Pioneering advanced recording technologies for post-earthquake-damage assessment and re-construction in Chilean heritage areas

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Abstract. The physical conservation of historic buildings is a challenge worldwide, but it is even more difficult in earthquake-prone areas. To avoid potential damage, mitigation strategies are required, such as periodic maintenance, repair and strengthening, usually not implemented at the scale of dwellings in heritage areas. Funding is generally available for monumental buildings—such as churches—leaving houses vulnerable to the effects of future earthquakes.

After earthquakes, damaged dwellings cannot be immediately reinforced to continue habitation; generating disruption. If buildings are repairable, the costs are high due to the difficulty of working with the existing remains, resulting in a preference for new constructions on-site and elsewhere. Large numbers of affected constructions make damage assessment difficult, impacting in slow and sometimes out-of-context responses.

This paper proposes an alternative to tackle these issues by using 3D-laser-scanning to document the as-built condition of houses after the 2010 earthquake in Lolol, a heritage village in Chile that was in progress of reconstruction and repair via the newly created Heritage Reconstruction Programme post-earthquake. The data obtained was used as a basis for designing alternative architectural interventions, with the potential of speeding up emergency responses and retrofits, leading to the re-use of the remaining built heritage. From this, the paper argues for the introduction of technology institutionally at a governmental level, to inform emergency strategies and a more sustainable, affordable and inclusive method for risk mitigation, repair and re-construction of domestic heritage in seismic-prone areas of Chile, which is also relevant for similar cases worldwide.

Keywords: Re-construction, damage assessment, 3D-laser-scanning, earthquakes, heritage intervention, reconstruction, Chile.

1 Chile as a Case Study

1.1 Earthquakes as a Regular Agent of Risk

Depending on the magnitude, area, type of construction and context, earthquakes produce a specific type of destruction in Chile, since they usually damage buildings but do not erase complete areas (Figure 1). Because of this, emergency measures and re-construction approaches can be based on what is left—e.g. partially destroyed constructions, ruins and rubble—and used as part of recovering strategies. This was the case with Lolol, a heritage village affected by the 2010 earthquake, occurring on 27 February in Chile's central-southern area, which had a magnitude of 8.8 M_w.

Fig. 1. A damaged house in Lolol after the 2010 earthquake. Source: Author.

1.2 Lolol

Lolol is located in the Colchagua Province, VI region of Chile. Dwellings are built as continuous façades but are also characterised by having porticos, which generate a particular spatiality to the public space (Figure 2). It was declared a *Typical Zone* in 2003. After the 2010 earthquake, Lolol experienced damage and destruction of structures, but no fatalities occurred in the heritage area.[1]

[1] Three fatalities were identified in the whole commune (Ministry of the Interior and Public Security 2010), which consists of a larger area than the village of Lolol.

Fig. 2. A damaged house with porticos in Lolol after the 2010 earthquake. Source: Author.

The urgency of addressing the issues and challenges for seismic-prone areas is key since earthquakes are a cyclical process rather than a one-time event, impacting the timing of responses and how re-construction approaches are designed. Another seismic event will certainly be hitting the same area within a period of time. This implies that any re-construction approach should offer sufficient resilience to prevent future damage to the same buildings, something that was embedded in vernacular constructions but has been progressively lost as contemporary techniques replace them.

The Chilean state does not have a specific institution to assist with reconstruction, neither was one created after the most recent earthquakes. Instead, each existing Ministry was in charge of its own area. For example, housing reconstruction was dependent on the Ministry of Housing and Urban Development (MINVU)[2]—in which heritage areas were included—while churches were in the charge of the Ministry of Public Works (MOP)[3] (Figure 3). This institutional arrangement meant that vernacular settlements were not treated as a group or heritage set, but each building was treated separately, generating coordination issues and impacting the heritage area as a whole unit.

[2] Its acronym in Spanish.
[3] Its acronym in Spanish.

Fig. 3. Lolol church after the 2010 earthquake. Source: Author.

Reconstruction of built heritage has occurred progressively over the years, and it is likely to continue to occur after future seismic events because mitigation strategies have not been implemented. This lack of prevention produces a built heritage that is continuously at risk. After large earthquakes, improvements are made to building codes, raising the standard for new constructions but not introducing consolidation measures for existing ones. This aspect leaves built heritage with an underlying vulnerability until such time as it is convenient for it to be replaced.

In Chile, there are many historical settlements located in various climatic conditions, which embody different ways of living and building, with dwellings characterised by a connection with their landscape, where the vernacular building techniques, such as adobe,[4] represent a construction culture that mixes indigenous and Spanish traditions, dating from the nineteenth and twentieth centuries. Reconstruction approaches after earthquakes in Chile have failed to preserve these values, mainly because the replacement of dwellings is preferred over repairs, in which the replication 'as it was before' is the most common strategy, generating authenticity issues [1].

After the 2010 earthquake, the Heritage Reconstruction Programme was created at the Regional Ministry Secretariat (SEREMI)[5] of the MINVU VI Region of Chile, and then replicated in other affected regions [2]. One of the main advances of this programme was to organise the post-earthquake work to allow repairs and retrofits using the total funding available for a new house, resulting in larger dwellings and the conservation of more built heritage dwellings (Figure 4).

Fig. 4. A dwelling under repair in Lolol in 2013, showing the use of metallic meshes to stabilise damaged adobe walls. Source: Author.

