's theory (Otero Chans et al. 2010c).

The design equation suggested by Otero et al. in 2010c for joint samples made from "sawn timber" is:

$$F = \pi\, d_h l_g f_{v,k,joint}$$

F = withdrawal force [N]

l_g = glued length [mm]

d_h = hole diameter [mm]

d_r = rod diameter [mm]

$f_{v,k,joint}$= joint characteristic shear strength = $f_{v,k,timber}{}^2 \frac{2\beta}{\beta^{2.3}+1}$ [N/mm²]

β= parameter = $\frac{\lambda}{f_{v,k,timber}}$

λ = rod slenderness = $\frac{l_g}{d_r}$

Subsequently in 2013 this formula has been generalised to be applicable also to adhesive connections made of glued laminated timber created from both softwood and hardwood species.

$$F = \pi\, d_h l_g f_{v,joint}$$

F = withdrawal force [N]

l_g = glued length [mm]

d_h = hole diameter [mm]

d_r = rod diameter [mm]

$f_{v,joint}$= joint characteristic shear strength = $0.6\rho_k^{\alpha} \left[1 - \frac{0.7\, k^3}{\rho_k + k^2}\right]$

k = $\lambda - 10$

λ = rod slenderness = $\frac{l_g}{d_r}$

ρ_k = characteristic wood density [kg/m³]

α = 0.4 for spruce and eucalyptus glulam and for solid timber from chestnut and tali species

[2] A modification has been made to the original formula due to a likely typographical error

The main parameters which influenced the internal shear stress of the joint were the wood density and the geometry of the connection (Otero Chans et al. 2013). It was reported that high wood density corresponds to an increase in the internal shear strength of the connection and in the pull-out resistance capacities of the joint. However, it was difficult to establish the no linear relationships which relates the mechanical properties of the wood species and the joint strength during the analysis of the tests results (Otero Chans et al. 2013).

It was also reported that minor variations of the density within the same timber species did not lead to relevant changes in the joint withdrawal strength (Otero Chans et al. 2010c). On the contrary, the comparison amongst specimens made with different wood species, thus very different characteristic wood densities highlighted visible modifications to the joint withdrawal strength.

The joint shear stress included in the formulation is also function of the rod slenderness. According to Otero Chans et al. (2013) the rod slenderness value should be maintained low to optimise the joint performance because it was proven that the increase in the glued length is not linearly correlated with an improvement in the joint pull-out capacity.

Despite the fact that the equation has been validated for four different timber species its application to other wood species has to be carefully verified but it is interesting to reference this excellent research work in order to emphasise how important the mechanical properties of the timber substrate in a Glued In Rod connection are.

3.2.23 Aicher

One of the most recent work on GIR was presented by Simon Aicher in the working group n°6 of CEN/TC 193, held in June 2015. He prepared a draft version of a standard for the evaluation of the shear strength of the bond in a Glued In Rod connection made of adhesives for load bearing timber structures (EN 301; EN 302) in glued laminated timber (Aicher 2015).

The test configuration selected for the determination of the shear strength at the bonding layer is a pull-pull test performed on a softwood glulam specimen (strength class: GL24) characterised by steel rods glued with glue line thicknesses of 2 or 4 mm parallel to the wood fibre (Aicher 2015).

The formula below, presented in the draft version of the CEN/TC 193 technical document, evaluates the shear strength at the bonding surface which represents one of the most important parameters of a glued in rod joint (Aicher 2015).

$$f_{v,\rho} = \frac{F_{t,max}}{d_r\ \pi\ l_g}$$

$f_{v,\rho}$ = bond shear strength [N]

F = tensile test failure load [N]

l_g = glued length [mm]

d_r = rod diameter [mm]

ρ = wood density at 12% moisture of the specimen [kg/m^3]

ρ_0 = glulam GL24 density according to EN 14080 [kg/m^3]

$$f_{v,\rho 0} = f_{v,\rho}\ \frac{\rho_0}{\rho}$$

Despite the fact that the use of the equation allows the assessment of the bond strength for Glued In Rod specimens with different glued lengths (200, 400 and 600mm) and timber densities, it is still unclear in which design formula this parameter should be used taking into consideration that at this moment in time design standards for Glued In Rods have not been presented or included in the EC5.

3.3 Observations

Valuable insights gained from the analysis of the aforementioned design rules and past research studies on Glued In Rods are:

- The discrepancy and inconsistency in results obtained by the analysis of these design equations are mainly due to a mix of methods and materials used to evaluate the joint withdrawal capacity, which is a heavily material dependent characteristic. Furthermore, different test configurations such pull-pull and pull-compression, different loading rates (Rossignon and Espion 2008: 420) set to the pull out machines, but also different "load-to-grain directions" (Tlustochowicz et al. 2011) might have had a strong influence on the results obtained by laboratory experimentations.

- It is important to define specific experimental tests to assess the mechanical properties of each adhesive which should not be classified only through the relative chemical composition in order to identify the correct adhesive rheology. This is important if we consider that different epoxy-based products can produce adhesive joints with different strength results, as stated by Feligioni et al. (2003). Nonetheless, information regarding the adhesive rheology should be included in the manufacturer's printed installation instructions (MPII)

- The shear strength, commonly identified with the name of anchorage strength, seems to be function of different factors in each design model. Sometimes it is only related to the geometrical parameters of the joint and other times it is related to the mechanical properties and type of adhesive. However, a proper formulation should contain the main property of the three materials which the joint is made of to consider the complex bonding process amongst resin, timber and steel.

- It seems that joints with perpendicular rod installation in respect to the wood grain perform better than samples with parallel rod-grain direction in glulam.

- The optimum failure mode which proves a good bond and a good joint performance during laboratory experiments is the failure that occurs at the wood-adhesive interface. However, in real application the joint should be designed to induce failure into the steel element by yielding of the steel rod.

- Some formulas have been not properly used in past research analysis on Glued In Rods. For example, formulas suggested for glulam application were used to predict the behaviour of Glued In Rods made of solid wood, or formulas based on the study of adhesive anchors made of reinforcing bars were utilise to analyse the load bearing capacity of adhesive joints in timber made of threaded steel rods, or again formulas suitable for applications perpendicular to the wood grain were incorrectly applied for applications parallel to the grain direction without considering that the mechanical properties of wood are different in each direction, due to the orthotropic properties of timber. In particular, one of the most accurate formulas suggested by the GIROD European project was often wrongly used due to the erroneous identifications of the bond line material parameters, which uniquely characterised the adhesive material in the connection. However, when comparing the design formulas suggested by different authors in literature it has to be carefully taken into consideration that some formulas express the withdrawal capacity by characteristic forces instead of mean values.

- The understanding of the contact surface properties between wood and glue is one of the main problems for the prediction of the pull-out capacity of adhesive anchors. Many of the listed design rules tend to be overly conservative because they only take into consideration the shear strength value of wood. The contact surface between timber and adhesive should be considered as a hybrid material made of timber and epoxy, therefore it has to be classified with a shear strength parameter that is influenced by both timber and resin mechanical properties.

3.4 COMPARISON AND CONTRADICTIONS

All the design formulas presented in this chapter were compared to each other by several researchers in past studies about Glued In Rods and a specific COST Action (Stepinac et al. 2013a) was conducted on this topic. The comparison amongst the pull-out strength values predicted by some of the design models listed in this chapter for a Glued In Rod connection, identified by a specific density (370 [kg/m^3]), glued length (200 mm), steel rod diameter (20 mm) and epoxy glue line thickness (2 mm) (Stepinac et al. 2013b, Steiger et al. 2015), reveals very different results.

Frequently, the inconsistency in the pull-out strength values had been justified by analysing the different parameters contained in each formulation. However the focal point is not represented by the presence in the design models of different variables but principally by the understanding and the identification of the test conditions and test materials used by each researcher to develop a mathematical formula in order to predict the withdrawal joint strength.

In other words the common mistake made in the past was the comparison amongst design rules whose formulations derived from completely different experimental conditions. The significant difference in the predicted pull-out strength values is not only caused by tests conducted on connection samples made of different materials but also by the strong influence that different test regimes (pull-pull, pull-compression, pull-pile, etc.) have on the final test results.

Through the reading of this chapter and the interpretation of the detailed critical analysis conducted for every single design rule, it is possible to realise that each formulation is the direct result of experiments carried out on samples assembled using different manufacturing techniques, tested in different test regimes and made of similar material (wood, adhesive and steel) but characterised by specific and diverse mechanical properties.

Most of the presented design rules, except for the ones contained in national design codes, had their origins in research activities in which due to the impossibility of finding any correlation between experimental results and existing design rules, researchers attempted to suggest a new design rule which would have certainly fit their own test results. Therefore, it is clearly likely that a Glued In Rod joint made by a combination of 3 materials, such as timber, steel and adhesive, with diverse mechanical properties represents every time a new connection characterised by a unique connection system (Steiger et al. 2015) whose performance is hardly predictable by the existing design models which are only valid for restrictive conditions.

However, one of the main purposes of reviewing the literature regarding the existing design formulas gathered in this chapter was to offer the possibilities of easily identifying which formulas could have been reasonably compared to each other due to the presence of similar conditions used for their formulations.

As rightly pointed out by Rossignon and Espion (2008) and Feligioni (2003), when analysing and comparing experimental tests results to existing design models for Glued In Rods it is extremely important to select amongst the possible design equations only the formulas whose derivational experimental work has very strong similarities, in terms of materials, test methods, grain-rod direction, to the test conditions chosen for a studied connection. Otherwise a wrong selection would lead to an incorrect and improper comparison.

In the research work conducted by Rossignon and Epsion (2008), the authors highlighted that their experimental data was approximately predictable by the mathematical formulations suggested by the GIROD European project, the EC5 design code 2003 and by Steiger et al. in 2004 (Rossignon and Espion 2008). In fact, as it is possible to infer from the schematic summary presented in *Table 3-1*, all the aforementioned research activities were based on experiments conducted on glulam samples using threaded steel rods glued by epoxy type adhesive parallel to the wood grain.

AUTHOR	TIMBER	GLUE	ROD (Threaded rods / Deformed bars)	GLUE LINE [mm]	TEST CONDITION: Pull-Compression (P-C)	TEST CONDITION: Pull-Pull (P-P)	GLUING METHOD: ⊥ to wood grain	GLUING METHOD: // to wood grain
Riberholt	GLULAM	Araldites Polyurethan	Threaded rods	0.5		P-P		//
Buchanan and Towsend	GLULAM	Araldites	Deformed bars	2 and 5				//
Deng	GLULAM	Epoxy	Threaded rods Deformed bars	dhole= from 1.15 to 1.4drod		P-P		//
Turkosky	GLULAM	Epoxy	Deformed bars	3- 5			⊥	
Kangas	GLULAM	Polyurethan Epoxy	Deformed bars	dhole= 1.25drod	P-C	P-P	⊥	
GIROD	GLULAM	Epoxy Polyurethan PRF	Threaded rods	0.5	P-C			//
Bernasconi	GLULAM	Epoxy	Threaded rods Deformed bars	up to 8	Pull-Pile		⊥	
Feligioni	SOLID	Epoxy	Threaded rods	1-3-5	P-C			//
Steiger	GLULAM	Epoxy	GSA System	No uniform	Pull-Pile	P-P	⊥	//
Rossignon	GLULAM	Epoxy	Threaded rods	4		P-P		//
Otero Chans	GLULAM SOLID	Epoxy	Threaded rods	1		P-P		//

Table 3-1: comparative analysis of previous experimental studies about Glued In Rods in timber

Nevertheless, it is important to clarify that a valid comparison between experimental results and withdrawal strength values predicted by design models should not be based on Steiger's formulation because it came from experiments which had involved the study of a very particular adhesive connection, called GSA. Specifically, an adhesive connection system which was characterised by major modifications to the geometrical properties of the steel rod in a Glued In Rod connection.

Despite the correlation presented amongst the 3 aforementioned design models and the experimental results, none of the listed design rule is able to exactly predict the data point trend and values obtained from the laboratory tests, proving that even the comparison amongst selected design regulations would not allow a precise prediction of the Glued In Rods axial strength.

The problem stems from the fact that each design formula owes its origin to the analysis and study of specific specimens of Glued In Rod connections tested in particular test conditions. Hence, the validity of the suggested design models is established only for applications which comply with certain restrictions.

Moreover, the mathematical design formulas' inability to correctly predict the test results confirms the significant influence that other parameters such as timber species, epoxy glue rheology and volume (glue line thickness) might have on the general pull-out behaviour of an adhesive anchor in timber, as highlighted respectively by Bernasconi in 2001 and Feligioni in 2003.

On one hand Rossignon and Espion (2008) are an example of authors who introduced a methodology for an appropriate comparison amongst design rules, on the other hand Yeboah et al. in 2013 proposed and compared their test outcomes to several design equations without considering that none of them was supposed to be used to describe the withdrawal behaviour of glued in rod connections made of "Basalt Fibre Reinforced Polymer [BFRP] rods" instead of steel threaded rods.

In the literature it is possible to perceive that even the use of steel reinforcing bar to replace threaded rods would negatively impact the pull-out withdrawal resistance of the joint due to a decrease in the mechanical interlocking between steel and glue. Even more the presence of BFRP rod would incredibly change the joint configuration, in particular the mechanical properties at the rod-adhesive interface.

For this reason the design formula listed in this chapter should not be used to study adhesive connection systems which have geometrical and mechanical properties which differ from the common definition of a Glued In Rod connection made of steel, resin and timber.

The critical analysis provided in this chapter explains the existing contradictions amongst the design equations and helps to understand the contradicting findings presented in several research studies which can be found in literature.

It can be concluded that the total absence of standardisation in the basic phases of evaluation, design and execution of adhesive anchors in timber and the fact that the performance of Glued In Rod connections is strongly product-dependent lead to invalid comparisons between experimental tests results and design model predictions.

4. PRELIMINARY MATERIAL ANALYSIS AND DATA COLLECTION

The research project followed the progressive development of the four main phases of the research methodology presented in Chapter 1.

4.1 TIMBER

Wood is a material whose anatomical properties highly influence its mechanical performance. In particular, in softwood the physical structures which mainly affect its performance are called tracheids, microscopic tubes closed at both ends and characterised by thin or thick walls; whereas in hardwood "narrow spindle-shaped cells" and "opened-ended elements", named respectively fibres and vessels, anatomically determine the wood strength (Davis 1997). From the microscopic analysis of the two timber species chosen for this experimentation, it was possible to note that Oak (Quercus robur) and Douglas Fir samples presented all the anatomical structures which characterised their species. As it possible to observe from Fig. 4-1 on the surface of a transverse section of cubic timber samples, vessels in Oak (Quercus robur) were easily noted by the presence of little holes and in Douglas Fir the stratification of tracheids with different wall thickness was identified by colour variations of the wood surface.

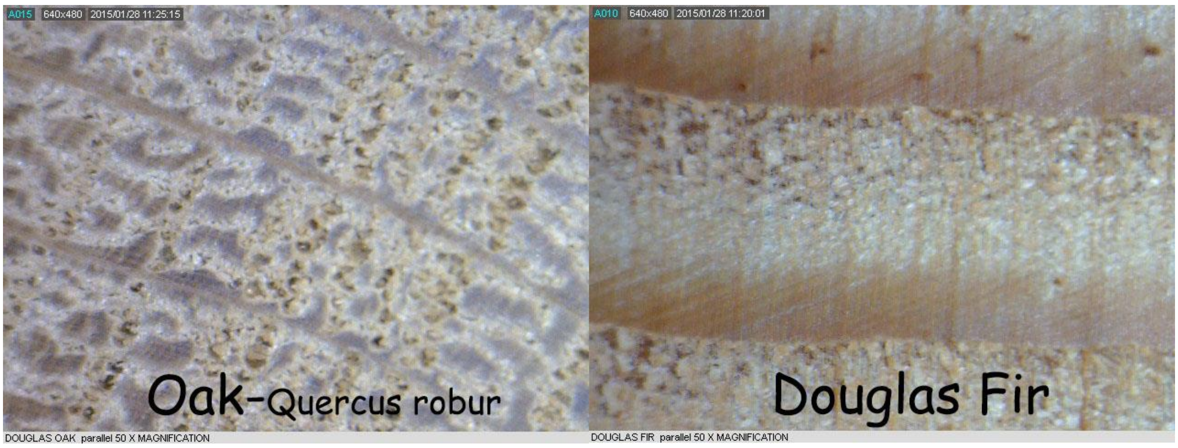


Fig. 4-1: microscopic pictures (50X magnification) of samples of Oak-Quercus robur (left) and Douglas Fir (right) timber species

4.1.1 Compression and Tensile strength

The properties of solid European White Oak (Quercus robur), hereafter 'Oak', and Douglas Fir wood samples were assessed following the British Standard BS 373:1957. These preliminary tests, aimed at assessing physical and mechanical properties of different timber species and typology, were particularly needed because of the lack of information provided by the manufacturing company on the structural grade of the studied wood specimens. Contrarily, the samples of glulam timber used in this research work had been classified as GL24 by the manufacturer, therefore, no tests were needed to acquire knowledge on their mechanical features.

In order to carefully characterise the solid wood, used in this research work as a substrate for the manufacturing process of adhesive anchors, tensile and compression tests parallel and perpendicular to the wood grain were performed.

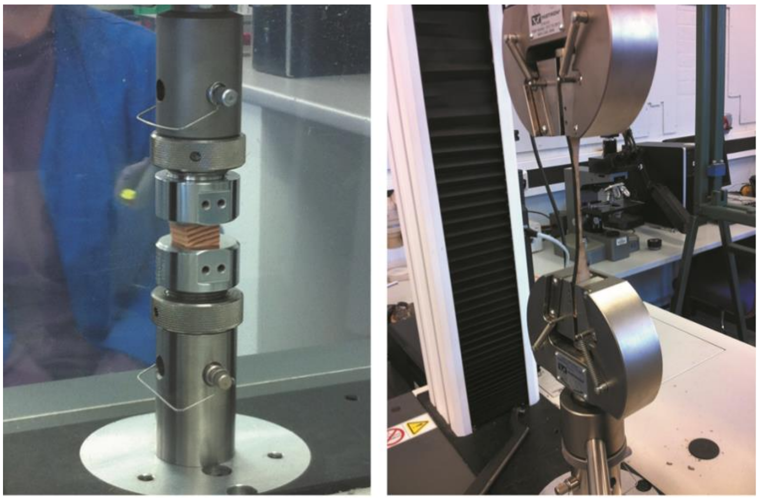


Fig. 4-2: compression (left) and tensile (right) tests on small specimens of wood

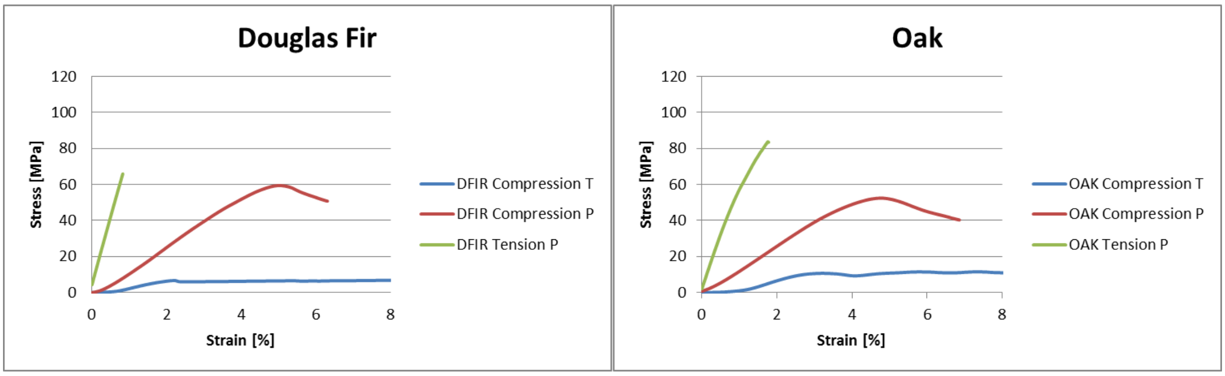


Fig. 4-3: test results from compression tests performed parallel (P) and perpendicular (T) to the wood grain and from tensile tests parallel to the wood grain (P) on Douglas Fir (left) and Oak (right) samples

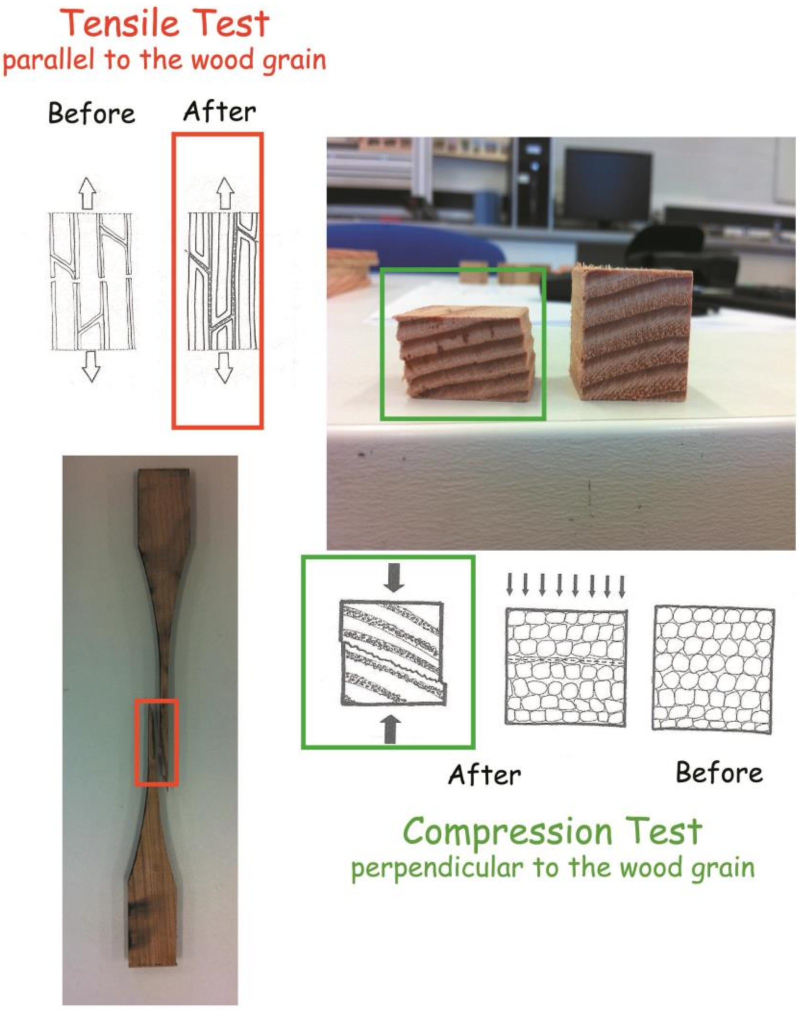


Fig. 4-4: analysis of failures modes from tensile and compression tests on timber samples. [Drawings extrapolated from Piazza et al. 2005]

Both timber species resulted in having high strength values when subjected to loads applied parallel to the wood grain, especially in tension. This feature can be generalised to all timber species because a good resistance parallel to the wood grain is developed during the natural growing condition of a tree and it is therefore classified as a natural property of wood itself (Piazza et al. 2005: 28). On the contrary, it is possible to note that the Douglas Fir and Oak samples were both less efficient in compression perpendicular to the wood grain.

The failure mode obtained during the tensile test parallel to the wood grain showed a clear separation of the wood fibres, which at a microscopic level would correspond to a failure of the cells' walls. Additionally, as it is possible to observe from Fig. 4-4, when wood was subjected to compression perpendicular to the wood grain the external force caused a failure which followed closely the wood grain direction, flattening the wood cells until cell lumens were completely compacted (Piazza et al. 2005).

It is critical to underline that a correspondence between the compressive and tensile resistance values obtained by the presented laboratory experiments and data provided by the regulation EN 338, which establishes the strength resistance classes for solid timber, cannot be found. This is mainly due to the fact that the regulation presents values of mechanical properties for structural timber which are expressed by characteristic values whose definitions take into consideration the natural defects of wood that in a timber element might cause a reduction in performance.

Contrarily, in this preliminary experimental investigation the development of tests was carried out in laboratory conditions on “net timber” which corresponds to a small portion of wood without knots or cracks or deviation of the fibre directions, all of which are examples of anatomical elements of a tree which would be defined as imperfections if contained in timber used for structural purpose (Piazza el al. 2005). Therefore resulting experimental values for the material resistance were higher than the characteristic values presented in the standard regulation EN 338.

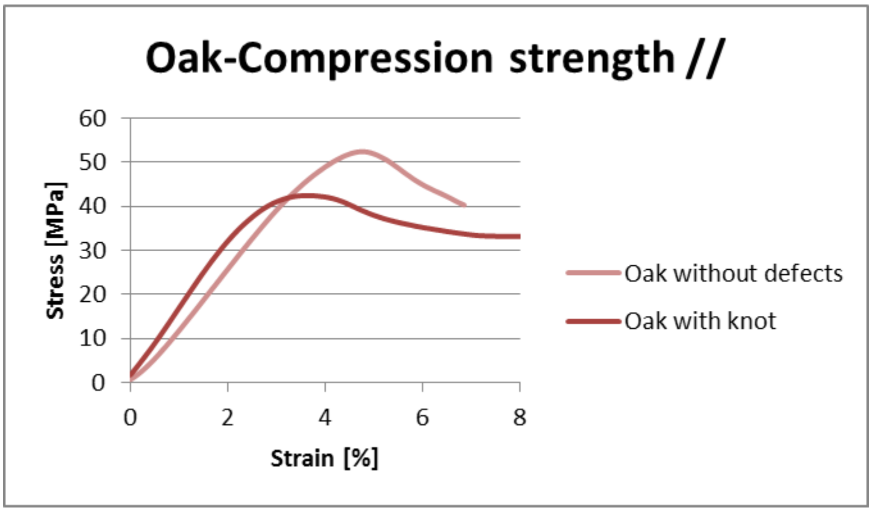


Fig. 4-5: comparison between Stress-Strain curves for a sample of “net” Oak without defects and a sample of Oak with knot.

Knots are defects developed in the timber structures during its natural growth and they cause a decrease in the wood strength because they create discontinuity in the wood grain line (Ross 2002). In order to show and quantify this significant reduction in the wood’s stress response, a single test was performed on a sample which was identified by the presence of a knot in order to compare its compression strength with a sample of “net” Oak.

As it is possible to note from the stress-strain graph in Fig. 4-5, the presence of a knot significantly affected the compression resistance of the sample when tested in compression parallel to the wood grain presenting a 20% decrease in strength. This difference in performance would be more visible in sample tested in tension parallel to the wood grain in the presence of defects. However, it is critical to underline that the classification presented in EN 338 does not classify the material itself (wood), but it gives information about the structural element made of wood. In fact if a timber element of a specific timber strength is reduced in dimension, it changes its mechanical properties due to a change in the amount of "defects" contained in the structural element (Piazza el al. 2005: 67).

In this specific research study the strength class classification for the solid timber used in these laboratory experiments was based on strong assumptions which related the studied Douglas Fir and Oak wood samples to the lowest strength classes respectively for softwood (C16) and hardwood (D18) described in BS EN 338: 2009.

4.1.2 Density and Moisture content

Further investigations were carried out to assess other physical properties of the studied wood samples such as density and moisture content.

A particular attention was focused on the determination of the humidity conditions of all the different wood species and typology used in this research investigation because past research studies defined the content of moisture (MC) as an important parameter whose variation can significantly affect the structural behaviour of timber in real application (Tlustochowicz et al. 2011).

The moisture content of solid wood (Douglas Fir and European White Oak) and Glulam timber, made from Spruce, was assessed by using a pin-type moisture meter before starting the experimental activity.

The average moisture content was around 7% amongst all wood species and types representing an appropriate moisture content value to classify the wooden samples suitable for Service Class 1 and 2, which are the EC5 Service Classes mostly recommended for the applications of adhesive connections in timber structures (Tlustochowicz et al. 2011).

In addition, the similarity showed in Table 4-1 amongst the moisture content values was a significant requirement to consider the three different timber species and typology comparable in this research work.

Timber			
Type	Solid (Douglas Fir)	Solid (Oak)	Glulam (Spruce)
Grade [EN 338:2009 (Solid)-EN 14080:2013 (Glulam)]	C16	D18	GL24
Density [Kg/m^3]	560	680	430
MC [%] by pin-moisture meter	7.5	6.9	7.4

Table 4-1: timber properties

4.2 STEEL BAR

During the laboratory experimentation carried out in this research work, threaded steel bars with a diameter of 8 mm were used to assemble adhesive anchors in timber. In particular threaded bars of different strength classes were chosen as described in Table 4-2.

Steel bar	
Diameter [mm]	8
Type and Grade	• Stainless steel bar: A2 Grade Type 304S15 • Metric threaded steel rod: Grade 8.8, 10.9 and 12.9

Table 4-2: steel bar properties

High tensile strength steel rods were selected in order to guarantee a failure mode which occurred into the connection and prevented the connection from failing by yielding of the steel bar. This latter failure mode is preferable in real applications as a safe ductile failure mode but it should not take place in laboratory conditions during a tensile test of adhesive connections in timber because it does not allow the assessment of the joint strength and the analysis of the bond properties at the adhesive/wood or steel/adhesive interfaces.

4.3 ADHESIVE

The selection of a correct adhesive plays a crucial role in the manufacturing of an adhesive anchor in timber. The adhesive transmits the load mainly through shear tensions at the gluing interface (Piazza et al. 2005) between steel and timber and for this reason its mechanical and physical properties mainly influence the structural performance of the connection.

For this research work the structural adhesives used to assemble adhesive connections in timber are epoxy resins. Epoxy is a thermosetting adhesive which is made by chemical reactions between a resin, which is the main component in the formulation, and an amine based curing agent (Clearly 2014, Rabilloud 2005). Moreover, epoxy resins are identified by good ability at filling gaps (Catucci 2011), great resistance to humidity and chemical substances and they have optimum mechanical and adhesion properties. However, the irreversible cross-linking process which characterises this adhesive type does not allow them to be melted after the hardening process (Gurit n.d.). In fact, this property belongs only to thermoplastic resins. As a consequence, epoxy resins often present a low volumetric reduction after curing. All the aforementioned characteristics mean that the application of epoxy resins is defined as particularly suitable for civil engineering work (Sgarito 2006: 42).

Epoxy resins derived their name from the formation of "epoxide functional groups" (Clearly 2014) before the cross-linking reaction. Epoxide groups are rings made of one atom of oxygen and two carbon atoms which are usually linked to hydrogen atoms (Sgarito 2006: 41) when the bond with the hardener (amines) takes place (Clearly 2014).

The epoxy resins used during the laboratory investigations carried out in this research work are amino (hardener)-based adhesive manufactured by the 2K polymer system company, based in Alfreton (UK), and characterised by different mix ratios and viscosity values. The main mechanical properties extrapolated from the manufacturer's information sheets of both epoxy adhesives are listed in Table 4-3.

Epoxy		
	EX 1:1	EX 3:1
Density [g/cm^3]	1.7	1.5
Compressive strength (7 days) [N/mm^2]	95	95
Tensile strength (7 days) [N/mm^2]	23	23
Flexural strength (24 h) [N/mm^2]	45	45
HDT (7 days) [°C]	49	49
Viscosity (20°C) [mPa.s (cps)] ± 50000	240000	720000

Table 4-3: adhesive properties (2kps 2014)

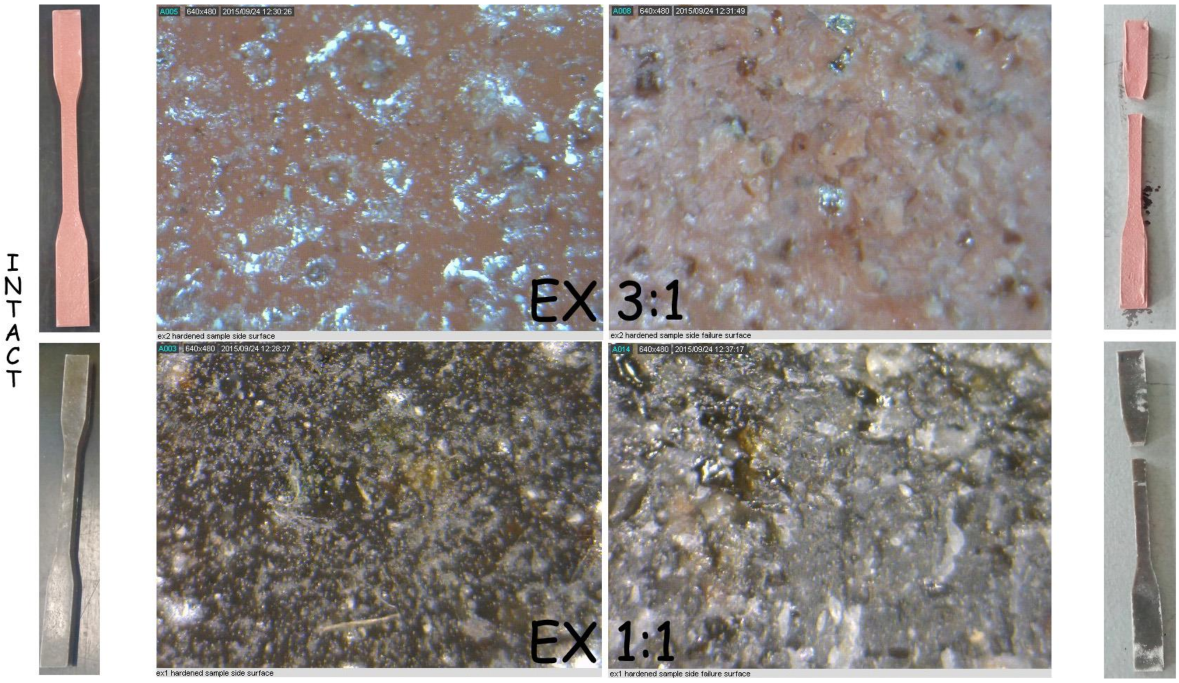


Fig. 4-6: microscopic pictures (50X magnification) of surfaces of hardened samples of epoxy resins EX 1:1 and EX 3:1 in intact (left) and failed conditions (right)

The adhesive property which mainly distinguishes EX 1:1 from EX 3:1 is viscosity. EX 3:1 is characterised by a slightly lower density and has a higher viscosity value than EX 1:1, which makes it suitable for overhead fixings. Furthermore, both epoxy resins can be easily identified by colour: dark-grey for EX 1:1 and light-red for EX 3:1, as shown in Fig. 4-6.

Currently, the use of the presented epoxy resins exclusively belongs to adhesive anchors in concrete and their use in a timber substrate is originally studied for the first time in this research study.

Tensile tests were performed on different adhesive hardened samples of EX 1:1 and EX 3:1 to determine their typical failure behaviour when subjected to tension.

