Mapping the Structural Frame of a Damaged Reinforced Concrete Building using As-Damaged Scans and As-Built BIM

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Abstract
After an earthquake, Terrestrial Laser Scanning (TLS) can capture point clouds of the damaged state of building facades rapidly, remotely and accurately. A long-term research effort aims to develop applications that can reconstruct 'as-damaged' BIM models of reinforced concrete (RC) framed buildings based on 'as-built' BIMs and scans of 'as-damaged' states. This paper focuses on a crucial step: generating an initial 'best-guess' for the new locations of the façade structural elements. The result serves as the seed for a recursive process in which the location and damage to each object is refined in turn. Mapping the 'as-built' BIM frame into the 'as-damaged' scan is challenging because each element may have different displacement and damage. The algorithm exploits the topology of RC frames to perform initial mapping of the structural grid onto the damaged facade. The approach was tested on a synthetic dataset prepared from a real earthquake-damaged building. Although successful, it has yet to be tested on other damaged buildings.

Keywords: BIM, Laser Scanning, Damage, Reinforced Concrete, Structural Frame

1 Introduction

Right after a natural disaster strikes and cause damage to building structures, semantically rich models of damaged buildings can be of great help for planning search and rescue (S&R) operations. Building Information Modeling (BIM) is a widely accepted technology for documenting building geometry and detailed functional information (Eastman et al., 2008) in design and after construction, resulting in the 'as-designed' and 'as-built' BIM model respectively. Ma et al. (2015) proposed a data schema for representing damaged buildings in an 'as-damaged' BIM format. However, the emergency situation in a disaster site does not allow a time-consuming process of manual compilation of 'as-damaged' models.

Remote sensing in general and Terrestrial Laser Scanning (TLS) in particular are suitable technologies for surveying damaged buildings. As direct contact with damaged buildings is hazardous, TLS provides a very accurate depiction of the facades within a short time and without the need to access them directly. However, compilation of a semantically rich 3D model from the sensing data is a significant technological challenge (Brilakis et al., 2010). In addition, as entering damaged buildings is dangerous, the scan usually records the exterior building façades, while the inside of the building remains unknown to the S&R teams. Researchers at the Virtual Construction Lab in the Technion are developing an ambitious system designed to automatically compile BIM models of Un-Reinforced Masonry (URM) infilled Reinforced Concrete (RC) framed buildings with moderate earthquake damage

(Zeibak-Shini et al., 2012; Ma, Sacks and Zeibak-Shini, 2015; Ma et al., 2015). The system is described in Figure 1. It is assumed that the 'as-built' BIM model is available. Before the earthquake, a series of seismic simulations are applied to the 'as-built' BIM model to derive a number of possible structural collapse models. Immediately after the earthquake, TLS is used to generate 'as-damaged' scans of the affected buildings. Next, the Scan-to-BIM process starts (module 3 and 4), matching the two data sources and reconstructing the 'as-damaged' BIM model in a coarse-to-fine fashion. Since the generated 'as-damaged' BIM includes only the exterior part of the building visible by the scanner, it will be compared with the candidate full models simulated in module 1. The selected full model with best match in the part of exterior facades will be adopted for planning S&R operation.

This paper focuses on module 3, in which the 'as-built' BIM skeleton is mapped to the 'as-damaged' scan and is then modified based on the damaged structural features of URM infilled RC framed building, The result is used as an initial guess of the skeleton of the damaged building, and will be used for reconstruction and further refinement of the 'as-damaged' BIM in module 4. The following section provides a background investigation of relevant research. Next, the mapping method is proposed and detailed through a case study. Finally, the results and future work are discussed.