However, that scheme was not fast in developing solutions. One of the reasons for this was the need to carry out damage assessments that require technical and professional expertise, and to gather information on the condition of each dwelling—as left by the earthquake—in order to start assessing any intervention. Extra funding and collaboration with professionals, students and universities were used to speed processes, yet they

[4] Clay and straw masonry.
[5] Acronym from Spanish: 'Secretaría Regional Ministerial'.

were not enough. For example, in Zúñiga, repairs from that programme did not start until three years after the 2010 earthquake.

Lolol was defined as a national priority by the aforementioned programme, as a way of showing the results of a repair strategy over complete replacement. After the same three years, from a total of 41 houses to have interventions in Lolol, 8 were finished and 11 were in progress. However, the process was much slower in other areas and a large number of affected dwellings never had interventions. This is because the housing subsidies—the governmental financing mechanism for housing reconstruction—are not designed for a post-earthquake situation. Overall, the main reason for the slowness of repairs has to do with documenting the situation post-earthquake in a fast and accurate way for the architectural designs. Thus, this paper will look at this stage of the process in order to see if the introduction of 3D-laser-scanning as an alternative method of analysis and architectural intervention post-earthquake could improve it.

2 3D-laser-scanning

3D-laser scanning—also known as LiDAR—is a recording technology that captures the built environment using laser measurements and a photo camera to capture colour information. The result is a coloured three-dimensional point-cloud with a precision of millimetres.

The amount and accuracy of data collected with this technique are of particular relevance to buildings due to the high level of accuracy, representing a step beyond other recording techniques. For example, whereas photogrammetry—specifically stereo-photogrammetry—is based on multiple photos to generate a 3D point-cloud, the result is usually less accurate [3], which impacts the architectural and damage assessment, and post-processing times tend to be longer. While photogrammetry is particularly useful for capturing detailed surfaces, e.g. painted murals, and it is potentially a more accessible tool than 3D-laser-scanning, its use in large areas with detailed results is yet to be studied.

Digital technologies have been used before to document the built heritage [4,5], for conservation [6], for post-earthquake assessment [7] and for digital preservation [8]. They have also been used in conjunction with other technologies, such as photogrammetry and thermography [9] and remote sensing techniques for automatic damage assessments [10-11-12, 13]. However, there is a knowledge gap in addressing the larger scale of a whole heritage area with the same level of detail as a single building. This is significant in post-earthquake areas since damaged buildings can number in the hundreds, where a rapid and scalable approach from the existing context is key.

2.1 On-site Data Capture in Lolol

The starting hypothesis is that terrestrial 3D-laser-scanning can be used as a powerful survey tool because of the amount of data that can be obtained in the limited period available in a post-earthquake situation before further changes or demolitions take place. To test this, three days were defined as a timeframe in the case study of Lolol. During this set period, a two-person team 3D-laser-scanned as much as possible.[6]

The method of collecting data was to set the terrestrial 3D-laser-scanner[7] in different locations separated by a range of 15 to 40 metres while spherical, and paper targets were placed as reference points that remained still. The exterior spaces were captured from the streets and pavements, and the interior spaces by accessing the buildings. Each scan took almost five minutes, including the photographs that provided the colour information (Figure 5).

Fig. 5. Example of the 3D point-cloud of Lolol in 2013 using three scans. Source: Author.

Currently, 3D-laser-scans can be geo-referenced and located automatically using post-processing software, but reference targets—chequerboards and spheres—were needed for the on-site capture, carried out in January 2013. These targets remained still in between scans, allowing them to be used as reference points to align the 3D scans more precisely later (Figure 6).

After capturing the data on-site, the scans were aligned with one another to form the complete 3D model, a process that took at least three weeks' work.[8] The scans were grouped in specific clusters to facilitate the process. The scans were aligned within a cluster first, and then all the clusters together to form the whole heritage area. Post-processing times included cleaning and editing after alignment and depended on the outcome required—e.g. architectural drawings, such as plans, sections and elevations, or images and videos, needing several additional days to create and render.

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[6] Only scanned during daylight, since this is needed for capturing the colour information. The fieldwork was done in 2013 as part of the author's PhD research (see acknowledgements) that included two more heritage areas: San Lorenzo de Tarapacá and Zúñiga in Chile. Although the on-site data capture was in 2013, the PhD was finished in 2018. In addition, the author has had personal circumstances that delayed the publication of this paper.

[7] Faro Focus 3D s120 used.

[8] Using Scene software and counting full-time days of work.

Fig. 6. Example of the targets used in the 3D data capture of Lolol in 2013. Source: Author.

Because 3D-laser-scanning only captures visible surfaces, the particular portico configuration of Lolol was harder to record as, in order to get the full information of each building, scans were needed both from inside the porticos and from the pavements. This made data collection on-site slower than expected. Since the idea was to cover as much data of the whole historic area as possible, there was not enough time to record more interior spaces. Only the church and one dwelling were scanned completely from inside, plus a couple of spaces that were interiorly scanned when agreed and accessible directly from the porticos and pavements. Top surfaces were not acquired since drones were not accessible at that time, which means that the top views show roofs, ceilings and trees obtained from below. Despite all this, the result is a three-dimensional point-cloud composed of 195 scans, and almost six billion points,[9] covering almost the entire public area designated as *Typical Zone* (Figure 7). The boundary between interior and exterior spaces is blurred and rich in gradual transition because of the porticos and interior spaces scanned.

[9] 5,981,474,370 points exactly.

