Mechanical behaviour of 3D printed vs thermoformed clear dental aligner materials under non-linear compressive loading using FEM

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Abbreviations:
FEA – Finite Element Analysis
FEM – Finite Element Modelling
CAD – Computer Aided Design
CAM – Computer Aided Manufacture
RP – Rapid Prototyping
CNC – Computer Numerical Controlled
STL – Stereolithography
SLA - Stereolithography Apparatus

Abstract

Clear dental aligners are commonly manufactured using thermoplastic materials such as Duran and Durasoft. Using conventional thermoforming methods there are inherent disadvantages including time consumption and poor geometrical accuracies that often occur. The use of digital technologies and 3D printing techniques for producing dental aligners is often preferred where possible. Innovation in 3D printing has resulted in bio-compatible materials becoming more readily available, including Formlabs Dental LT Clear resin, which is a 3D printable and Class IIa bio-compatible material. In this paper, we investigate the difference between thermoplastic materials such as Scheu-Dental Duran and Durasoft and 3D printed Dental LT using Finite Element Analysis (FEA)/Finite Element Modelling (FEM) in a dental aligner case based on an analysis of Von Mises stress distribution at molars, incisors and canines for a total of 33161 nodes using Finite Element Analysis (FEA). Maximum Von Mises stress distribution at all of the sections under the action of non-linear compressive forces equivalent to human biting force (up to 600N) were discovered to vary within a range of 0.2 to 7.7% for Dental LT resin. The Duran and Durasoft cases were comparable, thereby widening the scope for the use of Dental LT in various dentistry applications, including clear aligners.

Keywords: FEA; FEM; Dental LT Clear Resin; Duran; Bite Force; Stress

1. Introduction

The demand for cosmetic dental treatment, both in the UK and globally over the past two decades, has increased dramatically [1], with 75% of adult patients alone highlighting dissatisfaction with their dental appearance [2]. Significant increases in dentists using orthodontic appliances to treat patients who are unhappy with their smiles occurs mainly due to misaligned anterior teeth which can be corrected in relatively short timeframes (i.e. weeks or months) [1], this has contributed to an increased awareness towards oral hygiene resulting in significant increases in orthodontic treatments.

The use of orthodontic appliances and equipment has dramatically increased over the past few decades, mainly due to improvements in materials and manufacturing processes that have paved the way for improved treatments, but understanding the mechanical, geometric and physical properties of dental products, especially aligners, mouthguards and splints is imperative for successful patient acceptability. Utilising FEM (Finite Element Modelling) /FEA (Finite Element Analysis) techniques allows assessments to be made not only on specific cases, but also on the suitability of materials and the manufacturing processes utilised, for example Martorelli et al [3] has compared customized clear and removable orthodontic appliances manufactured using RP and CNC techniques using FEM simulations.

Advancements in 3D printing and digital technologies has in modern times contributed to improved dental care, the use of these techniques have been hailed as disruptive technologies capable of creating a significant step change in the dentistry field [4]. With disruptive technologies, such as desktop and intra-oral scanners, Computer Aided Design (CAD)/Computer Aided Manufacture (CAM) software and 3D printing paving the way, transitioning from analogue to digital dentistry workflows is becoming a common practice reality [5]. Utilising these technologies has allowed dental/orthodontic practice to extend beyond the sole use of traditional techniques, with advancements in imaging techniques, bio-printing, CAD/CAM amongst others contributing to improvements [4-8]. Through the use of bio-compatible and medically certified materials, the fabrication of aligners using 3D printing technology has been shown to produce geometrically accurate results [9]. SLA 3D printed resin specifically has also shown some antisotropic qualities when optimally orientated [10]. However, understanding the mechanical properties of these devices using conventional materials and 3D printed materials requires further investigation.

To treat patients with misaligned teeth, clear dental aligners are often used, this is treated by pressurizing teeth movements within biological limits, this dental procedure is often prescribed by an orthodontist or general dentist [11,12,13]. Clear dental aligners are a common aesthetic solution used by orthodontists to treat the alignment of misaligned teeth by developing various stages of aligner models over time [11].

Understanding the mechanical, geometric and physical properties of clear dental aligners is imperative for successful patient acceptability. Traditional thermoformed aligners have been recognised to have a number of limitations such as dimensional instability, poor wear resistance and low strength [14].

Khoda et al [15] highlighted that aligner and correction splints/retainer from materials such as Duran [16] (Scheu Dental, Iserlohn, Germany), and Erkodur [17] (Erkodent Erich Kopp GmbH, Pfalzgrafenweiler, Germany) are potentially more effective for teeth movement adjustments in comparison to Hardcast [18] (Scheu Dental), as their hardness and elastic modulus were nearly twice to that of Hardcast.

The use of FEA/FEM, both as digital design, fabrication and performance analysis tool within the dental product sector is essential including the design and fabrication of simulation models for measuring orthodontic forces [19], FEA analysis of force systems during bodily tooth movement with plastic aligners and composite attachments [20], FEA of in-vitro de-bonding of orthodontic retainers [21] and computational design, and experimental verification of thermoplastic polymeric orthodontic aligners [22, 23].