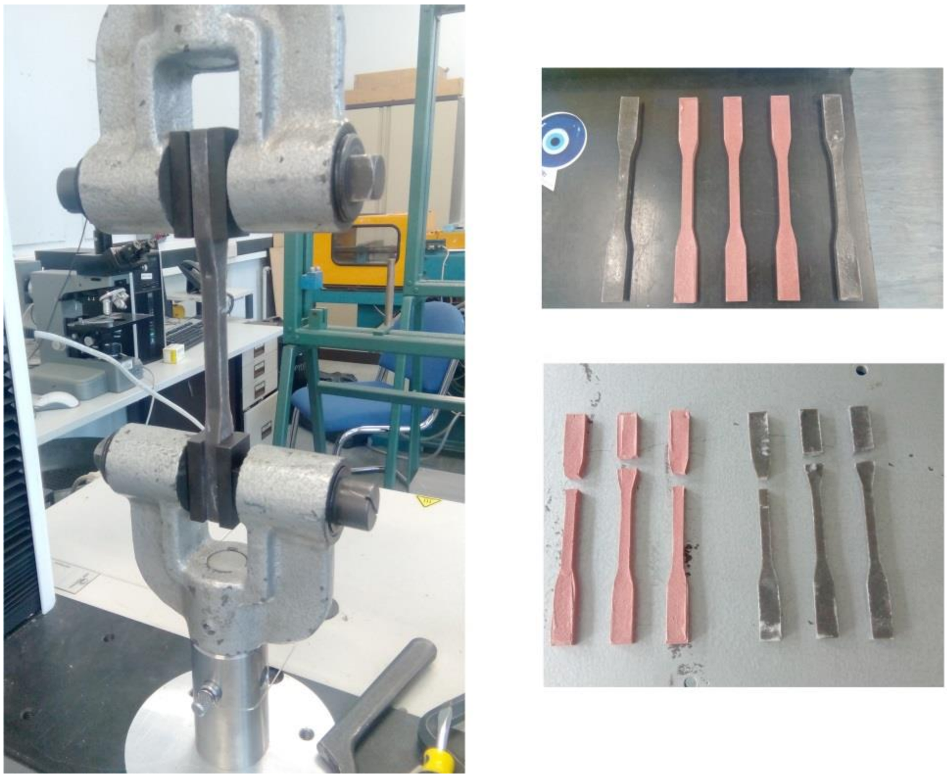


Fig. 4-7: tensile tests on hardened samples of epoxy resins EX 1:1 and EX 3:1

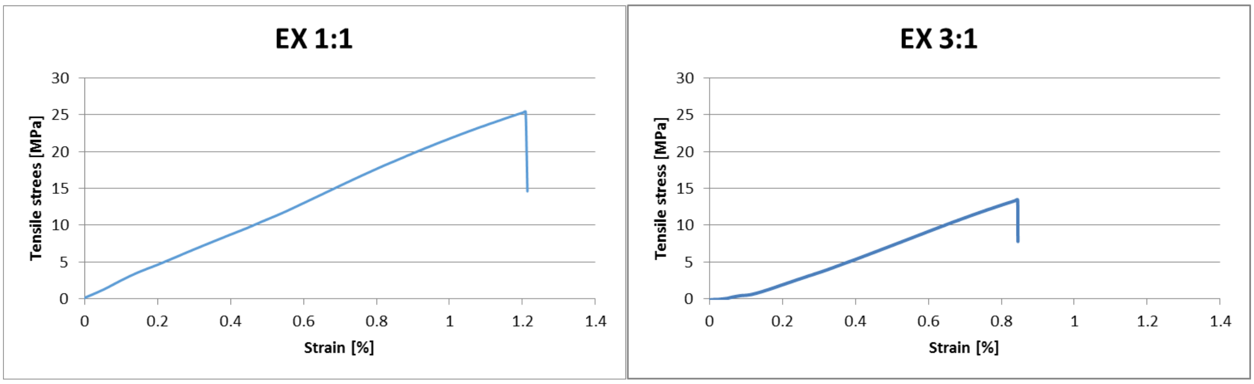


Fig. 4-8: results from tensile tests performed on hardened samples of EX 1:1 (left) and EX 3:1 (right)

Although the adhesive properties provided by the manufacturer in Table 4-3 define equal tensile strength for both epoxy resins, during laboratory tests EX 3:1 showed lower strength values than EX 1:1 (Fig. 4-8). However, from the analysis of the adhesive samples after being tested it was possible to identify the origin of this inconsistency between test results and information included in the manufacturers' product sheets. The main causes were identified by either imperfections of the hardened resin samples during the manufacturing phase, or a gripping issue during the tensile test which led to a premature failure of the specimens during the performance of the tensile tests.

It can be stated that the tensile tests were not performed following the standard regulation ASTM D638 because the experiments were not aimed at evaluating the tensile moduli but at identifying the type of failure mode which characterises EX 1:1 and EX 3:1. In fact, according to Feligioni et al. (2003) the study of the failure mode in relation to the glue rheology is an essential stage of the complete characterisation process of a resin used to assemble adhesive anchors in timber, especially when comparative studies amongst resins of the same type are undertaken.

In this specific case both epoxy glues presented a brittle failure mode classifying them as "brittle adhesive".

4.4 TIMBER-ADHESIVE

4.4.1 Lap-joints

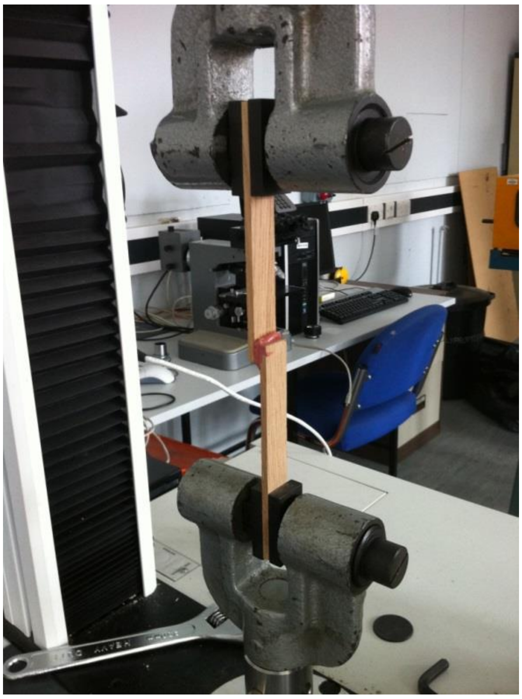


Fig. 4-9: tensile test on a single lap-joint

The contact surface between different species of solid wood (Douglas Fir and Oak) and types of epoxy resins (EX 1:1 and EX 3:1) was studied through the manufacturing process and tensile tests of 12 lap-joints (3 for each combination of materials) following the British Standard BS EN 1465:2009 in order to identify the bond strength at the adhesive-wood interface.

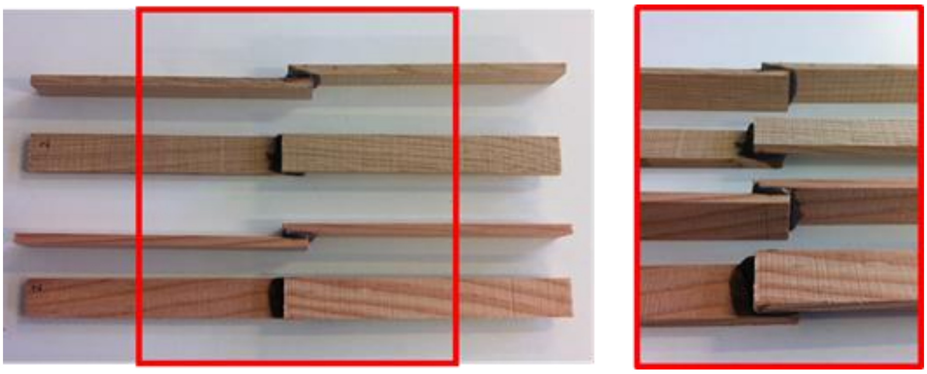


Fig. 4-10: lap-joints samples

A good bonding process involves the connection of different substrates through the use of an adhesive material which enables the formation of adhesion forces at the adhesive-substrate interface and cohesive forces within the adhesive itself. In particular, the forces which interact at the bonding layer are made by a mechanical adhesion between the resin and the surface roughness and by a specific physical and chemical interaction between glue and substrate (Catucci 2011).

In this experimentation the analysis of the bond strength was combined with an intense study of the samples failure modes in order to understand the interactions between epoxy resins and timber, including the evaluation of typical failures mode which may occur at the adhesive interface between adhesive and adherend (adhesive failure), within the glue (cohesive failure) or into the adherend material (substrate failure).

The main purpose of this study was exclusively to gain useful information about the bonding behaviour amongst different adhesive-adherend combinations of materials Glued In Rods joint could be made from.

The outcomes drawn from this experimental part cannot be used to adequately represent the pull-out performance of adhesive anchors in timber because tensile tests on lap-joints are small-scale experiments which do not accurately predict the real materials' behaviours in a resin connector in timber. For this reason, a complex experimental program on large-scale experiments on Glued In Rods in timber was subsequently performed and presented in detail in the following Chapters 5 and 6 in order to more realistically study the withdrawal capacity of adhesive connections in timber elements.

4.4.2 Bond strength analysis

The test results obtained by the tensile tests (Fig. 4-11) showed that both resins, EX 1:1 and EX 3:1, presented a good adhesion with both timber substrates.

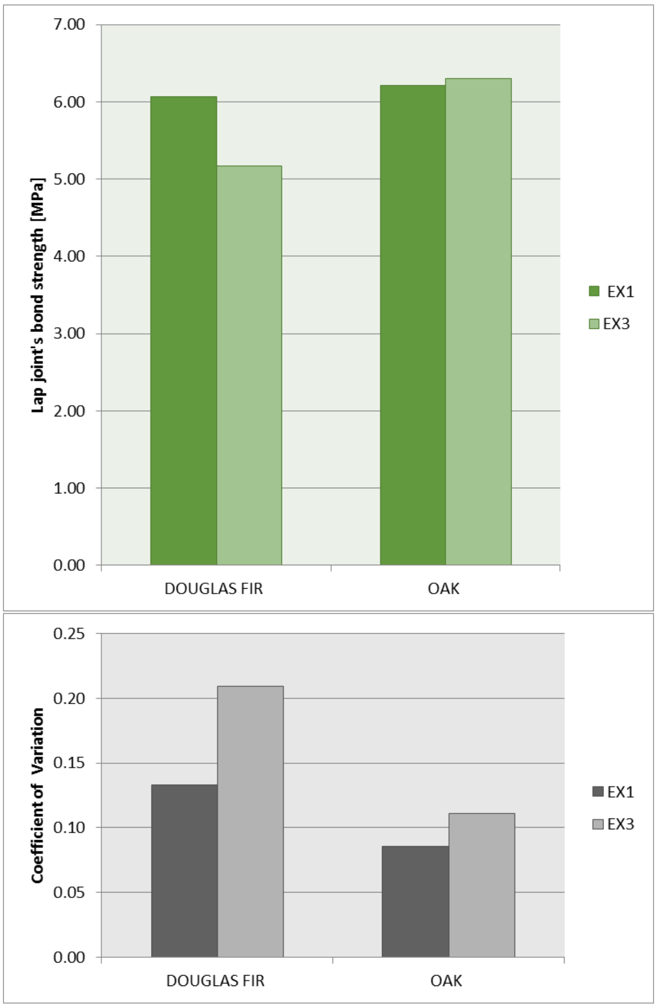


Fig. 4-11: histograms of lap joints' bond strength and relative coefficient of variation

Average bond strength values ranged between 5-6 MPa in all lap joints identified by smooth wooden surfaces and made from wood elements with similar moisture contents (≈7%). However the coefficients of variation of the bond strength of Oak samples made of either EX 1:1 and EX 3:1 are lower than Douglas Fir lap joint specimens, indicating the presence of less variable stress values. As it is possible to observe from the pictures in Fig. 4-12 and Fig. 4-13, most lap joints tested during this specific laboratory investigation showed a failure mode called "light fibre-tear failure" (Bak et al. 2013) at the bonding line between timber and epoxy which can be included in the category of adhesive failures.

Contrarily, in the Douglas Fir lap joints it was evident that some samples failed through a cohesive failure within the timber element, correctly named as substrate failure. Ideally, the adherends' failure mode should indicate an extremely good bond (Ebnesajjad and Landrock 2014) which has completely used all the adhesive strength and optimised the joint's strength by transferring the stress from the bond line into the wooden substrate.

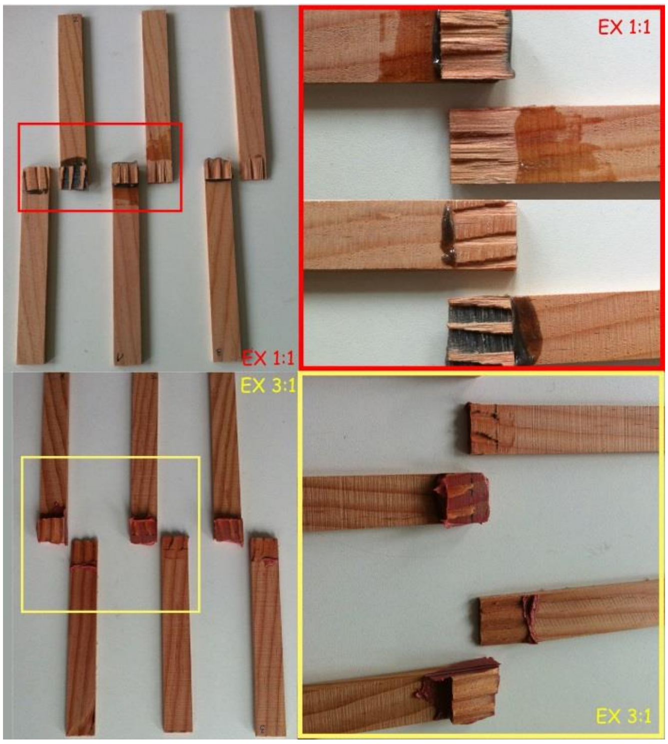


Fig. 4-12: samples of lap-joints made of Douglas Fir and EX 1:1 (top) and of Douglas fir and EX 3:1 (bottom)

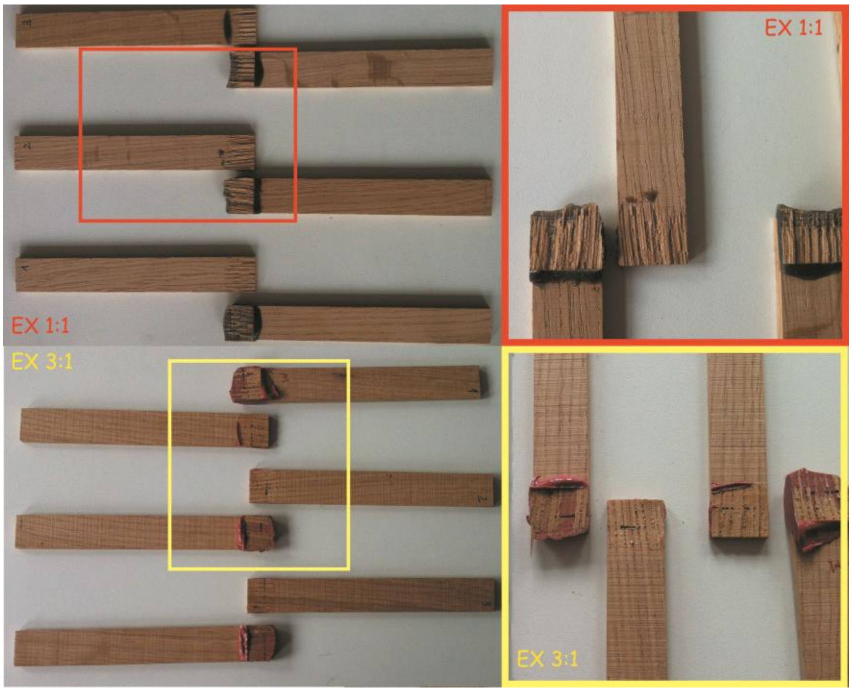


Fig. 4-13: samples of lap-joints made of Oak and EX 1:1 (top) and of Oak and EX 3:1 (bottom)

However, in this case the shear stresses obtained by this failure mode were significantly lower than the typical value of the Douglas Fir shear stress parallel to the wood grain.

Hence, it is likely that the failure in the timber element was mainly due to some manufacturing defects at the adhesive interface or in the substrate while the lap joint was assembled. In addition, bending effects caused by imperfect alignment of the samples in the testing machine might have contributed to premature failures in the wooden substrate.

Nevertheless, the best method to assess bond quality in an adhesive connection has to be largely based on the study of the ultimate strength and not exclusively on the analysis of the mechanism of bond failure (Ednesajjad and Landrock 2014).

4.4.3 Microscopic analysis

A microscopic analysis was undertaken to analyse in more detail the bond quality and the forces which interact between wood and adhesive. The depth of penetration of the glue inside the timber element and the failure mode provide important information regarding the relationship between adhesive and substrate properties.

Fig. 4-14: microscopic picture of the adhesive interphase region between wood and epoxy (left); microscopic picture of a lap-joint after being tested in tension (right)

As shown in Fig. 4-14, the bonding process between wood and epoxy created an interphase region, usually called also as transition area where it is clearly visible that the bonding process does not involve only the contact surface between the two materials but also a microscopic layer of wooden substrate. The interphase region generally can be identified by a variable thickness from nanometers to millimetres which depends on the physical properties of the substrate surface, the adhesive features and the curing condition of the bond (Catucci 2011). As it is possible to see from Fig. 4-14, it is in the interphase region that the adhesive "micro-penetration" takes place into wood (Kamke and Lee 2007) and therefore from the analysis of the interface region it is possible to extrapolate information about the bond performance.

However, the bond quality cannot exclusively be judged by the study of penetration but it is known that a good penetration will increase the possibility of having strong "secondary bonding forces and covalent bonding" which positively influence the bond performance (Kamke and Lee 2007).

The microscopic analysis of the lap joints after being tested revealed the presence of a uniform layer of wood fibres at the bonding surface between both epoxy resins and Oak (Fig. 4-13). The same failure mode was observed in Douglas Fir samples where it was possible to note that the failure was highly characterised by the wood grain direction and the orientation of the growth rings (Fig. 4-12).

However, in Douglas Fir lap joints the adhesive failure mode was identified by limited presence of wood fibres at the contact surface, showing that the adhesive penetration did not create a uniform bonding.

The reasons why it was possible to observe uniform and homogeneous bonding areas in Oak samples could be observed in some pictures of wooden surfaces taken by the use of a digital microscope. Clear comparisons could be made of the wood surfaces of both timber species with observations indicating that the presence of vessels, exclusively in Oak samples, positively influenced the bond performance by offering a bonding surface with diffuse porosity into which the adhesive can easily penetrate (Fig. 4-15 right).

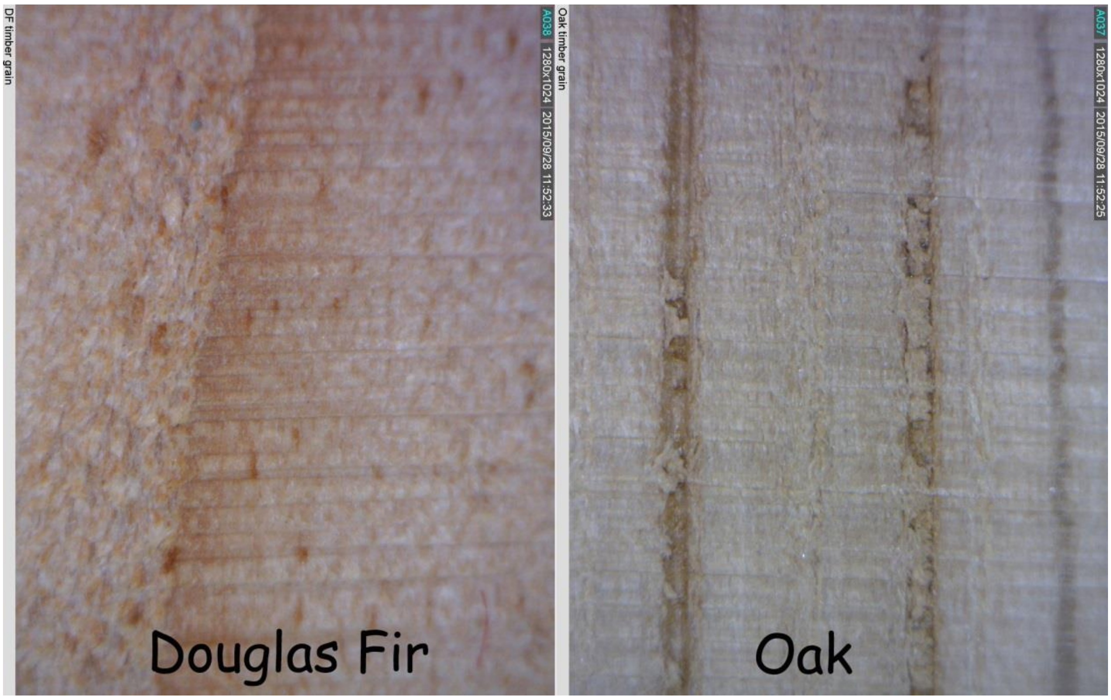


Fig. 4-15: microscopic picture of the surface of a tangential section for Douglas Fir sample (left) and Oak sample (right)

Despite little difference in the failure modes between lap joints made of Oak and Douglas Fir, it was possible to state that the use of both epoxy types on Oak and Douglas Fir substrates led to having good bonds. Both smooth surfaces were able to let the resin penetrate into the wood cells. Nonetheless, Oak offered a more porous substrate due to the anatomical structures of hardwood and showed bond strength values slightly higher than the softwood Douglas Fir.

4.4.4 Thermal analysis

A thermal analysis was conducted in laboratory conditions to investigate the bond process between epoxy resins and substrates made from Oak and Douglas Fir timber species. Four samples of lap joint were monitored by the use of a thermal imaging camera for 4 hours. Thermal pictures were taken from the beginning of the gluing process until the samples reached ambient temperature. This gap of time represents only an initial curing phase of the adhesive as it is well-known that a full hardening process would need several hours/days to complete.

In particular, this laboratory experimentation was aimed at studying the thermal behaviour at the bonding layer in order to understand the interaction between adhesive and adherend during the formation of chemical exothermic reactions between epoxy and wood at ambient temperature.

Because of the thermosetting properties of epoxy resins, during the bonding process it was possible to observe an increase in temperature due to the irreversible cross-linking reaction which takes place within the adhesive. Monitoring the curing phase is useful to help understand if the process is undertaken under correct conditions which should allow the adhesive to gain its full strength developing all the adhesive and cohesive forces needed to obtain a strong bond with timber (Catucci 2011).

The thermal camera was set by inserting the parameters listed in Table 4-4, which included different emissivity values to take into consideration the different wooden substrates analysed during the tests (emissivity values for Oak=0.89 and Douglas Fir=0.95). An insulation material was placed underneath the samples, as shown in Fig. 4-17, to prevent the measurements of the samples temperatures from being affected by external factors.

05/08/2015- Nottingham (UK)	Douglas Fir	Oak
Emissivity	0.95	0.89
Reflected temperature [°C]	24.4	24.4
Relative humidity (air)[%]	60	60
Atmospheric temperature [°C]	20.1	20.1
Object distance [m]	1	1

Table 4-4: thermal camera settings

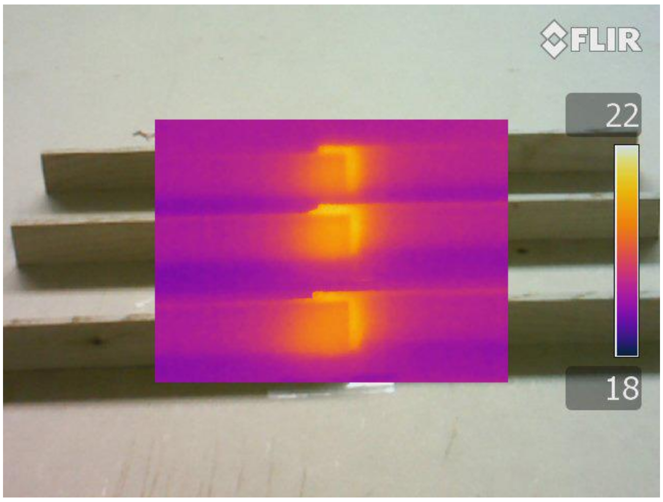


Fig. 4-16: thermal picture of lap-joints during curing phase where it is possible to observe an increase in temperature due to exothermic reactions in the adhesive connection

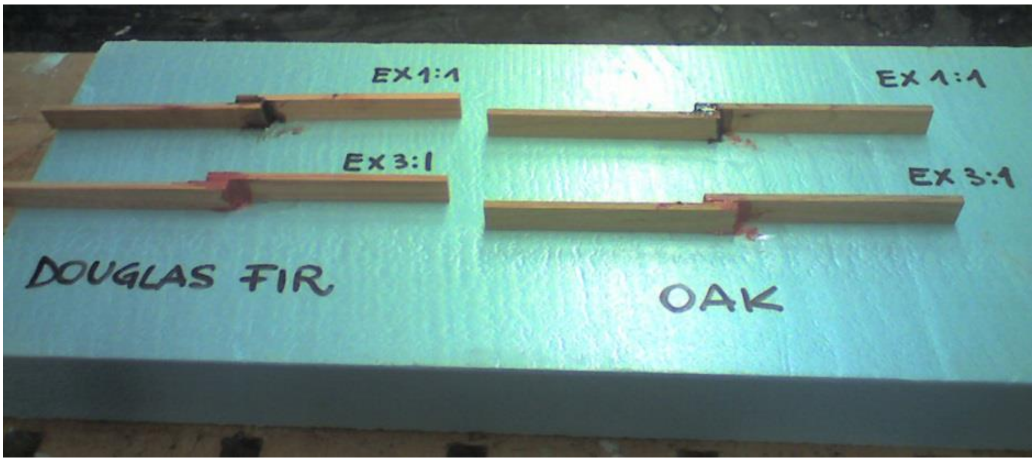


Fig. 4-17: lap-joint samples prepared for thermal analysis and laid on an insulation material

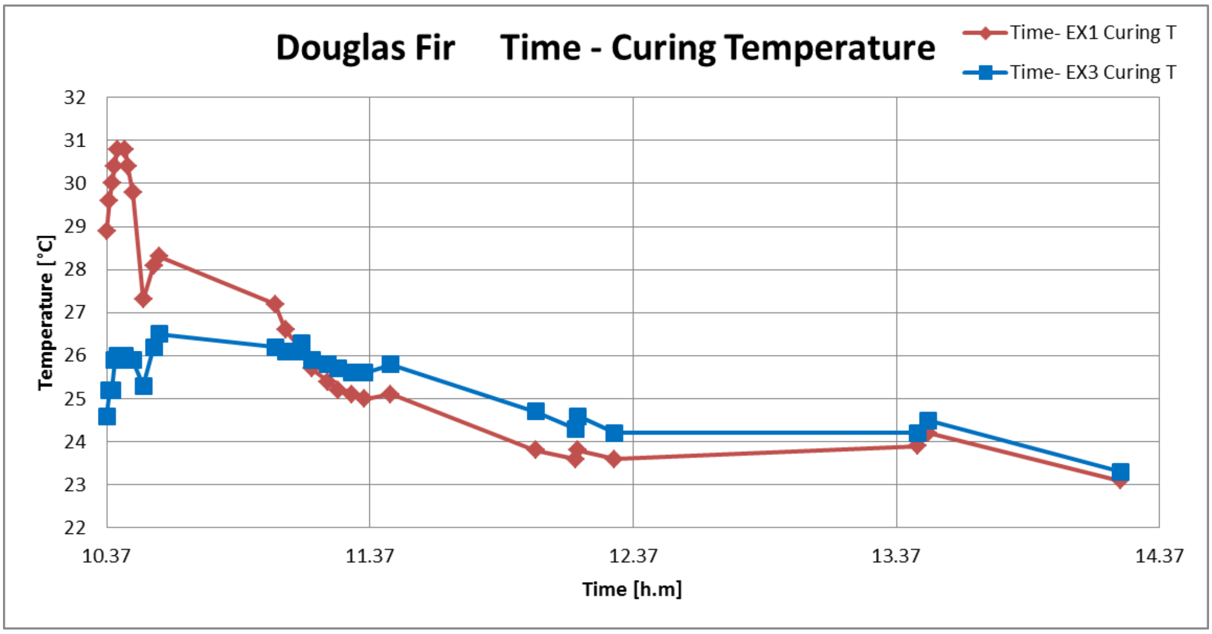


Fig. 4-18: Temperature-Time curves obtained by the use of a thermal camera for 4 hours to analyse lap- joints made of Douglas Fir wood species

From a preliminary analysis it was noted that for Douglas Fir lap joints made of EX 1:1 the temperatures, reached within the first 10 minutes, were significantly higher than the temperatures recorded for EX 3:1 samples. Although the graph in Fig. 4-18 clearly shows this initial difference in temperature of almost 5°C, further thermal analyses should be conducted to confirm this test outcome. All samples were manufactured simultaneously but the cartridges of the EX 1:1 had been opened and used before assembling the studied lap joints.

For this reason, it is likely that the chemical reaction within the nozzle of EX 1:1 had started in advance compared to EX 3:1 and the difference in temperatures might not be due to the chemical properties of the resins but to the fact that chemical reactions had been already initialised in EX 1:1.

Nonetheless, from Fig. 4-19 and Fig. 4-20 it is possible to observe that the temperatures reached during the chemical reactions between resin and wood were not influenced by the type of wooden substrate. Similar temperatures values are recorded for both Oak and Douglas Fir samples until the lap joint cooled down to lab temperatures. It was only in the first 10 minutes from the beginning of the gluing process that the Douglas Fir samples were characterised by temperatures a few degrees higher than Oak samples for both EX 1:1 and EX 3:1. However, since the thermal camera's accuracy is ±1°C, this difference in temperature may not be considered critical.

The use of a thermal camera for the study of the behaviour of adhesive connections in timber can be a useful tool which is able to provide information about the thermal reactions within the joints and to monitor the adhesive's process of gaining strength at ambient temperature. This latter information is particularly critical to guarantee that a resin will reach its maximum Heat Deflection Temperature (HDT) when subjected to elevated temperatures.

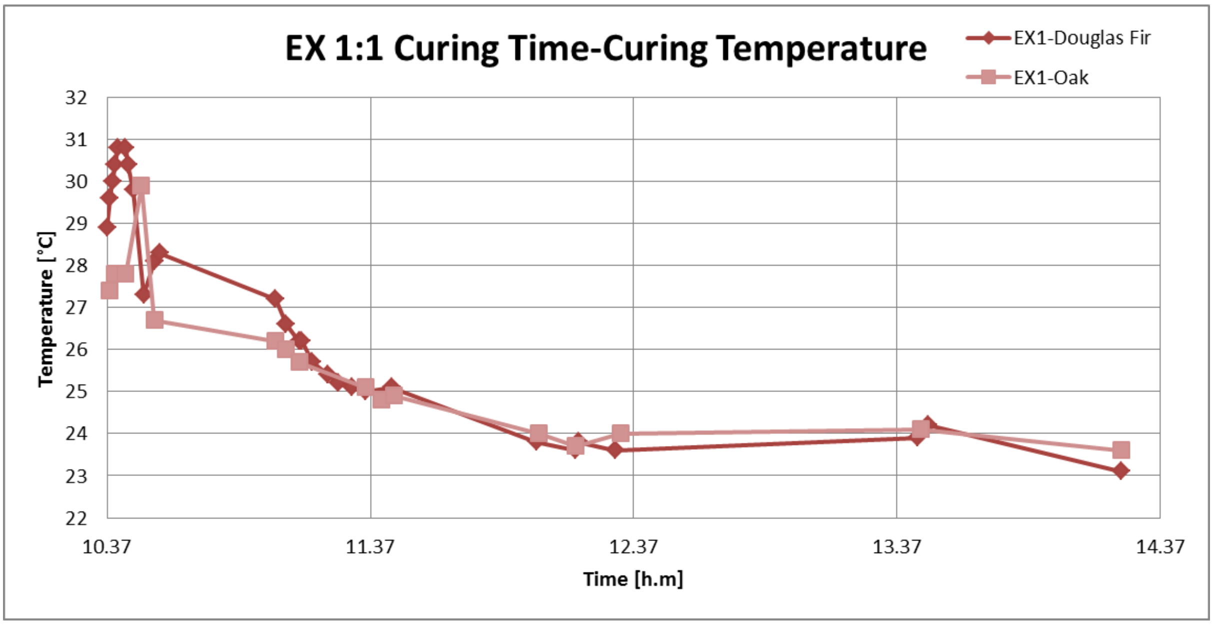


Fig. 4-19: Temperature-Time curves obtained by the use of a thermal camera for 4 hours to analyse lap-joints made of EX 1:1

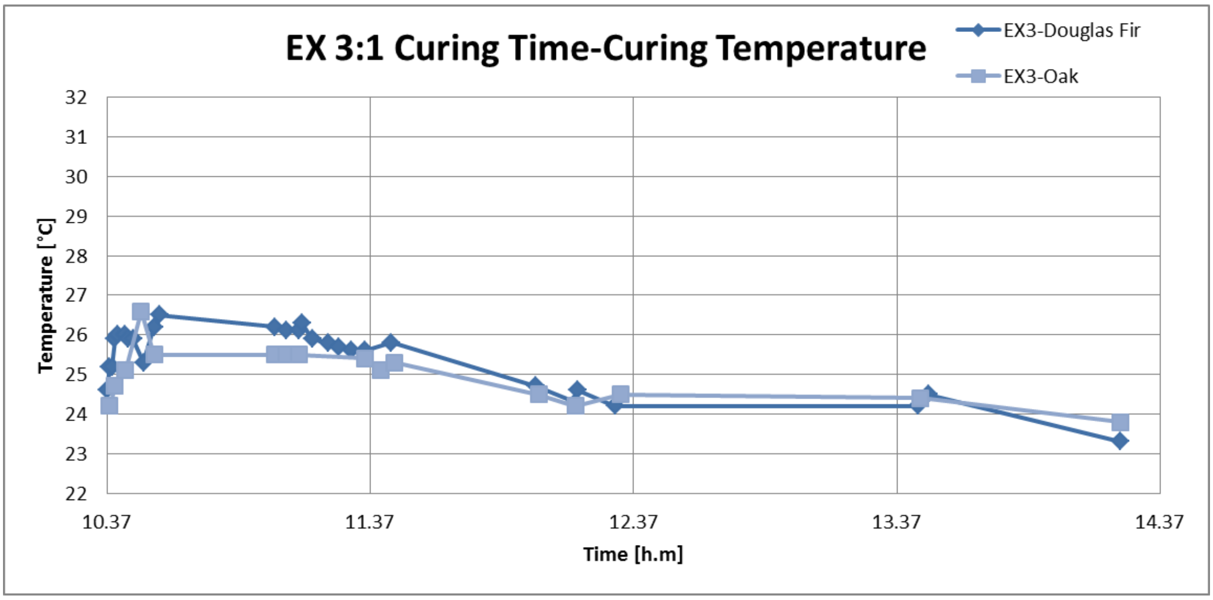


Fig. 4-20: Temperature-Time curves obtained by the use of a thermal camera for 4 hours to analyse lap-joints made of EX 3:1

4.5 SUMMARY

This chapter presents the anatomical, physical, chemical and mechanical properties of the materials chosen in this research work to assemble single adhesive anchors in timber, whose withdrawal performance will be assessed and reported in detail in the following chapters.

It originally explores the mechanical properties of new combinations of selected timber species (European White Oak - Quercus robur and Douglas Fir) and adhesive types (2kps EX 1:1 and EX 3:1) by performing:

- Compression and tension tests
- Bond strength analysis of lap joints
- Microscopic analyses
- Thermal analysis at the bonding layers.

The tests results enable a unique identification of the materials' performance and a good comprehension of the main load and heat transfer mechanisms amongst steel, timber and resin.

5. Short term experiments in cold state on new and traditional glued in rod joints

5.1 Test design

The short term experiments conducted in cold conditions on connections made of a single adhesive anchor followed a specific program, shown in Fig. 5-1, which was developed in two different experimental phases:

- *Experimental part 1* was aimed at studying and comparing the withdrawal behaviour between EX 1:1 adhesive connections with smooth and cylindrical boreholes, identified in this thesis with the abbreviation CYL, and prototypes of adhesive anchors in solid timber with an internal threaded bonding surface which were labelled as THR.
- *Experimental part 2* was aimed at examining in depth the pull-out capacity of the resin connections studied in the *Experimental part 1* by testing different glued lengths and manufacturing the connections by the use of epoxy resins with low and high viscosity (EX 1:1 and EX 3:1) in different timber substrates (solid and Glulam).

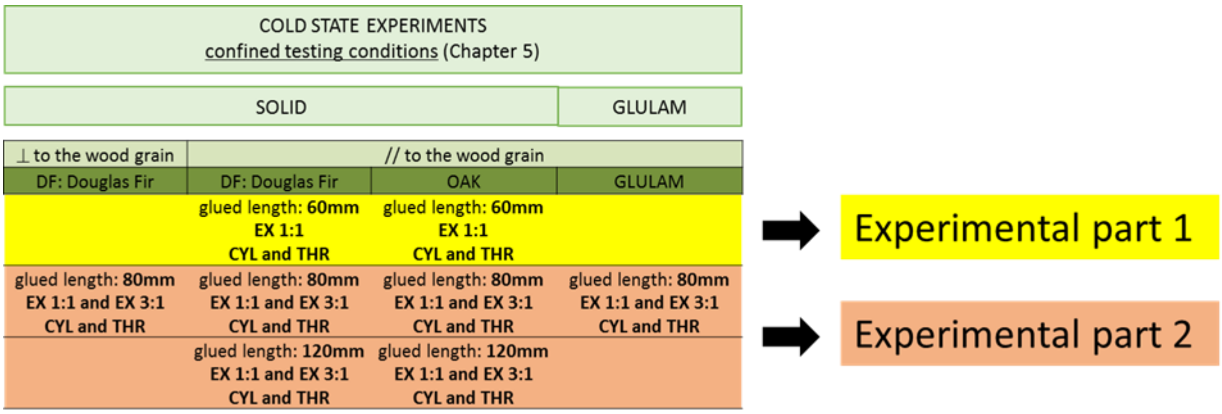


Fig. 5-1: test design

5.2 Experimental part 1: Threaded Borehole Shape and Use of Epoxy 1:1

5.2.1 Test description

An experimental test was conducted on 10 wooden samples of 1000 cm^3 volume (Fig. 5-2) made from Oak and Douglas Fir timber species to study the performance of new prototypes of adhesive anchors and to compare their load capacity to ‘traditional’ Glued In Rod joints, identified by smooth and cylindrical bonding surfaces, 60 mm glued length and 2 mm glue line thickness.