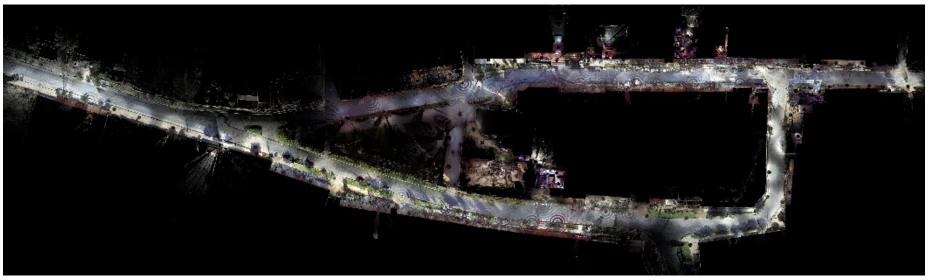

Fig. 7. Plan of Lolol, rendered from all the 2013 3D-laser-scans. Source: Author

The result has an accuracy of millimetres[10] and the data obtained can be measured, virtually cut and used as a basis for technical drawings, images, videos (Figure 8), 3D printed models and virtual reality environments, among other applications (Figure 9). In consequence, this technology can be considered a robust method for documenting buildings and faster to obtain more relevant data—such as distortions and cracks—than traditional post-earthquake documentation techniques.

Fig. 8. QR code and screenshots linking to a video of Lolol, exploring the data sectioned in plan view, exploring the interior spaces captured in 2013. Available here: https://vimeo.com/226779127 Source: Author.

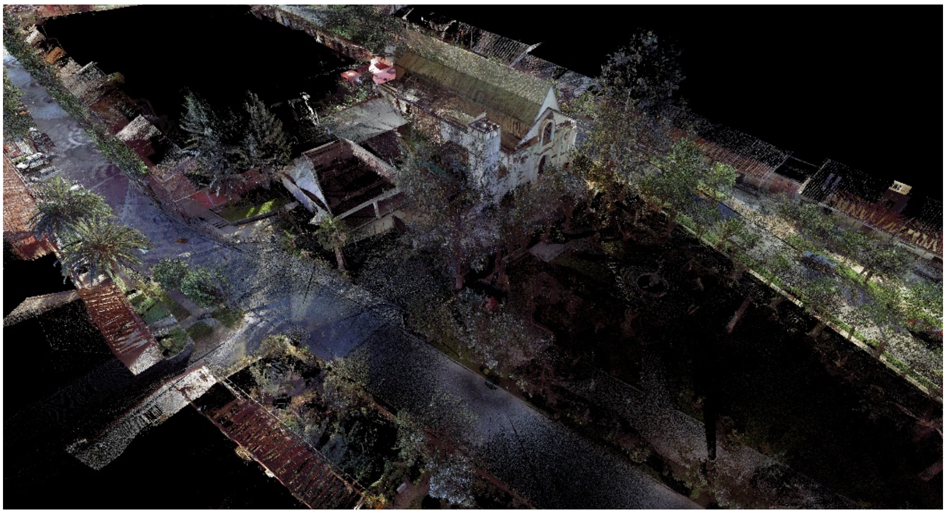

Fig. 9. View of Lolol, rendered from all the 3D-laser-scans taken in 2013. Source: Author.

[10] When using the model and procedure specified.

All methods of representation have aesthetic characteristics, but 3D-laser-scanning offers the possibility of its specific quality. Visualisations and videos have an aesthetic of immateriality since the 3D data is composed of millions of points that give the perception of transparency. The attempt is to show the 3D data obtained in the best possible way, conveying fundamental viewpoints and selecting the most representative images, most of which it is not possible to obtain in reality—such as a section of a building – but it is possible by dissecting the 3D data. This new aesthetic represents a subject for further studies (Figure 10).

Fig. 10. Section of Lolol, Chile, rendered from the 2013 3D-laser-scanning. Source: Author.

2.2 Limitations Encountered When Using Terrestrial 3D-laser-scanning

Because 3D-laser-scanning only captures surfaces, terrestrial laser scanners lack aerial information most of the time unless placed in a location higher than the target—e.g. the roof terrace of a nearby building, which was not possible in the case of Lolol. Therefore, for future scanning processes, it must be complemented by other techniques depending on the target and aims of the survey. There is a whole range of methods—such as air drones—to capture what has not been caught by the terrestrial 3D-laser-scanner, but these were not applied since they were not accessible at the time of the fieldwork (2013) and the focus was only on the terrestrial 3D-laser-scanning experimentation. Currently, a multi-resolution and multi-sensor documentation approach can obtain more comprehensive results by taking advantage of combining data—e.g. based on photogrammetry—on top of the same geo-referenced 3D-laser-scan base [14]. As a post-disaster method, 3D-laser-scanning needs to be complemented with archival and historical analysis, and with the inclusion of social data from the inhabitants.[11]

The most significant problem encountered when applying 3D-laser-scanning to the case study was the noise produced by moving elements on the scene, given that most of the data was captured in public spaces. People, cars, trees, pillars, vegetation or other objects that interfered with the data collection of buildings, cast shadows on the desired

[11] Obtained in Lolol before and during the scanning process through questionnaires to the inhabitants. This data has been excluded from this paper to focus only on the LiDAR record.

target. This was avoided by increasing the number of scans and by placing the scanner in different positions, which made data collection slower. However, that noise was edited and cleaned when necessary using post-processing software. For future—institutional—surveys, the traffic of people and cars can be controlled when the record is taken to diminish their effect on the 3D-laser-data.[12]

Improvements have already been made to the technology. The new environmental scanners can capture a better data range in less time, with new models that range up to 330 metres—instead of the 120 metres of the model used. Resistance to rain, dust and extreme temperatures are also features of the latest model of Faro scanners available, along with an improved embedded photo camera—with better resolution and quality.