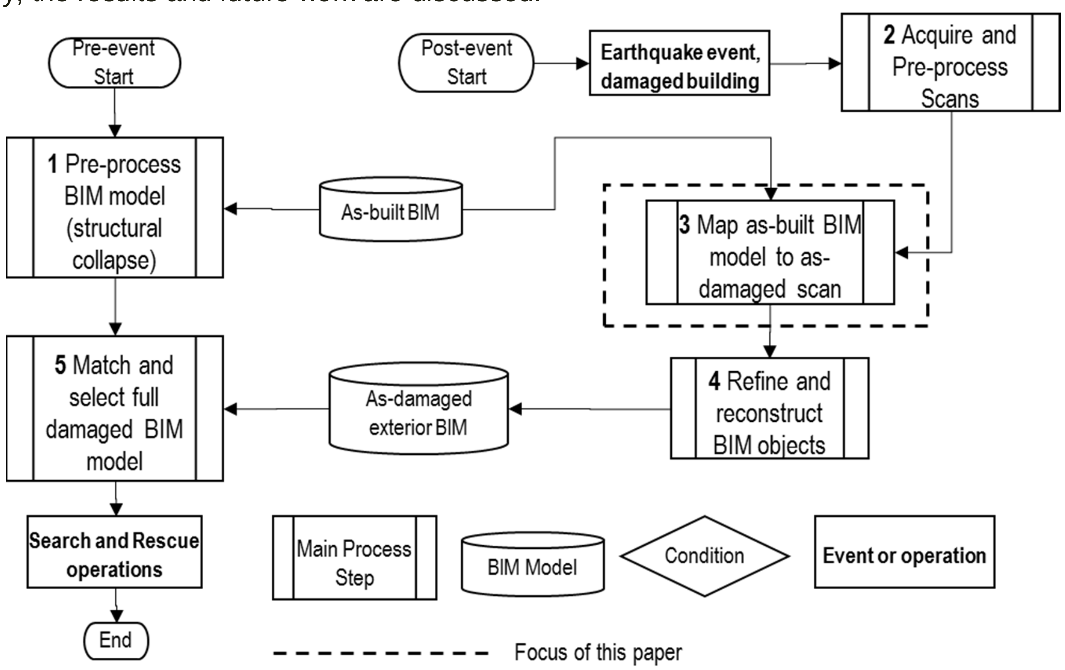


Figure 1. The overview of the S&R support system that automated compiles full 'as-damaged' BIM model.

2 Background

TLS together with other remote sensing technologies have been adopted in damage assessment research. Kashani et al. (2014) proposed a tornado damage evaluation by comparing two sets of point cloud data of a building scanned before and after the disaster. German et al. (2013) used image-processing method to identify earthquake-resulted crack and spalling in columns. Torok et al. (2014) used images obtained from an unmanned robotic platform to similarly identify cracks and main structural elements. However, none of these efforts has attempted to reconstruct an 'as-damaged' BIM model.

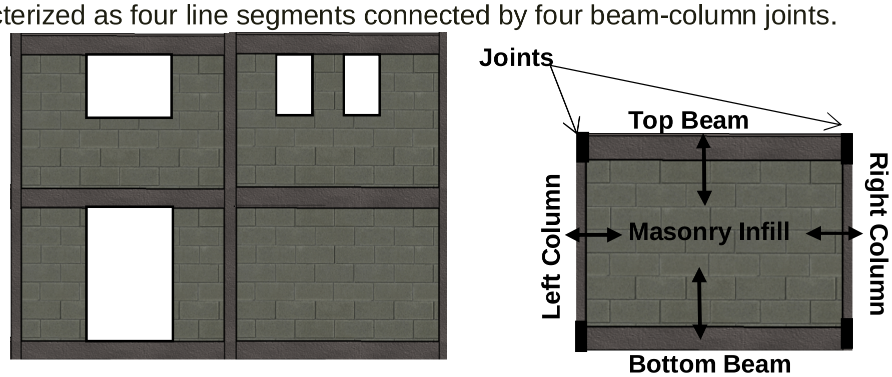
The Scan-to-BIM process has been demonstrated in some simple examples (Tang et al., 2010; Xiong et al., 2013), but it is still not considered to be a solved problem, because the scan only contains the geometry information, and automated compilation of a semantically rich BIM solely from the graphical model is very challenging. However, semantic information can be inherited if an 'as-built' BIM is available. But the task is even more challenging in case of damage occurrence, as the 'as-damaged' scan represents a different geometry of the same structure and matching it with the 'as-built' is an additional hurdle.