The adhesive joint's prototype was characterised by the use of an 8 mm steel bar glued by epoxy adhesive (variable glue line thickness between 0.5 and 2mm) into a threaded-shape internal borehole, 60 mm long.

The experiment aimed to analyse the different joints' behaviour and assess which performs best in term of strength and stress response.

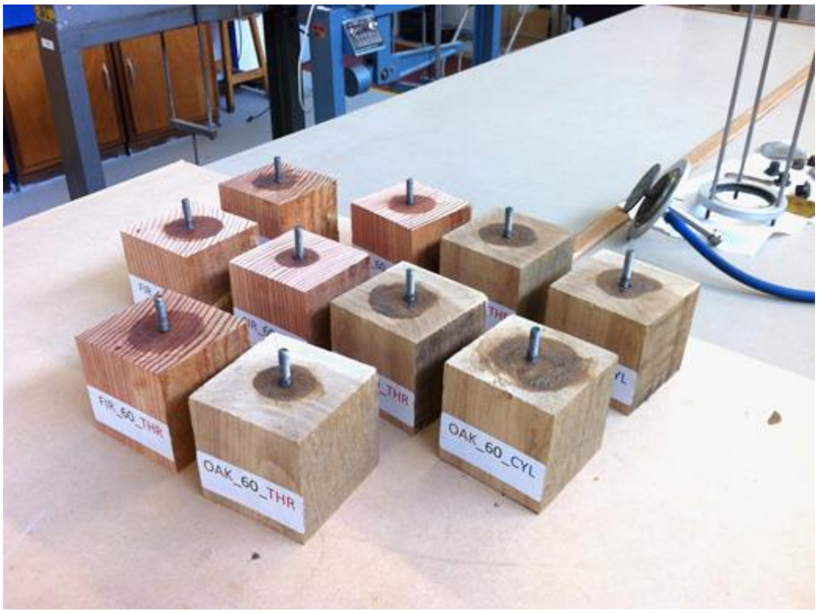


Fig. 5-2: test samples (10x10x10 cm) (Di Maria and Ianakiev 2015)

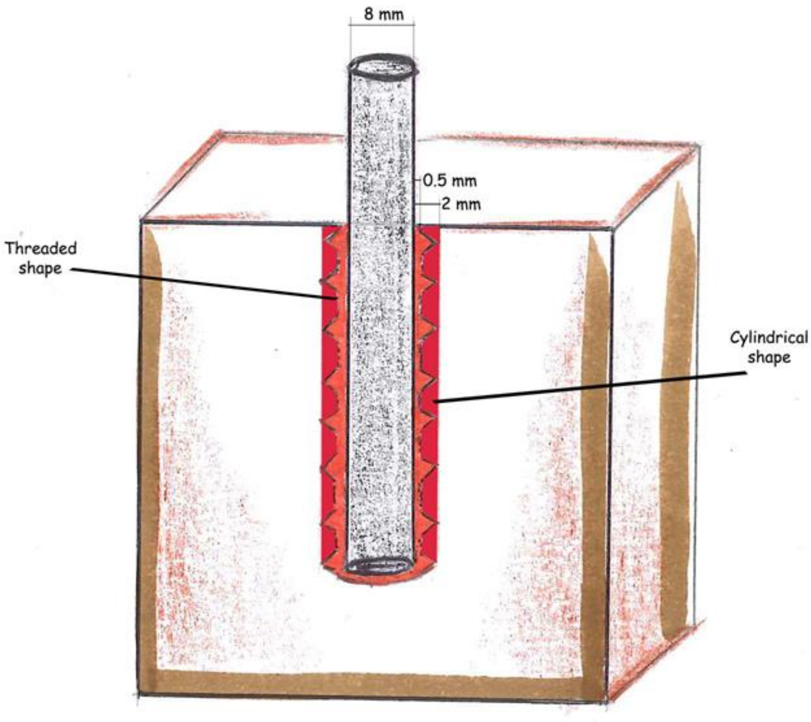


Fig. 5-3: sketch of a resin connectors in which are represented both internal hole shapes (cylindrical and threaded) for comparison

5.2.1.1 *New prototype of a glued in rod joint*

The new joint prototype is characterized by a new internal hole shape realized by a drill using a specific drill bit for woodworking (Fig. 5-4).

Fig. 5-4: drill bit for woodworking (12 mm external diameter) (Di Maria and Ianakiev 2015)

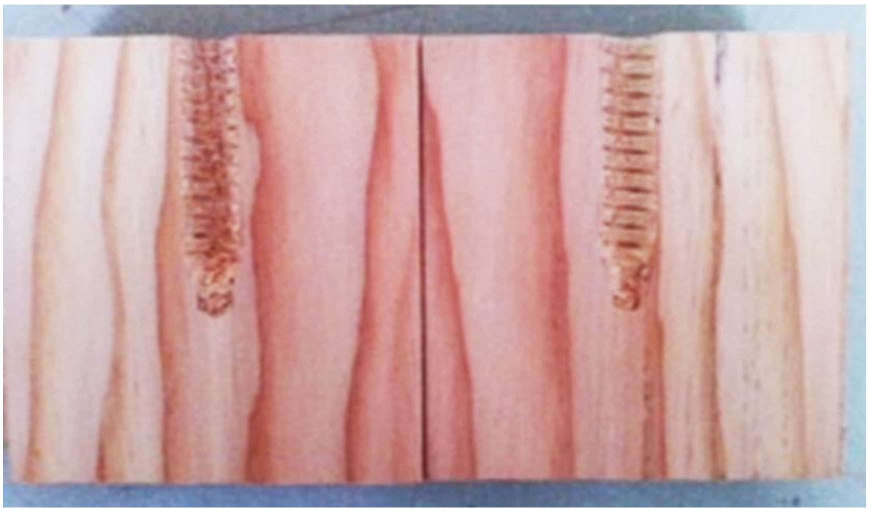


Fig. 5-5: internal rough and threaded surface in a Douglas Fir timber samples (Di Maria and Ianakiev 2015)

As it is possible to note from Fig. 5-5, the new borehole is characterised by a threaded and rough internal surface which represented an increased contact area between timber and adhesive, enhancing the penetration process of the resin towards the wooden substrate.

The innovative manufacturing procedure used during the drilling phase to assemble the presented new joint prototype was chosen to allow the epoxy resin to deeply penetrate into the interstices of the wooden adherend such as “cracks and damaged cells” which usually can increase the bond performance and consequently enhance the joint strength creating uniform stress distributions within the materials when loaded (Kamke and Lee 2007, Catucci 2011).

Furthermore through the visual comparison between Fig. 5-5 and Fig. 5-6, it is possible to identify that the volume of the threaded hole is smaller than the cylindrical one, as it could be contained entirely within the cylindrical hole shape as shown in Fig. 5-3. For this reason the manufacturing process of the new joint prototype required a reduced use of adhesive.

Fig. 5-6: internal cylindrical and smooth surface in an Oak timber samples which presents a change in the size diameter at the bottom of the hole to solve bar's stability issues.

5.2.2 Materials

The joints' samples (Fig. 5-2) were assembled using the materials listed in Fig. 5-7.

Timber		
Type	Solid (Douglas Fir)	Solid (Oak)
Grade	C16	D18
Density [Kg/m^3]	560	680
MC [%]	7.5	6.9
Steel bar		
Diameter [mm]	8	
Type	Threaded	
Grade	A2 Type 304S15	
Epoxy		
		EX 1:1
Density [g/cm^3]		1.7
Compressive strength (7 days) [N/mm^2]		95
Tensile strength (7 days) [N/mm^2]		23
Flexural strength (24 h) [N/mm^2]		45
HDT (7 days) [°C]		49

Fig. 5-7: materials for experimental part 1

The information related to the epoxy resin used in this laboratory experimentation had been extrapolated from the product information sheets (2kps 2014).

5.2.3 Manufacturing process for glued in rod joints

The installation mode for Glued In Rod joints is another critical aspect that has to be considered during any practical application of adhesive anchors. Steiger et al. (2015) graphically presented examples of adhesive anchors in timber whose imperfections are mainly caused by incorrect installation procedures.

Adhesive anchors in timber are highly dependent on the geometrical properties of each material the joint is made of; for this reason, for this laboratory investigation the joints' preparation followed a specific installation method which had been designed in order to solve issues related to erroneous installations of the steel rods in adhesive connections in timber, mainly known as 'off-centered rod' problems. The new hole shape and the insertion of some plastic supports in the joint allowed the steel bar to maintain a perfect vertical position without having to fix it in place during the resin curing time. A specific installation method for Glued In Rod joints had not been suggested by any of the previous research studies, but finding a solution for practical issues and providing standard installation rules can represent a great achievement to improve the practical installation of resin connectors in situ.

5.2.3.1 Innovative installation method

1. "Drill a first hole choosing the steel bar diameter and a depth length that is 1 cm deeper than the designed embedded length. This step will provide a base for the steel bar insertion.
2. Drill a second hole to the designed shape, diameter and depth.
3. Clean the hole through several blows and brushes.
4. In the hole cleared from any timber dust, insert the epoxy following the instructions suggested by the manufacturing company (2kps 2014).
5. Insert the threaded steel bar twisting with a back and forth movement until the end of the hole (2kps 2014).
6. Insert a specific plastic support ring through the steel bar to the joint's surface. This support will help the bar to maintain a vertical position during the resin curing phase" (Di Maria and Ianakiev 2015)

Fig. 5-8: installation method

It is important to underline that all timber samples were drilled parallel to the wood grain and the gluing process was strictly carried out following the instructions provided by the epoxy's manufacturer (2kps 2014). Since the selected epoxy resin is mainly produced for concrete applications, the loading time provided in the resin datasheet was increased up to 36 hours to achieve full strength and cure in wooden substrates.

5.2.4 Laboratory experimentation

5.2.4.1 Test method and test equipment

The samples were tested by a pull-out testing machine (Fig. 5-9) with a specific loading rate of 0.2 kN/sec to assess the pull-out capacity of each joint's prototype. All tests were performed as confined tests, therefore in a pull-compression test regime.

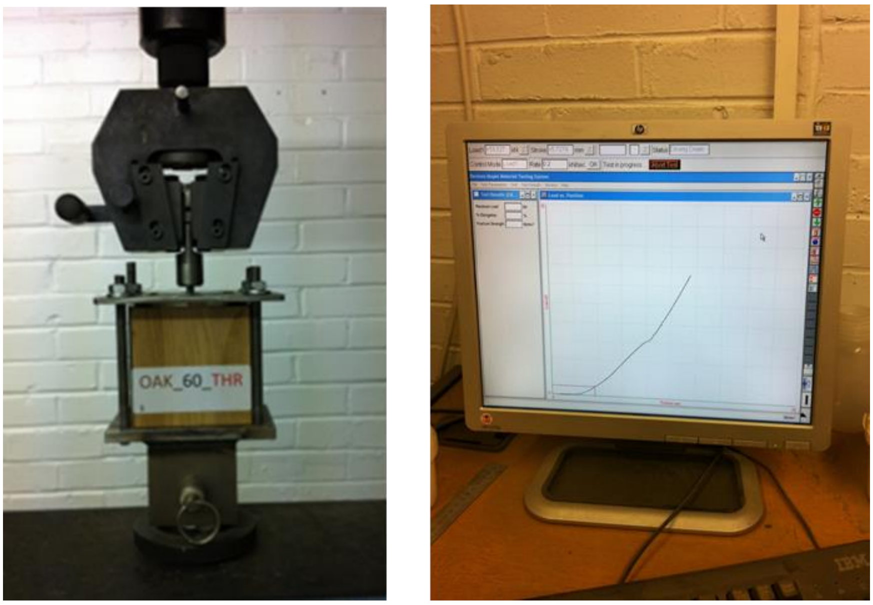


Fig. 5-9: *tensile loading test by Avery Devison testing machine*

5.2.5 Test results

Code	Glued Length [mm]	Glue line Thickness [mm]	Contact area [mm^2]	Moisture Content [%]	N [kN]	N_m [kN]	d_{net} [mm]	$d_{net,av}$ [mm]	$\tau_{adhesive/wood}$ [N/mm^2]	$\tau_{adhesive/wood,av}$ [N/mm^2]	$\tau_{steel/adhesive}$ [N/mm^2]	$\tau_{steel/adhesive,av}$ [N/mm^2]	Failure Mode
FIR_60_C_EX1_1	60	2	1885	6.9	28.41	27.58	7.17	6.57	15.1	14.6	18.8	18.3	adhesive-timber
FIR_60_C_EX1_2	60	2	1885	6.9	26.75		5.97		14.2		17.7		adhesive-timber
FIR_60_T_EX1_1	60	var 0.5-2	2026	6.9	27.95	28.33	5.74	6.47	13.8	13.8	18.5	18.8	adhesive-timber
FIR_60_T_EX1_2	60	var 0.5-2	2026	6.9	28.83		6.12		14.2		19.1		adhesive-timber
FIR_60_T_EX1_3	60	var 0.5-2	2026	6.9	28.20		7.57		13.9		18.7		steel failure
OAK_60_C_EX1_1	60	2	1885	7.5	22.88	24.00	4.72	4.93	12.1	12.1	15.2	15.9	adhesive-timber
OAK_60_C_EX1_2	60	2	1885	7.5	25.12		5.14		13.3		16.7		adhesive-timber
OAK_60_T_EX1_1	60	var 0.5-2	2026	7.5	23.81	24.93	5.40	5.60	11.8	11.8	15.8	16.5	adhesive-timber
OAK_60_T_EX1_2	60	var 0.5-2	2026	7.5	25.79		5.97		12.7		17.1		adhesive-timber
OAK_60_T_EX1_3	60	var 0.5-2	2026	7.5	25.18		5.43		12.4		16.7		adhesive-timber

Table 5-1: test results of experimental part 1

The test results in Table 5-1 show that adhesive joints made from Douglas Fir performed better having failure load values (N [kN]) almost 15% higher than the withdrawal strength of Oak samples. The change in the hole shape for the new joint prototypes (threaded samples: T) led to a slight increase in the withdrawal capacity and in the bond strength at the steel/adhesive interface.

In particular, the shear stress between steel and resin reached values around 18 MPa in Douglas Fir samples and 16 MPa in Oak samples confirming that the epoxy resin (EX 1:1) was able to successfully transfer load from steel to timber.

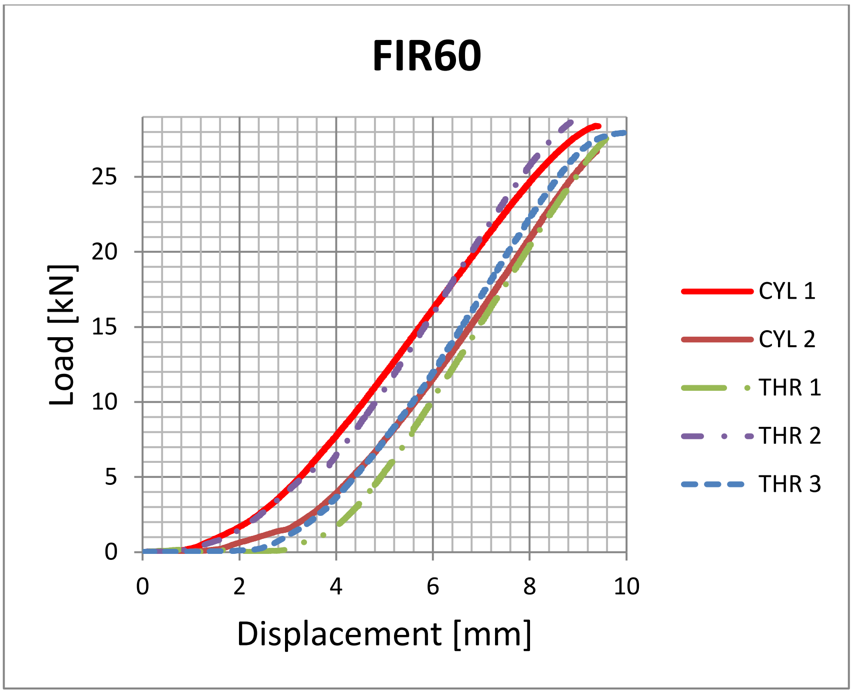


Fig. 5-10: load-displacement curves for Douglas Fir Glued In Rod joints (CYL: cylindrical and THR: threaded) (Di Maria and Ianakiev 2015)

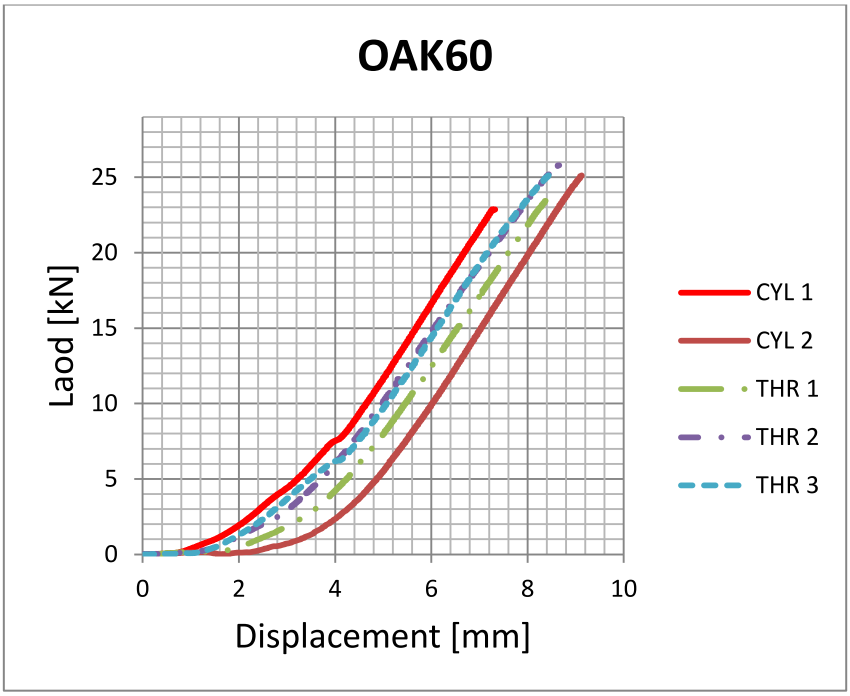


Fig. 5-11: load-displacement curves for Oak Glued In Rod joints (CYL: cylindrical and THR: threaded) (Di Maria and Ianakiev 2015)

The load-displacement graphs obtained from the results analysis do not show a visible improvement in the pull-out capacity of the joint for the new threaded shape. In fact, it is possible to observe that the mean failure load for cylindrical and threaded samples are very similar in both timber species (Oak and Douglas Fir).

In addition in Fig. 5-10 and Fig. 5-11, it is possible to observe that the load-deformation curves' slopes are all parallel to each other following the same trend in each test showing a similar behaviour of the studied adhesive connections in terms of stiffness.

Although the variation in the borehole from a cylindrical to a threaded shape did not affect the stiffness of the joints, the threaded borehole samples reached the highest pull-out load values and showed a regular trend in the pull-out test results, whereas the lowest values were obtained by the cylindrical samples that showed a significant variation in their results.

Furthermore, the threaded joint had a great advantage: it presented a critical reduction in the hole volume. In fact, in this specific test, the 'effective holes volume', calculated by deducting the steel bar volume from the entire borehole volume, was reduced from 3143 mm^3 (cylindrical shape) to 1973 mm^3 (threaded shape). Hence, the manufacturing process of the new joint prototype was characterised by almost 40% reduction in the use of resin during its manufacturing process.

The typical "load-slip-curve of fasteners" can be useful to identify and understand the mechanical behaviour of joints. Comparing the curves in the graphs (Fig. 5-10 and Fig. 5-11) to the "typical load-slip-curve of fasteners" (Augustin 2008), it was possible to note that all samples presented a significant initial slip which might be caused by problems in the grips between the steel bar and the testing machine during the initial testing phase leading to unprecise displacement values.

The curves obtained by the withdrawal tests were corrected by translating the origin of the axes into the "coordinate system for modelling and analysis". However, the recorded displacement values resulted in being not very accurate. This inaccuracy proved that modifications in the testing procedures had to be applied for further and subsequent experimental tests.

Moreover, from the comparison between the curve obtained by the performed pull-out tests and the "typical load-slip curve of fasteners" it was evident that all samples had a brittle failure mode. However, steel bars with high tensile strength had been chosen for this experimental activity and, for this reason, the failure had occurred in timber members. The expected failure mode, named as adhesive failure, at the adhesive-wood interface allowed the study of the real pull-out bearing capacity of the tested adhesive connections.

In real applications, the selection of steel rod with lower tensile strength would lead to having the failure in the steel bar, thus guaranteeing a ductile failure mode of the glued in bolt joint.

Fig. 5-12: cylindrical (CYL) tested samples (Di Maria and Ianakiev 2015)

The amount of timber that remained attached to the hardened resin could provide information regarding the bonding quality; for this reason a visual analysis of the tested samples plays a crucial role in investigating the structural performance of Glued In Rods in timber substrates.

Pictures in Fig. 5-12 and Fig. 5-13 show respectively the cylindrical and threaded joint samples after being tested by confined pull-out tests.

The cylindrical and smooth surfaces, drilled parallel to the timber grain in each wooden sample, are identified by a non-homogeneous distribution of wood fibres around the hardened resin.

On the other hand, the threaded hole shape provided to the adhesive joint prototypes (Fig. 5-13) a rough internal contact surface which allowed the resin to stick consistently through the wood fibres. The wooden parts attached to the cured resin on the steel bar in the threaded samples are significantly visible and sizeable. Moreover, as shown in Fig. 5-14, the epoxy resin was able to deeply penetrate into the threads creating a further mechanical connection between adhesive and substrate in samples made from both timber species.

This latter observation proves that through the manufacturing process of threads at the wood-adhesive interface it was possible to create a mechanical interlocking between timber and epoxy.

Fig. 5-13: threaded (THR) tested samples (Di Maria and Ianakiev 2015)

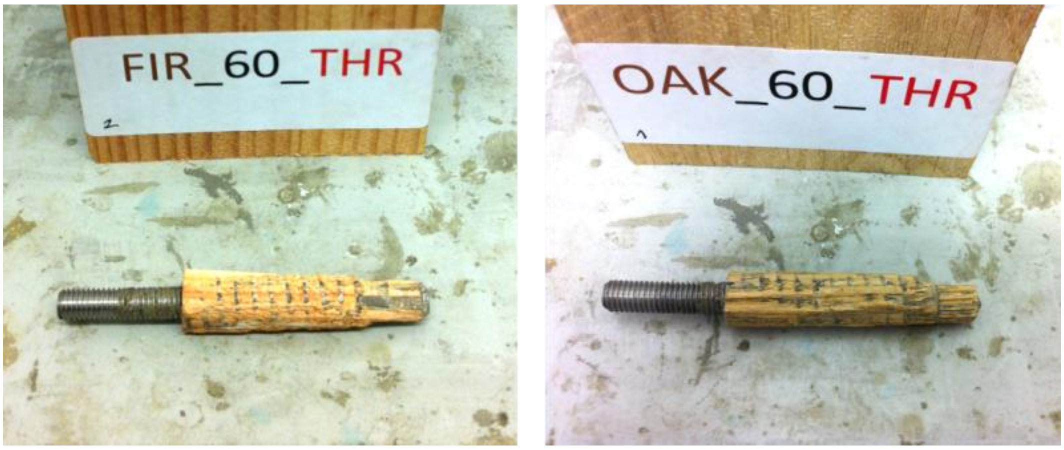


Fig. 5-14: threaded hole shape samples made from Oak and Douglas Fir timber species (Di Maria and Ianakiev 2015)

5.2.6 Result discussion from experimental part 1

- Douglas Fir joint samples reached the highest pull-out values during the experimental test;
- An improved bonding condition between timber and resin was reached using an irregular and rough surface for the drilled borehole in the timber samples;
- For timber samples characterised by short lengths (60 mm), threaded hole joints performed slightly better than the cylindrical hole joints;
- The new threaded hole joints have almost the same pull-out capacity of cylindrical hole joints but they require almost 40% less resin. This saving would be taken into consideration as a significant abatement in the joint's cost production.

5.3 Experimental part 2: New Threaded Borehole Shape and Use of Epoxy 1:1 and 3:1 in Glulam and Solid timber

5.3.1 Test description

This second experimental part was developed at NTU's lab and at 2K Polymer Systems company's laboratories; it aimed to finalise and improve the design methods applied during the pilot study and the first experimental part.

Three critical choices were made before starting the second experimental part:

1. the first choice regarded the change in the drill bit used to create the threaded shape in the timber samples. The drill bit adopted in the first experimental part was hard to use during the manufacturing process of the joint's prototype. For this reason, a different tool was needed to create the threaded bore hole in timber in order to make the design process more feasible in real installations of Glued In Rod joints. The new

solution for this practical design problem was identified with the use of a screw characterised by specific geometric parameters (external diameter 12 mm; internal 9 mm) which were consistent with the size of the drill bit used during the experimental part 1

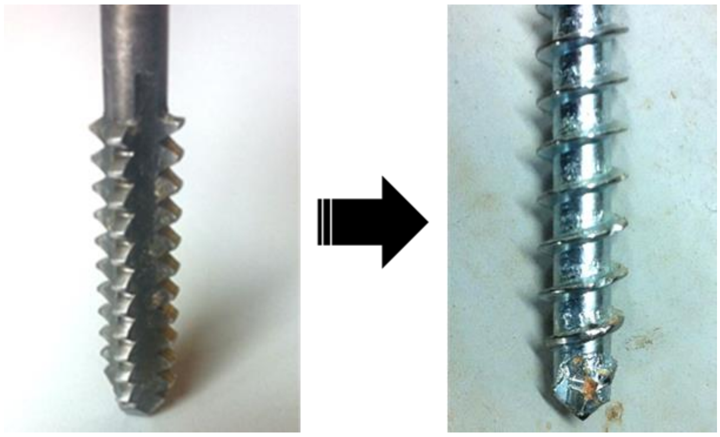


Fig. 5-15: drill bit (left) and screw (right)

2. the second choice was to introduce the use of a particular epoxy resin into the joint's production process. A two-component 3:1 ratio epoxy was chosen because is it characterised by a different viscosity value. The intention was to investigate how the viscosity property of adhesives could affect the glue penetration process into the wood fibres in order to identify the best bonding condition for both smooth and threaded timber surfaces for the studied joint prototypes
3. the third choice was to study the performance of the suggested joint prototype made from glulam timber.

In particular, this second experimental activity was carried out on 48 samples of adhesive anchors using solid timber (Oak and Douglas Fir timber species) and Glued Laminated Timber (GL 24: Spruce), 1:1 and 3:1 epoxy resins and 8 mm steel bars.

Fig. 5-16: test samples for experimental part 2 made of EX 1:1 and EX 3:1

The samples were identified with different glued lengths (80 mm and 120 mm) and different timber bonding surfaces with specific geometrical properties (new threaded and cylindrical bore hole shapes). The pull-out strength of these singular bar connections was tested by the same testing method adopted in the previous experimental phases.

5.3.2 Materials

The materials adopted for the experimental part 2 are listed in Fig. 5-17.

	Timber		
Type	Glulam (Spruce)	Solid (Douglas Fir)	Solid (Oak)
Grade	GL24	C16	D18
Density [Kg/m^3]	430	560	680
MC [%]	7.4	7.5	6.9
	Steel bar		
Diameter [mm]		8	
Type		Threaded	
Grade		A2 Type 304S15 8.8, 10.9 and 12.9	
	Epoxy		
		EX 1:1	EX 3:1
Density [g/cm^3]		1.7	1.5
Compressive strength (7 days) [N/mm^2]		95	95
Tensile strength (7 days) [N/mm^2]		23	23
Flexural strength (24 h) [N/mm^2]		45	45
HDT (7 days) [°C]		49	49
Viscosity (20°C) [mPa.s (cps)] ± 50000		240000	720000

Fig. 5-17: materials for experimental part 2

5.3.3 Manufacturing process

5.3.3.1 Threaded shape

In the presented experimental programme on the short-term pull-out behaviour of adhesive anchors, the manufacturing process of the connection for the creation of the threaded shape of the joint's borehole required modifications. Instead of drilling a hole by the use of the specific drill bit shown in Fig. 5-4, the threaded shape was made by drilling a screw in and out of the wooden substrate. The new threaded shape (Fig. 5-18: top) maintained the same external diameter of 12 mm of the previous drilled borehole (Fig. 5-18: bottom); furthermore, the use of a 12 mm screw for wood applications allows the creation of more defined threaded into the wooden substrate and a further reduction in the hole volume.

Fig. 5-18: threaded borehole shape made by a specific drill bit (bottom) and by a 12 mm screw (top)

It resulted in being an easy-to-use solution which increased the feasibility of using the adhesive joint prototype on site and in factory conditions.

5.3.3.2 *Resin shelf life*

The bond strength is highly dependent on the adhesive performance. If the adhesive loses strength, consequently the bond quality will be negatively affected.

During the experimental work presented in this chapter, some samples had shown erroneous test results because of manufacturing defects during assembly. All faulty samples were re-manufactured and tested in order to provide reliable information on the structural behaviour of the studied adhesive connections and are identified in the graphs in Fig. 5-30 with the red label 'Correction'.

This defective behaviour of some adhesive connections was mainly caused by an erroneous application of epoxy resin while manufacturing the joints. A single cartridge of epoxy was used to assemble several connection over a period of 1 week in order not to waste resin as it is one of the most expensive materials which characterised a Glued In Rod connection.

Although no anomaly had been identified in the gluing process, all samples manufactured by the use of epoxy resin injected from a cartridge previously opened and therefore not new presented very low withdrawal capacity during the pull-out tests.

The following experiments were performed to prove that the shelf life of a single cartridge once opened is time-limited.

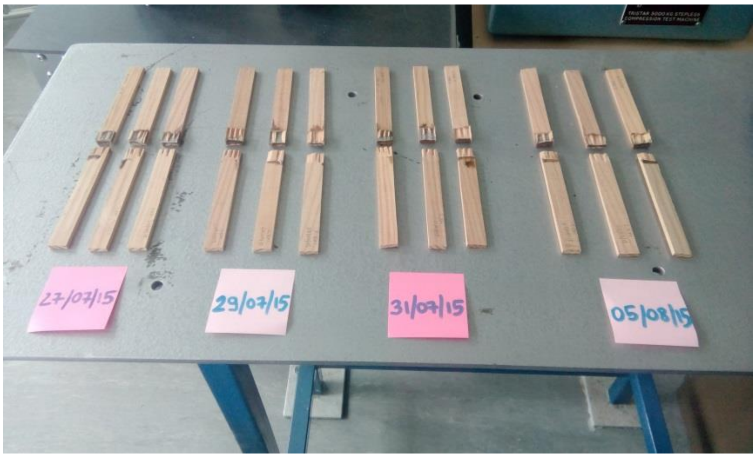


Fig. 5-19: same samples of tested lap joints for tests about the shelf life of epoxy contained in a single cartridge

A cartridge of epoxy resin (EX 1:1) had been used 1, 3, 5, 10 and 53 days after opening to assemble a set of 24 lap joints. Subsequently, tensile tests were performed to assess the bond strength values of the joints and the results are shown in Fig. 5-20.

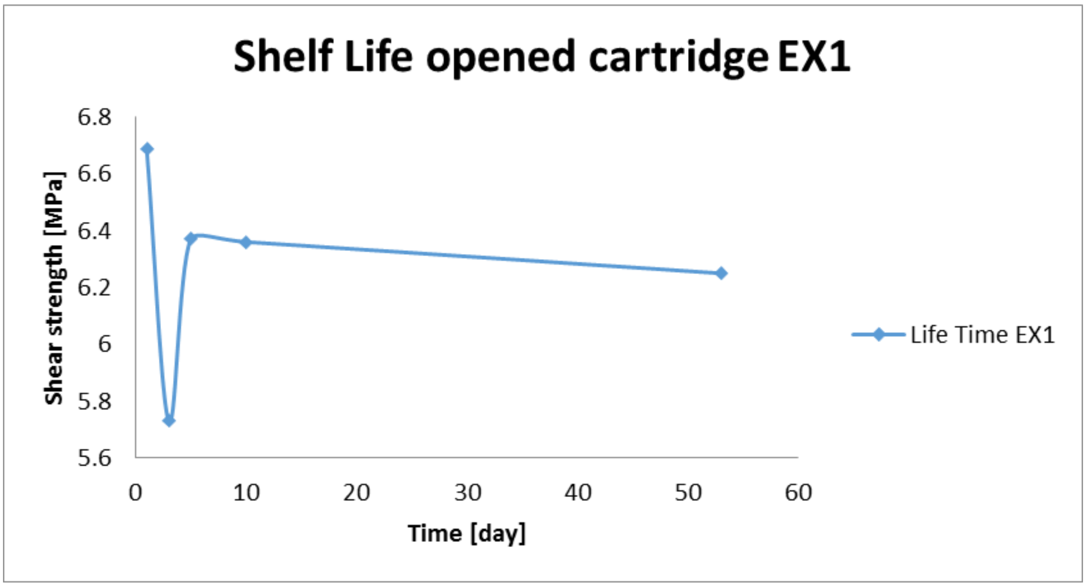


Fig. 5-20: bond strength-time curve

It is evident through the analysis of the bond strength values that lap joints made from a new cartridge of epoxy had the best performance. The adhesive bond in the joint lost strength as time went on as a direct consequence of the decrease in the mechanical properties of the adhesive.

It could be argued that the loss in strength of the connection is modest as it is less than 1 MPa, however the results obtained in small-scale experiments on lap joints can hardly predict the real performance of a Glued In Rod connection but can provide important information about the quality of an adhesive bond in a timber substrate. In this specific case, small scale experiments proved what had been found out in large-scale experiments underling that an optimum performance of a resin connector is strictly related to manufacturing conditions which must allow the adhesive to gain full strength during the assemblage of the connection.

The installation process of Glued In Rod joints both in situ and in laboratory has to be optimised in order to prevent adhesive from being wasted by consuming epoxy cartridges within 24h of opening.

5.3.4 Laboratory experimentation

5.3.4.1 Test method and test equipment

In order to reduce slipping problems in the preliminary phase of pull-compression tests, the fatigue testing machine shown in Fig. 5-21 was used to study the withdrawal behaviour of threaded and cylindrical samples of Glued In Rods in timber during the experimental part 2. The conditions of the pull-compression tests in confined regime were kept consistent with the testing procedures followed in the first experimental part, presented in detailed in Chapter 1.

Fig. 5-21: fatigue testing machine Dennison Mayer (load cell: 500 kN) located at the 2K polymer systems laboratories in Alfreton, UK

5.3.5 Test results and analysis

Data collected during the laboratory experimentation was analysed and subsequently summarised in tables collocated in the appendix of this thesis. As mentioned in the methodology framework in Chapter 1, the assessment of the maximum pull-out force of each sample was determined by the use of a graphic method called POLA (Point Of Loss Adhesion). By following POLA method through the instruction suggested in the regulation for adhesive anchor in concrete ETAG 001 (EOTA 2006), it was possible to correctly assess the withdrawal capacity of each resin connector.

Fig. 5-22 shows a load-displacement graph and represents the typical procedure followed for each tested joint to determine the maximum pull-out force in this research work.

As it possible to see in Fig. 5-22, the POLA method was often applied in combination with a 'Toe compensation' (Content et al. 2010). This latter modification was needed to adjust the load-displacement curve from occasional slipping problems at the machine grips/steel bar interface which occurred during the initial phase of tensile tests.

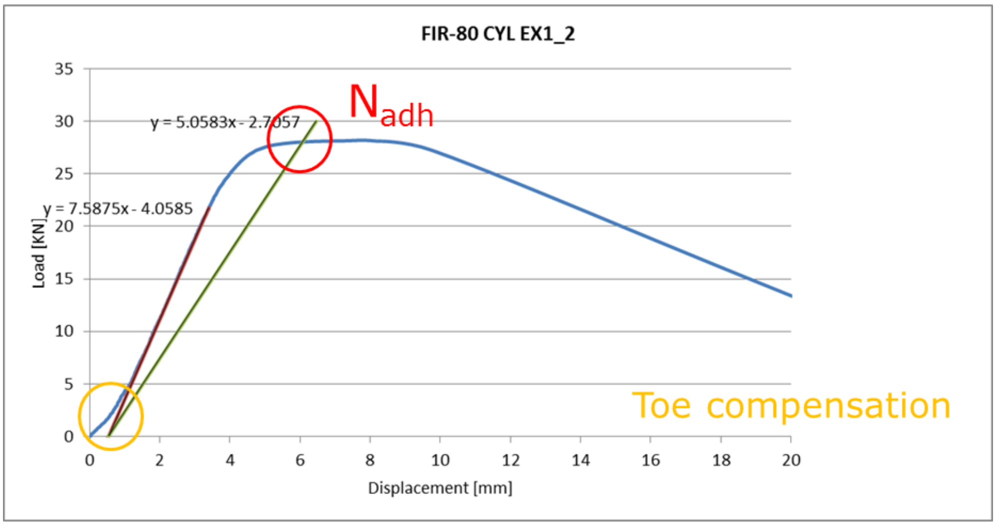


Fig. 5-22: load-displacement curve of a tested sample of adhesive anchor (Douglas Fir, 80 mm glued length, cylindrical hole shape, 2 mm glue line thickness, EX 1:1, steel bar of 8 mm diameter)

5.3.5.1 Confined tests parallel to the wood grain

The results of tests conducted by confined pull-out tests on adhesive anchors glued parallel to the wood grain are presented by histograms to easily compare their structural behaviour and analyse how different parameters such as timber substrate, glued length and epoxy type affect the joint performance.