Tasks that were done manually, such as aligning the scans, can now be done automatically. The latest software has reduced alignment times by providing automatic alignment algorithms based on the building's features.[13] In addition, new scanners have also improved functions for locating the scans in real-time using a tablet computer. This allows for a better understanding of the data captured so actions can be taken on-site if areas are occluded.[14] This real-time feature is especially relevant since it allows the data to be manipulated right after its collection, extremely useful in post-disaster areas that require immediate action.

Therefore, it will be assumed that terrestrial 3D-laser-scanning represents a precise recording method of the physical features of the built environment to argue for its crucial role in heritage re-construction.

3 Using the Record

This paper focuses only on the immediate post-earthquake response, using the data for creating physical emergency supports and for the repair and strengthening of existing structures. However, its application is relevant as a more comprehensive methodology for a wider long-term conservation strategy of housing in heritage areas that includes risk mitigation, planning and post-earthquake response, named as *re-construction.* This is to make a distinction between reconstruction—understood as current strategies of replication 'as before'—and *re-construction,* understood as to build again, as a step forward, respectful towards the past but adaptable to ever-changing social, cultural and physical contexts.

[12] In addition, the newest version of the post-processing software—Scene—features filters to reduce noise on detailed parts of buildings, such as decorative railings, not available in 2013.

[13] The latest software—unavailable in 2013—can perform cloud-to-cloud and top-view alignments, where what is captured serve for referencing the position of each scan. This means that it is currently possible to 3D-laser-scan without the need for reference targets. Targetless registration is not useful in monotonous contexts, e.g., a desert, and it is less accurate. When spherical references are used, as in the case study, accuracy ranges from 0.1 to 1 mm. If cloud-to-cloud alignment is used, accuracy can decrease by up to 10 mm.

[14] A locator device from Faro can provide that feature even in older models. The result would be all the scans aligned together at the end of the on-site data capture, significantly reducing post-processing times.

3.1 Post-earthquake Damage Assessment and Planning

The potential has been shown of 3D-laser-scanning as a quick survey tool, facilitating the required post-earthquake damage assessment. Here will be addressed its importance as a basis for design beyond the scale of one building to consider entire heritage areas without compromising the level of detail (Figure 11).

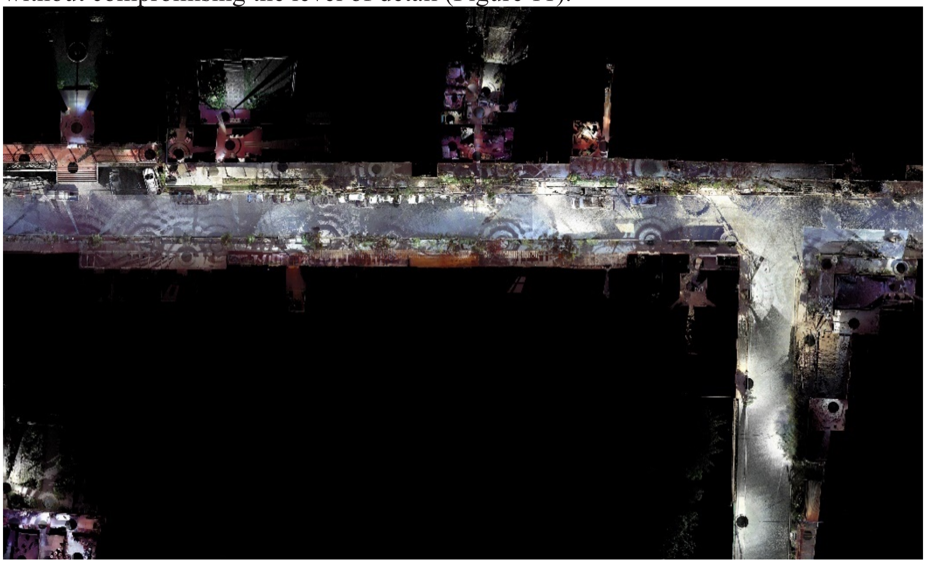

Fig. 11. Plan of the dwellings scanned in Lolol, Chile. Source: Author.

With that information, a wider re-construction approach can be planned, involving a series of intervention strategies according to the level of damage of each house, from emergency to the long-term, such as tailored supports, re-use and repair. Having established that, the focus of this paper is on the emergency actions and the repair of existing structures as one possibility.

These post-earthquake proposals are not definitive and do not claim to cover all possible aspects of re-construction. They stand as a series of strategies that may inform future designs, either separately or combined with other measures. The 3D-laser-scanning of Lolol was used to test these strategies, providing snapshots of the ideas. However, these are not as detailed as they could be and are presented just as a reference.

These alternative proposals are thought to match current governmental funding for emergency housing and reconstruction, in the hope they can be implemented—or at least not discarded because of insufficient funding. This is, of course, speculative since the cost of interventions depends on the specific conditions of each place, in terms of the availability and procurement of materials, workforce, market values and so on, but it helps to maintain interventions within certain limits.