Some research has been performed on matching different shapes of the same object. Generally, they can be divided into two categories: Laplacian-based mesh-to-mesh matching for objects that are subjected to non-rigid body deformation (Stoll et al., 2006; Yeh et al., 2011) and piecewise shape-to-shape matching for objects that are subjected to rigid body motion (Aristidou and Lasenby, 2010; Smeets et al., 2012). Rigid body motion is suitable to represent typical damage modes of reinforced concrete building components (Ma, Sacks and Zeibak-Shini, 2015). However, building components can also break into pieces, and this obscures the shape-to-shape corresponding relationship. In addition, the damage propagation pattern of building components is not pre-determined, which makes piecewise matching unpredictable. Thus none of the above methods is directly applicable to this problem.

3 Scope – Building Type and Damage Mode

3.1 RC Framed buildings with URM infills

In terms of building structure, this research focuses on reinforced concrete (RC) framed buildings with unreinforced masonry (URM) infills. RC framed structures are the most common structure type for multi-story buildings in many countries (Haldar et al., 2013). A typical frame unit of this kind of structure consists of two beams up and down, two columns left and right and a panel of infilled masonry, as shown in Figure 2(b). The structural grid can be characterized as four line segments connected by four beam-column joints.



(a) (b)

Figure 2. a) RC framed buildings with URM infills. b) A structural cell within the building frame and its members' topological relationships.

This type of building structure has a relatively stable topology between its components even after damage. The building frame of the exterior facades can be seen as a regular grid whose unit cell is one structural 'cell' as shown in Figure 2(b). Structural cells are repeated in all bays and floors of the building frame as presented in Figure 2(a). Each structural cell might include one opening, multiple openings or no openings at all.

At this stage of the research scope, windows and finishing layers on the building facades have not been considered.

3.2 Moderate-to-Heavy Damage

Liel and Lynch (2012) categorized earthquake damage types on RC framed buildings with URM infills, into five states: 'Negligible', 'Insignificant', 'Moderate', 'Heavy', 'Collapse'. This research studies RC framed buildings with URM infills that have undergone moderate-to-heavy damage; in which structural damage has occurred (moderate) and can be repairable or is too extensive (heavy) and repair might not be feasible. The 'collapse' damage state is not considered.

Damage such as structural failure of beams and columns or nonstructural out-of-plane failure of URM infills are to be considered. Total collapse of the building or its parts in case of a soft story where RC elements are totally demolished is not within the research scope. Instead, partial collapse of stories as a result of short-column failures is studied. Structural failures in beams and columns are more likely than failure within the volumes of the joints. Joints might move or rotate, whereas beams or columns tend to break at their interface with the joints. Therefore, and for the sake of a better first estimate of a damaged building's structural frame, we propose to represent the frame of the structure as composed of eight entities: two beams up and down, two columns right and left, and four joints, as shown in Figure 2(b).

Following an earthquake event, nonstructural out-of-plane failure of URM infills is very common. The masonry infill walls are prone to collapse, thus forming new voids. It is reasonable to assume that masonry infills will almost always collapse from the top down, revealing the base level of the upper beams in the affected structural cell of the RC frame.

Figure 3. Typical out-of-plane failure of URM infills in RC framed building, showing top-down collapse creating new voids that reveal the underside of the RC beams.

The approach described in the next section below exploits these geometrical, topological and behavioral features of RC frames with URM infills to identify an initial estimate of the damaged structural grid by mapping the 'as-built' grid onto the 'as-damaged' scan.

4 Proposed Approach

The goal of module 3 of the overall S&R support system (detailed in Figure 1) is to generate the exterior structural frame of the damaged building, as is shown in Figure 4.The approach for module 3 was developed and tested using a case study of a building damaged in the 2003 Bingol Earthquake (EERI, 2015). The input, including the 'as-built' BIM model and synthetic point cloud of the damaged building, were prepared using software developed specifically for preparing research specimens of this kind (Ma, Sacks, Zeibak-Shini, Aryal and Filin, 2015).