All the mechanical properties of the tested joints in this thesis are expressed by mean values as each type of joint prototype was tested 3 times. Average values are always presented with the relative coefficient of variation to provide statistic information about data dispersion.

Test results were not expressed by characteristic values as the repeatability number (3) chosen for the conduction of the experiments was too low to enable the assessment of a correct statistic distribution for each data series.

5.3.5.1.1 GLULAM-FIR-OAK 80mm EX 1:1 and EX 3:1

In Fig. 5-23 it is possible to better understand the withdrawal performance of cylindrical and threaded adhesive anchors which are characterised by the same glued length of 80 mm and different timber substrates (solid timber: Douglas Fir and Oak, Glulam) and adhesives (EX 1:1 and EX 3:1).

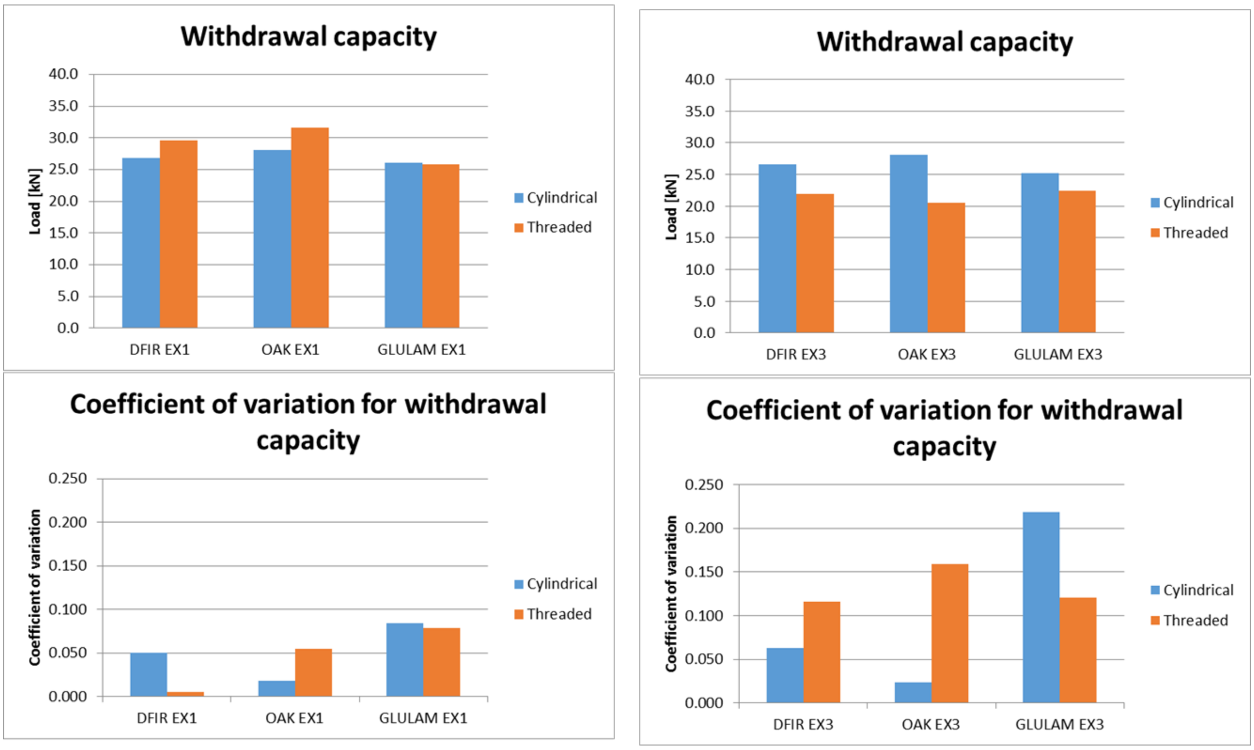


Fig. 5-23: withdrawal capacity and relative coefficient of variation for 80 mm adhesive anchors glued by EX 1:1 (left) and EX 3:1 (right) in different timber substrates (Glulam, solid wood)

The histograms on the left side of Fig. 5-23 show the performance of adhesive connectors made of a low viscosity epoxy resin EX 1:1, whereas on the right part of Fig. 5-23 it is visible the withdrawal capacity of joints made of a high viscosity epoxy, EX 3:1.

The highest and lowest withdrawal loads are reached by samples made from the same timber typology and species: solid Oak. The maximum values is visible for threaded samples made by EX 1:1 while the lowest is shown by threaded Oak samples made of EX 3:1.

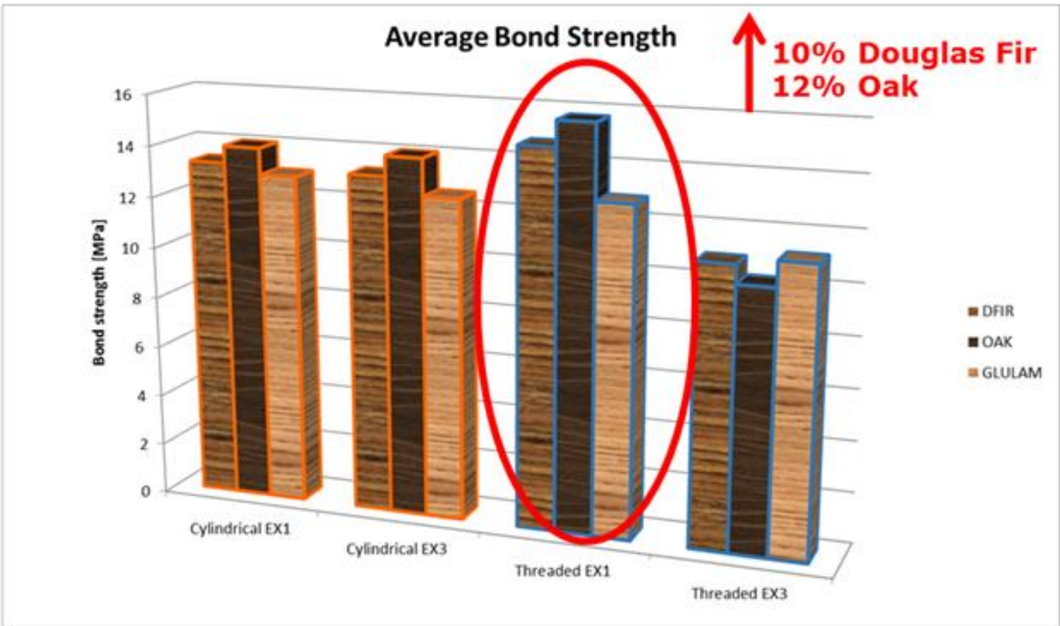
Amongst the cylindrical joints made from solid wood, Oak samples performed better than Douglas Fir connections. However, it is critical to highlight that resin connectors made from Glulam presents lower pull-out capacity than all the other tested connections. The internal physical structure of a Glued Laminated Timber sample may offer a less porous timber substrate to the epoxy adhesive which should deeply penetrate into the wood fibres to create a strong bond. This observation reveals the importance of the chemical and mechanical interaction between adhesive and adherend in a resin connection in timber substrates.

It is possible to note that no differences are shown between the performance of cylindrical samples made of either solid wood or Glulam and EX 1:1 or EX 3:1 indicating that the viscosity parameter for an epoxy resin plays a crucial role only when a change in the hole shape is taken into consideration. In fact, the analysis of this set of data results clearly highlights in which conditions the threaded joint prototype performed well. The best performance of a threaded-shape joint in terms of withdrawal capacity is obtained by adhesive connections made from Douglas Fir or Oak and by the use of a low viscosity resin, EX 1:1.

From the bottom part of Fig. 5-23 it is visible that EX 1:1 presented the lowest coefficients of variation when applied to different timber substrates; on the contrary the use of EX 3:1 characterised samples by high dispersion data.

By the calculation of the bond strength at the adhesive-steel interface, it is possible to quantify the increase in strength obtained by the new joint prototype comparing the performance of cylindrical and threaded joints made of EX 1:1 in solid timber. The average bond strength had a 10% increase in Douglas Fir samples and a 12% increase in Oak specimens (Fig. 5-24).

In Fig. 5-24 it is evident how the combination of joint's characteristics such as threaded hole shape and high viscosity epoxy led to having the weakest connection in terms of average bond strength in all studied timber substrates: solid Douglas Fir, Oak and Glulam (spruce). In addition, in Glulam the use of a threaded and rough borehole did not work efficiently even with the use of a low viscosity resin; therefore the new design solution did not improve the pull-out bearing capacity of Glued In Rods made from Glued Laminated Timber but increased the structural performance in solid wood applications with EX 1:1.



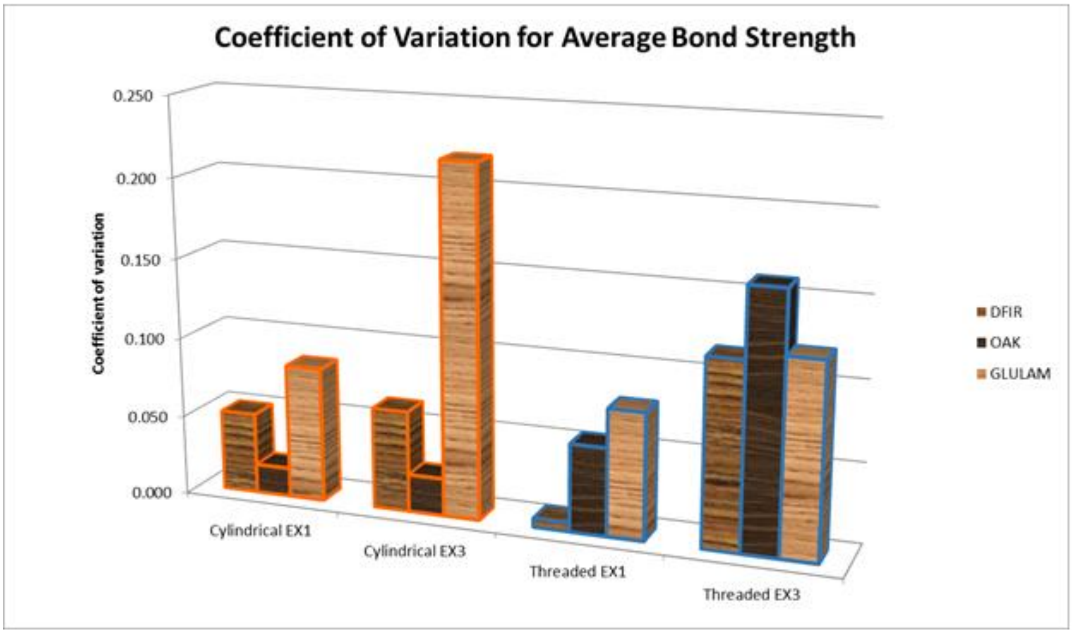


Fig. 5-24: comparison amongst the bond strength of Glued In Rod connections characterised by different adhesives (EX 1:1 and EX 3:1), bonding surface's texture (CYL and THR) and timber substrates (Douglas Fir, Oak and Glulam)

5.3.5.1.2 FIR-OAK 80-120 mm EX 1:1 and EX 3:1

The graphs in Fig. 5-26 represent by histograms how the bond strength at the adhesive-steel interface of adhesive anchors with cylindrical and threaded boreholes in solid timber varies in relationship with different glued length of 80 mm and 120 mm.

In adhesive joint's manufactured by the use of EX 1:1 (Fig. 5-26: top) and EX 3:1 (Fig. 5-26: bottom) the bond strength decreases in correspondence to an increase in the embedded length.

Although it could be stated that deeper an adhesive anchor is installed in a timber substrate higher its withdrawal capacity is, in reality withdrawal capacity and glued length are not related by a direct proportional relationship. In fact, it could be detected by the experiments presented in this thesis that by increasing the glued length and maintaining a constant steel rod diameter, the pull-out capacity of adhesive connections in timber increases up to a certain value of bonded length beyond which the increase in the joint performance is not significant. This concept can be assumed as a general statement for Glued In Rod connections.

The decrease in strength, shown in Fig. 5-26, is the direct consequence of this observation. In fact, samples of adhesive joints made of EX 1:1 and EX 3:1 with a 120 mm glued length presented pull-out forces slightly higher than the withdrawal capacity of the samples identified by a 80 mm bonded length (Fig. 5-25).

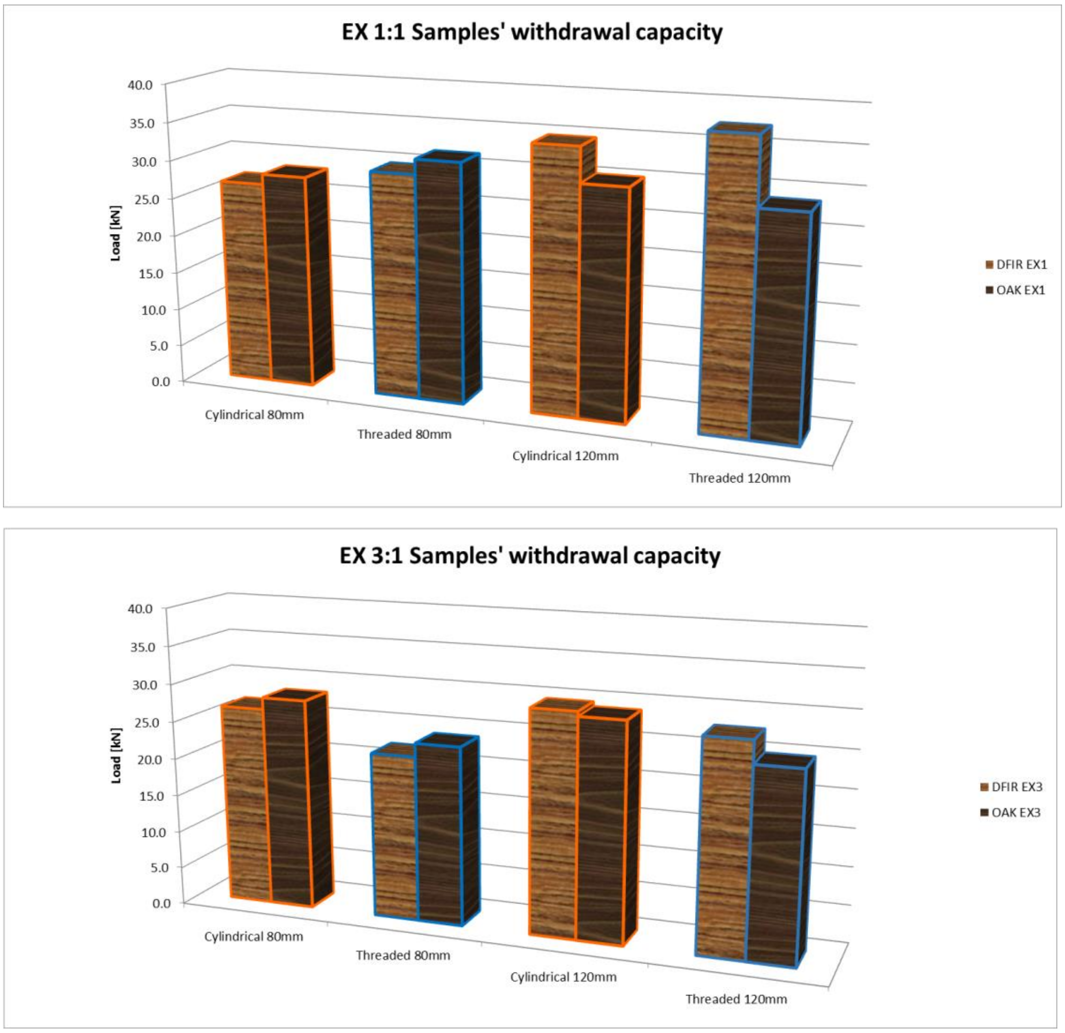


Fig. 5-25: withdrawal capacity of cylindrical and threaded joint samples made from solid timber and characterised by different glued length (80 mm and 120 mm) and epoxy resins (EX 1:1 and EX 3:1)

An increase in the glued length corresponds to an increase in the adhesive contact surface. Taking into consideration that for joints 120 mm long the shear strength is obtained by dividing a slightly increased pull-out force by a bigger bonding area, the resultant bond strength is lower than the shear stress which characterised the joints glued for 80 mm.

For a joint 120 mm long is obtained by dividing a slightly increased pull-out force by a bigger bonding area, the result is a bond strength which is lower than the shear stress which characterised the joints glued for 80 mm.

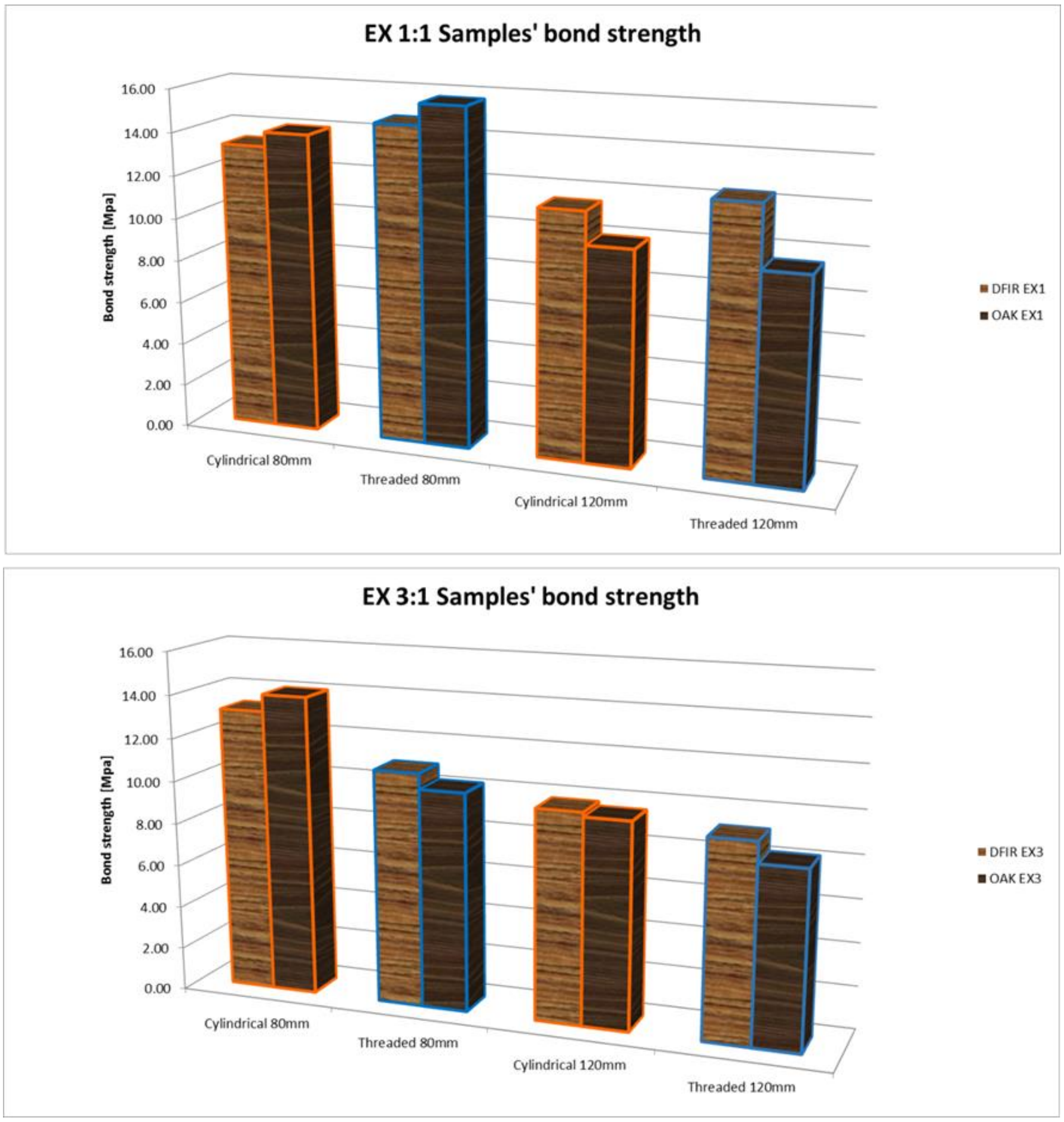


Fig. 5-26: bond strength of cylindrical and threaded joint samples made from solid timber and characterised by different glued length (80 mm and 120 mm) and epoxy resins (EX 1:1 and EX 3:1)

Through the analysis of Fig. 5-26 (top) it is also possible to identify in terms of bond strength the positive effect that the use of a low viscosity epoxy resin (EX 1:1) has on the performance of threaded joints even with higher glued length values.

This increase in bond strength is clearly visible for samples made from Douglas Fir and not for Oak samples. However, it is critical to underline that during the tensile tests of these aforementioned Oak joints (EX 1:1 THR 120mm) defects in the steel bars did not allow the proper assessment of the joint's performance. In fact, the joint prematurely failed by the bar yielding. If steel bars in perfect condition had been used, it would have been possible to see the improvement that the threaded shape show in the pull-out capacity of the joint even in Oak samples.

On one hand the visual comparison amongst the adhesive anchors performance in Fig. 5-26 confirms that the use of low viscosity epoxy resin, such us EX 1:1, in the manufacturing process of Glued In Rod joints can improve the connections' structural behaviour of both 'traditional' (cylindrical hole shape) and new prototypes (threaded hole shape) of resin connectors. On the other hand, Fig. 5-26 accentuates the idea that EX 3:1, high viscosity epoxy, should be used only for 'traditional' Glued In Rods preferably to assemble short-glued length adhesive joints.

The quality of an adhesive bond can be evaluated not only by the maximum value of the withdrawal force of each tested connection but also through the visual analysis of the adhesive anchors after being tested.

Fig. 5-27 shows the most common failure mode amongst all tested adhesive joints: adhesive failure at the epoxy-wood interface. In particular, samples made by low viscosity epoxy resin EX 1:1 showed very homogeneous and compacted failure surfaces both in cylindrical and threaded samples showing a perfect penetration of the resin into the wood porosity and into the threads which were artificially created at the borehole's internal surface. Significant amount of wood fibres are attached to the steel bar, as also verified in the experimental part 1, and the filled-up threads are able to establish a mechanical connection between epoxy and timber enhancing the joint's strength.

On the contrary tested adhesive anchors made of high viscosity resin EX 3:1, which is identified in Fig. 5-28 by red colour, are characterised by a non-uniform distribution of the hardened resin along the joint's length. In this specific case, the presence of air bubbles affected the quality of the bonding in both cylindrical and threaded joint specimens; however there are some cylindrical samples (Fig. 5-28: OAK CYL 80mm) characterised by an 80 mm glued length which presented a homogeneous failure mode.

Nonetheless, in joints with a threaded borehole it is possible to observe how the high viscosity property did not allow the resin to perfectly fill up the internal hole. In this specific case the joint (Fig. 5-28: OAK THR 120 mm) presented a mixed failure mode which combines the failure at the adhesive-timber surface with the cohesive failure of the resin, shown by white parts in the red EX 3:1 areas.

Fig. 5-27: cylindrical and threaded samples of adhesive anchors of made by EX 1:1 (grey) after being tested by pull-compression tests in confined regime

Fig. 5-28: cylindrical and threaded samples of adhesive anchors made by EX 3:1 (red) after being tested by pull-compression tests in confined regime

The visual analysis of the failed samples confirmed what had been previously found out by test results: high viscosity epoxy EX 3:1 generated a weak bond between resin and wood in the threaded prototypes of adhesive anchors in solid timber.

5.3.5.1.3 FIR-OAK 60-80-120 mm EX 1:1

All information gathered during the experimental part 1 and 2 on the structural behaviour of adhesive anchor in solid timber is shown in Fig. 5-29 and Fig. 5-30.

From Fig. 5-29 it is possible to observe the minor influence that the glued length has on the withdrawal force of a resin connector in timber.

Pull-out capacity and glued length are not directly proportional; in fact, by doubling the glued length from 60 mm to 120 mm the joints only presented a 20% increase in their withdrawal capacity. Therefore, it is likely that beyond a certain value of glued length (> 200 mm) the improvement in the joint strength would not be significant.

Due to no-direct proportionality between bond length and pull-out force, the bond strength decreases by enhancing the joint's embedded length. However, from Fig. 5-30 it is possible to clearly identify trends amongst the plotted data which may give the possibility of predicting, by interpolation, the bond strength of joints characterised by different glued lengths which range between 60 and 120 mm.

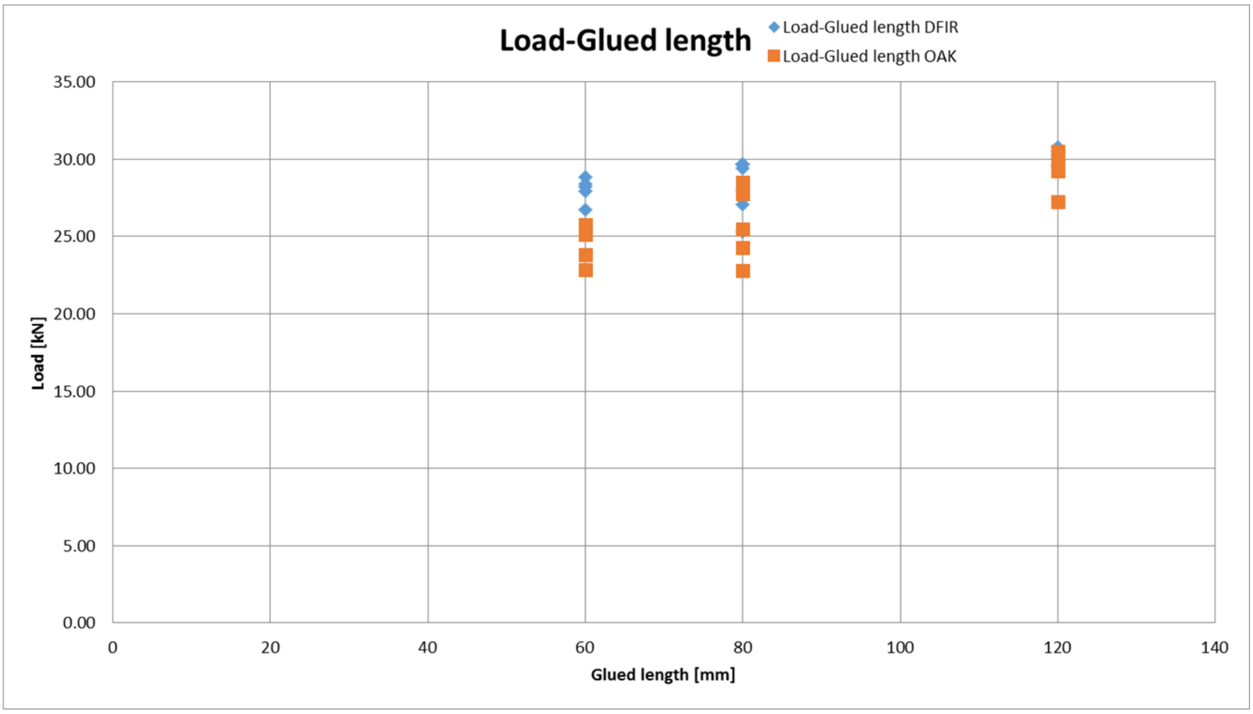


Fig. 5-29: load-glued length relationship of samples of adhesive connections made from solid timber (Douglas Fir, Oak) tested during the experimental part 1 and 2

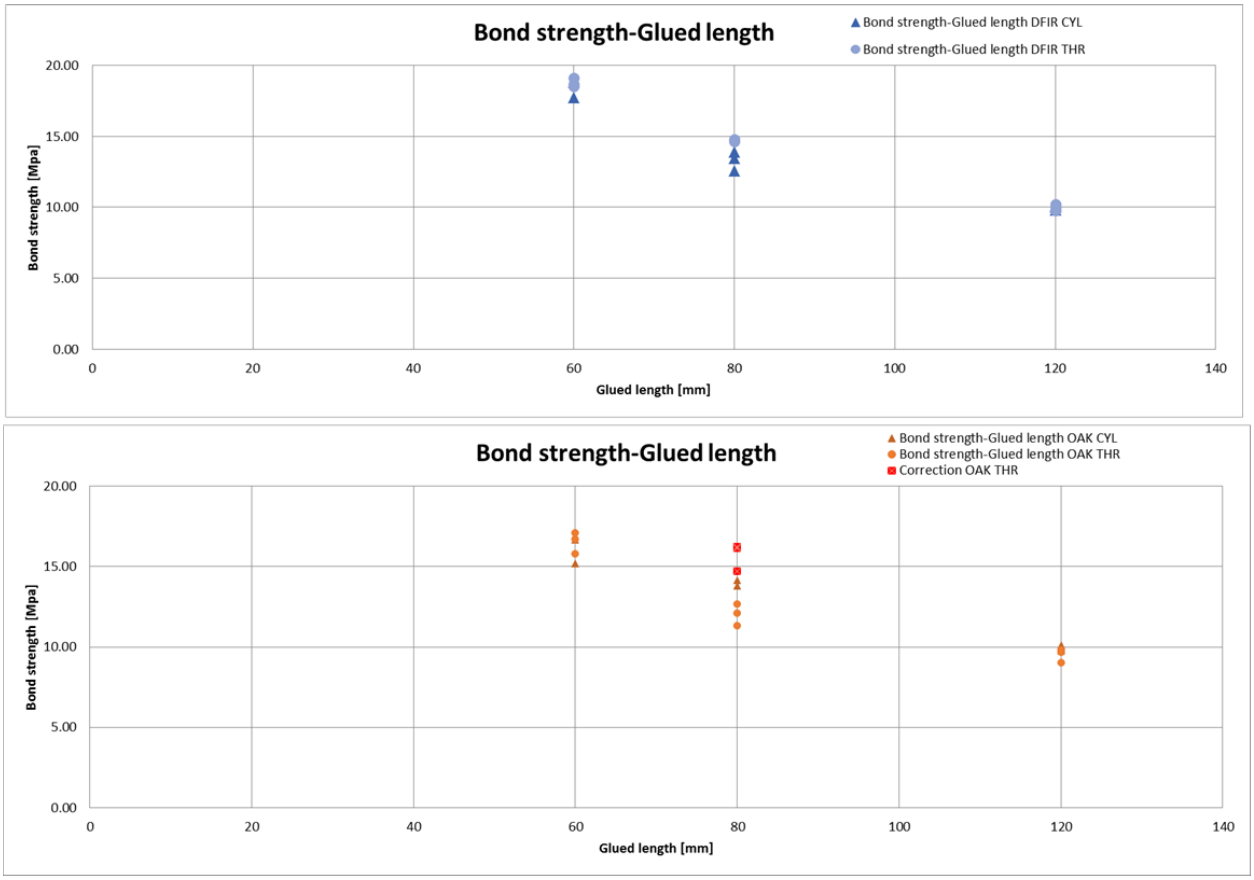


Fig. 5-30: bond strength-glued length relationship of samples of adhesive connections made from solid timber (Douglas Fir, Oak) tested during the experimental part 1 and 2 including correction of test results conducted on some threaded Oak samples

5.3.5.2 Confined tests perpendicular to the wood grain

Although the laboratory experimentation presented in this thesis was mainly aimed at investigating the pull-out behaviour of adhesive connection made of steel rods glued parallel to the wood grain, a further set of experiments was conducted on anchors glued by EX 1:1 into a solid timber substrate (Douglas Fir) following a perpendicular direction to the wood grain. 'Traditional' (Fig. 5-31) and new prototypes of Glued In Rods identified by an 80 mm glued length were subjected to tensile forces in order to examine which effects a different rod-wood fibre direction has on the joint's structural efficiency.

5.3.5.2.1 FIR 80 mm EX 1:1

Fig. 5-31: tested sample of a resin connector made of an 8 mm steel bar glued perpendicular to the wood (solid Douglas Fir) grain in a cylindrical borehole

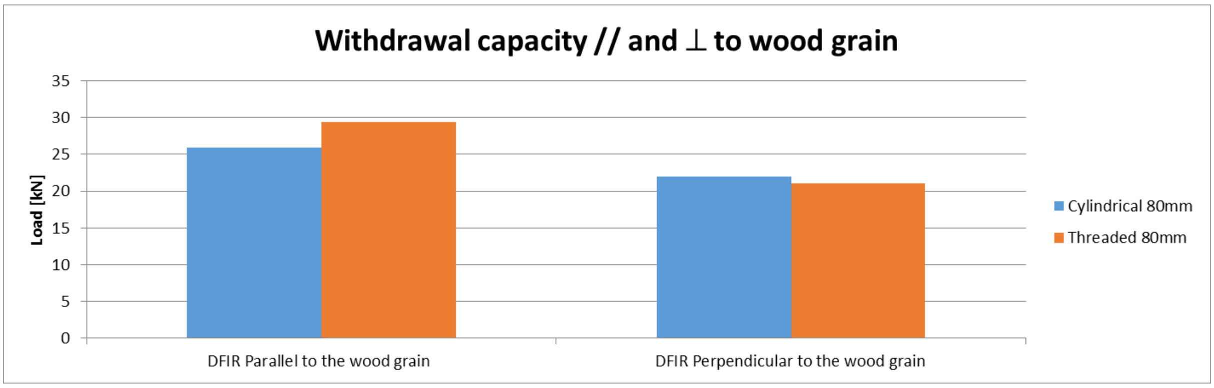


Fig. 5-32: histograms for the comparison between the withdrawal capacity of cylindrical and threaded samples of resin connectors assembled by inserting and gluing steel rods parallel and perpendicular to the wood grain (timber= solid Douglas Fir; glued length= 80mm; epoxy= EX 1:1)

Confined tension tests were performed following the same testing conditions applied during the experimental part 1 and 2; test results are presented in Fig. 5-32 which allows a direct comparison between samples characterised by rods glued parallel (Fig. 5-32: left) and perpendicular (Fig. 5-32: right) to the wood grain direction. The withdrawal capacity of joints glued perpendicular to the wood grain is significantly lower than the connections made by following a parallel direction to the wood grain for the steel bar installation. In particular, it is possible to observe a 15% decrease in strength in the cylindrical samples and a 30% loss in the threaded joint's prototypes. As explained in Chapter 4, the physical and mechanical properties of a wooden substrates in a direction which is perpendicular to the wood grain are critically lower than the withdrawal performance which can be obtained by wood members used parallel to the wood grain. Therefore, low strength in tension combined with a perpendicular penetration of the epoxy resin in respect to the wood grain caused a decrease in the pull-out capacity of the tested adhesive anchors in timber.

Despite further experiments should be conducted to validate the aforementioned observation, the test outcomes revealed that the use of a threaded internal shape in the manufacturing process of adhesive anchors inserted perpendicular to the wood grain is not recommended.

5.3.6 Correlational study between test results and theoretical results: the application of Cook's theory

Amongst the theoretical approaches presented in detail in Chapter 2 to describing the adhesive bond in a resin connector, in this research thesis, it had been chosen to transfer the theories suggested by Cook et al. (1993, 1998) for adhesive anchors in concrete to Glued In Rods in timber because of the presence of close analogies which can be drawn between these types of connection systems.

5.3.6.1 GLULAM 80 mm EX 1:1 and EX 3:1

The theory presented by Cook et al. in 1991 describes the internal shear strength distribution in an adhesive anchor in concrete by the use of an elastic model whose mathematical expression, discussed in Chapter 2, depends on the axial stiffness of the steel rod and the stiffness of the whole adhesive connection. For this reason, Cook's theory can be applied to adhesive anchors in timber only if extremely precise displacement information is collected during the tensile tests execution.

Due to the presence of frequent slipping problems during the tests performed in this laboratory experimentation, it was possible to apply Cook's theory exclusively to a specific set of experiments: 12 joints made from Glulam with steel bars glued by high and low viscosity epoxy resin (EX 3:1 and EX 1:1) into 80 mm cylindrical and threaded boreholes in timber.

From this set of pull-out tests it had been possible to assess precise joint displacements thanks to the absence of external disturbing factors and the use of high-performance extensometers. As a result, even the joints' stiffness was accurately determined.

For each adhesive joint in timber Cook's theoretical approach was adopted to work out the main properties which characterise an adhesive bond: $\tau_{(z=0)}$ (bond strength at the bottom of the glued length), $\tau_{\max\,(z=glued\,length)}$ (bond strength at the top of the glued length close to the wood surface) and λ' (parameter which takes into consideration the stiffness of a resin connector).