Currently, there is no differentiation between short- and long-term re-construction. The short-term strategies proposed here acknowledge processes that occur in reality and that are not part of current reconstruction policies, to be implemented between the emergency and permanent housing. These are based on the housing subsidies for heritage areas after earthquakes, establishing a thoughtful approach to that long-term reconstruction that allows for careful consideration in terms of re-using and retrofitting, a key element for historical constructions.

3.2 Tailored Emergency and Repair Strategies

The main aspects proposed are the intervention within the same site, assuming that inhabitants will be living there, with a progressive design and construction separated into two different phases. First, securing safe habitation through emergency shelters and supports. As heritage areas are less populated than urban areas and plots have larger dimensions, temporary shelters are usually installed towards the back of each site. Even if temporary camps are provided locally, inhabitants come back to their properties sooner rather than later, inhabiting those spaces that are perceived as safe, even when they are not.

Second, addressing re-construction to improve that period between the emergency and the final result. This is mainly understood as re-use and retrofit of the affected dwelling, using the post-earthquake 3D record. The aim is to fit in that timeframe, recognising that current reconstruction approaches are slow and that there is a gap in how to improve living conditions in between the emergency and the permanent housing solution.

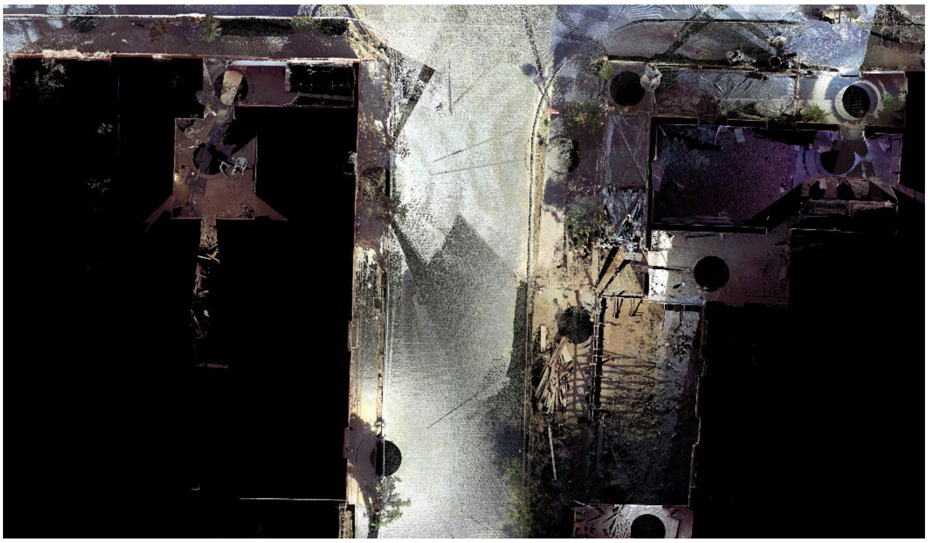

Fig. 12. Partial plan of a dwelling abandoned (left) and a dwelling under repair (right) as scanned during 2013 in Lolol, Chile. Source: Author.

For this, the guiding principles proposed are economy of resources, prefabrication and planning, aiming for a final progressive dwelling that will not have disrupted the affected family as much as if they had been displaced for the whole construction period. This process can also serve as an involvement strategy with the residents, who will benefit from the first-hand experience of repairing, reinforcing and rebuilding their dwellings.

The specific conditions of each household and site will be provided by the 3D-laser-scanning record and organised into complementary approaches. The idea is to use the record with the inhabitants to understand how they occupy their spaces, and then create a strategy of use during this period composed of emergency shelter at the back, and emergency supports to ensure safe passage and use of installations within the affected dwelling—such as a toilet and the kitchen. This also includes assessing damage to identify priorities for repair, re-use and re-construction of affected spaces, with actions such as the dismantling of walls to create reusable material and the construction of new spaces when required. This includes imagining the different stages of the dwellings in the near future (Figures 13 and 14).

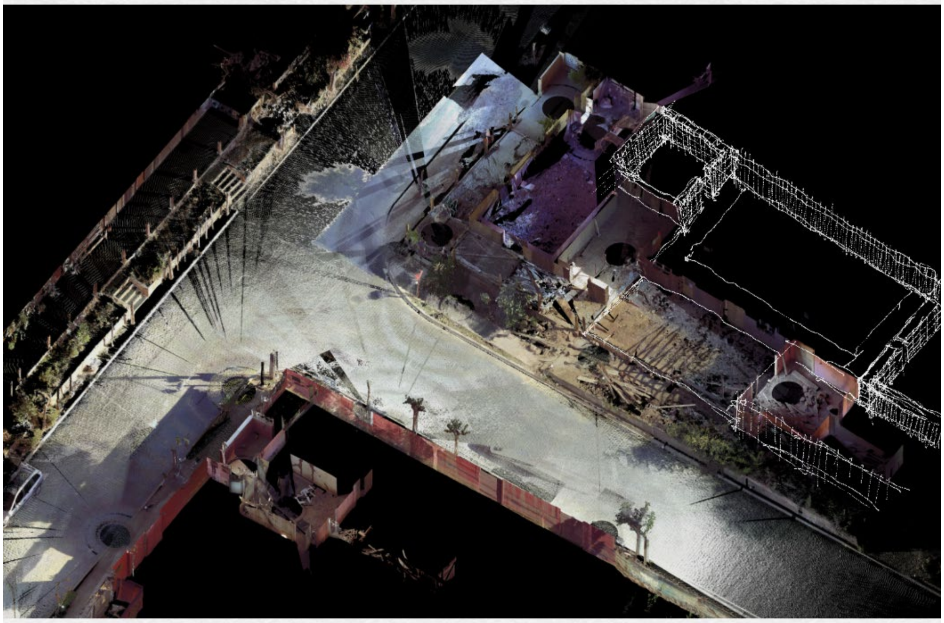

Fig. 13. Scheme of interventions within the site of an affected dwelling in Lolol, Chile, conforming to the interior courtyard based on the 3D-laser-scan data. Source: Author.