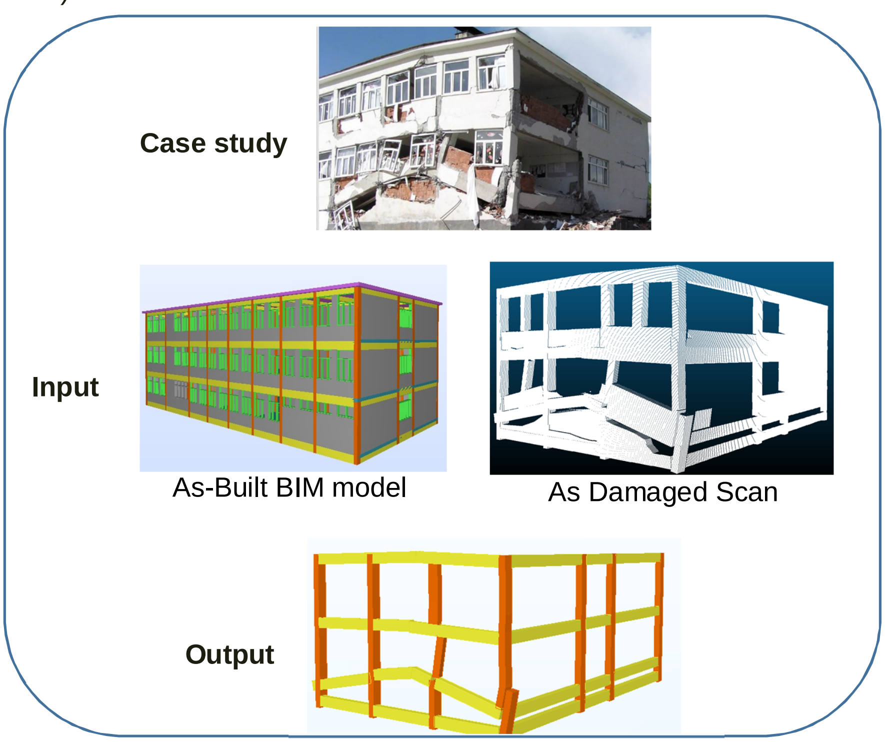


Figure 4. Case study, Input and Output of the overall approach

4.1 Identification of Structural Cells in 'As-Built' BIM

The 'as-built' BIM model was prepared in Tekla Structures 20.0, and exported as an IFC file. Part of the exterior façade was extracted using the same viewport in which the photo of the damaged building was taken. A computer program was developed to extract the structural frame objects (only beams and columns) of the building. Each structural cell is enclosed by two beams and columns. Based on the 3D frame, the structural cells can be grouped by the two facades, three floors / six bays. The results are shown in Figure 5.