As an example, Fig. 5-33 shows significant outcomes obtained from the calculation of the average shear strength at the wood-adhesive contact surface by using the pull-out test results and by adopting Cook's theory to samples of cylindrical adhesive connections made of Glulam, EX 1:1 and 8 mm steel bars.

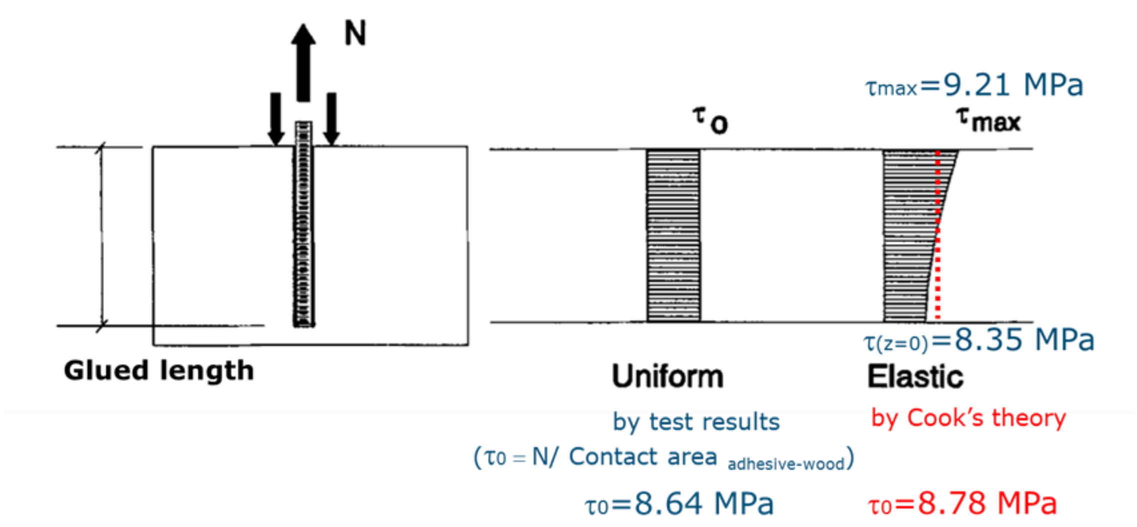


Fig. 5-33: background drawing (Cook 1993) used to outline the outcomes in terms of bond strength of test results (uniform internal distribution) and of the application of Cook's theory (no-uniform internal distribution: elastic model) to samples of cylindrical adhesive connections made of Glulam, EX 1:1 and 8 mm steel bars.

It is visible from Fig. 5-33 that the average shear strength obtained by Cook's equation ($\tau_0 = 8.78\ MPa$) presented results which are consistent with the τ value which had been previously assessed through the use of the information gathered from the test results ($\tau_0 = 8.64\ MPa$), confirming the validity of Cook's elastic-model stress distribution when applied to adhesive anchor in timber substrates.

By applying Cook's theory to all the tested samples, it is possible to state that for short length (80 mm) it is reasonable to assume a uniform distribution of the stress along the joint's embedded length because of the presence of not significant difference in the bond strength between $\tau_{(z=0)}$ and τ_{max} values.

In addition, the presented investigation highlights the key role that the parameter λ' has in the analysis of a resin connector's performance. In fact, by comparing the bond coefficients assessed in this study with the parameters listed by Cook et al. in 1991, it is easy to identify a direct correspondence amongst λ' numerical values (Fig. 5-34). The same type of epoxy resin (amine-based) produced similar λ' coefficients in different material substrates, concrete in Cook's studies and timber in this research thesis. This observation confirmed what previously affirmed by Cook et al. (1991) regarding the main dependence of λ' on the adhesive material the joint is made of.

Adhesive number (1)	Type of adhesive (2)	Bond Properties		
		τ_0 (N/mm²) (3)	τ_{max} (N/mm²) (4)	λ' ($mm^{-0.5}$) (5)
E5	Epoxy (mercaptan)	14.6	15.9	0.017
E11	Epoxy (mercaptan)	13.6	14.0	0.017
E12	Epoxy (amine)	13.1	14.5	0.018
E15	Epoxy (amine)	12.4	13.7	0.019
E6	Epoxy (amine)	12.1	13.1	0.017
E7	Vinylester (capsule)	12.1	13.0	0.015
E2	Epoxy (mercaptan)	10.0	10.7	0.014
E4	Polyester (capsule)	9.4	10.0	0.014
E10	Epoxy (amine)	9.2	9.8	0.014
E9	Polyester (pouch)	8.9	9.6	0.015
E16	Epoxy (amine)	8.9	9.5	0.015
E13	Vinylester	8.6	8.8	0.011
E1	Epoxy (amine)	8.2	8.6	0.012
E14	Vinylester	7.9	8.1	0.009
E3	Epoxy (amine)	6.4	6.7	0.013
E8	Polyester (pump)	6.3	6.6	0.013

Temperature [°C]	Code	Wood type	d_{hole}	Length [mm]	Hole type	Epoxy type	λ'
20	GL_80_C_EX1_1	Glulam	12	80	Cylindrical	Epoxy 1	0.0199
20	GL_80_C_EX1_2	Glulam	12	80	Cylindrical	Epoxy 1	0.0191
20	GL_80_C_EX1_3	Glulam	12	80	Cylindrical	Epoxy 1	0.0191
20	GL_80_T_EX1_1	Glulam	10.5	80	Threaded	Epoxy 1	0.0170
20	GL_80_T_EX1_2	Glulam	10.5	80	Threaded	Epoxy 1	0.0178
20	GL_80_T_EX1_3	Glulam	10.5	80	Threaded	Epoxy 1	0.0182
20	GL_80_C_EX3_1	Glulam	12	80	Cylindrical	Epoxy 3	0.0182
20	GL_80_C_EX3_2	Glulam	12	80	Cylindrical	Epoxy 3	0.0199
20	GL_80_C_EX3_3	Glulam	12	80	Cylindrical	Epoxy 3	0.0204
20	GL_80_T_EX3_1	Glulam	10.5	80	Threaded	Epoxy 3	0.0178
20	GL_80_T_EX3_2	Glulam	10.5	80	Threaded	Epoxy 3	0.0182
20	GL_80_T_EX3_3	Glulam	10.5	80	Threaded	Epoxy 3	0.0178

Fig. 5-34: comparison between λ' parameters in previous Cook's studies on adhesive anchors in concrete (1991: top) and in this experimental work (bottom) about resin connectors in timber

Due to the fact that the application of Cook's theory involves the use of parameters which are experimentally determined, it cannot be adopted to predict the behaviour of adhesive anchor in timber; however, it can be used to identify λ': a parameter which provides important information about the whole connection stiffness and that may be particularly useful in comparative studies to analyse and classify adhesive anchors in timber made of different adhesive type and/or wood species substrates.

5.3.7 Results discussion from experimental part 2

- The new joint prototype characterised by a threaded internal borehole is able to provide an increase of up to 12% in the withdrawal capacity only if:
    1. it is assembled with low viscosity epoxy resins (EX 1:1)
    2. it is made from solid timber
    3. it is manufactured by inserting steel rods parallel to the wood grain direction.

Fig. 5-35: bond quality comparison by microscope images (50X magnification) of threaded samples of adhesive anchors in timber glued by high (EX 3:1: top) and low (EX 1:1: bottom) viscosity epoxy resins after being tested.

Wooden residual parts of adhesive connections attached to joints' steel elements after failure are shown by the use of microscope images in Fig. 5-35. In particular, Fig. 5-35 allows the visual comparison between 2 samples of threaded adhesive anchors glued by the use of high (EX 3:1) and low (EX 1:1) viscosity epoxy.

The images in Fig. 5-35 provide extremely clear information about the quality of the bonding process which took place in different adhesive anchors at the steel-adhesive and wood-adhesive contact surfaces. In the threaded joint prototype assembled by the red EX 3:1 it is evident how a high-viscosity prevents the resin from completely filling up the threads which appear empty. On the contrary, EX 1:1 perfectly glided over and into the threads creating a strong mechanical and adhesive grip between resin and timber; the good bond quality is identified by the presence of wood fibres which overlap the hardened epoxy located into the threaded hole. Therefore, the visual assessment of the bond quality from the tested samples is in accordance with the low withdrawal performance achieved by threaded joints made of

EX 3:1 during the laboratory experimentation. For this reason the use of high viscosity resin during the manufacturing process of the studied prototypes of adhesive connections in timber is not suggested.

- 'Traditional' Glued In Rod connections identified by a cylindrical hole shape can be successfully assembled by both high and low viscosity epoxy resins. However, the use of low epoxy resin may lead to a more homogeneous gluing process without the creation of air bubbles at the adhesive-adherend contact surface and within the resin, especially for joints with glued length values higher that 80 mm.
- The innovative installation method adopted for both cylindrical and threaded samples simplifies the joint's manufacturing process and further reduces the amount of adhesive needed for the production of adhesive anchor in timber.
- Cook's theory can be applied to adhesive anchors in timber to establish if a uniform stress distribution along the joint embedded length is able to correctly represent the real joint's structural behaviour. Moreover, the coefficient of stiffness λ' may be a critical parameter to be taken into account in comparative studies about Glued In Rod connections in timber substrates.

5.4 SUMMARY

5.4.1 Bond strength of tested adhesive connections in timber

Table 5-2 presents a summary of the test results collected from the experimental parts 1 and 2. In particular, the results are reported in terms of bond strengths by tables as they should appear in a product data sheet if the studied EX 1:1 and EX 3:1 were proposed for application in adhesive anchors in timber.

Bore hole shape	Epoxy	Anchor size	Drilled Hole [mm]	Temperature: 20°C		Glued length [mm]			
						60	80	100	120
Cylindrical	EX 1:1	M8	12	τ_m [N/mm^2]	Douglas Fir [C16]	18.30	13.30	12.40	11.40
Cylindrical	EX 1:1	M8	12		Oak [D18]	15.90	13.90	11.60	9.90
Cylindrical	EX 1:1	M8	12		Glulam [GL24]	/	12.90	/	/

Bore hole shape	Epoxy	Anchor size	Drilled Hole [mm]	Temperature: 20°C		Glued length [mm]			
						60	80	100	120
Cylindrical	EX 3:1	M8	12	τ_m [N/mm^2]	Douglas Fir [C16]	/	13.20	/	9.78
Cylindrical	EX 3:1	M8	12		Oak [D18]	/	14.00	/	9.57
Cylindrical	EX 3:1	M8	12		Glulam [GL24]	/	12.50	/	/

Bore hole shape	Epoxy	Anchor size	Drilled Hole [mm]	Temperature: 20°C		Glued length [mm]			
						60	80	100	120
Threaded	EX 1:1	M8	10.5	τ_m [N/mm^2]	Douglas Fir [C16]	18.70	14.70	12.40	12.30
Threaded	EX 1:1	M8	10.5		Oak [D18]	16.50	15.70	11.40	9.50

Table 5-2: bond strength values of adhesive anchors in timber (red numbers refer to bond strength valued obtained by interpolation method)

It is important to note that all bond strengths are expressed by average values. In reality, characteristic values of the pull-out resistance and bond strength of the tested samples should be calculated following the current BS EN 14358:2016. However, for this laboratory experimentation the adoption of the aforementioned regulation was not possible due to the small number of observations collected for each joint prototype. In fact, the standard BS EN 14358:2016 required a minimum of 40 specimens for a non-parametric calculation of characteristic values for timber elements. For this specific case, a non-parametric approach would be suitable for small number of samples instead of parametric analyses which are, contrariwise, based on normal Gaussian distributions of big data (Cavalli et al. 2014).

And lastly, Table 5-2 includes only the results of joints which successfully performed during the experiments. For this reason, the outcomes obtained from threaded samples made of EX 3:1 and from glulam are not reported because they identify no efficient solutions for the practical installation of adhesive anchors in timber.

5.4.2 Recommendation for the design of Glued In Rods in timber in cold state

From the outcomes drawn by the analysis of the experimental program presented in this thesis about the structural behaviour of adhesive anchors in timber in cold states, it is possible to comprehend that the determination of a specific bond strength value for each combination of materials, a Glued In Rod joint is made of, is essential to identify the pull-out performance of an adhesive joint in timber.

Due to the lack of resins specifically formulated for adhesive anchors in timber, the selection process of an adhesive for Glued In Rod applications in timber should be undertaken by taking into account the physical and mechanical properties reported in technical datasheets by manufacturers.

In particular, adhesive manufacturers have the important task of providing bond strength values for each combination of materials (steel-timber-adhesive) in which their specific adhesives can successfully perform for Glued In Rods applications in timber substrates.

5.4.2.1 Bond strength parameter of Glued In Rods in timber

The determination of the bond strength of an adhesive anchor in timber should be assessed by the performance of tensile tests, whose execution has to be standardised by a specific regulation possibly issued by the European Organisation for Technical Approval (EOTA). This standard regulation has to contain all information about pull-compression tensile tests and provide correction factors ($\text{e.g.}\,\alpha\,, \beta$) to take into consideration about the test regimes (confined-unconfined) and the wood grain-steel bar direction (parallel-perpendicular to the wood grain).

Furthermore, it has to present a standard formula to identify the bond strength of the connection at the steel-adhesive contact surface which may appear as the following equation:

$$\boldsymbol{\tau}_{\boldsymbol{bond}} = \frac{N}{\pi\, d_r\, l_g}\, \alpha\, \beta\ [MPa]$$

$\boldsymbol{\tau}_{\boldsymbol{bond}}$ = bond strength at the steel-adhesive interface [MPa]

N = maximum pull-out load assessed by pull-compression tension test[N]

d_r = rod diameter [mm]

l_g = glued length [mm]

α = correction factor related to testing conditions in which $\boldsymbol{\tau}_{\mathrm{bond}}$ is assessed (confined-unconfined test regimes)

β = correction factor which takes into consideration the direction followed to glue the steel bar into a timber element (parallel-perpendicular to the wood grain)

Therefore, an adhesive company which declares its intent to promote a specific adhesive for Glued In Rods' applications has to:

a) identify best graded timber typology and species and relative moisture content in order to achieve optimum bonding condition
b) list restrictive conditions for the use an adhesive anchor in timber made from a hygroscopic material (wood) in specific environmental condition
c) provide detailed information about the joint manufacturing and installation phases specifying hole shape and relative glue line thickness
d) provide bond shear strength values for adhesive connections characterised by different glued length and timber substrates following a standard regulation. Characteristic values of bond strengths $\boldsymbol{\tau}_{\boldsymbol{R\,k,bond}}$ should be expressed according to BS EN 14358:2016 and listed in tables.

5.4.2.2 New formula proposed to assess the withdrawal capacity of Glued In Rods in timber

The innovative design formula for the determination of the withdrawal capacity of Glued In Rods in timber, presented in this thesis, is mainly based on the idea of manufacturing an adhesive connection only by structural graded materials. In particular, the use of dried and graded timber plays a crucial role in classifying a Glued In Rod joint. The timber used to assemble an adhesive anchor in timber has to be graded according to EN 338: 2009 for solid wood and to EN 14080: 2013 for glulam; similarly, steel bars or threaded steel rods have to be selected according to existing standard regulations (EN ISO 898-1:2013) in order to guarantee a safe structural performance.

The equation proposed in this research thesis is characterised by the presence of 2 geometric features of the connection, steel rod diameter and glued length, and of an experimentally-determined parameter $\boldsymbol{\tau_{R\,k,bond}}$.

Through the adoption of a calculation process similar to the method suggested by Cook et al. in 1991 for the design of adhesive anchor in concrete, the withdrawal capacity of a single adhesive anchor in timber can be assessed multiplying a product-dependant bond strength of the connection by the contact area at the steel-adhesive interface.

Therefore, by knowing the main geometric parameters of a Glued In Rod joint and $\boldsymbol{\tau_{R\,k,bond}}$ of an adhesive when applied to a specific timber substrate the design of single adhesive anchors in timber should be undertaken by the use of the following formulas:

i. $P_{Rk} = \pi\, \boldsymbol{\tau_{R\,k,bond}}\, d_r\, l_g$

P_{Rk} = characteristic withdrawal load [N]

$\boldsymbol{\tau_{R\,k,bond}}$ = bond strength at the steel-adhesive interface [MPa]= *f (timber species, adhesive type, glued length, rod diameter, hole diameter).* It has to be:

- determined by standard experiments
- expressed as a characteristic value by BS EN 14358:2016
- provided by adhesive manufacturers

d_r = rod diameter [mm]

l_g = glued length [mm]

ii. According to the current Eurocode 5 (BS EN1995-1-1:2004), the characteristic value of the withdrawal load should be subsequently converted into the design value by applying the following equation:

$$P_d = \frac{k_{mod}\, P_{Rk}}{\gamma_m}$$

P_d = design withdrawal load [N]

P_{Rk} = characteristic withdrawal load [N]

k_{mod} = modification factor = *f (material type, service class, load duration class)*

γ_m = partial factor for material property = *(1.3 for solid timber, 1.25 for glulam, 1.3 connections)*

6. ADHESIVE CONNECTIONS IN TIMBER AT ELEVATED TEMPERATURE

6.1 FIRE RESISTANCE OF ADHESIVE CONNECTIONS

6.1.1 Fire resistance of a timber structure

The fire resistance of a timber structure is strongly dependent on the behaviour of its mechanical connections during a fire event (Piazza et al. 2005). Even a correct fire design of a timber element would let the whole structure collapse if the connections are not able to maintain their mechanical properties at elevated temperatures (Harris 2004). In many cases, the metal connections represent the weakest elements in a timber structures when exposed to fire conditions due to the high thermal conductivity of steel even if the metal element is located inside the wooden material (Piazza et al. 2005). For this reason, it is crucial to assess the performance of the connections of a timber structure when subjected to high temperatures (Piazza et al. 2005).

The fire design of timber structures is based on the concept that the residual strength after a fire event can be calculated using the full strength of the original dimension of the beam cross section reduced by the charred layer, whose depth can be easily assessed knowing the charring process or more precisely the charring rate of the studied timber species (Harris 2004, Piazza et al. 2005: 563). In fact, timber species is one of the most influencing parameters for the determination of the charring rate (Piazza et al. 2005). In other words, a decrease in the structural performance of a timber structure in case of fire it is mainly due to the reduction of the beam cross section and not because of the loss of the mechanical properties of the timber elements (Follesa n.d.).

The lack of standard regulations for Glued In Rod joints in timber structures represents the main issue about the practical use of these resin connections in real applications and it regards the design of the connection in cold states and at elevated temperatures. In past research projects several design equations were suggested to predict the behaviour of adhesive anchors in timber but none of the previous studies provided detailed information about the fire design of Glued In Rods in timber.

Only few researchers conducted laboratory tests on adhesive connections in timber subjected to elevated temperatures through the use of different test methodologies and test materials in order to understand the real fire performance of adhesive anchors in timber. However, little information is provided in literature about the fire resistance of Glued In Rods in timber and more research activities are needed to investigate further the performance of Glued In Rods in timber at elevated temperatures.

Hence, the study of the effect that elevated temperatures have on the mechanical behaviour of an adhesive anchor in timber is essential to enable knowledge of the performance and the design of the connection for its use in practical applications.

6.1.2 Past research work

Past research investigations analysed the effect that high temperatures have on Glued In Rods in timber structures. While some experiments were carried out to discover how a variation in the air temperature in hot climate countries could affect the mechanical performance of adhesive connections in timber elements; most of the research studies regarded the analysis of laboratory experiments performed on adhesive joints, assembled using glued laminated timber and resins manufactured by different companies, in order to test the performance of adhesive connections under fire exposure. Specifically, tests under constant temperatures required a pre-heating process which usually took place in an oven before the application of the tensile load. Contrarily, tests performed under a constant tensile load presented a simultaneous heating and loading process in furnace.

The chart, presented in Fig. 6-1, summarises the most common tests and test methods performed at elevated temperatures on Glued In Rod connections in timber in past research studies.

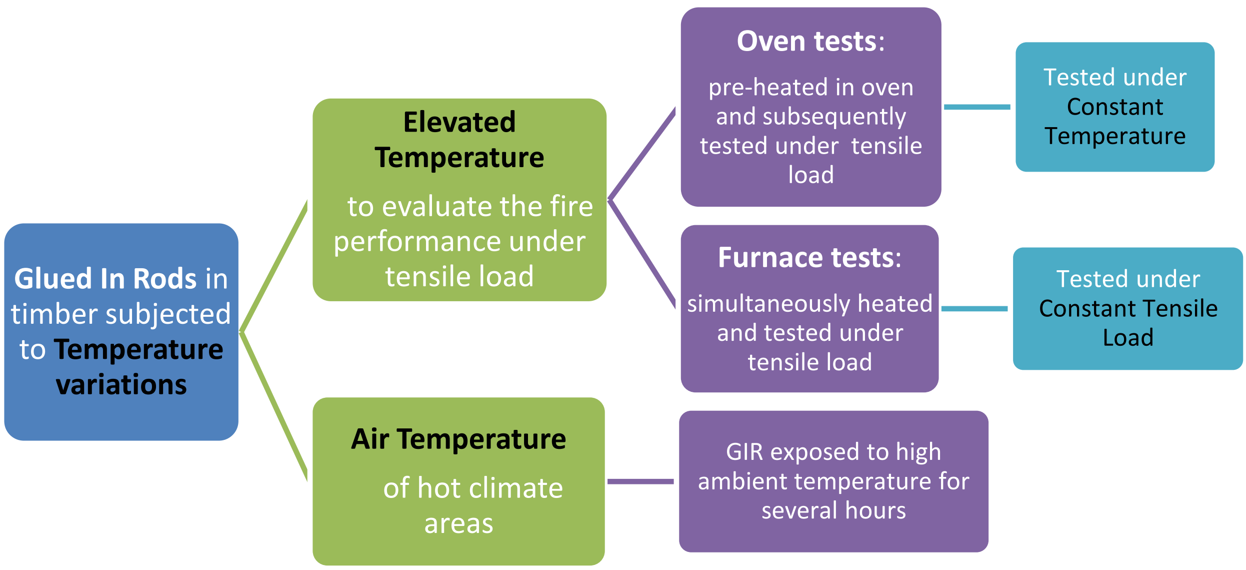


Fig. 6-1: chart of test methods for glued in rods in timber subjected to temperature variations

6.1.2.1 Glued in rods in timber subjected to ambient temperature variation

Gaining a good understanding of the effects that an extended solar exposure can cause on the mechanical behaviour of adhesive anchors in timber is essential to correctly design and install the connections in a timber structure.

The thermal response of Glued In Rods subjected to air temperatures variations during 3 consequently summer days was modelled by Faye et al. in 2004. The research outcome proved a strong relationship between the air temperature trend and the internal heating and cooling process of a Glued In Rod connection in timber, characterised by a 80x160 mm cross section.

In detail, the finite element analysis carried about by Faye et al. in 2004 clearly showed a 4/5 hour delay for the adhesive in reaching ambient temperature. This aspect is particularly interesting because it proves that high temperature in adhesive connections in timber might be reached, not only due to a fire exposure but also because of a severe solar exposure in hot climate countries.

Similar results were previously obtained by some laboratory experimentations developed by Aicher et al. in 1998 who studied the internal temperature distribution of Glued In Rod joints subjected to a specific temperature cycle of six hours during which the samples had been heated up, kept at constant temperature (50°C) and consequently cooled down to 20°C.

From the graphic outcomes of his studies, It is possible to observe that the distribution of internal temperatures showed higher temperatures compared to the wood surface temperatures. This effect is mainly due to the installation of the thermocouples which, for this particular laboratory experimentation, had been located inside the steel bar. In addition, it is important to underline that the joint had been completely exposed to air temperature variation without considering that in real applications of Glued In Rod connections in timber structures, the steel parts would be hidden and not subjected to a direct heating process. However, it is interesting to note that the wood temperature, measured close to the adhesive layer, reached almost 45°C. For this reason, it can be stated that similar values of hot air temperatures obtained by solar heating could affect the joint performance in real applications as most epoxy resins are characterised by Heat Distortion Temperatures (HDT) around 50°C. Hence, it is advisable to limit the use of adhesive connections to service classes 1 and 2 of EC5 (Tlustochowicz et al. 2011).

6.1.2.2 Glued in rod joints in timber subjected to elevated temperatures

In past research studies two different methods have been frequently used to test an adhesive anchors in timber at elevated temperatures. The first method involves the use of an oven to heat the connection up to a selected temperature. The connection is usually left in an oven overnight to allow the sample reach a homogeneous temperature in all its parts. Subsequently, the sample is removed from the oven and a tensile test is performed to assess its withdrawal capacity.

This second testing phase always requires the use of special wrapping fabrics to maintain the sample at a constant temperature before and during the tensile test. In literature the possibility of heating up the sample in an electric furnace reaching a constant temperature before testing the sample under tensile load has not been explored yet.

Another method used to study an adhesive anchor at elevated temperatures involves the use of an electric or real furnace where the sample is heated up, usually following the standard time-temperature curve of ISO 834, while subjected to a constant tensile load. For example in Harris's experimentation (Harris 2004) the constant load corresponded to 30% of the design load in cold states.

Both testing methods enable knowledge of the fire performance of the joint but their comparison often revealed several inconsistences. The oven tests resulted in being less severe than the experiments carried out in furnace, showing failure temperatures much higher than the temperatures obtained by the furnace heating process (Harris 2004, Barber in Harris 2004: 87). This inconsistency between the two aforementioned methods is mainly due to the fact that in the oven the adhesive joint and therefore its adhesive material are heated without being subjected to tension loads; on the contrary, in the furnace the adhesive connection is tested in tension while heated (Harris 2004:87). Hence, it is clearly likely that Glued In Rods in timber performed diversely if tested under different testing regimes.

6.1.2.2.1 Test performed under Constant temperature

Harris in 2004 presented an interesting research study on the fire resistance of Glued In Rod connections. Tensile tests were performed to study the withdrawal strength of adhesive anchors at specific high temperatures (50°C, 75°C and 100°C). The samples had been kept for 16 hours in an oven in order to assure a homogeneous and constant temperature distribution inside the specimens before assessing their load bearing capacity.

From Harris's oven tests, it is possible to observe that samples of adhesive anchors in timber made of different epoxy resins performed in a different way but they all lost strength when heated up. Moreover, it is possible to note that some connections presented higher pull-out values when heated up to 50°C compared to their withdrawal capacity recorded at ambient temperature (20°C). This phenomenon is mainly due to resin post-curing effects, whose development represents a negative aspect for the validity of tests performed under constant temperatures.

It is possible to draw similar conclusions from the research study conducted by Lartigau et al. 2011 where tests at constant temperatures were performed on Glued In Rods in timber manufactured by the use of two different epoxy resins. “Epoxy S” maintained its mechanical properties up to 40°C and showed the consequences of post-curing processes at 29 and 32°C. However, joints made of “epoxy R” completely lost their structural integrity at 38°C. In spite of the fact that no information was provided by authors regarding the relationship between failure temperature and glass transition temperature (Tg) or Heat Deflection Temperature (HDT), the investigation carried out by Lartigau et al. (2011) highlights how the thermal performance of an adhesive connection in timber is closely related to the thermal and mechanical properties of the adhesive the joint is made of.

6.1.2.2.2 Test performed under Constant load

Further investigations were conducted by Harris in 2004 about the behaviour of Glued In Rods at elevated temperatures. The tests were performed under constant load on 105x105 mm LVL samples (16 mm steel rod, 300 mm glued length) in pull-pull test regime parallel to the wood grain. Screws were inserted perpendicular to the wood grain and used to prevent the sample from splitting failures. The connections started to lose strength at the HDT (50-60°C). According to Harris (2004), Glued In Rods in timber are characterised by a low fire performance (10-20 min) and can be used only for timber structures which require “low or non-existent fire resistance”. On the contrary, in previous research studies Buchanan and Barber (1996) evaluated the fire resistance of “full-size tension members” and their research outcomes showed a good fire performance of Glued In Rods in glulam below a specific critical temperature of 50°C.

One of the research studies which proved a good fire resistance (R60) of an adhesive anchor in solid timber (red spruce) under the standard time-temperature curve ISO 834 was the laboratory experimentation carried out by Piazza et al. (2005). Samples’ failure occurred when the glass transition temperature of the adhesive was reached (Piazza et al. 2005). Despite the tests proved that the adhesive anchor had a fire resistance time of 60 minutes, it can be noted from the graphic outcome of this research study that the heating process within the sample had not been homogeneous and the right part of the sample had been subjected to more severe heating conditions than the left side. For this reason, the time fire resistance recorded in this investigation may have been affected by a no uniform temperature distribution which allowed the left side of the connection to fully maintain its bond strength and to resist longer to the fire event.

Moreover in this specific test, it is important to highlight that the sample was tested in a pull-compression test regime and the anchor had been glued perpendicular to the wood grain. In cold state experiments, Glued In Rod joints characterised by bars glued parallel or perpendicular to the wood fibre showed different withdrawal capacity. For this reason, more experiments are needed to investigate the impact that the gluing direction can have on the structural behaviour of Glued In Rods in timber at elevated temperatures.

The most recent report about the analysis of the performance of adhesive joints in timber at elevated temperatures was included in a draft regulation written by Aicher (2015) aimed at providing design regulations for Glued In Rods in laminated timber. A test method to assess the "bond temperature resistance" (residual strength) of adhesive anchors in timber was presented. The test is based on the study of the joint behaviour under a constant tensile load, in pull-pull test regime, expressed as a percentage of the withdrawal strength of the connection in a cold state. In this specific test the author defined a specific time-temperature curve to follow during the heating process of the connections made of 2 heating cycles and defined a maximum target temperature to be maintained constant throughout the duration of the test.

The document presents a very interesting definition of the constant load as a function of an experimental bond strength of the connection. However, the choice of selecting a target temperature for the "bond line" around 60°C could make the test difficult to be performed in real applications because most of the epoxy resins on the market have HDT values lower that 60°C. Therefore, the presented method would not be easily applicable to Glued In Rod joints made of epoxy resins.

It is important to highlight that all the aforementioned studies on the structural behaviour of adhesive anchors in timber subjected to temperature variations involved the use of different test methods, test equipment and materials which make the comparisons amongst the test results not always correct and valid, as explained in detail in Chapter 3 for the design rules of Glued In Rods in timber in cold states.

6.2 LABORATORY INVESTIGATION OF ADHESIVE CONNECTION IN TIMBER SUBJECTED TO ELEVATED TEMPERATURE

6.2.1 Test description

The presented laboratory experimentation was aimed at performing tests on adhesive connections at elevated temperatures. Two-component epoxy resins (EX 1:1 and EX 3:1) with different viscosity values had been used to glue 8mm steel rods into pre-drilled holes, characterised by cylindrical (CYL) and threaded (THR) internal surfaces, in timber samples in order to investigate the performance of adhesive joints exposed to elevated temperatures and assess the bond strength at critical temperatures. The samples were loaded by a constant load and heated up in an electric furnace until failure.

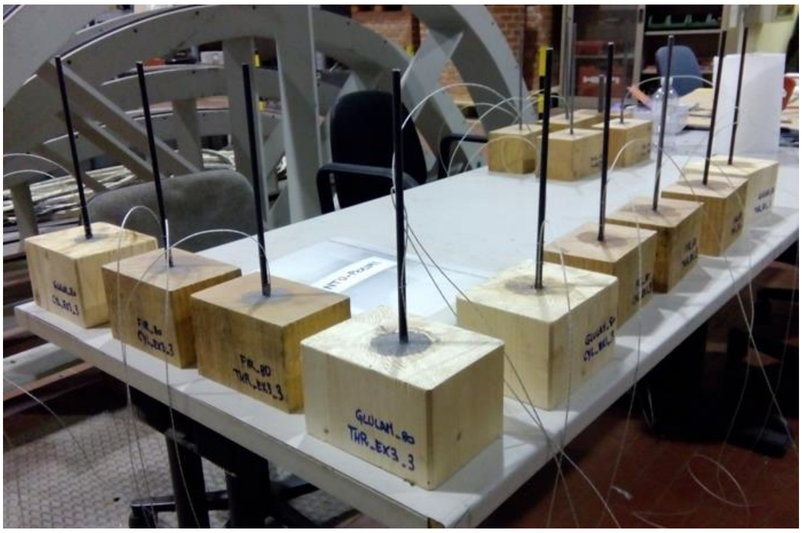


Fig. 6-2: samples of adhesive anchors in timber for tests at elevated temperatures

Tests at elevated temperatures were performed on 24 samples (3 for each joint type) of adhesive connections in solid (Douglas Fir) and Glulam timber, as summarised in Fig. 6-3.

EXPERIMENTS AT ELEVATED TEMPERATURES
confined testing conditions (Chapter 6)

SOLID	GLULAM
// to the wood grain	
DF: Douglas Fir	GLULAM
glued length: **80mm** **EX 1:1 and EX 3:1** **CYL and THR**	glued length: **80mm** **EX 1:1 and EX 3:1** **CYL and THR**

Fig. 6-3: test design

6.2.2 Materials

The properties of the materials used to manufacture the joints are listed below (Fig. 6-4).

Timber		
Type	Solid (Douglas Fir)	Glulam (Spruce)
Grade	C16	GL24
Density	560	430
MC [%]	10.1	9.2
Charring rate β_0	0.65	0.65
Steel bar		
Diameter [mm]	8	
Type	Threaded	
Grade	12.9	
Epoxy		
	EX 1:1	EX 3:1
Density [g/cm^3]	1.7	1.5
Compressive strength (7 days) [N/mm^2]	95	95
Tensile strength (7 days) [N/mm^2]	23	23
Flexural strength (24 h) [N/mm^2]	45	45
HDT (7 days) [°C]	49	49
Viscosity (20°C) [mPa.s (cps)] ± 50000	240000	720000

Fig. 6-4: materials properties

6.2.2.1 Timber

The laboratory experimentation was carried out on 24 samples of Glued In Rod joints made of solid timber (Douglas Fir [C16]) and glulam (Spruce [GL24]) characterised by a cross section of 150x100 mm and a height of 100 mm.

The specimens of both timber species were conditioned by using a climatic chamber. The temperature and the humidity of all samples were kept constant ensuring that the conditions imposed by BS EN 408-2003 were satisfied (T= 20±2 °C and U=65±5%).

Fig. 6-5: BINDER climatic chamber used for samples conditioning

The moisture content of all samples was firstly measured using a pin-moisture meter and subsequently assessed by a standard oven dry method suggested by EN 13183-1:2002, heating the samples "until a difference in mass between two successive weightings separated by an interval of 2 hours [was] less than 0,1 %" (EN 13183-1:2002).

MOISTURE CONTENT DETERMINATION	
by pin-moisture meter	
GLULAM (spruce)	DOUGLAS FIR
7.4%-8.1%	7.2%-7.9%
by oven dry method (103±2)°C	
GLULAM (spruce)	DOUGLAS FIR
9.2%	10.1%

Table 6-1: timber moisture content

The moisture content assessed through the use of the pin-moisture content meter revealed a 2% difference in the moisture content values calculated by the oven dry method for both timber types. However, the moisture contents obtained by the use of the same method revealed similar values for glulam and Douglas fir samples. Having a similar moisture content lower than 12% is an essential requirement to consider the two different timber typologies comparable and to classify the wooden material in Service class 1, according to EC5 (CEN 2004).

Fig. 6-6: heating cabinet used to assess timber moisture contents

6.2.2.2 Adhesives properties (Tg, HDT)

The identification of the temperature value beyond which the adhesive joint would lose its strength is one of the most crucial topics when dealing with the performance of Glued In Rods at elevated temperatures.

When thermosetting resins are exposed to elevated temperatures, their strength and stiffness decrease due to a break in the covalent chemical bonds (Sgarito 2006). For this reason, knowing the temperature beyond which the use of the resin materials is limited provides important information about its thermal performance (Gurit n.d.; Sgarito 2006) in an adhesive connection in timber.

The glass transition temperature Tg identifies the point at which a cured thermosetting epoxy, which never becomes liquid when heated, starts to have a “rubbery” consistency (Niederer 2006, EPOTEK 2012). Hence, Tg has often been identified as the thermal parameter which provides the most relevant information about the behaviour of resins subjected to heating processes.

Nonetheless, the definition of the glass transition temperature for an epoxy resin is not unique and not identified by “a single exact value” of temperature due to the fact that Tg can be assessed by different test methods (DMTA: ASTM D3418, DSC: ASTM E1545; ASTM D1640; ASTM D4065) and determined within a quite wide range of values (Niederer 2006).

The Dynamic Mechanical Thermal Analysis (DMTA) and the Differential Scanning Calorimeter (DSC) test can be performed to determine the glass transition temperature. While DMTA is able to assess the mechanical properties (bending modulus; loss tangent) of a small specimen of resin subjected to bending while heated; the second method named DSC exclusively regards the study of the heat flow and energy absorption in a hardened resin sample during a simple heating process which does not involve any loading phase. From the Dynamic Mechanical Thermal

Analysis it is possible to record four different values of Tg [Tg1, Tg2, Tg3, Tg(Peak Tan δ)], temperatures which identify significant phases of the change in different resin parameters during the heating process (Gurit n.d, Sgarito 2006). The DSC test leads to determining Tg and ΔH, which represents the residual energy in a cured sample of resin. The latter parameter is extremely important to understand the percentage of maximum cure that the sample has reached during the curing process (Gurit n.d.).