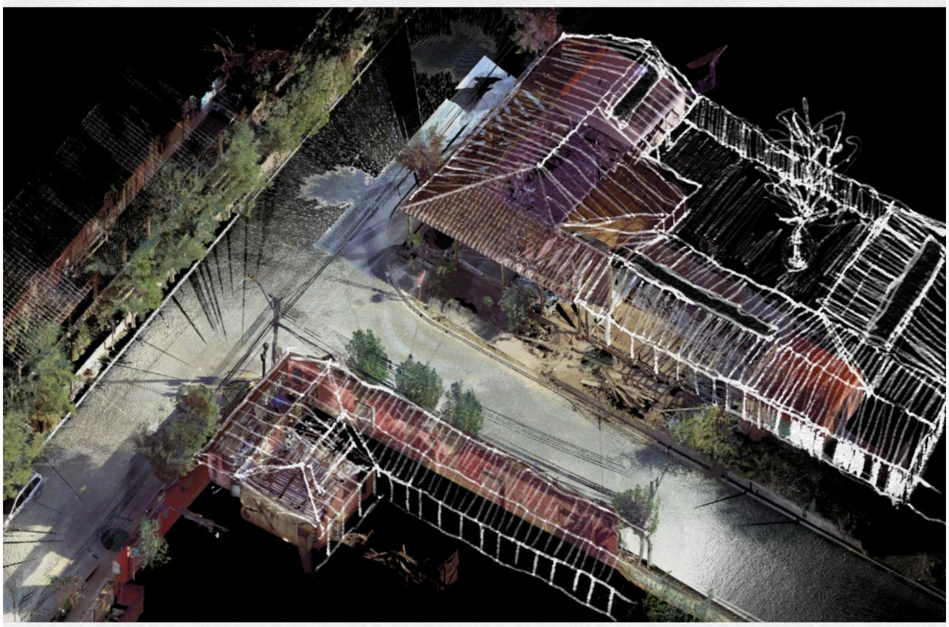

Fig. 14. Scheme of completed interventions for an affected dwelling in Lolol, Chile. Source: Author.

A proposed emergency shelter (Figure 15) based on prefabricated panels—1.22 m by 2.44 m—is suitable for implementing fast and efficient temporary habitations, that can be adapted to different situations and negotiate transportation through difficult routes of existing dwellings. The novelty is using the contextual information provided by the 3D-laser-scanning to analyse its design and location in relation to the damaged house, remains and paths of use, as part of a strategy of occupation of the site that will be complemented by temporary supports and repairs, also based on that information.

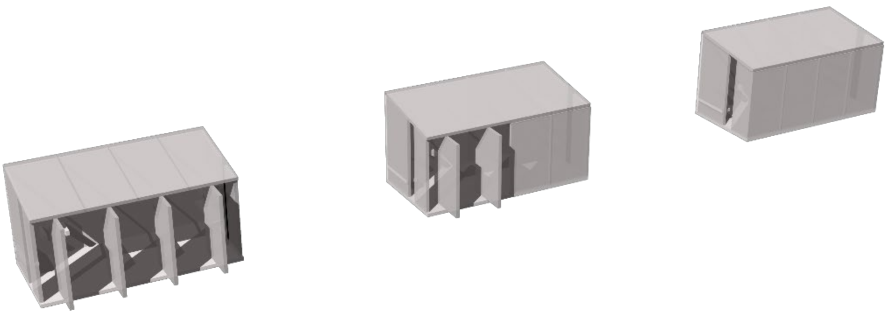

Fig. 15. Flexible emergency shelter with panels with a central pivot, which could rotate to provide ventilation and shade during summer, conforming to a portico. Source: Author.

These features create a flexible space, which may be maintained and used by the inhabitants in the future, if located and installed after careful analysis of the site, e.g. to conform to an interior courtyard or patio (Figure 16).

Fig. 16. Proposed view of the flexible emergency shelter installed in the back garden of the site conforming to an interior courtyard. Source: Author.

In addition, by using the 3D-laser-scan information, post-earthquake distortions can be identified to design specific supporting objects, depending on the level of damage, which can even be designed as permanent to increase seismic resistance. For example, wall supports that follow exactly the shape of the distorted surface according to the 3D-laser-scan (Figure 17). This building's prosthetic has the potential to become an integral part of the building or to be used as a basis to expand the dwelling in the future, once removed from its initial location, becoming a trace of previous earthquake damage.[15]

[15] If they cannot be created as unique pieces or if displacements are produced due to aftershocks, some reinforcements will still work if adaptable elements that can absorb differences between the 3D data and the reality are added. For example, standard supports to be used on both sides of a damaged adobe wall, with adjustable tensors connecting them.