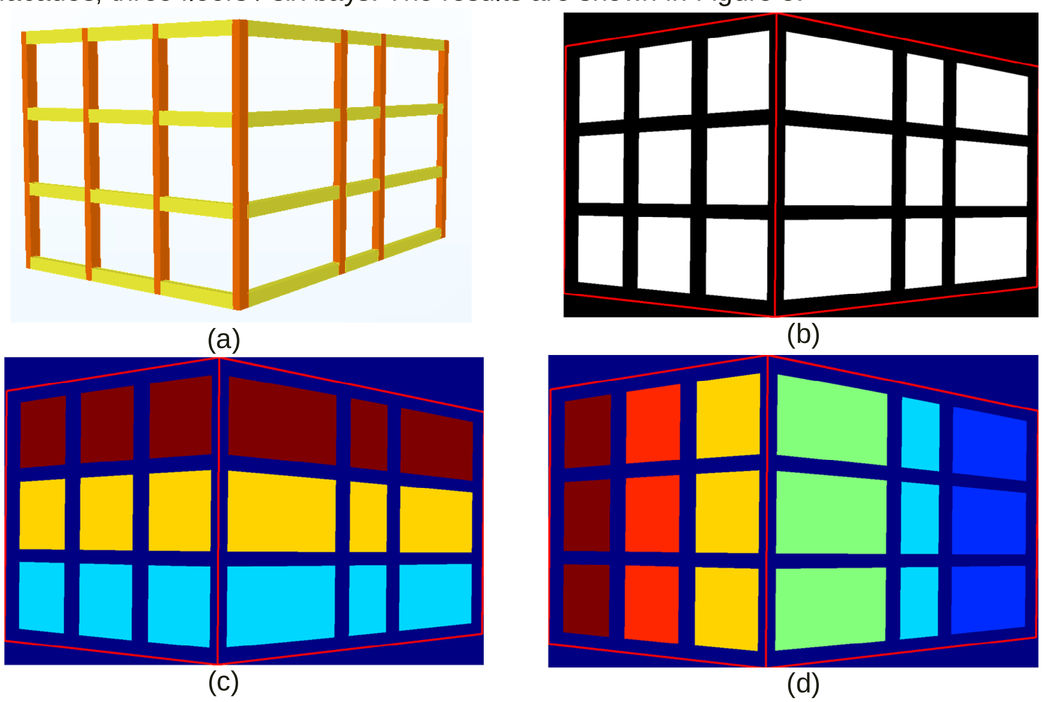


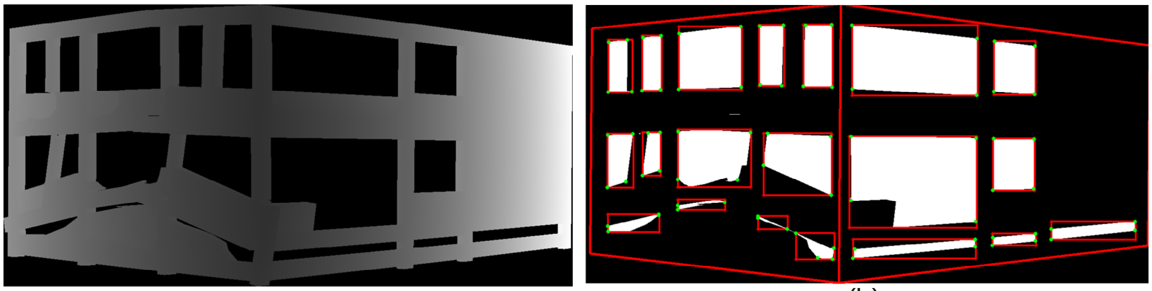
Figure 5. a) The frame of the 'as-built' model. b) Structural cell grouped by façade, c) by floor and d) by bay.

On the other hand, the structural cells in the 'as-damaged' scan are not obvious, because the texture-less building façade (with plaster on the surface) makes it very difficult to distinguish the beams, columns and infills whose exterior surfaces are coplanar. However, in each damaged structural cell, voids within infills provide distinct features. Considering the fact that voids usually reveal the upper beam in the cell, identification of voids' top edges can help locate the beam and consequently other structural members of the cell, forming the as-built stable topological configuration.

4.2 'As-Damaged' Void Extraction

The masonry infill walls are prone to collapse as a result of natural disasters, thus forming new voids or merging existing voids. Therefore three conditions can occur: voids in the 'as-damaged' model represent 'as-built' openings (with or without change in geometry and size), merged neighboring 'as-built' openings within the same cell, or newly formed openings as a result of collapsed infills.

Voids can be extracted by tracing the boundaries of "no-return" regions in the range image of the scan (See Figure 6). The range image represents the point cloud in a spherical coordinate system rather than a Euclidean system, and is a compact representation that enables very efficient processing of the data (Zeibak and Filin, 2012). The top-left, top-right, bottom-left and bottom-right corners of each void are determined using its bounding box, which first defines the top, bottom, right and left sides of the void.