Although both tests allow the study of the performance of resins at elevated temperatures, test results revealed inconsistency in the identification of the glass transition temperature (Gurit n.d.) and some past research studies defined the DSC as the most appropriate method which should be used for a correct assessment of Tg (Sgarito 2006).

For this reason, most adhesive manufacturers have indicated another thermal parameter called Heat Distortion Temperature HDT (BS EN ISO 75-1/2:2013) as the best indicator of the performance of resin materials especially if stressed at elevated temperatures (Graham 2013). The test method described in BS EN ISO 75-1/2:2013 is aimed at determining the temperature (HDT) at which a standard deflection Δs is recorded in a resin sample, subjected to selected loading and heating conditions.

Despite the test method specified by ISO 75 to determine the loss in stiffness is less accurate compared to DMTA (Gurit n.d.) and it is not suggested for design analysis of materials at elevated temperatures (BS EN ISO 75-1/2:2013), the specific value of HDT could provide useful information about the short-term thermal performance of thermosetting resins and products made of resin materials (Graham 2013, Kemmish 1995), such as adhesive connections.

Nevertheless, whichever parameter between Tg and HDT is taken into consideration to study a resin material, it is extremely important to gather detailed information about the test methods used to assess these thermal parameters in order to not draw inconsistent comparisons amongst materials. The listed details should be provided by the resin manufacturers and included in the resin data sheet either for Tg or for HDT.

- Tg: test method [e.g. DSC, DMTA: "the frequency of oscillation, the clamp type, the temperature ramp rate" (TAinst n.d.)], sample dimension.
- HTD: sample dimension (thickness), flexural stress applied [method A, B or C (BS EN ISO 75-1/2:2013)].

The connections tested in this investigations were assembled using epoxy resins characterised by different mix ratio, 1:1 and 3:1, and by Heat Deflection Temperatures of 49°C, information included in the technical data sheets of EX 1:1 and EX 3:1 manufactured by 2K polymer systems Ltd.

6.2.3 Manufacturing process for cylindrical and threaded glued in rods

6.2.3.1 Samples' bore hole shape: cylindrical and threaded

The shape of the cylindrical bore hole of 'traditional' Glued In Rod joints was modified at the bottom of the hole in order to provide a base for the steel bar insertion (Fig. 6-7). In addition, the use of support rings at the top part of the hole, close to the wooden surface, helped the bar maintain a perfect vertical position during the curing phase of the epoxy resin.

The threaded shape was realised by the use of a 12 mm diameter screw, specifically named as self-tapping screw for timber constructions.

The choice of studying the performance of adhesive joint prototypes, identified by a threaded internal hole shape, and of 'traditional' Glued In Rods in timber was mainly aimed at evaluating whether an adhesive connection characterised by different geometrical properties of the bore hole could differently perform at elevated temperatures.

Fig. 6-7: sample characterised by a cylindrical hole shape (a: left) and by a threaded hole shape (b: right)

As it is possible to observe from Fig. 6-7, the glue line thickness had a constant value of 2 mm in the cylindrical samples and it varied between 0.5 and 2 mm in the connections with a threaded bore hole.

6.2.3.2 Installation method

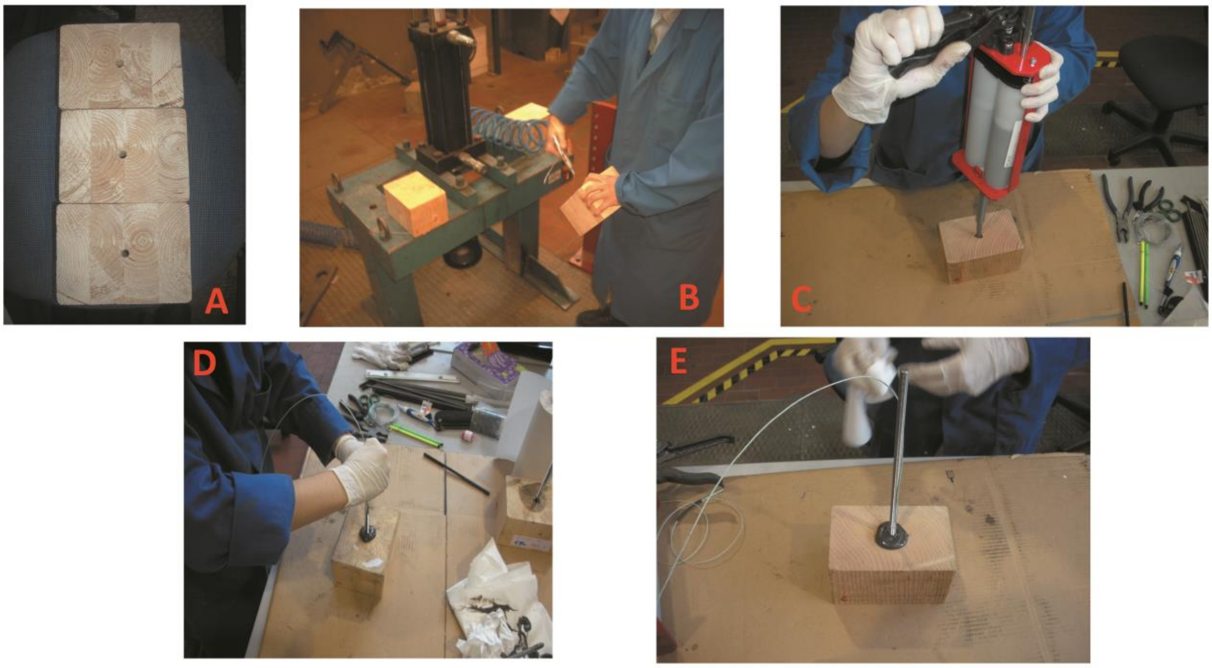


Fig. 6-8: installation method for glued in rod joints: drill a hole according to the designed shape, diameter and depth (A), clean the hole through several blows and brushes (B), insert the epoxy following the installation method suggested by the manufacturer (C), insert the threaded steel bar twisting with a back and forth movement (D), sample ready for curing process (E)

The selected glued length for all the samples was 80 mm which corresponds to 10 times the steel rod diameter. The gluing process followed a specific installation method as described in Chapter 5.

6.2.3.3 Thermocouples installation

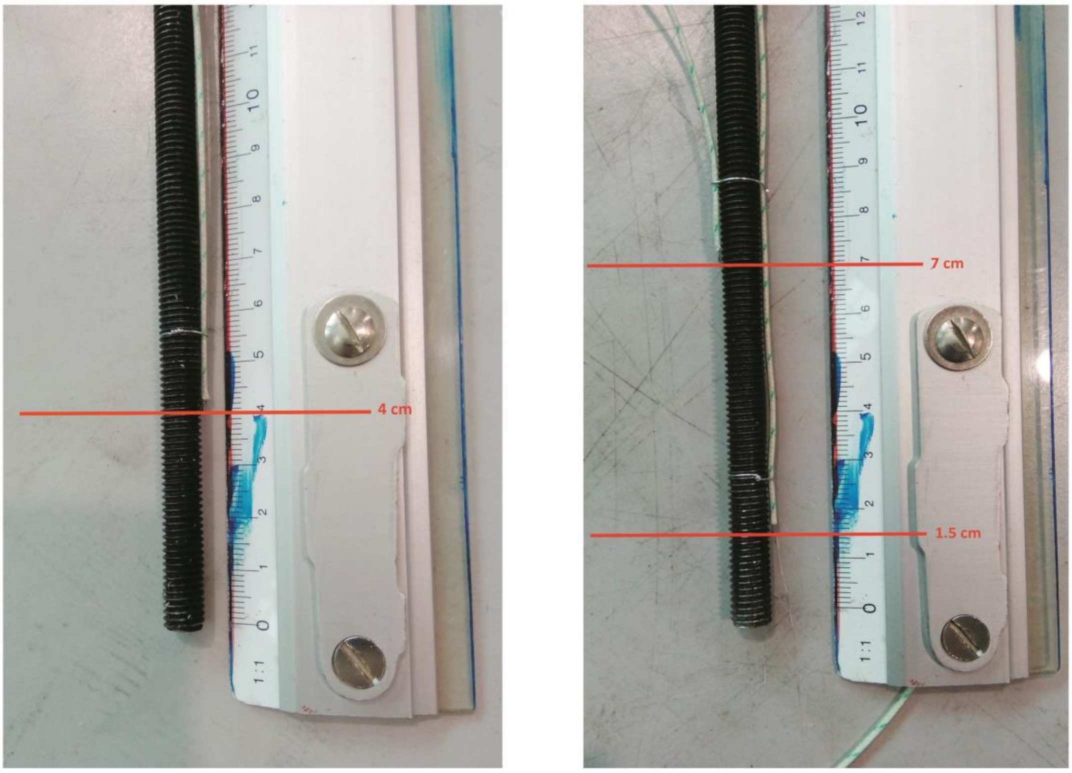


Fig. 6-9: thermocouples installation for samples with a threaded hole shape (left) and for samples with a cylindrical bore hole (right)

The use of two thermocouples, installed at different depths (1.5cm and 7cm) of the embedded length in the samples with a cylindrical hole shape, allowed the measure of the internal temperature of the epoxy adhesive in the connection and, furthermore, the control of a homogeneous heating flux in the adhesive anchor.

Conversely, all the samples identified by a threaded shape of the borehole had only one thermocouple installed on the steel bar at half of the embedded length (4 cm).

Subsequently, all thermocouple had been connected to a data logger which enabled the recording of temperatures every 0.2 seconds.

6.2.4 Laboratory experimentation

6.2.4.1 Test methodology and test equipment: an electric furnace

The tests were conducted using an electrical furnace where samples of adhesive connections were tested in pull-compression test regime under a constant load. The pull-out test had been selected because it is widely considered as the most appropriate testing configuration to evaluate the fire performance of adhesive connectors (Del Senno et al. 2005). The withdrawal capacity of the samples was tested in confined conditions using a confinement steel plate with a hole diameter of 18mm.

The time-temperature curve used during each test was different from the standard curve imposed by ISO 834. The electric furnace was heated up to 160°C in 30 minutes and left working at 160°C until reaching the specimen failure. Some samples had been heated by using a different time-temperature curve which is identified by a linear heating trend. In this specific case, an increase of 200°C in temperature was set every 20 minutes. Subsequently, a gap of time of 3 hours was needed before the execution of successive tests to let the oven cool down to laboratory room's temperature. The latter heating method resulted in being a more severe heating process for the connections which presented charred parts after the tests. It is important to underline that the test set up was chosen in order to prevent the steel bar from being heated during the test. Therefore, the heating process of the connection took place only by transmission of heat from the outside towards the inside through the timber material.

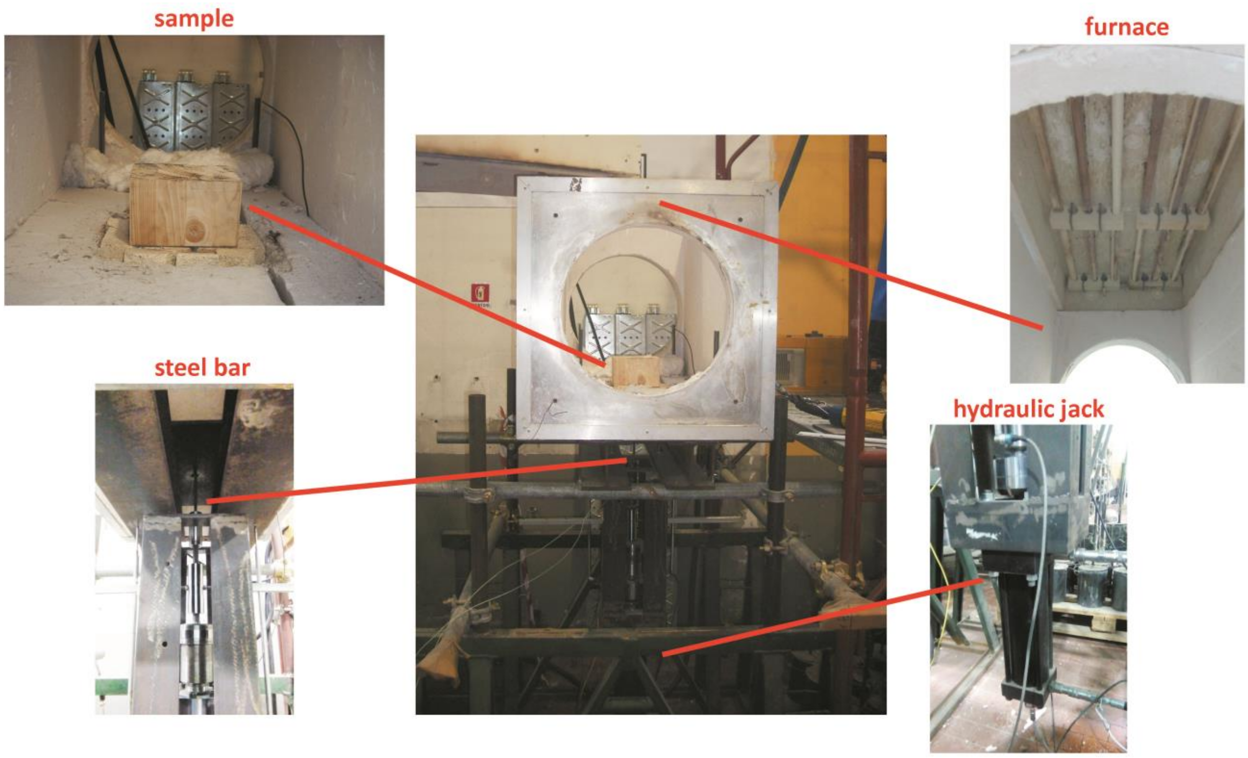


Fig. 6-10: test equipment

6.2.4.2 Test loading condition

The constant load applied to the samples during the heating process in the electric furnace had been assessed as 50 % of the average failure loads, obtained by tensile tests in cold states, representing an approximate design load for the connection (Muciaccia 2015).

Three samples for each joint type were assembled and tested, samples properties are reported in the table below (Table 6-2). Samples which failed before reaching the selected constant load as a result of inappropriate installation of the sample in the electric furnace are not listed.

Code	Epoxy type	Bar diameter [mm]	Wood type	Specimen size [mm]	Length [mm]	Hole type	Epoxy type	Sample	n° thermocouple	Constant load N [kN]	N_m [kN]
DF_80_C_EX1_1	EX 1:1	8	Douglas FIR	150x100x100	80	Cylindrical	Epoxy 1	1	2	13.6	
DF_80_C_EX1_2	EX 1:1	8	Douglas FIR	150x100x100	80	Cylindrical	Epoxy 1	2	1	13.3	13.5
DF_80_C_EX1_3	EX 1:1	8	Douglas FIR	150x100x100	80	Cylindrical	Epoxy 1	3	2	13.6	
DF_80_T_EX1_2	EX 1:1	8	Douglas FIR	150x100x100	80	Threaded	Epoxy 1	2	1	14.6	14.6
DF_80_T_EX1_3	EX 1:1	8	Douglas FIR	150x100x100	80	Threaded	Epoxy 1	3	1	14.5	
GL_80_C_EX1_1	EX 1:1	8	Glulam	160x120x100	80	Cylindrical	Epoxy 1	1	2	12.9	
GL_80_C_EX1_2	EX 1:1	8	Glulam	160x120x100	80	Cylindrical	Epoxy 1	2	2	13.0	13.0
GL_80_C_EX1_3	EX 1:1	8	Glulam	160x120x100	80	Cylindrical	Epoxy 1	3	2	13.0	
GL_80_T_EX1_2	EX 1:1	8	Glulam	160x120x100	80	Threaded	Epoxy 1	2	1	13.1	13.1
GL_80_T_EX1_3	EX 1:1	8	Glulam	160x120x100	80	Threaded	Epoxy 1	3	1	13.1	
DF_80_C_EX3_1	EX 3:1	8	Douglas FIR	150x100x100	80	Cylindrical	Epoxy 3	1	1	13.0	
DF_80_C_EX3_2	EX 3:1	8	Douglas FIR	150x100x100	80	Cylindrical	Epoxy 3	2	1	13.0	13.0
DF_80_C_EX3_3	EX 3:1	8	Douglas FIR	150x100x100	80	Cylindrical	Epoxy 3	3	2	13.0	
DF_80_T_EX3_1	EX 3:1	8	Douglas FIR	150x100x100	80	Threaded	Epoxy 3	1	1	11.0	
DF_80_T_EX3_2	EX 3:1	8	Douglas FIR	150x100x100	80	Threaded	Epoxy 3	2	1	11.0	11.0
DF_80_T_EX3_3	EX 3:1	8	Douglas FIR	150x100x100	80	Threaded	Epoxy 3	3	1	11.0	
GL_80_C_EX3_1	EX 3:1	8	Glulam	160x120x100	80	Cylindrical	Epoxy 3	1	1	10.0	10.0
GL_80_C_EX3_3	EX 3:1	8	Glulam	160x120x100	80	Cylindrical	Epoxy 3	3	2	10.1	
GL_80_C_EX3_1	EX 3:1	8	Glulam	160x120x100	80	Threaded	Epoxy 3	1	1	11.0	
GL_80_C_EX3_2	EX 3:1	8	Glulam	160x120x100	80	Threaded	Epoxy 3	2	1	11.0	11.0
GL_80_C_EX3_3	EX 3:1	8	Glulam	160x120x100	80	Threaded	Epoxy 3	3	1	11.0	

Table 6-2: samples features and selected constant load values for tests at elevated temperatures

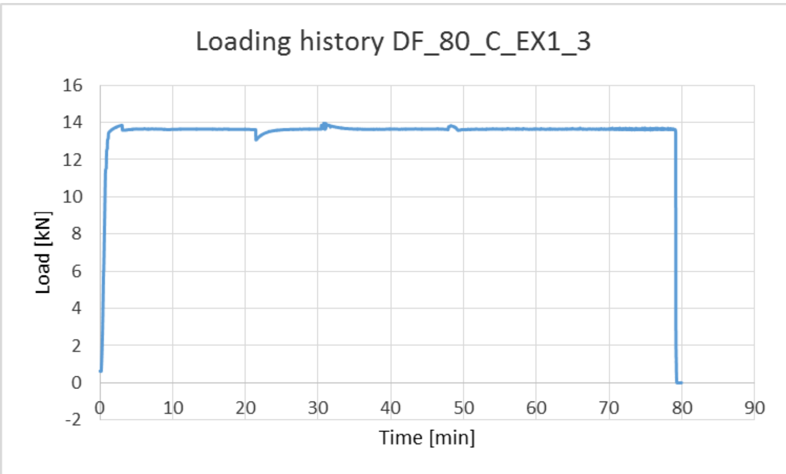


Fig. 6-11: example of loading history for a glued in rod sample tested under constant load at elevated temperatures

6.2.5 Test results

Code	Wood type	Bar diameter [mm]	Glued Length [mm]	Hole type	Epoxy type	Bond Failure mode	T_{deep} [°C]	$T_{shallow}$ [°C]	T_{av} [°C]	T_{av} [°C]	T_{av} [°C]	N [kN]	N_m [kN]	τ_u [Mpa]	$\tau_{u,m}$ [Mpa]	d [mm]	d_{av} [mm]	d_{av} [mm]
DF_80_C_EX1_1	Douglas FIR	8	80	Cylindrical	EX 1:1	steel-adhesive	45.8	45.4	45.6			13.6		6.77		2.83		
DF_80_C_EX1_2	Douglas FIR	8	80	Cylindrical	EX 1:1	steel-adhesive	43.6	-	43.6	46.4		13.3	13.5	6.61	6.71	2.81	3.02	
DF_80_C_EX1_3	Douglas FIR	8	80	Cylindrical	EX 1:1	steel-adhesive	50.2	49.6	49.9			13.6		6.76		3.42		
DF_80_T_EX1_2	Douglas FIR	8	80	Threaded	EX 1:1	steel-adhesive	48.6	-	48.6	48.7		14.6	14.6	7.27	7.24	2.33	2.44	
DF_80_T_EX1_3	Douglas FIR	8	80	Threaded	EX 1:1	steel-adhesive	48.7	-	48.7			14.5		7.21		2.55		
GL_80_C_EX1_1	Glulam	8	80	Cylindrical	EX 1:1	timber-adhesive / steel-adhesive	44.7	33.8	39.2		45.3	12.9		6.43		0.61		2.25
GL_80_C_EX1_2	Glulam	8	80	Cylindrical	EX 1:1	steel-adhesive	43.1	42.6	42.9	42.8		13.0	13.0	6.47	6.46	2.10	1.81	
GL_80_C_EX1_3	Glulam	8	80	Cylindrical	EX 1:1	steel-adhesive	47.8	45.0	46.4			13.0		6.47		2.71		
GL_80_T_EX1_2	Glulam	8	80	Threaded	EX 1:1	steel-adhesive	43.2	-	43.2	43.5		13.1	13.1	6.49	6.51	1.41	1.73	
GL_80_T_EX1_3	Glulam	8	80	Threaded	EX 1:1	steel-adhesive	43.8	-	43.8			13.1		6.52		2.06		
DF_80_C_EX3_1	Douglas FIR	8	80	Cylindrical	EX 3:1	steel-adhesive	51.8	-	51.8			13.0		6.47		2.90		
DF_80_C_EX3_2	Douglas FIR	8	80	Cylindrical	EX 3:1	steel-adhesive	50.8	-	50.8	54.2		13.0	13.0	6.47	6.47	3.19	3.25	
DF_80_C_EX3_3	Douglas FIR	8	80	Cylindrical	EX 3:1	steel-adhesive	60.3	59.5	59.9			13.0		6.47		3.66		
DF_80_T_EX3_1	Douglas FIR	8	80	Threaded	EX 3:1	steel-adhesive	56.1	-	56.1			11.0		5.47		2.17		
DF_80_T_EX3_2	Douglas FIR	8	80	Threaded	EX 3:1	steel-adhesive	59.2	-	59.2	57.8		11.0	11.0	5.47	5.47	2.83	2.43	
DF_80_T_EX3_3	Douglas FIR	8	80	Threaded	EX 3:1	steel-adhesive	58.0	-	58.0		53.1	11.0		5.47		2.28		2.71
GL_80_C_EX3_1	Glulam	8	80	Cylindrical	EX 3:1	steel-adhesive	45.4	-	45.4	49.7		10.0	10.0	4.98	4.99	2.85	3.06	
GL_80_C_EX3_3	Glulam	8	80	Cylindrical	EX 3:1	steel-adhesive	54.3	53.8	54.1			10.1		5.00		3.27		
GL_80_C_EX3_1	Glulam	8	80	Threaded	EX 3:1	steel-adhesive	50.6	-	50.6			11.0		5.47		2.40		
GL_80_C_EX3_2	Glulam	8	80	Threaded	EX 3:1	steel-adhesive	39.6	-	39.6	50.6		11.0	11.0	5.48	5.48	1.52	2.10	
GL_80_C_EX3_3	Glulam	8	80	Threaded	EX 3:1	steel-adhesive	54.1	-	54.1			11.0		5.49		2.40		

Table 6-3: test results

From the tests results in Table 6-3, it is possible to note that all failure temperatures are highly dependent on the epoxy resin use to assemble the connections. The bond strength of samples made of EX 3:1 showed slightly lower values than EX 1:1 specimens as a consequence of the lower constant load applied during the tensile test. In effect, the high viscosity of EX 3:1 in cold state affected the bonding quality providing adhesive connections with lower withdrawal capacity than sample made of EX 1:1.

Regarding the visual analysis of the samples after being tested, it is evident that all samples presented a predominant failure mode which can be classified as a bond failure at the steel-adhesive interface (Fig. 6-12).

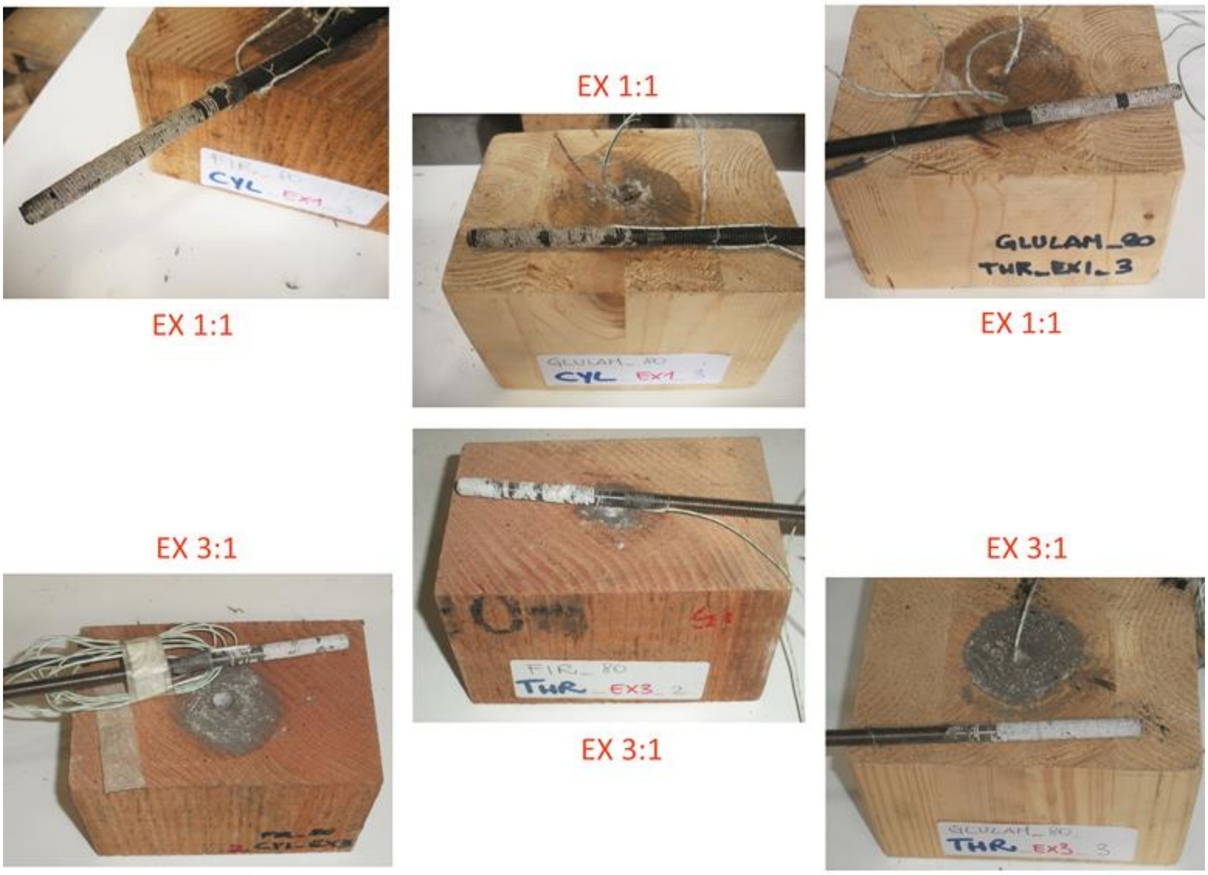


Fig. 6-12: failure modes of some tested samples

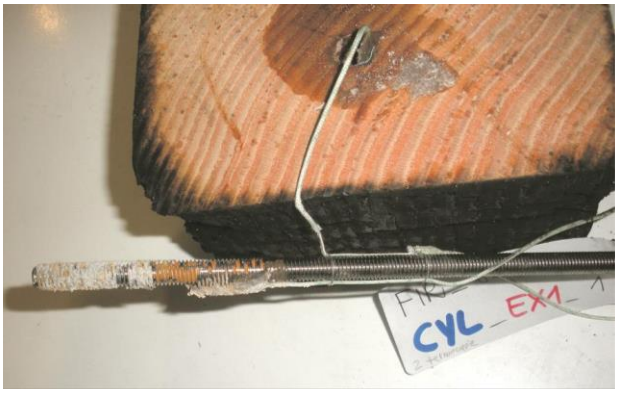


Fig. 6-13: thermal degradation of the external part of the embedded steel rod as a consequence of a severe heating process

In particular the aforementioned failure mode occurred in some samples in combination with a visible thermal degradation of the external part of the embedded steel rod as a consequence of a severe heating process which had reached temperatures up to 450°C in the electric furnace (Fig. 6-13).

Furthermore, it is visible from the pictures of the tested samples that a critical increase in temperature combined with the application of a tension load changed the epoxy texture showing a “crumbling effect” (Harris 2004: 64) of the adhesive material in the connection. This observation proves that the samples’ failures had occurred in the connection due to a loss in strength of the thermosetting materials (EX 1:1 and EX 3:1).

Fig. 6-14: “crumbling effect” in the epoxy resin after being exposed to elevated temperatures

6.2.6 Results discussion

- Although several past research studies about adhesive anchors in timer identified the glass transition temperature as the thermal property of adhesives which should be taken into consideration to study their thermal performance [Piazza et al. 2005, Faye et al. 2004], the test results of this laboratory experimentation showed failure temperatures very close to the HDTs of both epoxy resins. Hence, the critical temperature beyond which the connection started losing its strength can be identified by the Heat Deflection Temperature, which is the most important thermal parameter to consider for the analysis of the performance of adhesive anchors in timber exposed to elevated temperatures.
- The selected electric furnace is a valid testing machine to study the thermal behaviour of adhesive anchors. The simultaneous increase in temperatures with the application of a constant load provides useful information on the performance of adhesive connections in timber at elevated temperatures, although the effects of creep are inevitably induced during the loading phase of the sample.
- Both resins reached failure temperatures few degrees higher in sample made of solid timber than in glulam specimens. This little difference might be due to the presence of only one thermocouple in some samples which did not allow the measurement of the correct average temperature at the bonding layer. However, from the graphs plotted in Fig. 6-15, it is possible to observe that EX1 and EX3 samples failed at well-defined ranges of temperatures which correspond respectively to 40-50°C for EX1 and 50-60°C for EX3.

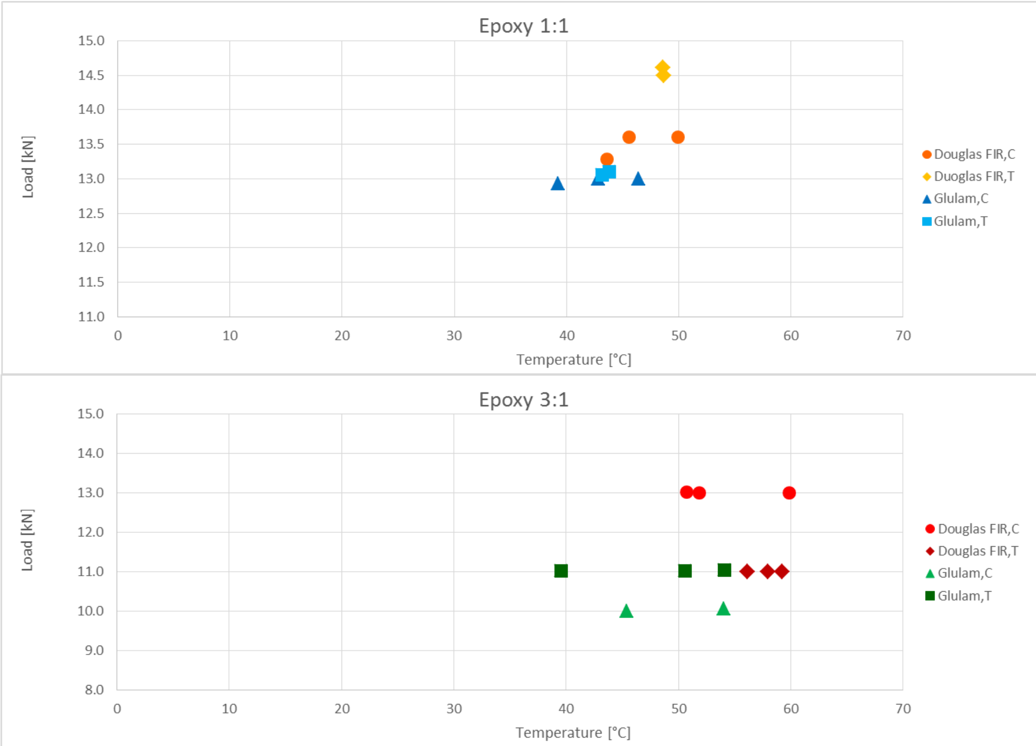
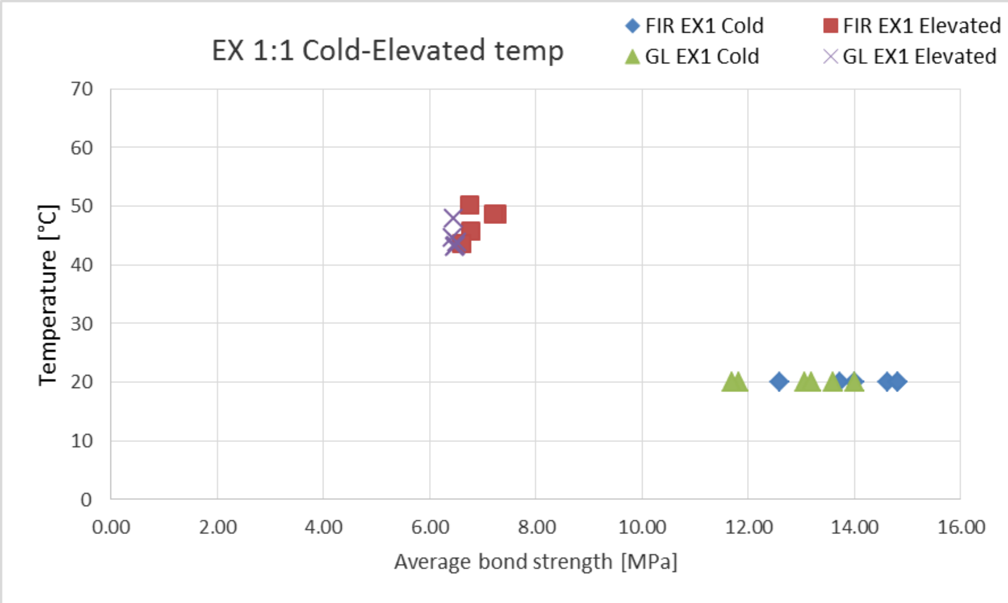


Fig. 6-15: load-failure temperatures of all tested connections

(Douglas Fir samples: cylindrical and threaded; Glulam samples: cylindrical and threaded)

- An increase in temperature at the bonding layer up to the HDT causes a significant decrease in the withdrawal capacity of the adhesive connection and consequently in the bond strength. The bond strength value at critical temperatures (HDT) is almost 50% of the mean shear strength obtained by experiments carried out in cold states. This proves that the performance of the joint at elevated temperature is highly dependent on the thermal properties (HDT) of the epoxy resin used to assemble the connection.

$$\tau(\text{HDT}) \approx 0.5\ \tau(20°\text{C})$$



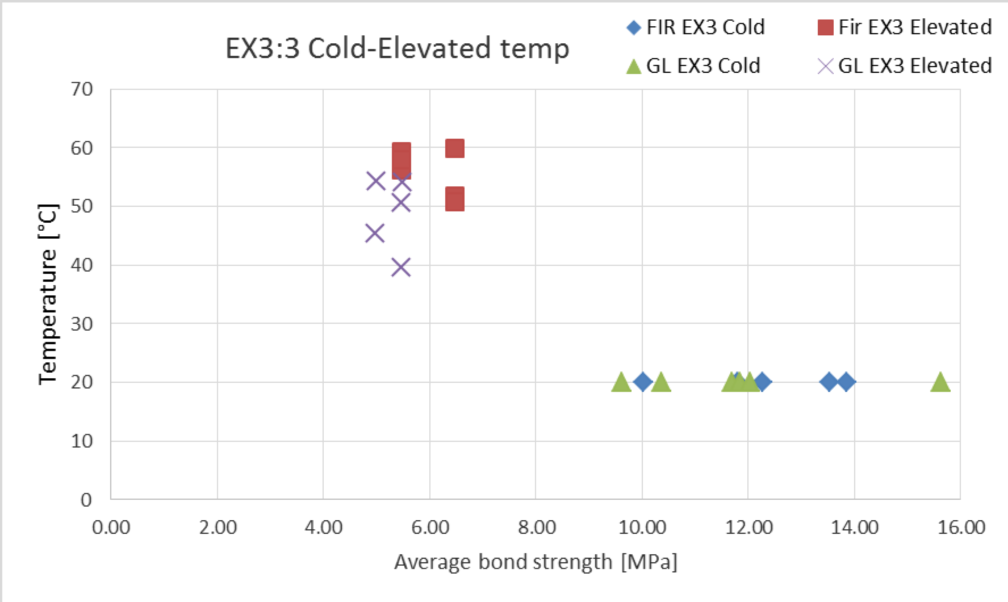


Fig. 6-16: temperature-average bond strength in cold state and at elevated temperatures for samples made of EX 1:1 (above) and EX 3:1 (below)

- No significant differences were identified between the performance of cylindrical and threaded samples at elevated temperatures. Hence, the failure temperature reached by the samples made of EX 1:1 and EX 3:1 is not affected by the shape of the internal borehole but it is influenced by the thermal properties of both epoxy resins (HDT). In addition, no significant differences in failure temperatures have been found between the two different timber typology (solid timber, glulam) used as substrates for the tested adhesive connections mainly because they were made from the same timber species (spruce).
- Due to the fact that the time-temperature curve ISO 834 was not used to heat the specimens up during the tests, it is not possible to provide any information regarding the

fire resistance time which characterised the studied adhesive anchors. However, it was possible to note that, under equal loading condition, the failure temperature was not affected by the use of different time-temperatures curves.