The traditional method of manufacturing a clear dental aligner requires a dentist/orthodontist to obtain a negative impression of a patient's dentition; following this, Plaster of Paris or Alginate is poured into this negative impression to create a model cast suitable for vacuum thermoforming for the manufacture of traditional clear dental aligners using biocompatible thin clear plastic sheets [11, 21, 24]. Using the improved digital workflow, it has been possible to introduce static scanners to provide the capability of scanning dental impressions to allow the production of high accuracy 3D printed dental models which provide superior dimensional accuracy in comparison to the conventional materials based dental models. The vacuum thermoforming process to manufacture the clear dental aligners remains the same, but due to the superior accuracies of 3D printed base dental models, the thermoformed clear dental aligners are also more accurately reproduced. To further improve the accuracy of these clear dental aligners, a directly 3D printable material as Dental LT clear resin [25] has been supplied by FormLabs, which can be 3D printed into a clear dental aligner bypassing the intermediate steps of obtained dental impressions and producing dental models. Being a Class IIa biocompatible material, patients can safely use it as clear dental aligner inside their mouths.

However, apart from geometrical accuracy and bio- compatibility, mechanical properties of these 3D printed aligners must be validated with respect to the conventional thermoformed clear aligners.

Resistance to forces equivalent to human biting action is an important mechanical property of the aligners which must be assessed; mechanical characterization of these aligners, under the action of compressive forces equivalent to human bite forces would be a useful parameter in evaluating the aligner mechanical strength. Mechanical characterization could be performed by experimental methods using compression testing machines. However, FEM techniques could also be adopted initially as an economical option for evaluating these properties over a wider range of loading conditions [26, 27].

In this paper, we investigate the performance of clear dental aligners subjected to compressive mechanical loading equivalent to human biting forces by using FEM. A clear dental aligner from a patient's dentition has been designed using FEM from a scanned Standard Tessellation Language (STL) file [5]. Using the material properties of conventional dental aligner materials such as Duran and Durasoft and comparing this Dental LT resin material, FEA has been utilised to evaluate the mechanical behaviour under the action of non-linear compressive forces equivalent to human biting force [16, 17, 28].

2. Materials and Methods

To create the clear dental aligner, scans of the mandibular region of a patient's dentition were taken using a 3Shape E1 lab scanner with a blue LED multiline, with an accuracy of 10-12μm based on real patient teeth. An STL file was then processed in Maestro Studio CAD/CAM software to create the initial CAD model. An initial set of processing steps were completed on the original dentition as required by the predicted successive stages during the planning of a treatment process for a patient. Additional steps were undertaken, including the marking of missing teeth, measurement of each tooth, identification of ideal arch length and the checking of inter-proximal reduction, and this was then followed up with point to point plotting. Point to point plotting is an extremely important process as this ensures no sharp edges or overlapping of the aligner with gums occurs. Once complete, the thickness of the aligner for the required alignment is defined and then applied to the aligner model. At this point, the STL model would be ready for post processing, either for further FEM/FEA analysis.

Aligner models were designed with standard thermoplastic aligner materials such as Duran [16] and Durasoft [27], in addition to Dental LT clear resin [25] which is manufactured using a Formlabs Form 2 SLA 3D printer. Dental LT was identified as a suitable 3D printed dental aligner material for analysis due to its conformity to EEN ISO 1641:2009, EN-ISO 10993-1:2009/AC:2010, EN-ISO 10993-3:2009, EN-ISO 10993-5:2009 and EN 908:2008 and the recent activity of FormLabs in the digital dentistry industry [25]. The material properties for each of the three materials are applied to a CAD model of a 1mm thick dental aligner which has been produced and tested using the FEM and FEA principles described in Section 2.1 and 2.2.

2.1. Finite Element Modelling (FEM) Process

After generating the dental aligner CAD file, it was imported for further analysis into SolidWorks 2018 CAD program supplied by Dassault Systèmes, as shown Figure 1.