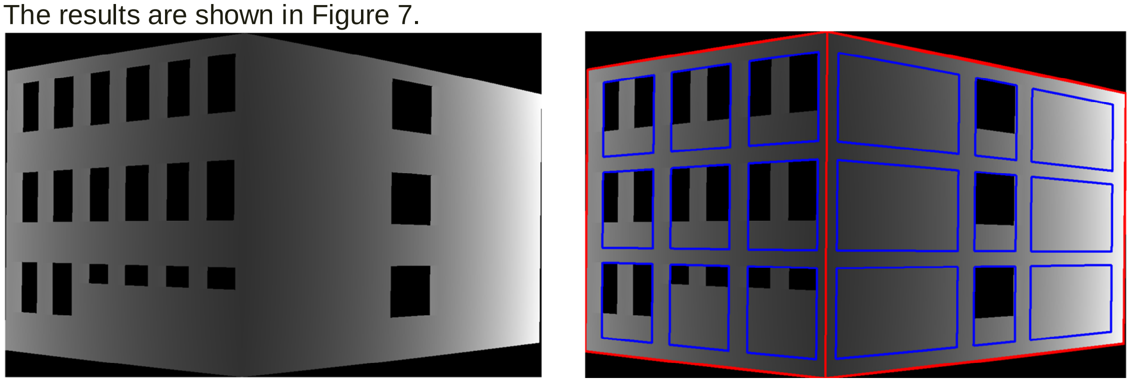
(a) (b)

Figure 6. a) Range image of the 'as-damaged' scan. b) Bounding box and four corners of the 'as-damaged' voids in the range image.

Because the source of the void is not unique, each damaged structural cell could have multiple voids, and thus the correspondence between void and structural cell is not obvious. However, following moderate-to-heavy damage, the number of structural cells will not change, and the position of each structural cell relative to its neighbors should be conserved. As a result, the structural grid of the 'as-built' BIM model is very useful and can serve as a first guess to identify the grid in the 'as-damaged' scan (zone the damaged facades into cells).

4.3 Associating 'As-damaged' Voids with Structural Cells

First, in order to map the 'as-built' BIM with the 'as-damaged' scan, they should be placed in the same reference frame and be represented in the same data format. Thus, the 'as-built' BIM model is scanned in the same viewport where the damaged building was scanned using previously developed TLS emulator (Ma, Sacks, Zeibak-Shini, Aryal and Filin, 2015). Accordingly the structural grid, and in this case specifically the boundaries of the structural cells of the 'as-built' BIM model, can be mapped into the range image of the 'as-built' scan. The results are shown in Figure 7.



(a) (b)

Figure 7. a) Range image of the emulated 'as-built' scan. b) Identified boundaries of 'as-built' structural cells (In blue).

On the other hand, the overall boundary of the damaged building's facades can be derived based on the extent of the 'as-damaged' scan. Due to the partial collapse of the ground floor in the case study building, the overall height is smaller than it was before the damage. Thus, in a reduced scale, the 'as-built' structural grid is used to divide the 'as-damaged' scan into initial cells, as shown in Figure 8.