- The design of adhesive anchors at elevated temperatures in timber should take into account that whether temperatures close to the HDT are reached at the adhesive layer, the joint starts to lose its strength. However, in these laboratory experimentations it is important to underline that some samples made of EX 1:1 reached a failure temperature which is almost 5°C lower than the HDT. Additionally, as it is possible to note from the temperature-slip graphs Fig. 6-17, most of the EX 1:1 joints started to lose strength at ≈42°C and at ≈45°C for connections assembled by EX 3:1 (Table 6-4), respectively 7°C and 4°C lower than the Heat Distortion Temperatures which is equal to 49°C for both epoxies (2kps 2014).

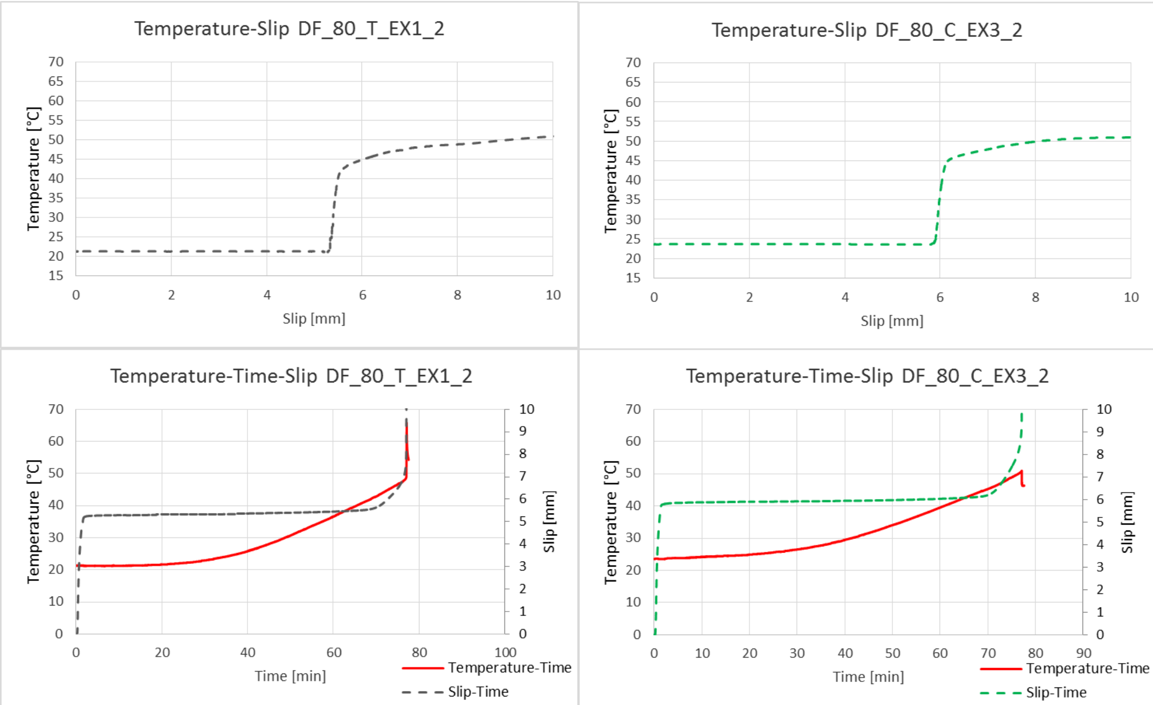


Fig. 6-17: temperature-time and temperature-slip curves for a tested joint made of EX 1:1 (left) and EX 3:1 (right)

- EX 3:1 performed better that EX 1:1 showing failure temperatures beyond the relative HDT value of 49°C. However, it can be stated that both epoxy resins had a thermal performance highly predictable from their Heat Distortion Temperatures.

	Bar diameter [mm]	Glued length [mm]	Average Temperature at significant initial slip [°C]	Average Temperature at Failure [°C]	Average Slip at Failure [mm]
EX 1:1	8	80	42	45.3	2.25
EX 3:1	8	80	45	53.1	2.71

Table 6-4: average slip and failure temperatures for EX 1:1 and EX 3:1

- The presented study identified a critical temperature equal to HDT±5°C for a safe performance at elevated temperatures of the studied adhesive anchors in timber made of EX 1:1 and EX 3:1, characterised by specific geometrical and material properties. It is important to remember that the epoxy resins used in this experimentation have been regulated and approved only for adhesive anchors in concrete. Their use in timber members is totally experimental and more tests are needed to confirm their application for Glued In Rods in timber.

6.2.7 Summary

Adhesive anchors in timber have been often defined as connections which can provide good fire protection. Through the analysis of the results obtained by this experimental activity it is possible to state that Glued In Rods in timber may have a good fire performance only if properly designed.

Modifications to the timber cross section size (Harris 2004, Gerard 2010) and/or to the joint design should be made when reaching internal temperatures in the wooden element close to HDT, temperate beyond which the tested connections lose a significant percentage of the bond strength assessed in cold conditions (20°C).

6.2.7.1 Edge distances

The edge distance plays a crucial role in the behaviour of the connection when subjected to elevated temperatures. For this reason the fire design of the connection should take into account that the edge distance should be increased considering the reduction in the cross section due to the charring process and ensuring that a temperature close to HDT value would not be reached within the bonding layer of the adhesive connections. This design method would prevent a failure mode caused by loss of the adhesive strength properties at a quite low (Harris 2004) range of temperatures (40-60°C). In other words, the distance between the steel rod and the timber edge (edge distance) should guarantee the beginning and the development of the charring process preventing the connection from failing due to a loss of the adhesive mechanical properties.

Piazza et al. (2005) suggested that the edge distances provided by the EC5 for axially loaded screws in timber should be applied to Glued In Rods because it was experimentally determined that a residual timber layer of 20-25 mm is sufficient to protect the bar after 60 minutes of fire exposure (R60) from thermal degradation in an adhesive connection. However, this design suggestion would also be adaptable for Glued In Rods applications in which steel rods are glued perpendicular to the wood grain.

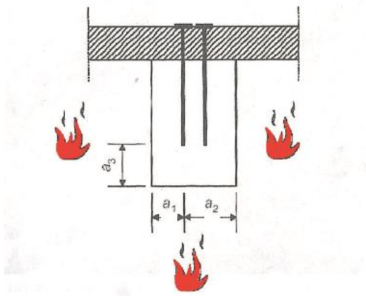


Fig. 6-18: edge distances for axially loaded screws according to EC5 (Piazza et al. 2005: 601)

$$a_1 \geq \beta t_{fi,d} + 28$$

$$a_2 \geq a_1 + 40$$

$$a_3 \geq a_1 + 20$$

Where

a_1, a_2, a_3= edge distances [mm]

β = charring rate [mm/min]

$t_{fi,d}$ = connection's fire resistance time [min]

6.2.7.2 Finite Element Analysis

A critical temperature around 50°C for epoxy resins was identified also in Buchanan and Barber's (1996) studies where a basic finite element analysis was developed by the TASEF software. Adhesive connections made of a single bar or multiple bars in timber beams with different geometrical properties reached critical temperatures after 15-30 min of fire exposure (ISO 834).

However, it is extremely important to underline that direct and valid comparison with conclusions drawn by previous research studies on the behaviour of Glued In Rods in timber under fire exposure can be made only if the research activities had involved the use of same materials, same joint manufacturing process and test methods. As already explained in Chapter 3, research outcomes drawn by a specific laboratory experimentation can be hardly generalised because the performance of an adhesive anchorage is strongly dependent of the products the joint is made of and on the methods used to manufacture and test its load bearing capacity, even at elevated temperatures.

A more accurate Finite Element Model was presented by Schnabl and Turk in 2006. Their FEM shows the temperature distribution in a spruce timber beam subjected to a standard fire exposure (ISO 834) for 30 minutes. The timber beam, modelled in Schnabl and Turk's studies, presents similar features in terms of cross-section dimension, timber species and moisture content (spruce, 100x150 mm cross section, 13% moisture content) to the samples' properties of the joints tested and presented in this chapter; for this reason, the finite element simulation can be taken into consideration to investigate the internal temperature variation within a timber beam cross section in which an adhesive anchor may be installed.

The timber beam had been modelled using an accurate charring model, consistent with the EC5, which reproduced the complex process of pyrolysis of wood considering different thermal properties for cold wood and charred wood (Schnabl and Turk 2006). Moreover, in Schnabl and Turk's (2006) research work the study of the generation of heat and its distribution inside the wood sample is combined with the moisture content transfer in order to simulate and reproduce what the real behaviour of a timber beam under fire exposure is.

From the aforementioned FEM, it is possible to observe that after 10 minutes from the beginning of the fire event, the internal part of the beam cross section, where adhesive anchors may have been installed, reached temperature close to 50°C and at 20 minutes the whole cross section was characterised by temperatures above 100°C.

According to the experimental results obtained by the laboratory investigation presented in Chapter 6, the adhesive layer in the tested adhesive connections failed at temperature values between 45-50°C close to the epoxy HTD (49°C) losing almost 50% of the "cold state" bond strength $\tau(20°C)$. Therefore, if adhesive connections were installed into the modelled timber beam, a design modification of the joint would be necessary to allow the connection to have a fire time resistance equal or bigger than 10 minutes.

Despite the reduced-cross section method suggested by EC5 is based on the assumption that the residual cross section would keep unchanged its mechanical strength as it was in 'cold conditions', in reality the charred layer prevents the internal cross section from reaching high temperatures but not from having a gradual increase in temperature towards the inner of the timber element. For this reason, when designing adhesive anchors in timber exposed to elevated temperatures, it is extremely important to monitor and study the internal temperatures distribution in the timber cross section because it is likely that critical temperature for adhesive materials, such as 49°C for the studied epoxy resins, would be reached during fire exposure.

6.2.7.3 *Recommendation*

Consequently, in order to allow the joint to enhance its resistance to elevated temperatures, different actions can be undertaken during the structural design process:

i. To increase the fire resistance of the timber cross sections by using an additional protective timber layer and adapting the formula provided by EC5 for unprotected joints to adhesive anchors:

$$a_{fi} = \beta k_{flux}\,(t_{req} - t_{fi,d}) \quad \text{for } t_{req} \leq 30 \text{ min}$$

a_{fi} = additional protection thickness [mm]

β = charring rate [mm/min]

k_{flux} = heat flux coefficient (k_{flux} =1.5)

t_{req}= required time of the fire resistance [min] (Piazza et al. 2005, Augustin 2008: 238)

$t_{fi,d}$= connection's fire resistance time [min]; experimentally determined and dependent on the geometrical properties and the main features of the materials (timber typology, steel rod diameter, adhesive type) which the joint is characterised by.

Where the minimum edge distance (d_{min}) for a Glued In Rod, according to what was anticipated by Piazza et al. (2005), may be calculated by

$$d_{min} = \beta t_{fi,d} + 30 \text{ mm}$$

However, more experiments are needed to prove if a standard residual cross section, identified by a minimum thickness of timber cover of 30 mm from the adhesive layer, can avoid the adhesive failure of the connection and can guarantee its structural integrity.

ii. To adopt a design approach which keeps the cross section size of the timber element and modify the design of the adhesive anchor, improving its withdrawal capacity by changing the embedment length (Muciaccia 2016) and/or the rod diameter in order to resist the tensile load which is applied to the adhesive anchor at elevated temperatures.

In this specific case, it is essential to know the complete temperature-average bond strength curve for a correct design of the adhesive connections exposed to elevated temperatures. Hence, knowing the relationship between temperature and bond stress would provide important information about the loss of the bond strength at different ranges of elevated temperature and it would be useful to safely design Glued In Rods in timber under fire exposure.

Further important aspects have to be taken into careful consideration when dealing with the structural behaviour of adhesive anchors in timber subjected to elevated temperatures:

a. Due to the differences in timber thermal conductivity with the wood grain orientation, the process of heat transfer within a timber member is different in directions which are parallel or perpendicular to the wood grain (Timber thermal conductivity // 0.38 [W m^{-1} K^{-1}]; ⊥ 0.15 [W m^{-1} K^{-1}], Piazza et al. 2005: 571). For this reason, the evaluation of the direction of the bar against the wood grain direction plays a significant role not only in cold conditions but also in the analysis of the joint performance at elevate temperature.

b. In case of a timber structure needs fire protection, when designing multiple Glued In Rods in a timber element the edge distances have to be selected considering both the stress interactions amongst the bars and the design modifications required by the adhesive joints in case of fire.

c. The structural design of adhesive anchors in timber at elevated temperatures has to be studied and modified for real installations in which the connections would be exposed to extended solar exposure in hot climate countries. In fact, it has been demonstrated by different authors (Aicher et al. 1998, Faye et al. 2004) that a solar exposure longer than 5 hours can internally heat the joint up to critical temperatures.

In conclusion, it can be stated that it is essential to take into consideration during the design process of an adhesive anchor in timber how an increase in temperature due to both a fire event and a solar heating process might affect its structural performance in situ.

Further investigations regarding the residual strength of the connection when subjected to temperatures which remain lower than the HDT (Harris 2004: 67) would be of particular interest for this engineering topic. Moreover, the performance of further experimental activities and finite element analyses is essential to gain a good understanding of the behaviour of adhesive anchors in timber at elevated temperatures and to study how parameters such as embedded length, direction of the glue line against the wood fibres, timber species might influence the performance of Glued In Rods in timber at elevated temperatures.

7. Conclusion and Recommendations

7.1 Contradictory existing design rules

Worldwide research activity on Glued In Rod connections in timber has been conducted over the last 30 years mainly to investigate their load-bearing capacity. Numerous publications suggested diverse and contradictory procedures for the design of adhesive anchors in timber. This thesis achieved the purpose of clarifying why the application of different design rules in the past had caused the relay of inconsistent information about the use of adhesive anchors in the timber engineering field. In fact, through an intense investigation it was possible to state that all the existing design formulas cannot be generalised and therefore generally applied for the prediction of the pull-out capacity of Glued In Rod joints in timber as they are mathematical expressions which stemmed from research studies based on the use of different methods and investigative methodologies for both the manufacturing and testing phases.

7.2 Design of adhesive anchor in timber subjected to tension

7.2.1 In cold condition

- The critical analysis of the literature review and the outcomes drawn from the presented laboratory experimentation revealed and highlighted a high dependency of an adhesive connection in timber on its geometric properties. In particular, the variation in minor geometric characteristics of an adhesive connection in timber can significantly affect its withdrawal capacity.

  For this reason, the withdrawal capacity of a Glued In Rod in timber can hardly be predicted by generalised mathematical formulas which do not include experimentally determined parameters. A correct design formula should contain a strength bond parameter which characterises the product-dependency of each adhesive anchor.

- The thesis addressed the issue related to the lack of a current standard regulation for the design of Glued In Rods in timber. In order to fill the gap in knowledge about this topic, the thesis proposed a simple and innovative design process which is mainly composed of two critical phases:
  1. The identification of a specific bond strength parameter which is highly dependent on the physical and mechanical properties of the materials used to assemble the joint.

Adhesive manufacturers are in charge of formulising specific adhesive for applications in timber substrates and of providing detailed information about the compatibility between adhesive and selected timber species and typologies. For each combination of adhesive-wooden substrate the assessment of the bond strength parameter $\boldsymbol{\tau}_{\boldsymbol{bond}}$ has to be undertaken by following a regulation which needs to be urgently issued by a technical body for standardisation (e.g. EOTA).

The standard regulation should include a formula to assess the bond strength at the steel-adhesive interface of an adhesive anchor in timber including corrective factors to take into consideration the influence that test regimes and bar-wood grain direction would have on the withdrawal performance of the connection. Moreover for the standardisation process aimed at determining bond strength parameters for each combination of steel-adhesive-timber material, it is suggested to adopt the performance of tensile tests in pull-compression configuration as it enables the determination of the joint's strength by avoiding premature substrate failures and by optimising the consumption of testing materials.

$$\boldsymbol{\tau}_{\boldsymbol{bond}} = \frac{N}{\pi d_r l_g} \alpha \beta$$

$\boldsymbol{\tau}_{\boldsymbol{bond}}$ = bond strength at the steel-adhesive interface [MPa]
N = maximum pull-out load assessed by pull-compression tension test[N]
d_r = rod diameter [mm]
l_g = glued length [mm]
α = correction factor related to testing conditions in which $\boldsymbol{\tau}_{\mathrm{bond}}$ is assessed (confined-unconfined test regimes)
β = correction factor which takes into consideration the direction followed to glue the steel bar into a timber element (parallel-perpendicular to the wood grain)

2. The calculation of the withdrawal capacity of a single adhesive anchor in timber by knowing the aforementioned bond strength parameter, bar diameter and glued length of the connection.

$$P_{Rk} = \pi \boldsymbol{\tau}_{\boldsymbol{R\,k,bond}} d_r l_g$$

P_{Rk} = characteristic withdrawal load [N]

$\boldsymbol{\tau_{R\,k,bond}}$ = bond strength at the steel-adhesive interface [MPa]= *f (timber species, adhesive type, glued length, rod diameter, hole diameter).* It has to be:

- determined by standard experiments
- expressed as a characteristic value by BS EN 14358:2016
- provided by adhesive manufacturers

d_r = rod diameter [mm]

l_g = glued length [mm]

- The use of the presented equations leads to the calculation of a correct value of the withdrawal capacity of an adhesive anchor in timber and, therefore, allows engineers to design the connection in order to guarantee its safe ductile failure mode in real installation.

7.2.2 At elevated temperatures

- The study of the behaviour of adhesive anchors in timber at elevated temperature led to identifying the importance of defining by standard tests the fire resistance time which characterises an adhesive connection in timber and the relationship between bond strength and temperature when subjected to elevated temperatures.
- A safe design of an adhesive anchor subjected to elevated temperature can be undertaken by adopting 2 different strategies:
    1. The edge distance from a steel anchor should be selected in order to prevent the bonding layer from reaching temperatures which are critical for the adhesive material: the HDT (Heat Deflection Temperature). An additional timber layer might be adopted to protect the connection by following the formula provided by EC5 for unprotected joints where the connection's fire resistance time has to be experimentally determined by adhesive manufacturers following standard regulation which needs to be formalised.

$$a_{fi} = \beta k_{flux}\,(t_{req} - t_{fi,d}) \quad \text{for } t_{req} \leq 30 \text{ min}$$

a_{fi} = additional protection thickness [mm]

β = charring rate [mm/min]

k_{flux} = heat flux coefficient (k_{flux} =1.5)

t_{req}= required time of the fire resistance [min] (Piazza et al. 2005, Augustin 2008: 238)

$t_{fi,d}$= connection's fire resistance time [min]; experimentally determined and dependent on the geometrical properties and the main features of the materials (timber typology, steel rod diameter, adhesive type) which the joint is characterised by.

2. By knowing the complete bond strength-temperature curve of a Glued In Rod joint made of a specific combination of materials (steel-adhesive-timber), designers can modify the joint's geometrical properties by selecting different glued length (Muciaccia 2016) and/or rod diameter in order to let the joint successfully perform at elevated temperatures without modifying the dimension of the timber cross section.

- The definition of the design process for adhesive anchors at elevated temperatures in timber should be finalised only after gaining full knowledge on the withdrawal behaviour of Glued In Rods in a cold state.

7.3 TECHNICAL GUIDELINES FOR THE USE OF ADHESIVE ANCHORS IN TIMBER DURING THE MANUFACTURING, TESTING AND INSTALLATION PHASES

The experimental research program developed in this thesis led to the identification of important technical recommendations which can be summarised in technical guidelines for the use of adhesive anchors in timber. It is important to underline that the following information is gathered from laboratory investigations based on the study of adhesive connections made from solid timber (Oak, Douglas Fir) and Glulam (Spruce) and made of threaded steel bars and epoxy resins (EX 1:1 and EX 3:1) manufactured by the 2K Polymer Systems company, therefore the validity of the following statements is strictly related to the use of the aforementioned materials.

7.3.1 In cold condition

7.3.1.1 Manufacturing phase.

- The development of specific epoxy resins formulated for timber applications by adhesive manufacturers would improve and facilitate the use of Glued In Rods in timber. Regarding the chemical composition, when selecting a resin for adhesive anchors in timber it is extremely important to evaluate the compatibility between the adhesive formulation and the permeability of the wood species used as substrate in the joint.

- Adhesive materials such as epoxy resins used for adhesive anchors in concrete should be carefully used on timber elements. However when adhesives formulated for concrete applications are applied to a timber substrate, the loading time of the resin reported in the technical datasheet should be increased in order to let the resin achieve full strength in wooden elements.
- The use of specific resins for wood should be promoted and developed by the resin manufactures in order to modify its composition and optimise the bond with a wooden substrate, by changing its "molecular weight distribution, solid contents and addition of filler and other additives" (Kamke and Lee 2007) and therefore its viscosity in relationship to wood species, because the resin formulation has a "tremendous influence over the penetration behaviour of adhesive into wood" (Kamke and Lee 2007).
- The test results showed that adhesive anchors made of EX 1:1 performed better than connections assembled by using EX 3:1 in most of the carried out tests. This aspect indicates that for adhesive anchors in timber the viscosity property of the adhesive has a crucial role in the definition of the bonding quality. Low viscosity epoxy is needed to allow the resin to deeply penetrate into the timber fibres and to create a strong bond with the wooden substrate.
- The adoption of a new 'easy-to-use' prototype of Glued In Rods identified by the presence of a threaded and rough internal bonding surface can simultaneously provide:
    A. an increase of up to 12% in the withdrawal capacity of an adhesive anchor in timber
    B. a decrease in the joint's cost due to a significant reduction (30-40%) in the use of epoxy resins compared to a 'traditional' cylindrical Glued In Rod in timber

  only if:

    - it is assembled with low viscosity epoxy resins (EX 1:1)
    - it is made from solid timber
    - it is manufactured by inserting steel rods parallel to the wood grain direction.

7.3.1.2 Testing phase

- The theoretical approach suggested in Cook's studies (1991) to describe the internal shear stress distribution at the adhesive-adherend interface in adhesive joints can be successfully applied to adhesive anchors in timber. The determination of relevant "bond properties" can help to establish if a uniform stress model is able to correctly represent the real joint's behaviour. Moreover, the coefficient of stiffness λ' can be adopted to classify adhesive anchors made of different materials in laboratory conditions.

- The application of the POLA method to adhesive anchors in timber may offer a great possibility of assessing in a standard way the maximum pull-out load which characterised an adhesive anchor in timber during laboratory experimentations.

7.3.1.3 Installation phase

- The innovative installation method, presented in this thesis, characterised by the presence of technical solutions for solving stability issues of the steel element of an adhesive anchor in timber, can simplify the manufacturing process of 'traditional' Glued In Rod connections allowing a correct installation of the steel bar during the complete resin curing time.
- The threaded internal borehole of the studied prototype of Glued In Rod connections leads to an easier installation process of the steel bar because of the prototype's geometrical properties which permit the steel rod to be perfectly in place into the timber element even during the resin curing time.
- Opened cartridges of epoxy resins should not be used to assemble adhesive anchors in timber. Information about the resin shelf life is provided by the manufacturing company (2kps) of the adhesives but usually no information regarding the shelf life of an opened cartridges is suggested. This piece of information is particularly important for practical applications of adhesive anchors and workers in situ should be advised not to use opened cartridges during subsequent working days on the same construction site. For in situ and in laboratory experimentations the installation process of Glued In Rod joints has to be optimised in order to prevent adhesive from being wasted. Epoxy cartridges should be consumed within 24h of opening.

7.3.2 At elevated temperature

- A change in the internal borehole's shape of an adhesive anchor in timber did not affect the thermal performance of the joint at elevated temperatures confirming that the structural performance of a Glued In Rod Joint at elevated temperatures is highly dependent on the thermal properties of the resin used to assemble the connection.
- The Heat Deflection Temperature has to be taken into careful consideration to study and comprehend the thermal response of an adhesive anchor in timber. In particular, when selecting adhesives for adhesive joints which are part of timber structures designed for fire events, it is extremely important to gather detailed information about the test method used to assess the Heat Deflection Temperature in order not to draw inconsistent comparisons amongst materials. The HDT value and its relative test method should be provided by the resin manufacturers and included in the resin data sheet.

- From the experiments conducted under elevated temperature, it is possible to state that samples made of high viscosity epoxy performed well, highlighting the ability of EX 3:1 to be resistant to elevated temperatures (50-60°C) which are almost 10°C higher than the temperatures reached by samples made of EX 1:1 (40-50°C). For this reason, it is advisable that adhesive anchors in timber should be manufactured by using epoxy resins specifically formulated for timber substrates. In this specific case, an epoxy resin suitable for applications in adhesive anchors in timber should be characterised by the low viscosity property of EX 1:1 and the good fire performance of EX 3:1 in order to allow Glued In Rod connections to show good withdrawal performances in timber both in cold states and at elevated temperatures.

  In particular, according to the test results collected from the studied connections, good bonding conditions and best withdrawal performances are achieved using EX 3:1 at elevated temperatures for cylindrical adhesive anchors identified by short length (60-80mm); on the contrary, the best use of EX 1:1 is in a cold state when used to assemble threaded joints with short-medium length (60-120mm).

7.4 LIMITATIONS AND SUGGESTIONS FOR FUTURE WORK

- The experimental program developed in this thesis is based on the short-term analysis of the withdrawal behaviour of 'traditional' and new prototype of single adhesive anchors in timber.

  Despite the performance of several tensile tests in cold condition and at elevated temperatures, knowledge on the long-term performance, creep effect and shear capacity of resin connectors in timber was not gained.

  For this reason in order to acquire full knowledge on this type of adhesive connections in timber, it is extremely critical to complete their investigation taking into consideration the aforementioned variables. Furthermore, the evaluation of the performance of the resin connectors when subjected to shear forces would release additional information for the structural use of Glued In Rod in timber structures.
- Moreover, the development of further experimental programs to investigate the structural behaviour of adhesive connections made of multiple steel anchors and the performance of finite element analyses are essential activities which are required to gain a good understanding of the behaviour of adhesive connections in timber in cold and fire conditions.

- Lastly, standard regulations for the design and installation of adhesive anchors in timber should be urgently approved by technical bodies for standardisation, e.g. the European Organisation for Technical Approval (EOTA).

7.5 CONTRIBUTION TO KNOWLEDGE

The research work presented in this thesis contributes to developing a deeper understanding of the withdrawal capacity of adhesive anchors in timber structures in cold conditions and at elevated temperatures. The dissertation provides guidelines for designers, researchers, scientists and engineers on all the stages that the process of using adhesive connections involves: manufacturing, installation, testing and design.

In particular, the thesis examines the issue related to the lack of a standard regulation for the design of Glued In Rod connections in the current EC5. In the first place, the existing contradictions amongst the design equations suggested by previous research studies are clarified by a critical comparative study which reveals the main reasons for the absence of a valid design method for adhesive anchors in timber.

Consequently, through an original exploration of the applicability of theoretical approaches and design methods used for adhesive anchors in concrete substrates to Glued In Rods in timber, the thesis provides an innovative design procedure based on the definition of a product-dependant bond strength parameter whose identification enables the calculation of the withdrawal capacity of a single adhesive anchor in timber structures.

An extensive experimental program in a cold state leads to identifying novel technical solutions for Glued In Rods which, in restrictive manufacturing conditions, simultaneously provide an increase in the withdrawal capacity of the connection and a decrease in the joint's cost due to a reduction in the use of epoxy resin.

Although a specific cost analysis of the studied adhesive connection systems is not included in this research work, important insights regarding how to reduce resin waste are provided.

Moreover, the significance of the findings obtained by the analysis of the behaviour of adhesive anchors in timber at elevated temperatures is represented by the release of valuable information to guarantee a safe structural performance in situ when resin connectors in timber are subjected to both a fire event or a solar heating process.

The thesis clearly identifies the main actions which should be undertaken and prioritised in order to improve the stagnant and confused situation in which the use of Glued In Rods has been over the last 30 years:

- A standard regulation has to be issued by a technical body for standardisation to establish a standard procedure to assess the "product-dependent" characteristic bond strength of an adhesive anchor in timber in cold and fire conditions.
- A standard calculation method of the withdrawal capacity of a single adhesive anchor in timber has to be developed for future inclusion in building codes.
- An adhesive manufacturer who declares his intent to promote a specific adhesive for Glued In Rods' applications has to:
    - identify best graded timber typology and species and relative moisture content in order to achieve optimum bonding condition
    - list restrictive conditions for the use an adhesive anchor in timber made from a hygroscopic material (wood) in specific environmental condition
    - provide detailed information about the joint manufacturing and installation phases specifying hole shape and relative glue line thickness
    - provide bond shear strength values for adhesive connections characterised by different glued length and selected timber substrates according to the aforementioned standard regulation.

The studied prototypes of Glued In Rods might be used for on-site interventions as repairing system for rehabilitation of historic buildings and as pre-fabricated joints for structural connections in new timber structures or in timber road barrier/guardrails.

In any application, workers who are in charge of assembling Glued In Rod connections in timber either in situ and in factory have to attend certified courses delivered by adhesive manufactures.

In conclusion, all the design recommendations presented in this thesis provide good starting points for the development of harmonised standards for adhesive anchors in timber, in order to fill the gap in knowledge about the structural design of Glued In Rods.

APPENDIX: TEST RESULTS (CHAPTER 5)

- GLULAM-FIR-OAK 80 mm EX 1:1 and EX 3:1

Temperature [°C]	Code	Wood type	Length [mm]	Hole type	Epoxy type	Sample	N_u [kN]	$N_{u,m}$ [kN]	dev.st	CV	τ_u [Mpa]	$\tau_{u,m}$ [Mpa]	dev.st	CV
20	GL_80_C_EX1_1	Glulam	80	Cylindrical	Epoxy 1	1	26.3				13.06			
20	GL_80_C_EX1_2	Glulam	80	Cylindrical	Epoxy 1	2	28.1	26.1	2.19	0.084	14.00	12.96	1.09	0.08
20	GL_80_C_EX1_3	Glulam	80	Cylindrical	Epoxy 1	3	23.8				11.82			
20	GL_80_T_EX1_1	Glulam	80	Threaded	Epoxy 1	1	23.5				11.69			
20	GL_80_T_EX1_2	Glulam	80	Threaded	Epoxy 1	2	26.5	25.8	2.03	0.079	13.20	12.83	1.01	0.08
20	GL_80_T_EX1_3	Glulam	80	Threaded	Epoxy 1	3	27.4				13.61			
20	GL_80_C_EX3_1	Glulam	80	Cylindrical	Epoxy 3	1	23.5				11.69			
20	GL_80_C_EX3_2	Glulam	80	Cylindrical	Epoxy 3	2	20.8	25.3	5.51	0.218	10.36	12.56	2.74	0.22
20	GL_80_C_EX3_3	Glulam	80	Cylindrical	Epoxy 3	3	31.4				15.63			
20	GL_80_T_EX3_1	Glulam	80	Threaded	Epoxy 3	1	23.8				11.84			
20	GL_80_T_EX3_2	Glulam	80	Threaded	Epoxy 3	2	19.3	22.5	2.70	0.120	9.62	11.17	1.34	0.12
20	GL_80_T_EX3_3	Glulam	80	Threaded	Epoxy 3	3	24.2				12.04			

Temperature [°C]	Code	Wood type	Length [mm]	Hole type	Epoxy type	Sample	N_u [kN]	$N_{u,m}$ [kN]	dev.st	CV	τ_u [Mpa]	$\tau_{u,m}$ [Mpa]	dev.st	CV
20	FIR_80_C_EX1_1	Douglas Fir	80	Cylindrical	Epoxy 1	1	25.32				12.59			
20	FIR_80_C_EX1_2	Douglas Fir	80	Cylindrical	Epoxy 1	2	27.99	26.8	1.35	0.05	13.92	13.32	0.67	0.05
20	FIR_80_C_EX1_3	Douglas Fir	80	Cylindrical	Epoxy 1	3	27.05				13.45			
20	FIR_80_T_EX1_1	Douglas Fir	80	Threaded	Epoxy 1	1	29.41				14.63			
20	FIR_80_T_EX1_2	Douglas Fir	80	Threaded	Epoxy 1	2	29.72	29.6	0.16	0.01	14.78	14.72	0.08	0.01
20	FIR_80_T_EX1_3	Douglas Fir	80	Threaded	Epoxy 1	3	29.67				14.76			
20	FIR_80_C_EX3_1	Douglas Fir	80	Cylindrical	Epoxy 3	1	27.22				13.54			
20	FIR_80_C_EX3_2	Douglas Fir	80	Cylindrical	Epoxy 3	2	27.85	26.6	1.68	0.06	13.85	13.22	0.83	0.06
20	FIR_80_C_EX3_3	Douglas Fir	80	Cylindrical	Epoxy 3	3	24.68				12.27			
20	FIR_80_T_EX3_1	Douglas Fir	80	Threaded	Epoxy 3	1	23.75				11.81			
20	FIR_80_T_EX3_2	Douglas Fir	80	Threaded	Epoxy 3	2	20.15	22.0	2.55	0.12	10.02	10.92	1.27	0.12
20	FIR_80_T_EX3_3	Douglas Fir	80	Threaded	Epoxy 3	3	/				/			

Temperature [°C]	Code	Wood type	Length [mm]	Hole type	Epoxy type	Sample	N_u [kN]	$N_{u,m}$ [kN]	dev.st	CV	τ_u [Mpa]	$\tau_{u,m}$ [Mpa]	dev.st	CV
20	OAK_80_C_EX1_1	Oak	80	Cylindrical	Epoxy 1	1	27.77				13.81			
20	OAK_80_C_EX1_2	Oak	80	Cylindrical	Epoxy 1	2	28.49	28.1	0.50	0.02	14.17	13.99	0.25	0.02
20	OAK_80_C_EX1_3	Oak	80	Cylindrical	Epoxy 1	3								
20	OAK_80_T_EX1_1	Oak	80	Threaded	Epoxy 1	1	29.58				14.71			
20	OAK_80_T_EX1_2	Oak	80	Threaded	Epoxy 1	2	32.65	31.6	1.73	0.05	16.24	15.71	0.86	0.05
20	OAK_80_T_EX1_3	Oak	80	Threaded	Epoxy 1	3	32.50				16.16			
20	OAK_80_C_EX3_1	Oak	80	Cylindrical	Epoxy 3	1	28.01				13.93			
20	OAK_80_C_EX3_2	Oak	80	Cylindrical	Epoxy 3	2	28.88	28.2	0.66	0.02	14.36	14.00	0.33	0.02
20	OAK_80_C_EX3_3	Oak	80	Cylindrical	Epoxy 3	3	27.58				13.72			
20	OAK_80_T_EX3_1	Oak	80	Threaded	Epoxy 3	1	23.77				11.82			
20	OAK_80_T_EX3_2	Oak	80	Threaded	Epoxy 3	2	17.24	20.5	3.27	0.16	8.57	10.19	1.62	0.16
20	OAK_80_T_EX3_3	Oak	80	Threaded	Epoxy 3	3	20.46				10.18			