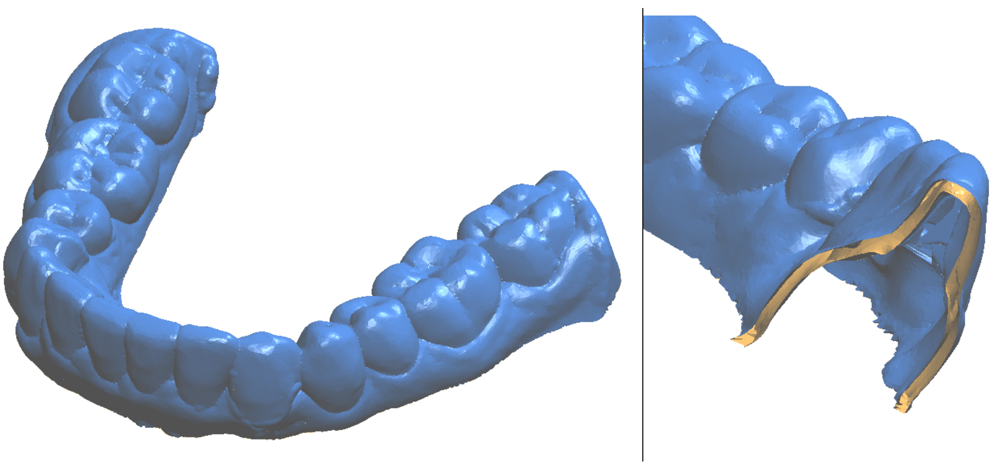


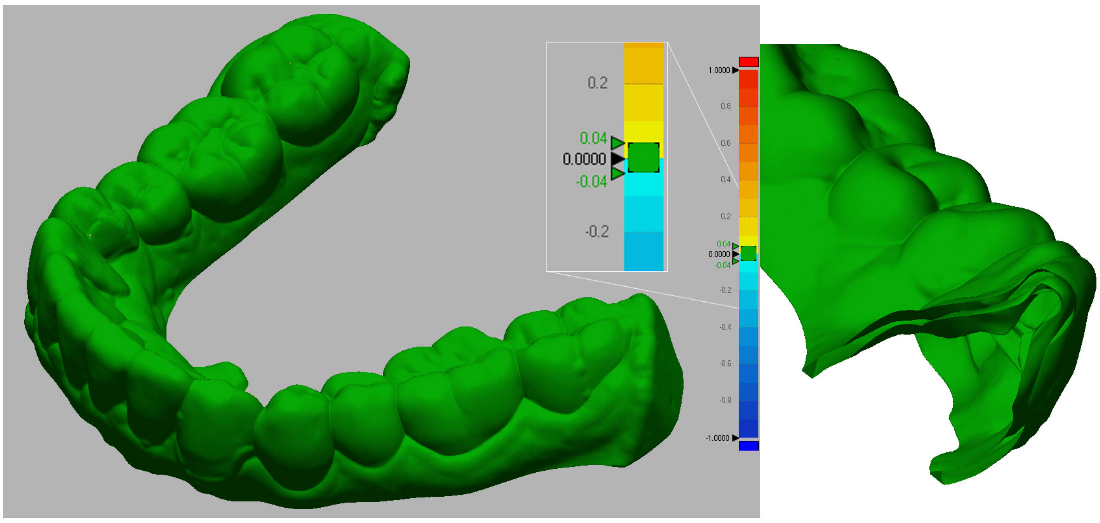
Figure 1. STL image file of the modelled clear dental aligner with cross sectional view

SolidWorks was utilised for FEA due to the numerical efficiency and versatility when analysing complex shapes [29]. However, to perform FEA simulation tests within SolidWorks, the program must be able to discretize the SolidWorks part into a series of simply shaped tetrahedral solid elements to create a mesh of finite elements.

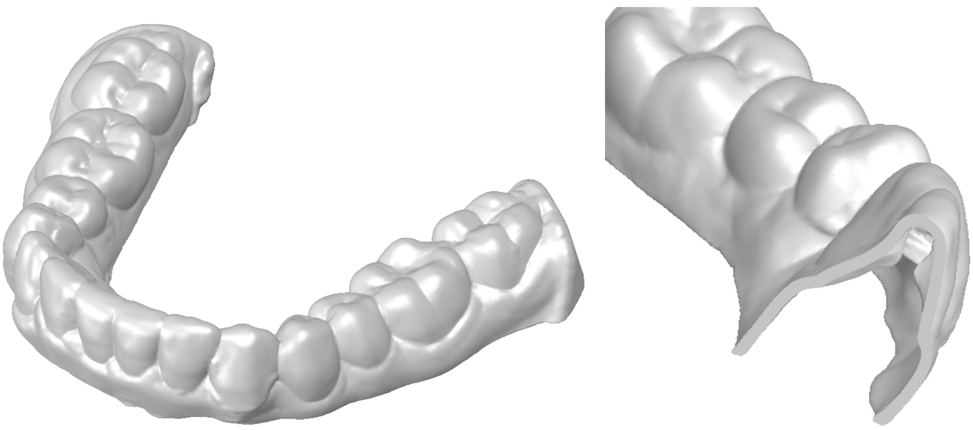
FEM modelling from a STL file is challenging considering the myriad geometry which can be scanned from each different patient. If there are any geometry issues with the part, the simulation mesh creation phase will not be successful. As the original STL part was not a SolidWorks native parametric model, this had led to a complex surface model mesh with several different types of errors when imported into the SolidWorks Simulation Suite. These were: holes in the surface model (i.e. incomplete base mesh), polygons trapped within the model and several faces in the same place (i.e. a false main surface), floating vertexes, and double edges. These errors ensured that SolidWorks was not able to produce a simulation mesh for the dental aligner part.

To overcome this, a software solution was utilised called GeoMagic Design X 2018 [30] created by 3D Systems. GeoMagic Design X was used on the STL file to optimise the surface mesh and remove floating geometry debris, generating a complete surface body file without removing the geometry detail shown. This model had a geometry deviation of ±0.04mm deviation from the original STL file as shown in Figure 2(a). This was converted by GeoMagic Design X into a SolidWorks compatible solid body and deemed suitable for FEA analysis as shown in Figure 2(b). Upon importing the model into SolidWorks, the model was successfully meshed. This model was a high-quality (i.e.

second order) based solid mesh using 10 node tetrahedron elements. There was a total of 91107 degrees of freedom, 16545 total number of elements and 33161 nodes. The mesh was valid as it had successfully converged. Using a p-adaptive meshing technique, only 3 simulations solutions were run to achieve a result of <1% change in maximum von Mises stress compared to a previous result, and reducing the mesh element size is unnecessary after the third run. The view of the mesh is presented in Figure 2(c) with the graph (Figure 2d) showing successful mesh convergence using a p-Adaptive method.