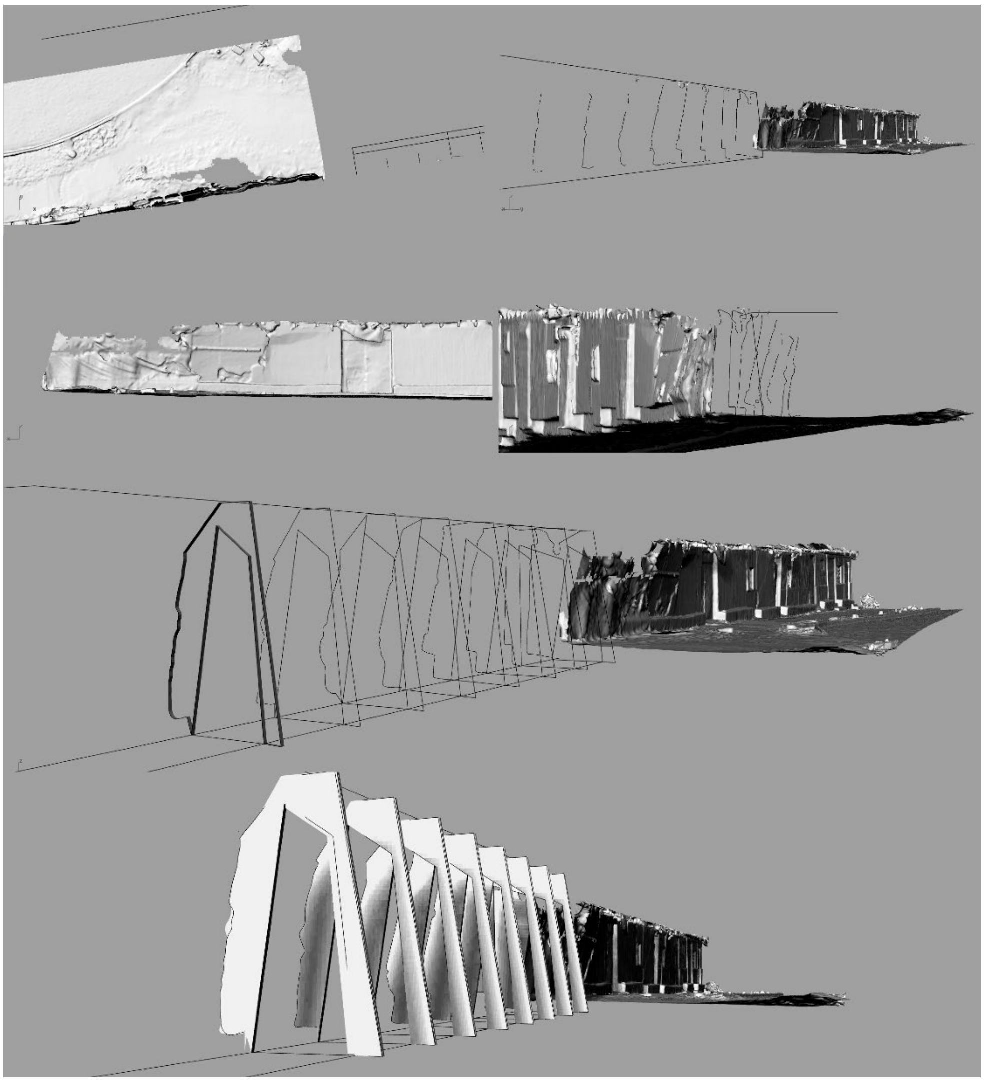

Fig. 17. Emergency supports designed to fit the contours of the distorted wall after the 2010 earthquake in Lolol. Source: Author.

Their use—exteriorly or interiorly—can reduce the need for complete rebuilding if applied on time, a view shared with Jigyasu [15]. Exterior supports can take the shape of porticos to hold damaged façades together and avoid their collapse over the public space (Figure 18) while allowing a safer pedestrian passage.

Fig. 18. Exterior emergency supports proposed as temporary corridors. Source: Author.

Interiorly, these supports would help to address the risk of inhabitants passing under potentially vulnerable parts of the house, which may be dangerous in the event of a new seismic event, reducing demolitions. These would allow damaged dwellings to be used during certain hours of the day, in the form of access passages to toilets and kitchens connected to exterior spaces for evacuation in case of an earthquake. These elements can stay in place permanently if needed, or be re-used in the definitive dwelling. They can be prefabricated with millimetre detail informed by the 3D data, and their installation can follow paths of use according to the location of the spaces.

All these emergency strategies are complementary and depend on the specific condition of each house. Understanding that inhabitants usually continue to live on their sites even while works are in progress, the supports can create safe passages from the entrances of the houses to their back gardens, where the emergency shelter would be installed, ensuring a safer habitation within the same site. Following that, it is proposed that residents could act as potential supervision on-site 24/7, able to contact governmental technical professionals if issues arise. Besides, mobile technology and specialised apps, which could use the 3D-laser-scan data as a basis, would potentially allow the works to be tracked more efficiently than the sporadic technical visits during Lolol's reconstruction.

Fig. 19. View of the same affected dwelling in Lolol from the 3D-laser-scanning. Source: Author.

All these strategies must be carefully thought through because spaces are partially used, which can be challenging considering the configuration of continuous façades in Lolol. This requires planning from dismantling to building, which would need to be worked out in connection to storage spaces and passing routes. This is especially relevant if the materials from the dismantling are to be recycled and used in the final dwelling.