- FIR 80-120 mm EX 1:1 and EX 3:1

Wood type	Length [mm]	Hole type	Epoxy type	Sample	N_u [kN]	$N_{u,m}$ [kN]	dev.st	CV	τ_u [Mpa]	$\tau_{u,m}$ [Mpa]
Douglas Fir	80	Cylindrical	Epoxy 1	1	25.32				12.59	
Douglas Fir	80	Cylindrical	Epoxy 1	2	27.99	26.8	1.35	0.05	13.92	13.32
Douglas Fir	80	Cylindrical	Epoxy 1	3	27.05				13.45	
Douglas Fir	80	Threaded	Epoxy 1	1	29.41				14.63	
Douglas Fir	80	Threaded	Epoxy 1	2	29.72	29.6	0.16	0.01	14.78	14.72
Douglas Fir	80	Threaded	Epoxy 1	3	29.67				14.76	
Douglas Fir	80	Cylindrical	Epoxy 3	1	27.22				13.54	
Douglas Fir	80	Cylindrical	Epoxy 3	2	27.85	26.6	1.68	0.06	13.85	13.22
Douglas Fir	80	Cylindrical	Epoxy 3	3	24.68				12.27	
Douglas Fir	80	Threaded	Epoxy 3	1	23.75				11.81	
Douglas Fir	80	Threaded	Epoxy 3	2	20.15	22.0	2.55	0.12	10.02	10.92
Douglas Fir	80	Threaded	Epoxy 3	3	/				/	
Douglas Fir	120	Cylindrical	Epoxy 1	1	35.08				11.63	
Douglas Fir	120	Cylindrical	Epoxy 1	2	34.22	34.6	0.61	0.02	11.35	11.47
Douglas Fir	120	Cylindrical	Epoxy 1	3	34.48				11.43	
Douglas Fir	120	Threaded	Epoxy 1	1	34.57				11.46	
Douglas Fir	120	Threaded	Epoxy 1	2	42.22	37.4	5.41	0.14	14.00	12.39
Douglas Fir	120	Threaded	Epoxy 1	3	35.35				11.72	
Douglas Fir	120	Cylindrical	Epoxy 3	1	30.67				10.17	
Douglas Fir	120	Cylindrical	Epoxy 3	2	28.04	29.5	1.86	0.06	9.30	9.78
Douglas Fir	120	Cylindrical	Epoxy 3	3	29.80				9.88	
Douglas Fir	120	Threaded	Epoxy 3	1	29.70				9.85	
Douglas Fir	120	Threaded	Epoxy 3	2	28.08	27.7	1.15	0.04	9.31	9.18
Douglas Fir	120	Threaded	Epoxy 3	3	25.31				8.39	

- OAK 80-120 mm EX 1:1 and EX 3:1

Wood type	Length [mm]	Hole type	Epoxy type	Sample	N_u [kN]	$N_{u,m}$ [kN]	dev.st	CV	τ_u [Mpa]	$\tau_{u,m}$ [Mpa]
Oak	80	Cylindrical	Epoxy 1	1	27.77				13.81	
Oak	80	Cylindrical	Epoxy 1	2	28.49	28.1	0.50	0.02	14.17	13.99
Oak	80	Cylindrical	Epoxy 1	3						
Oak	80	Threaded	Epoxy 1	1	29.58				14.71	
Oak	80	Threaded	Epoxy 1	2	32.65	31.6	1.73	0.05	16.24	15.71
Oak	80	Threaded	Epoxy 1	3	32.50				16.16	
Oak	80	Cylindrical	Epoxy 3	1	28.01				13.93	
Oak	80	Cylindrical	Epoxy 3	2	28.88	28.2	0.66	0.02	14.36	14.00
Oak	80	Cylindrical	Epoxy 3	3	27.58				13.72	
Oak	80	Threaded	Epoxy 3	1	23.77				11.82	
Oak	80	Threaded	Epoxy 3	2	17.24	23.8	3.27	0.14	8.57	10.19
Oak	80	Threaded	Epoxy 3	3	20.46				10.18	
Oak	120	Cylindrical	Epoxy 1	1	30.22				10.02	
Oak	120	Cylindrical	Epoxy 1	2	29.41	30.0	0.57	0.02	9.75	9.96
Oak	120	Cylindrical	Epoxy 1	3	30.51				10.12	
Oak	120	Threaded	Epoxy 1	1	27.25				9.04	
Oak	120	Threaded	Epoxy 1	2	29.24	28.7	1.27	0.04	9.70	9.52
Oak	120	Threaded	Epoxy 1	3	29.62				9.82	
Oak	120	Cylindrical	Epoxy 3	1	29.01				9.62	
Oak	120	Cylindrical	Epoxy 3	2	28.74	28.9	0.19	0.01	9.53	9.57
Oak	120	Cylindrical	Epoxy 3	3					/	
Oak	120	Threaded	Epoxy 3	1	29.32				9.72	
Oak	120	Threaded	Epoxy 3	2	21.05	24.7	4.21	0.17	6.98	8.20
Oak	120	Threaded	Epoxy 3	3	23.83				7.90	

- GLULAM 80 mm EX 1:1 and EX 3:1: application of Cook's theory

Temperature [°C]	Code	Wood type	d_{hole}	Length [mm]	Hole type	Epoxy type	Sample	N_u [kN]	$N_{u,m}$ [kN]	dev.st	CV	d [mm]	d_m [mm]	dev.st	CV	k [N/mm]
20	GL_80_C_EX1_1	Glulam	12	80	Cylindrical	Epoxy 1	1	26.25				0.980				26783
20	GL_80_C_EX1_2	Glulam	12	80	Cylindrical	Epoxy 1	2	28.15	26.1	2.19	0.084	1.177	1.048	0.112	0.106	23909
20	GL_80_C_EX1_3	Glulam	12	80	Cylindrical	Epoxy 1	3	23.77				0.988				24060
20	GL_80_T_EX1_1	Glulam	10.5	80	Threaded	Epoxy 1	1	23.50				1.033				22751
20	GL_80_T_EX1_2	Glulam	10.5	80	Threaded	Epoxy 1	2	26.53	25.8	2.03	0.079	1.094	1.075	0.037	0.034	24257
20	GL_80_T_EX1_3	Glulam	10.5	80	Threaded	Epoxy 1	3	27.36				1.100				24883
20	GL_80_C_EX3_1	Glulam	12	80	Cylindrical	Epoxy 3	1	23.51				1.070				21962
20	GL_80_C_EX3_2	Glulam	12	80	Cylindrical	Epoxy 3	2	20.83	25.3	5.51	0.218	0.779	1.000	0.196	0.196	26747
20	GL_80_C_EX3_3	Glulam	12	80	Cylindrical	Epoxy 3	3	31.43				1.151				27299
20	GL_80_T_EX3_1	Glulam	10.5	80	Threaded	Epoxy 3	1	23.81				0.998				23861
20	GL_80_T_EX3_2	Glulam	10.5	80	Threaded	Epoxy 3	2	19.34	22.5	2.70	0.120	0.763	0.928	0.143	0.154	25366
20	GL_80_T_EX3_3	Glulam	10.5	80	Threaded	Epoxy 3	3	24.22				1.022				23696

Temperature [°C]	Code	Wood type	d_{hole}	Length [mm]	Hole type	Epoxy type	Sample	$\tau_{steel/adh}$[Mpa]	$\tau_{u,m}$ [Mpa]	$\tau_{adh/wood}$[Mpa]	$\tau_{adh/wood\ m}$[Mpa]	x*tanhx	x	λ'
20	GL_80_C_EX1_1	Glulam	12	80	Cylindrical	Epoxy 1	1	13.06		8.70		0.20	0.46	0.0199
20	GL_80_C_EX1_2	Glulam	12	80	Cylindrical	Epoxy 1	2	14.00	12.96	9.33	8.64	0.18	0.44	0.0191
20	GL_80_C_EX1_3	Glulam	12	80	Cylindrical	Epoxy 1	3	11.82		7.88		0.18	0.44	0.0191
20	GL_80_T_EX1_1	Glulam	10.5	80	Threaded	Epoxy 1	1	11.69		8.90		0.17	0.42	0.0170
20	GL_80_T_EX1_2	Glulam	10.5	80	Threaded	Epoxy 1	2	13.20	12.83	10.05	9.78	0.18	0.44	0.0178
20	GL_80_T_EX1_3	Glulam	10.5	80	Threaded	Epoxy 1	3	13.61		10.37		0.19	0.45	0.0182
20	GL_80_C_EX3_1	Glulam	12	80	Cylindrical	Epoxy 3	1	11.69		7.80		0.17	0.42	0.0182
20	GL_80_C_EX3_2	Glulam	12	80	Cylindrical	Epoxy 3	2	10.36	12.56	6.91	8.37	0.20	0.46	0.0199
20	GL_80_C_EX3_3	Glulam	12	80	Cylindrical	Epoxy 3	3	15.63		10.42		0.21	0.47	0.0204
20	GL_80_T_EX3_1	Glulam	10.5	80	Threaded	Epoxy 3	1	11.84		9.02		0.18	0.44	0.0178
20	GL_80_T_EX3_2	Glulam	10.5	80	Threaded	Epoxy 3	2	9.62	11.17	7.33	8.51	0.19	0.45	0.0182
20	GL_80_T_EX3_3	Glulam	10.5	80	Threaded	Epoxy 3	3	12.04		9.18		0.18	0.44	0.0178

Temperature [°C]	Code	Wood type	d_{hole}	Length [mm]	Hole type	Epoxy type	Sample	λ'_m	(λ' *l) /radq d	τ_{max} Cook	$\tau_{max\ m}$ Cook	τ_0 Cook	$\tau_{0\ m}$ Cook	$\tau_{average}$ Cook
20	GL_80_C_EX1_1	Glulam	12	80	Cylindrical	Epoxy 1	1		0.4600	9.3100		8.4050		
20	GL_80_C_EX1_2	Glulam	12	80	Cylindrical	Epoxy 1	2	0.0193	0.4400	9.9269	9.2073	9.0379	8.3589	8.7831
20	GL_80_C_EX1_3	Glulam	12	80	Cylindrical	Epoxy 1	3		0.4400	8.3850		7.6340		
20	GL_80_T_EX1_1	Glulam	10.5	80	Threaded	Epoxy 1	1		0.4200	9.4217		8.6477		
20	GL_80_T_EX1_2	Glulam	10.5	80	Threaded	Epoxy 1	2	0.0177	0.4400	10.6944	10.3918	9.7366	9.4704	9.9311
20	GL_80_T_EX1_3	Glulam	10.5	80	Threaded	Epoxy 1	3		0.4500	11.0594		10.0269		
20	GL_80_C_EX3_1	Glulam	12	80	Cylindrical	Epoxy 3	1		0.4200	8.2482		7.5706		
20	GL_80_C_EX3_2	Glulam	12	80	Cylindrical	Epoxy 3	2	0.0195	0.4600	7.3871	8.9375	6.6690	8.0955	8.5165
20	GL_80_C_EX3_3	Glulam	12	80	Cylindrical	Epoxy 3	3		0.4700	11.1770		10.0468		
20	GL_80_T_EX3_1	Glulam	10.5	80	Threaded	Epoxy 3	1		0.4400	9.5974		8.7378		
20	GL_80_T_EX3_2	Glulam	10.5	80	Threaded	Epoxy 3	2	0.0180	0.4500	7.8188	9.0593	7.0889	8.2381	8.6487
20	GL_80_T_EX3_3	Glulam	10.5	80	Threaded	Epoxy 3	3		0.4400	9.7618		8.8876		

REFERENCES

2kps - 2K Polymer Systems Limited (2014) *Product information*.

Adam, M., Lühring, A., Popp, M., Fecht, S. and Vallée, T. (2016) 'Pre-applicable structural adhesives for timber engineering: Glued-in G-FRP rods.' *International Journal of Adhesion and Adhesives*. Elsevier pp. 1–7.

Aicher, S., Wolf, M. and Dill-Langer, G. (1998) 'Heat flow in a glulam joist with a glued-in steel rod subjected to variable ambient temperature.' *Otto-Graf Journal*, 9 pp. 185–204.

Aicher, S. (2015) *CEN/TC 193-First draft Glued-in rods in glued laminated timber - testing, requirements and bond shear strength classification*. AENOR.

Aicher, S. (2003) 'Structural Adhesive Joints Including Glued-in Bolts.' *In* Thelandersson, S. and Larsen, H. J. (eds) *Timber Engineering*. John Wiley and Sons Ltd, pp. 333–363.

Andreolli, M. (2011) *Giunti Semirigidi Con Barre Incollate Per Strutture Lignee*. Università degli studi di Trento.

Ascione, F. (2008) *Modellazione di giunti di FRP*. Università degli Studi di Roma 'Tor Vergata.'

Augustin, M. (2008) 'Ultimate limit states-Joints.' *In Handbook 1-Timber structures*. 1st ed., TEMTIS.

Bainbridge, R. J. and Mettem, C. J. (1999) 'Bonded-in rods for timber structures-towards a European basis for structural design.' *In Adhesive in Timber Systems - Society Of Chemical Industry*. London.

Bainbridge, R., Mettem, C., Harvey, K. and Ansell, M. (2002) 'Bonded-in rod connections for timber structures - Development of design methods and test observations.' *International Journal of Adhesion and Adhesives*, 22(1) pp. 47–59.

Bak, K. M., Dinesh, M., Kalaichelvan, K., Vijayaraghavan, G. K. and Arumugam, V. (2013) *Study on the effect of adhesive thickness of single lap joints using acoustic emission and FEA*. [Online] [Accessed on 19th October 2016] http://www.ugcfrp.ac.in/images/userfiles/34110-Bak-1.pdf.

Bengtsson, C. (2002) 'Glued-In Rods.' *In COST ACTION E13-WG 2*, pp. 100–110.

Bengtsson, C., Kemmsies, M. and Johansson, C. J. (2000) 'Production control methods for glued-in rods for timber structures.' *In Proceedings of the CIB-W18 Meeting Thirty-Three 33-7-8*. Delft, The Netherlands.

Bernasconi, A. (2001) 'Behaviour of axially loaded glued-in rods- Requirements and resistance, especially for spruce timber perpendicular to the grain direction.' *In Proceedings of the CIB-W18 Meeting Thirty-Four 34-7-6*. Venice, Italy.

Bond, B. and Hamner, P. (n.d.) *Wood Identification for Hardwood and Softwood Species Native to Tennessee*. [Online] [Accessed on 18th October 2016] https://extension.tennessee.edu/publications/Documents/PB1692.pdf.

British Standards Institutions (2009) *BS EN1995-1-2:2004 Eurocode 5: Design of timber structures Part 1-2: General- Structural fire design*. London, UK: British standards institution.

British Standards Institutions (2007) *BS EN 13183-2:2002 Moisture content of a piece of sawn timber Part1: Determination by oven dry method*. London, UK: British standards institution.

British Standards Institutions (2014) *BS EN14080:2013 Timber structures. Glued laminated timber and glued solid timber. Requirements.* London, UK: British Standards Institutions.

British Standards Institutions (2009) *BS 338:2009 Structural timber-Strength classes*. London, UK: British standards institution.

British Standards Institutions (2013) *BS EN ISO 75-1:2013 Plastics — Determination of temperature of deflection under load Part 1 : General test method*. London, UK: British standards institution.

British Standards Institutions (2009) *BS EN 1465:2009 Adhesives. Determination of tensile lap-shear strength of bonded assemblies*. London, UK: British standards institution.

British Standards Institutions (2006) *BS EN408:2003 Timber structures – Structural timber and glued laminated timber – Determination of some physical and mechanical properties*. London, UK: British standards institution.

British Standards Institutions (2016) *BS EN 14358:2016 Timber structures — Calculation and verification of characteristic values*. London: British Standards Institutions.

British Standards Institutions (2008) *BS 373:1957 Methods of testing small clear specimens of timber*. London, UK: British standards institution.

British Standards Institutions (2014) *BS EN1995-1-1:2004 Eurocode 5: Design of timber structures Part 1-1: General- Common rules and rules for buildings*. London, UK: British standards institution.

British Standards Institutions (2013) *BS EN ISO 75-2:2013 Plastics — Determination of temperature of deflection under load Part 2: Plastics and ebonite*. London, UK: British Standards Institutions.

British Standards Institutions (2014) *BS EN1995-1-1:2004 Eurocode 5: Design of timber structures Part 1-1: General- Common rules and rules for buildings*. London, UK: British standards institution.

Buchanan, A. H. and Barber, D. (1996) 'Fire resistance of epoxied steel rods in glulam timber.' *NZ Timber Design Journal*, 5(2) pp. 12–18.

Cailotto, A. (2013) *Fracture under mode I, II and III of graphite components*. Università degli studi di Padova.

Catucci, V. A. (2011) *Relazione attività di ricerca del I anno*. Politecnico di Bari, Bari, Italy.

Cavalli, A., Malavolti, M., Morosini, A., Salvini, A. and Togni, M. (2014) 'Mechanical performance of full scale steel-timber epoxy joints after exposure to extreme environmental conditions.' *International Journal of Adhesion and Adhesives*. Elsevier, 54 pp. 86–92.

CEN (2004) *EN 1995-1-1:2004+A1 Eurocode 5: Design of timber structures - Part 1-1: General - Common rules and rules for buildings*.

CenciLegno (2008) 'L'utilizzo della resina epossidica nelle strutture lignee. Introduzione ai sistemi CNP.'

Cleary, R. (2014) *Considering the Use of Epoxies in the Repair of Historic Structural Timber*. University of Pennsylvania, Philadelphia, US.

CNR Commissione di studio per la predisposizione e l'analisi di norme tecniche relative alle costruzioni (2007) *CNR-DT 206 Istruzioni per la Progettazione, l'Esecuzione ed il Controllo delle Strutture di Legno*. Roma, Italy.

Connolly, T. and Mattem, C. J. (2003) *Development of Eurocode-type design rules for axially loaded bonded-in rods. LICONS Low intrusion conservation systems for timber structures - Report for annual meeting*. Siena, Italy.

Content, M., Rate, M. A. and Board, P. (2010) 'Ipc-tm-650 test methods manual 1,' (2) pp. 1–2.

Cook, R. A., Fagundo, F. E., Biller, M. H. and Richardson, D. E. (1991) *Tensile behaviour and design of single, adhesive anchors*. *Engineering and Industrial Experiment Station*. Gainesville. Florida.

Cook, R. A. (1993) 'Behavior of chemical bonded anchors.' *Journal of Structural Engineering*, 119(9).

Cook, R. A., Doerr, G. T. and Klingner, R. E. (1993) 'Bond stress model for design of adhesive anchors.' *ACI Structural Journal*, 90(5) pp. 514–524.

Cook, R. A., Fagundo, F. E., Biller, M. H. and Richardson, D. E. (1991) *Tensile behaviour and design of single, adhesive anchors*. *Engineering and Industrial Experiment Station*. Gainesville. Florida.

Cook, R. A., Kunz, J., Fuchs, W. and Konz, R. C. (1998) 'Behaviour and Design of Single Adhesive Anchors under Tensile Load in Uncracked Concrete.' *ACI Structural Journal*, 95(1) pp. 9–26.

Cortis, L. and Rossi, L. (2011) *Ancoraggi*. INAIL-Dipartimento Tecnologie di Sicurezza ex ISPESL.Roma, Italy.

COST (n.d.) *COST-Enhance mechanical properties of timber, engineered wood products and timber structures*. [Online] [Accessed on 26th July 2015] http://www.cost.eu/COST_Actions/fps/Actions/FP1004.

COST (n.d.) *COST-Assessment, Reinforcement and Monitoring of Timber Structures*. [Online] [Accessed on 26th July 2015] http://www.cost.eu/COST_Actions/fps/Actions/FP1101.

COST (n.d.) *COST-Wood Adhesion and Glued Products*. [Online] [Accessed on 26th July 2015] http://www.cost.eu/COST_Actions/fps/Actions/E13.

COST (n.d.) *COST-Bonding of Timber*. [Online] [Accessed on 26th July 2015] http://www.cost.eu/COST_Actions/fps/Actions/E34.

Custódio, J., Broughton, J. and Cruz, H. (2012) 'Rehabilitation of timber structures: novel test method to assess the durability of bonded-in rod connections.' *Materials and Structures*, 45(1–2) pp. 199–221.

Davis, G. (1997) 'The performance of adhesive systems for structural timbers.' *International Journal of Adhesion and Adhesives*, 17(3) pp. 247–255.

Del Senno, M., Piazza, M. and Tomasi, R. (2004) 'Axial glued-in steel timber joints-experimental and numerical analysis.' *Holz als Roh - und Werkstoff*, 62(2) pp. 137–146.

.

Deng, J. X. (1997) *Strength of Epoxy Bonded Steel Connections in Glue Laminated Timber*. University of Canterbury.

Di Maria, V. and Ianakiev, A. (2015) 'Adhesive Connections in Timber : A Comparison between Rough and Smooth Wood Bonding Surfaces.' World Academy of Science, Engineering and Technology, International Science Index 99*, International Journal of Chemical, Nuclear, Materials and Metallurgical Engineering*, 9(3) pp. 395–401.

Dominowski, R. L. (1980) *Research method*. Englewood Cliffs, New Jersey: Prentice Hall.

Ebnesajjad, S. and Landrock, A. H. (2014) *Adhesive Technology Handbook*. Third, Elsevier.

Eistetter, S. (1999) *Strength of cement bonded steel connections in glued laminated timber*. University of Canterbury.

Eligehausen, R., Cook, R. A. and Appl, J. (2006b) 'Behavior and Design of Adhesive Bonded Anchors.' *ACI Structural Journal*, 103(6) pp. 822–831.

Eligehausen, R., Malée, R. and Silva, J. (2006a) *Anchorage in Concrete Construction*. 1st ed., Ernst and Sohn.

EOTA (2006) *ETAG 001-Guideline for European technical approval of metal anchors for use in concrete- Part 1 and 5*. Brussels: European Organisation for Technical Approvals.

EPOTEK Epoxy Technology Inc. (2012) 'Tg - Glass Transition Temperature for Epoxies' pp. 1–2.

Estévez Cimadevila, J., Otero Chans, D. and Martín Gutiérrez, E. (2013) 'Adhesive multi-bulbs: A novel anchoring system using threaded steel rods glued into wood.' *Construction and Building Materials*, 48 pp. 131–136.

Farmer, I. W. (1975) 'Stress distribution along a resin grouted rock anchor.' *International Journal of Rock Mechanics and Mining Sciences and*, 12(11) pp. 347–351.

Faye, C. and Le Magorou, L. (2004) 'French data concerning glued-in rods.' *In Proceedings of the CIB-W18 Meeting Thirty-Seven 37-7-10*. Edinburgh, Scotland.

Feligioni, L., Lavisci, P., Duchanois, G., De Ciechi, M. and Spinelli, P. (2003) 'Influence of glue rheology and joint thickness on the strength of bonded-in rods.' *Holz als Roh - und Werkstoff*, 61(4) pp. 281–287.

Fellow, R. and Liu, A. (2008) *Research Methods for constructions*. 3rd ed., Oxford: Wiley-Blackwell.

Follesa, M. (n.d.) *Edifici XLAM e il fuoco*. [Online] [Accessed on 21st July 2016] http://www.promolegno.com/tecnologia/resistenza-al-fuoco/?L=%2525252Fproc%2525252Fself%2525252Fenviron.

Gehri, E. (n.d.) *High Performing Jointing Technique Using Glued-in Rods*. [Online] [Accessed on 10th November 2016] http://support.sbcindustry.com/Archive/2010/june/Paper_095.pdf.

Gerard, R. (2010) *Fire Resistance of Connections in Pre-Stressed Heavy Timber Structures*. University of Canterbury, Christchurch, New Zeland.

Gindl-Altmutter, W., Muller, U. and Konnerth, J. (2012) 'The significance of lap-shear testing of wood adhesive bonds by means of Volkersen's shear lag model.' *European Journal of Wood and Wood Products*, 70(6) pp. 903–905.

Graham, H. (2013) 'HDT versus Tg - Don't be misled. What is the difference between the HST and the Tg of a material).' *Creative Resin Systems*.

Gubana, A. (2008) *Collegamenti unioni incollate. Presentazione del documento CNR-DT 206/2007*. Facoltà di Ingegneria, Università di Udine, Italy.

Gurit (n.d.) *Introduction to Formulated Products*. [Online] [Accessed on 21st July 2016] http://www.gurit.com/files/documents/gurit-introduction-to-formulatedpdf.pdf.Gurit (n.d.) *Introduction to Formulated Products*. [Online] [Accessed on 21st July 2016] http://www.gurit.com/files/documents/gurit-introduction-to-formulatedpdf.pdf.

Gustafsson, P. J. (1987) 'Analysis of generalized Volkersen-joints in terms of non-linear fracture mechanics.' *In Proceedings of the CIB-W18A Meeting Twenty 20-18-2*. Dublin, Ireland.

Gustafsson, P. J. and Serrano, E. (2000) 'Predicting the pull-out strength of glued-in rods.' *In Proceedings of 6th World Conference on Timber Engineering*. Canada, p. 7.4.4.1-7.4.4.8.

Gustafsson, P. J., Serrano, E., Aicher, S. and Johansson, C. J. (2001) 'A strength design equation for glued-in rods.' *In Symposium on Joint in Timber Structures, 55th RILEM Annual Week*. Stuttgart, Germany, pp. 1–10.

Harris, S. (2004) *Fire Resistance of Epoxy-grouted Steel Rod Connections in Laminated Veneer Lumber (LVL). Fire Engineering Research Report 04/07*. University of Canterbury, Christchurch, New Zeland.

Harvey, K. and Ansell, M. P. (2000) 'Improved Timber Connections Using Bonded-In GFRP Rods.' *In Proceedings of 6th World Conference on Timber Engineering-paper P04*. Whister Resort, Canada.

IStructe and TRADA (2007) 'Glued joints.' *In Manual for the design of timber buildings*, pp. 146–162.

Johansson, C. J. (2002) *GIROD Glued-in rods for timber structures*. SP Technical Research Institute of Sweden. [Online] [Accessed on 4th April 2016] http://www.costfp1101.eu/images/Wroclaw/Johansson_GIRODrev2012-10-09 2.pdf.

Johansson, C. J., Serrano, E., Gustafsson, P. J. and Enquist, B. (1995) 'Axial strength of Glued-in Bolts Calculation model based on non-linear fracture mechanics - A preliminary study.' *In Proceedings of the CIB-W18 Meeting Twenty-Eight 28-7-9*. Copenhagen, Denmark.

Kamke, F. A. and Lee, J. N. (2007) 'Adhesive penetration in wood- A review.' *Wood and Fiber Science*, 39(2) pp. 205–220.

Kangas, J. (1993) 'Design of joints based on in V-shape glued-in rods.' *In Proceedings of the CIB-W18 Meeting Twenty-six 26-7-4*. Athens, Georgia, USA.

Kangas, J. (2000) 'Capacity, fire resistance and gluing pattern of the rods in V-connections.' *In Proceedings of the CIB-W18 Meeting Thirty-three 33-7-10*. Delft, The Netherlands.

Kemmish, D. J. (1995) *High Performance Engineering Plastics*. RAPRA Technology Ltd.

Kumar, R. (2014) *Research methodology: a step-by-step guide for beginners*. 4th ed., Los Angeles: SAGE.

Lartigau, J., Coureau, J.-L., Morel, S., Galimard, P. and Maurin, E. (2015) 'Effect of temperature on the mechanical performance of glued-in rods in timber structures.' *International Journal of Adhesion and Adhesives*, 57(November) pp. 79–84.

Lartigau, J., Coureau, J.-L., Morel, S., Galimard, P. and Maurin, E. (2015) 'Mixed mode fracture of glued-in rods in timber structures.' *International Journal of Fracture*, 192(1) pp. 71–86.

Lartigau, J., Coureau, J.-L., Morel, S. and Maurin, E. (2011) 'Effect of temperature on mechanical performance of glued-in rods [Poster].' COST Action IE0601 'Wood Science for Cultural Heritage' .Paris, France.

LegnoDOC srl (2003) *Physical Testing and Prototyping Sub-task 5.3 Development of structural Eurocode-type principles: evaluation of draft design rules-Formal Report LICONS Low Intrusion conservation systems for timer structures CREF-1999-71216*.

Lilleyman, J. (2013) *Testing and analysis of glued in bolts in timber*. Nottingham Trent University.

Martín, E., Estevez, J. and Otero, D. (2013) 'Influence of geometric and mechanical parameters on stress states caused by threaded rods glued in wood.' *European Journal of Wood and Wood Products*, 71(2) pp. 259–266.

Mastin, L. (2008) *The basics of philosophy*. [Online] [Accessed on 29th April 2015] http://www.philosophybasics.com/branch_positivism.html.

Muciaccia, G. (2015) *Conversation with Valentina Di Maria*. Politecnico di Milano, Milan, Italy.

Muciaccia, G. (2016) *Conversation with Valentina Di Maria*. Politecnico di Milano, Milan, Italy.

Niederer, B. B. (2006) 'If you can' t take the heat … Understanding the effects of high temperatures on cured epoxy.' *EPOXYWORKS Spring*, pp. 1–3.

Otero Chans, D., Cimadevila, J. E. and Gutiérrez, E. M. (2008) 'Glued joints in hardwood timber.' *International Journal of Adhesion and Adhesives*, 28(8) pp. 457–463.

Otero Chans, D., Cimadevila, J. E. and Gutiérrez, E. M. (2013) 'Withdrawal strength of threaded steel rods glued with epoxy in wood.' *International Journal of Adhesion and Adhesives*, 44 pp. 115–121.

Otero Chans, M. D., Estévez Cimadevila, J., Martín Gutiérrez, E. and Vázquez Rodríguez, J. A. (2010a) 'Influence of timber density on the axial strength of joints made with glued-in steel rods: An experimental approach.' *International Journal of Adhesion and Adhesives*, 30(5) pp. 380–385.

Otero, D., Estévez, J., Martín, E. and Vázquez, J. A. (2010b) 'Failure modes in double-sided pull-out test of threaded steel rods glued in hardwood.' *11th World Conference on Timber Engineering 2010, WCTE 2010*, 4 pp. 3186–3194.

Otero Chans, D., Cimadevila, J. E. and Gutiérrez, E. M. (2010c) 'Model for predicting the axial strength of joints made with glued-in rods in sawn timber.' *Construction and Building Materials*. Elsevier Ltd, 24(9) pp. 1773–1778.

Parida, G., Johnsson, H. and Fragiacomo, M. (2013) 'Provisions for Ductile Behaviour of Timber-to-Steel Connections with Multiple Glued-In Rods.' *Journal of Structural Engineering*, 139(9) pp. 1468–1477.

PennState (n.d.) *Introduction to Factorial Experimental Designs*. The Methodology Center. [Online] [Accessed on 4th April 2016] https://methodology.psu.edu/ra/most/factorial.

Petercox (n.d.) *Commercial resin repairs*. [Online] [Accessed on 1st July 2017] https://www.petercox.com/commercial/epoxy-resin-repairs/.

Piazza, M. and Tomasi, R. (2004) 'H1 I sistemi di connessione e le connessioni di carpenteria.' *Promo Legno*, pp. 1–39.

Piazza, M., Tomasi, R. and Modena, R. (2005) *Strutture in legno. Materiale, calcolo e progetto secondo le nuove normative europee.* Hoepli.

Pizzo, B. and Schober, K. U. (2008) 'On site interventions on decayed beam ends.' *In COST ACTION E34 -WG1: Bonding on Site*, pp. 46–55.

Rabilloud, G. (2005) 'Adhesives in Electronics.' *In Handbook of Adhesives and Sealants: Volume 1*. Elsevier.

Riberholt, H. (1986) *Glued bolts in Glulam*. Serie R:210, Technical university of Denmark, Department of Structural Engineering.

Riberholt, H. (1988) 'Glued bolts in glulam - Proposal for CIB CODE.' *In Proceedings of the CIB-W18 Meeting Twenty-One 21-7-2*. Parksville, Vancouver Island, Canada.

Ross, P. (2002) *Appraisal and Repair of Timber Structures*. Thomas Telford.

Rossignon, A. and Espion, B. (2008) 'Experimental assessment of the pull-out strength of single rods bonded in glulam parallel to the grain.' *Holz als Roh - und Werkstoff*, 66(6) pp. 419–432.

Schnabl, S. and Turk, G. (2006) 'Coupled heat and moisture transfer in timber beams exposed to fire.' *In Proceedings of the 9th world conference on timber engineering. Portland, USA*.

Scottbader (n.d.) *Crystic Crestomer® Adesivi strutturali*. [Online] [Accessed on 19th October 2016] http://www.resintex.it/pdf/Adesivi_Strutturali_Crestomer.pdf.

Serrano, E. (2001) 'Glued-in rods for timber structures — a 3D model and finite element parameter studies.' *International Journal of Adhesion and Adhesives*, 21(2) pp. 115–127.

Serrano, E. (2004) 'A numerical study of the shear-strength-predicting capabilities of test specimens for wood-adhesive bonds.' *International Journal of Adhesion and Adhesives*, 24(1) pp. 23–35.

Serrano, E., Steiger, R. and Lavisci, P. (2008) 'Glued-in rods.' *In COST Action E34 Bonding of Timber-Working Group 1: Bonding on site*, pp. 37–45.

Sgarito, L. (2006) *Analisi sperimentale degli effetti di temperature elevate sul comportamento strutturale dei rinforzi in FRP*. Alma Mater Studiorum- Università di Bologna, Bologna, Italy.

Spaggiari, A. (2010) *Efficient modelling of complex adhesively bonded structures by standard finite element techniques*. University of Modena and Reggio Emilia.

STA The structural Timber Association (2015) 'Special connections using glued-in rods.' *TheStructuralEngineer Number 14 - Timber Engineering Notebook series,* (14) pp. 38–43.

Steiger, R., Gehri, E. and Widmann, R. (2004) 'Glued-in steel rods: a design approach for axially loaded single rods set parallel to the grain.' *In Proceedings of the CIB-W18 Meeting Thirty-Seven 37-7-8*. Edinburgh, Scotland.

Steiger, R., Serrano, E., Stepinac, M., Rajčić, V., O'Neill, C., McPolin, D. and Widmann, R. (2015) 'Strengthening of timber structures with glued-in rods.' *Construction and Building Materials*.

Stepinac, M., Hunger, Tomasi, R., Serrano, E., Rajčić, V. and Van de Kuilen (2013a) *Comparison of design rules in glued-in rods and design rule proposal for implementation in European standards*. *COST Action FP1004, STSM: assessment, reinforcement and monitoring of timber structures*. Trento.

Stepinac, M., Hunger, F., Tomasi, R. and Serrano, E., Rajčić, V. and Van de Kuilen (2013b) 'Comparison of design rules for glued-in rods and design rule proposal for implementation in European standards.' *In Proceedings of the CIB-W18 Meeting Forty-Six 46-7-10*. Vancouver, Canada.

Stepinac, M. (2012) 'Joints in beech-LVL timber frames : STSM Report for COST Action FP1004.'

Stepinac, M. and Rajčić, V. (2015) *Design of glued-in rods. COST Action FP1004-WG2 workshop: assessment, reinforcement and monitoring of timber structures*. Eindhoven.

Stoeckel, F., Konnerth, J. and Gindl-Altmutter, W. (2013) 'Mechanical properties of adhesives for bonding wood-A review.' *International Journal of Adhesion and Adhesives*. Elsevier, 45 pp. 32–41.

TAinst (n.d.) *Thermal solutions- Measurement of the Glass Transition Temperature Using Dynamic Mechanical Analysis*. [Online] [Accessed on 21st July 2016] http://www.tainstruments.com/pdf/literature/TS64.pdf.

Tlustochowicz, G., Serrano, E., Steiger, R. (2011) 'State-of-the-art review on timber connections with glued-in steel rods.' *Materials and Structures*, 44(5) pp. 997–1020.

TRADA (2000) *Bonded-in Rod Connections For Timber Structures (GIRODS)*. [Online] [Accessed on 23rd October 2013] http://research.ttlchiltern.co.uk/girod/girod.htm.

Turkovsky, S. B. (1989) 'Designing of glued wood structures joints on glued-in rods.' *In Proceedings of the CIB-W18 Meeting Twenty-two 22-7-13*. Berlin, Germany.

Valoroso, N. (2007) 'Giunti e connessioni adesive. Una sfida per la moderna industria della costruzione.' *L'edilizia*, pp. 68–73.

Von Diether, B. (n.d.) *Writing chapter 3: the methodology*. [Online] [Accessed on 30th April 2015] http://dissertationwriting.com/write-dissertation-methodology-help.shtml.

Wernersson, H. and Gustfsson, P. J. (1987) 'The complete stress-slip curve of wood-adhesive in pure shear.' *In Proceedings of the CIB-W18A Meeting Twenty 20-18-3*. Dublin, Ireland.

Wiktor, R. (1994) *Glulam connections using epoxy glued-in rebars*. The University of British Columbia, Vancouver, Canada.

Yeboah, D., Taylor, S., McPolin, D. and Gilfillan, R. (2012) 'Pull-out behaviour of axially loaded basalt fibre reinforced polymer (BFRP) rods bonded parallel to the grain of glulam elements.' *TheStructuralEngineer Number*, pp. 42–51.

Yeboah, D., Taylor, S., McPolin, D. and Gilfillan, R. (2013) 'Pull-out behaviour of axially loaded Basalt Fibre Reinforced Polymer (BFRP) rods bonded perpendicular to the grain of glulam elements.' *Construction and Building Materials*. Elsevier Ltd, 38 pp. 962–969.

Yeboah, D., Taylor, S., McPolin, D., Gilfillan, R. and Gilbert, S. (2011) 'Behaviour of joints with bonded-in steel bars loaded parallel to the grain of timber elements.' *Construction and Building Materials*. Elsevier Ltd, 25(5) pp. 2312–2317.