2(a)



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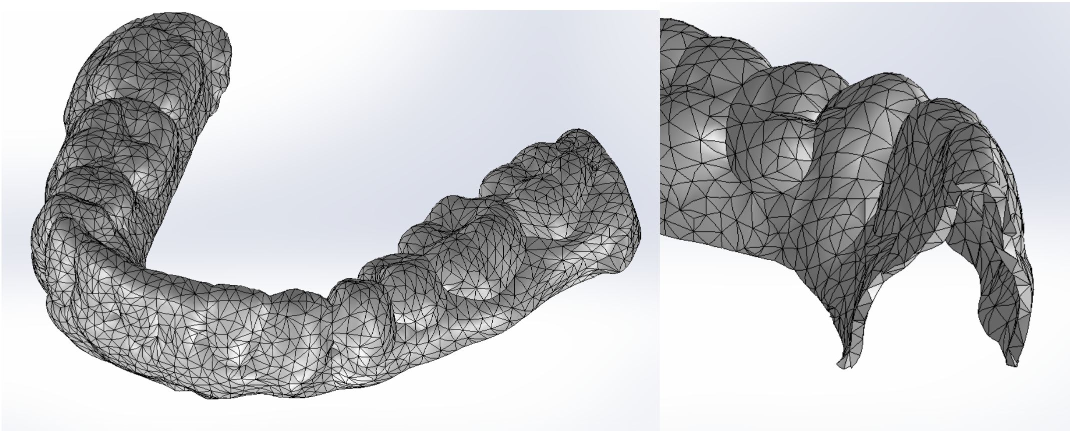
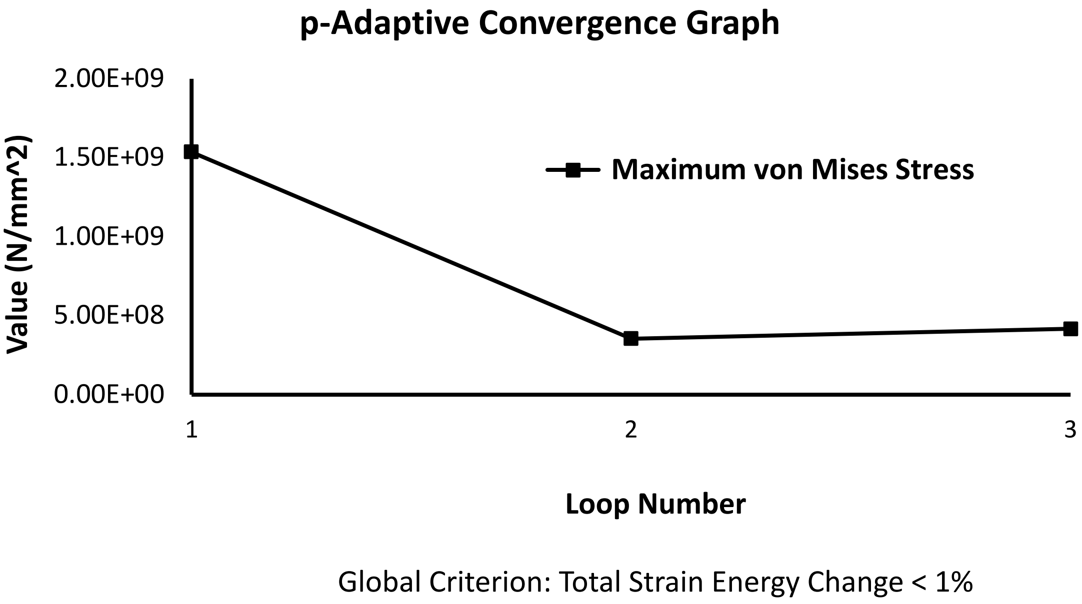


2(c)



2(d)

Figure 2. Geomagic Design X Aligner Model: (a) Optimised Surface Mesh converted from STL model, (b) Solid Body Model converted from Optimised Surface Mesh, (c) Discretised Solid Body Model for FEA Analysis with (d) p-Adaptive Convergence

However, the simulation could not be solved when executed with the same input parameters. A viable solution could be employed by continuing to refine the mesh and ensure that the polygon density would decrease, allowing the FEA solver to run. The advantage of 3ds Max software over GeoMagic Design X is the lower cost, which was why it was used previously. However, this required additional time than anticipated, and therefore GeoMagic Design X was used on the original STL file to create the part file shown in Figure 2a. Both software's can be used for FEM, with 3ds Max being less efficient at a lower cost, whilst GeoMagic Design X being much more efficient at a much higher expense to the software user.

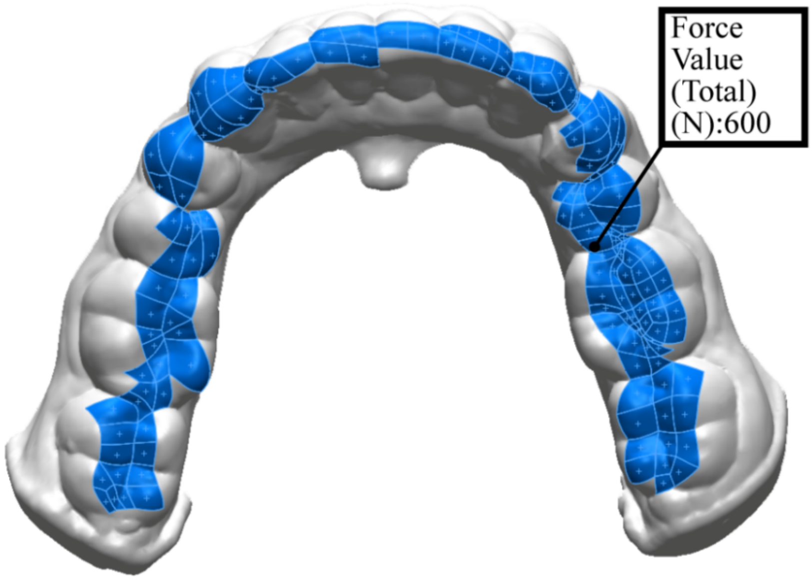
2.2 Finite Element Analysis (FEA)