To clear the areas that would be re-constructed, one proposal is to dismantle the affected part of the construction while building supports and storing the materials. It is proposed installing a metal structure at the back of the site, next to the shelter, that can serve for storing material temporarily or as walls for future extensions if located strategically from the beginning. This metal structure of thick and hollow walls would be filled with material from the dismantled part, clearing the area for re-construction, and taking advantage of that effort as an initial process of building. For example, if filled with old adobe bricks, the structure would ensure stability while the adobe would serve only as insulation material. It could be taken out again or these could just become the first walls of a future extension of the house (Figure 20). All of this could be planned using the 3D data.

Fig. 20. View of the same affected dwelling in Lolol from the 3D-laser-scanning with proposed storage-walls for materials to be re-used. Source: Author.

4 Integrating Technology in Chilean Institutions

At a practical level, it is recommended to integrate accurate recording technologies, including 3D-laser-scanning for the conservation of Chilean built heritage—pre- and post-earthquakes. The starting point would be to include the risk management approach by creating a new institution that could provide guidance and coordination to current Chilean institutions.

This institution would implement public policies beyond governments and continue throughout disasters, embedding expertise and experience within current structures, at a national and local level. The idea is for this proposed institution to govern above other Ministries so that interventions can be comprehensive, integrated and geographically coordinated; not separated by funding or individual programmes. The challenge would be to maintain stable coordination and participation with other Ministries, local authorities and inhabitants, in order to create collaborations between existing funded programmes. Within this institution, a Heritage Department would be vital for implementing specific heritage policies, continuous recording and anticipating overall plans for Chilean heritage areas. Monuments, dwellings, and even public spaces would be incorporated in future intervention plans. This should consider constant coordination—or even integration—with the Undersecretariat of Cultural Heritage and the National Service of Cultural Heritage, part of the Ministry of Cultures, Arts and Heritage, created in 2017.

The equipment and expertise of 3D-laser-scanning—complemented by other techniques—should be embedded at the state level, to carry out constant documentation of built heritage and develop mitigation strategies. If connected with academia, the process and results can enhance debates and create collaborations, e.g. higher education students assisting in damage assessments, which would increase their practical knowledge and prepare them for future participation in the protection and appropriate intervention of built heritage. Preliminary studies could be carried out based on the records to set mitigation measures and management plans in the case of future earthquakes, aimed at avoiding the unnecessary destruction that can be identified and prevented. All of this would increase the coordination needed, and involve related professionals and local communities in the decision-making processes and in the development of public policy.

5 Conclusions

As a post-earthquake documenting tool, 3D-laser-scanning provides accurate information accessible at any time. Its usefulness for post-earthquake recording has been demonstrated in Lolol as a response to the need for a rapid, user-safe, accurate and potentially complete survey of damaged built heritage, but more than three days should be considered in order to include more interior spaces. If embedded at the institutional level—as suggested in the previous section—it can be considered as an affordable documenting tool, in comparison to traditional recording methods currently used, such as hand-measured drawing and photography. This is especially true if combined with other recording techniques—such as photogrammetry—that can complement the aspects not captured by the laser, such as aerial information and occluded areas. This offers huge potential, especially considering affordability and integration of inhabitants in a constant recording process, yet its application on a large scale is still a subject for further studies.

3D-laser-scanning, if integrated as an analytical method, in combination with archival, social and architectural analysis, can increase the number of preserved heritage buildings since it can help to tackle current emergency and reconstruction actions. This is because it constitutes a measurable survey that can be carried out immediately after the earthquake, providing relevant data for informed decision making during the emergency period. Furthermore, the information can—at the same time—serve for repair and design purposes, which is a key omission in current post-disaster surveys in Chile. 3D-laser-scanning data provides the contextual metric information required to make that process applicable to a high number of houses using similar resources. In addition, if previous records are available, comparative analysis can provide valuable information on how the structures and damage have evolved during that period.

For design purposes, it has been shown how a 3D-laser-scan provides an accurate basis on which to develop proposals in a short period of time, entirely changing the way post-earthquake interventions are carried out. A three-day 3D-laser-scan survey replaces more days of professionals on-site taking the required measurements for repair designs. Also, additional applications are obtainable from the same 3D data—such as tailored supports and digital evaluation.

3D-laser-scanning is a fast-moving technology. The specific procedure used to 3D-laser-scan in the case study is, in part, already obsolete by the time of submission of this paper. As seen, most of those limitations could be overcome by taking actions when scanning on-site, by using the latest technological advances and by complementing it with other methods, such as aerial mapping, photogrammetry, and social surveying. In this context, the real limitations of 3D-laser-scanning as a post-earthquake surveying tool if undertaken by the authorities might include budget (non)availability for acquiring and servicing the equipment; a failure for it to be involved at pace in public policies; and suboptimal administrative management of the data.

Mitigating the effects of earthquakes is not a task that can be done by only one institution of government. It is a multisectoral approach where every stakeholder plays a part in the challenge. Introducing technology to solve the aspects that make the processes of re-construction slower, such as documenting the as-built situation of the houses pre- and post-earthquakes, allows for this process to happen smoothly and for engagement to be maintained throughout.

Finally, if there is insufficient funding to provide the buildings with mitigation measures, the 3D-laser-scan of them can offer a range of possibilities for interventions if they are affected by an earthquake. Ultimately, it can provide a three-dimensional virtual model of the buildings that can survive in the digital realm for the future—if appropriately archived—which can be seen as another way of conservation.

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