Important material parameters for various materials were obtained from specific data sheets for Duran [16], Durasoft [27] and Dental LT [25]. The important material properties for a non-linear FEA analysis were then defined for each respective material as given in Table-1.

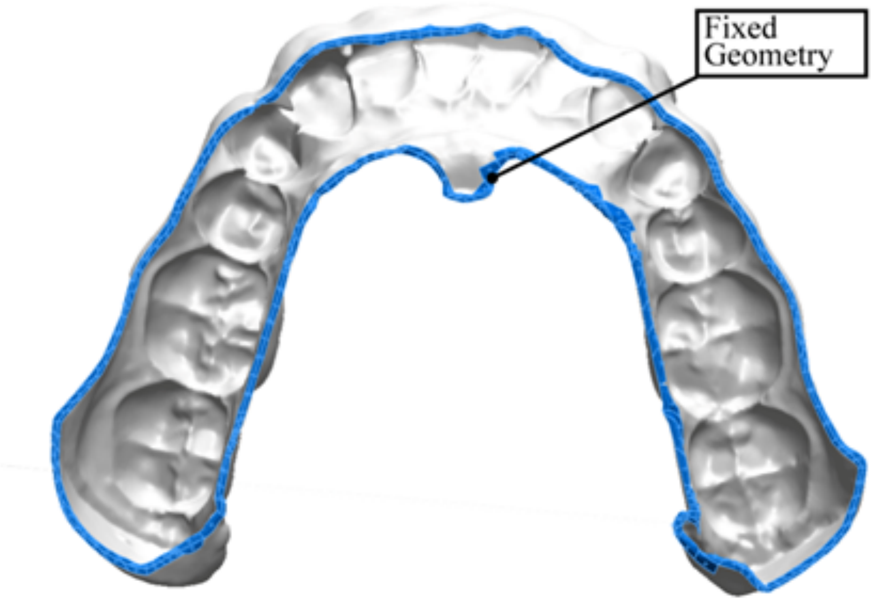
Table-1: Material properties of the three data sheets considered for FEA analysis

Sheet Name	**Elastic Modulus(GPa)**	**Poisson's Ratio**	**Mass density(kg/m^3)**	**Compressive Strength(MPa)**	**Yield Strength(MPa)**
Duran	2.2	0.37	1270,	92.9	2.65
Durasoft	1.9	0.49	1200	69	63
Dental LT	2.06	0.35	1200	342	211

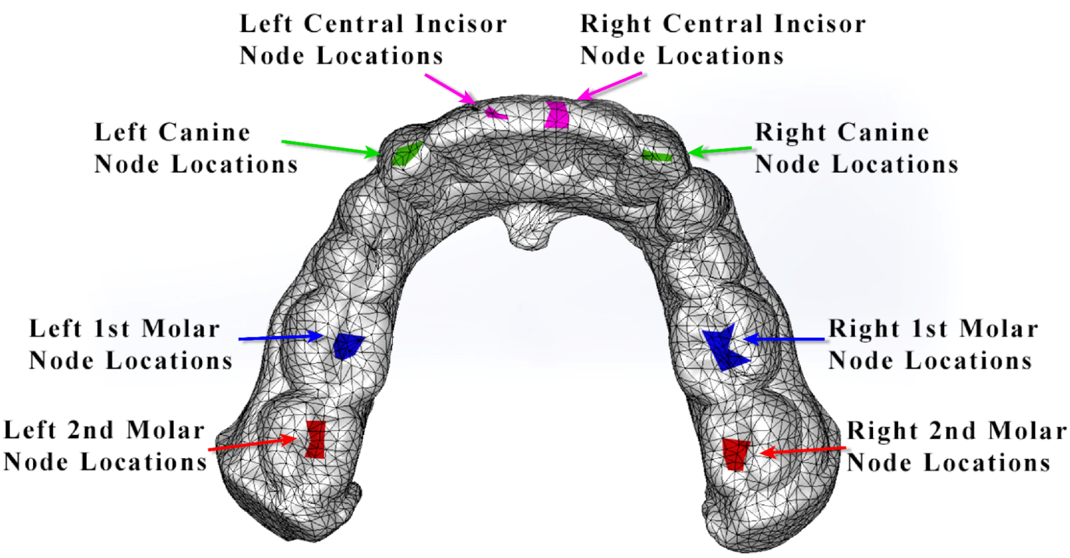
Static non- linear analysis was performed, equivalent to a bite force pattern [31] and was applied for a period of 30 seconds on the 3D models of the Duran, DuraSoft and Dental LT aligners at 8 different sections broadly encompassing the complete mandibular as shown in Figure 3(c). The geometry boundary conditions fixed the model at the base rim of the aligner (restraining all degrees of freedom to be immovable), and a force applied from above as this simulates real-world compression testing configurations, shown in Figure 3(a)-(b). A collection of nodes was chosen based on the most common mastication areas covering molars, canines and incisors as shown in the Figure 3(a). This collection of nodes acted as a surface to be subjected to the action of non-linear compressive forces. For each tooth location, eight nodes were selected as load application points as shown in Figure 3(c). Figure 4 shows the compressive bite force pattern was obtained by applying static non-linear load under the given boundary conditions.



(a)



(b)



(c)

Figure 3. Boundary conditions (highlighted light blue) of the force applied (a), the fixed geometry areas restraining the model in all translational degrees of freedom (c) and nodal sections of the clear dental aligner considered for FEA under the action of non-linear compressive forces (c)

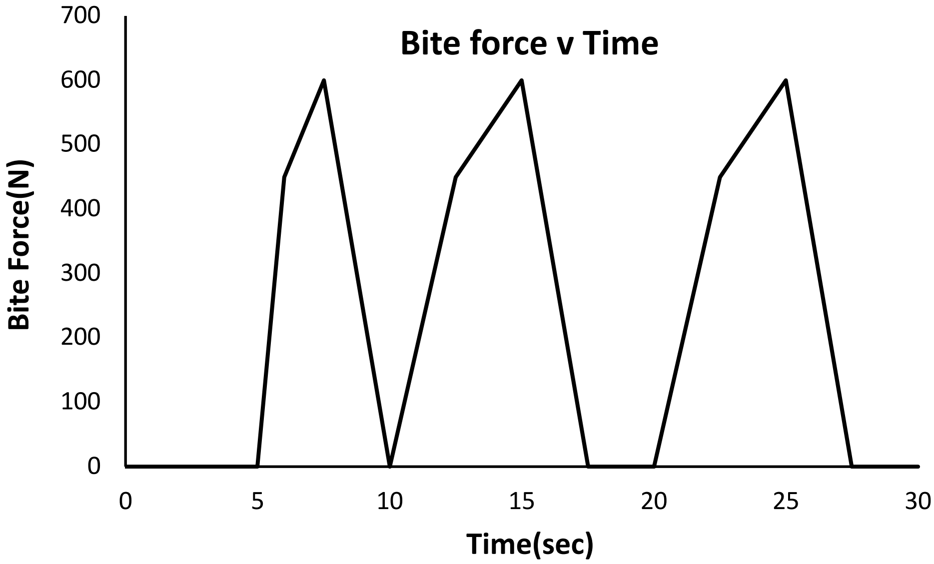


Figure 4. Applied Non-Linear Compressive Bite Force Variation With Time

Von Mises stresses are obtained across all the nodal sections and their variation with time indicates the stress resistance of each aligner material based on the non-linear compressive force pattern.

3. Results

Table-2 provides the geometrical measurements collected using a digital Vernier calliper for various teeth sections of the aligners physically obtained from 3D printing (Dental LT) and thermoforming (Duran); this data was collected as part of a study conducted by Jindal et al [32]. Average relative differences of the mean crown heights (distance between the points of intersection of midline of tooth on the buccal surface with gum line and at incisal edge has been taken as the height of the crown for the selected tooth on the aligner) between 3D printed (1.94%) and thermoformed (4.52%) aligners with respect to the base reference digital STL file indicated superior geometrical accuracies obtained for 3D printed aligners.

Table 2: Geometrical comparison among STL, 3D printed (Dental LT) and thermoformed (Duran) aligners [32]

Tooth Section		**STL File**		**3D printed (Dental LT)**		**Thermoformed (Duran)**	
	Height of crown (mm) [1]	Mean Height of crown(mm) [2]	Standard Deviation(mm) [3]	Relative Difference (%) [4]= ([1]-[2])*100/[1]	Mean Height of crown(mm) [5]	Standard Deviation(mm) [6]	Relative Difference (%) [7]= ([1]-[5])*100/[1]
Left 2nd Molar	6.14	6.10	0.06	0.65	6.13	0.08	0.16
Left 1st Molar	7.50	7.69	0.03	2.53	6.69	0.07	10.80
Left Canine	9.53	9.59	0.08	0.63	8.65	0.05	9.23
Left Central Incisor	8.20	8.27	0.06	0.90	8.72	0.08	6.39
Right Central Incisor	8.55	8.07	0.08	5.61	8.72	0.08	1.99

Right Canine	9.08	9.32	0.05	2.64	9.08	0.06	0.00
Right 1st Molar	6.10	6.16	0.09	0.98	6.07	0.08	0.49
Right 2nd Molar	7.46	7.58	0.07	1.61	6.93	0.06	7.10

Non-linear compressive forces were applied at six different nodes for eight separate sections, including left and right canines, left and right molars and left and right incisors, based on which Von Mises stress distribution was obtained for each aligner material. A stress distribution representative vase is visualised in Figure 5 for the Durasoft aligner.

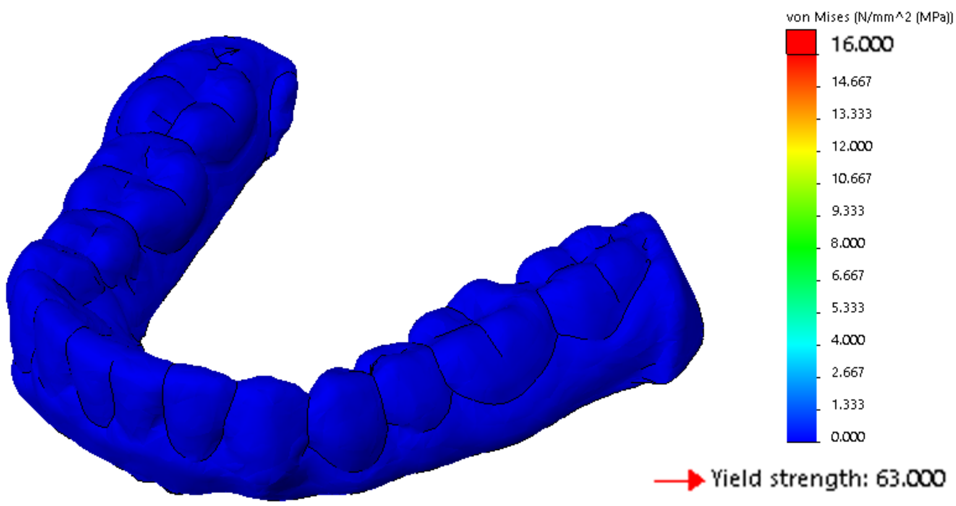


Figure 5. Stress distribution for Durasoft Aligner and boundary conditions

The general trend for the stress vs time behaviour for a complete cycle was replicated as per the applied force vs time behaviour to all materials. Figure 6 represents this trend for left molar section for Dental LT resin.

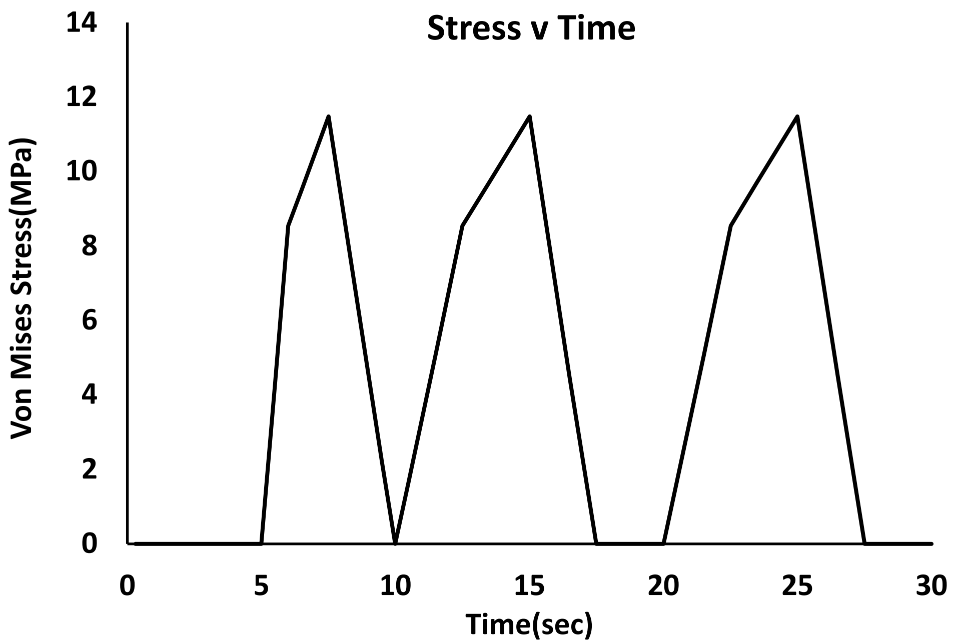


Figure 6. Von Mises stress distribution for left molar Dental LT resin aligner with time

A comparison of the maximum Von Mises stresses across all nodal points for each tooth section has been shown in Figure 7. Figure 7 clearly indicates a minor reduction in stress distribution for the Dental LT resin aligners in comparison to conventional materials of Duran and Durasoft. Although, the stress reduction is minimal, it is an indicator that could encourage the application of Dental LT resin as a clear dental aligner material in practice.

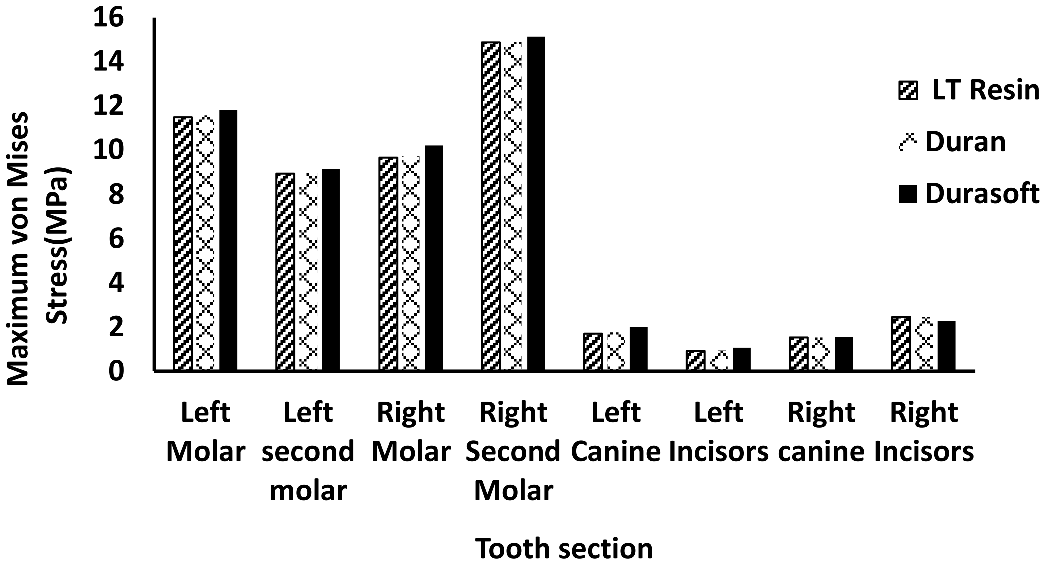


Figure 7. Maximum Von Mises stress at various tooth sections for all materials

4. Discussion

Clear dental aligners materials were compared for dimensional accuracy and mechanical strength under non-linear compressive loading at various sections of a specific patient's mandible dentition. Dental LT resin, which is a biocompatible material for clear dental aligner application, was evaluated for mechanical properties by developing an FEM model from a scanned STL file of a patient's dentition and subjected to non-linear cyclic mechanical loading equivalent to human biting forces. Geometrically, the 3D printed Dental LT clear aligner was more accurate as it is a digitally reproduced product. The average relative differences for the mean crown heights (distance between the points of intersection of midline of tooth on the buccal surface with gum line and at incisal edge has been taken as the height of the crown for the selected tooth on the aligner) of molars, canines and incisors between Dental LT and Duran aligners with respect to the base reference scanned STL file were 1.94% and 4.52% respectively.

Von Mises stress distribution was obtained across various sections of molars, canines and incisors which sustain a substantial load of the total biting forces. Across the dentition, the maximum Von Mises stresses for left and right molars varied between 8.98MPa to 15.13MPa to sustain a bite force of nearly 600N for conventional aligner materials such as Duran and Durasoft. Maximum Von Mises stresses for the same molar sections in Dental LT resin-based aligners varied between 8.94MPa to 14.88MPa. These results indicated that the maximum stress at all the sections (including incisors and canines) obtained for a total of 33161 nodes were within a range of 0.2 % to 7.7% in comparison to other conventional recommended aligner materials such as Duran and Durasoft.

This indicated that, to resist a non-linear cyclic compressive force (up to a maximum of 600N) equivalent to human biting force, a geometrically more accurate, faster processed, bio-compatible, 3D printable and mechanically strong material, such as Dental LT resin, offers an ideal alternative material to the conventional materials for clear dental aligner applications. To eliminate difficulties in fabrication of conventional aligners made out of Duran and Durasoft, a 3D printable transparent and bio-compatible material would be most suitable. However, despite the availability of such a material like Dental LT resin, its mechanical properties evaluation is imperative. Since these studies, indicate satisfactory utility of Dental LT resin as a clear dental aligner material, hence, it provides new cost effective opportunities to the clear aligner market. Clear aligners produced using Duran and Durasoft involve more steps including impressions, scanning, 3D modelling of stages, 3D printing of dental models for each stage and final vacuum thermoforming of the clear sheet to form the clear aligner. However, if Dental LT resin is used for manufacturing clear aligners, then the steps of 3D printing of dental models and thermoforming are eliminated completely. Instead of these, direct 3D printing of aligners is done. Elimination of the manual thermoforming process helps in improving the accuracies of the aligner. Similarly, elimination of the 3D printing of dental models saves on substantial material weight, cost and production time.

5. Conclusion

With the advent of digital and 3D printing technologies for providing geometrically accurate and time-saving manufacturing solutions, all methods of fabrication have been shifting away from conventional manufacturing methodologies. For biomedical devices, prosthetics and implants, 3D printing is an even more preferred alternative, owing to the significance of producing complex and accurate geometries suitable for complicated human anatomy and structures. However, apart from accuracy, 3D printing could only be preferred if the printed object is bio-compatible for the human body and has sufficient mechanical strength to resist external loading. Clear dental aligners are manufactured using thermoplastics like Duran and Durasoft using conventional process of thermoforming, thereby leading to dimensional inaccuracies, which ultimately leads to patient discomfort and prolonged treatment. Dental LT resin is a material which can be 3D printed and is certified as Class IIa biocompatible for the human body. Therefore, the scope for it being used as an aligner material is wider in comparison to other materials, provided its mechanical strength is comparable with Duran and Durasoft.

In this paper, dimensional measurements of crown heights for Dental LT and Duran clear aligners have indicated, superior geometrical accuracies for the Dental LT aligners. In addition, the Von Mises stress distribution of Dental LT resin with Duran and Durasoft at different sections (molars, incisors and canines) of the mandible dentition under the action of non-linear compressive forces equivalent to human bite force (up to

600N) using FEM has been found to be comparable. Therefore, these studies suggest that Dental LT resin provides an excellent alternative to the conventional materials for manufacturing clear dental aligners and other applications of dentistry due to its 3D printable compatibility for superior accuracy and time saving features, in addition to bio-compatibility and sufficient mechanical strength.

The FEA results provides a significant guideline towards mechanical load bearing capacity of these aligners, which would further motivate scientists and dentists to conduct other mechanical load tests experimentally. With a steady stream of new Class IIa biocompatible materials capable of being 3D printed becoming readily available, the dentistry industry is well positioned to take advantage of new digital dentistry techniques and manufacturing processes.

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