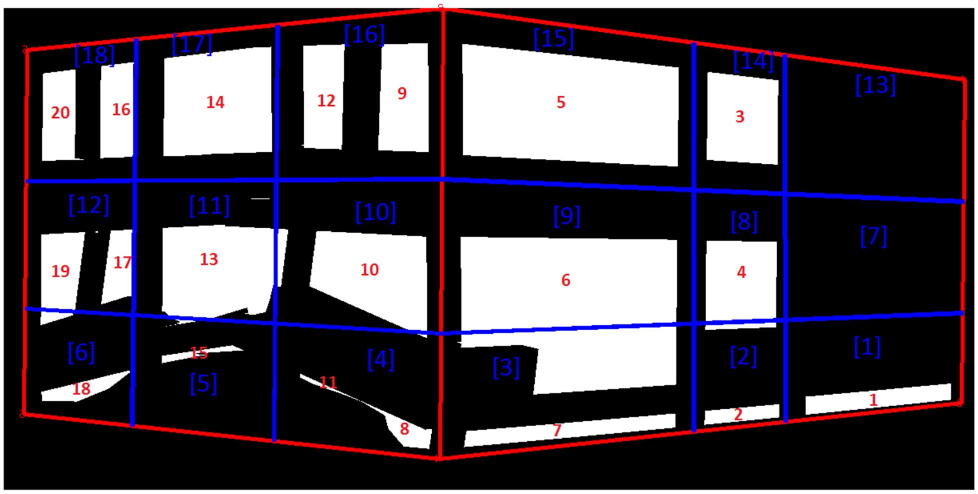


Figure 8. Initial cells in the 'as-damaged' scan derived by scaling and mapping the 'as-built' in the range image (In blue).

Each void should correspond to one structural cell. The correspondence is derived based on criteria of overlapping area between cells and voids. Very small voids (smaller than a threshold) are neglected. Table 1 shows the association results and percentage of maximum overlap between the void and the associated cell. In summary, 75% (15 out of 20) of the voids are totally within their corresponding cells. The other 25% (5 out of 20) spread over more than one cell. The decision on such voids' association is made based on their highest overlapping percentage with the overlapping cells. This way, a void belongs to a cell which covers the highest overlapping percentage of the void among all other cells. For the case study building, 20 voids are associated with 18 cells. Manual inspection of the results showed 100% success of the association.

Table 1 Void-to-Cell Association based on maximum overlapping percentage.

Void ID	Cell ID	Max. Overlap%
1	[1]	100
2	[2]	100
3	[14]	100
4	[8]	92.4
5	[15]	100
6	[9]	66.5
7	[3]	100
8	[4]	100
9	[16]	100
10	[10]	99.6
11	[4]	100
12	[16]	100
13	[11]	94
14	[17]	100
15	[5]	100
16	[18]	100
17	[12]	100
18	[6]	100
19	[12]	90.9
20	[18]	100

Following damage, the beams and columns might bend or break in some of the structural cells; this will result in a reduction of these cells height and shape. As a result, the 'as-built' cell grid in a uniform reduced scale is not the perfect skeleton of the damaged building. Thus the mapping derived at this point is only an initial estimate, and will be refined through recursive iteration of the solution process as a whole (with reference to Figure 1). These latter steps are beyond the scope of this paper.

4.4 Reconstruction of the 'As-damaged' building skeleton

In URM infill RC structures, the voids in the masonry are usually framed along their top edges by an RC beam. In addition, following the damage, masonry infills will collapse downwards, thus revealing the bottoms of the beams at the top of each cell. Thus it is reasonable to assume that the top edges of the voids in the scan are generally coincident with the base level of the upper beam in the structural cell.

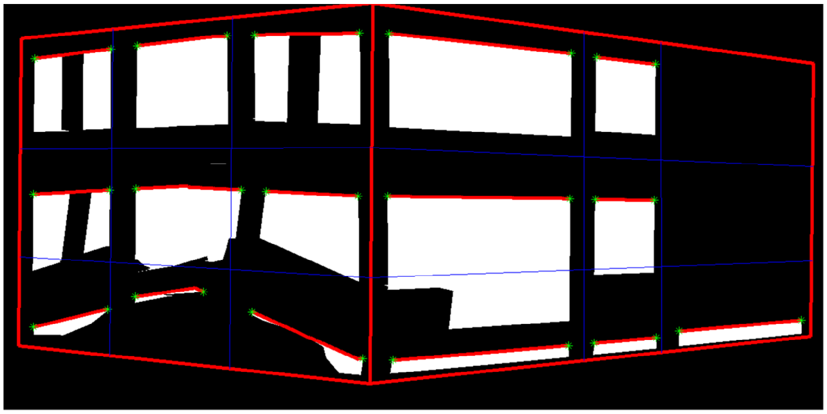


Figure 9. Identification of voids' top edges in each structural cell.

Based on this assumption, the new base levels of damaged beams are derived by extending and connecting the top edges of the identified voids belonging to the same cell, as is shown in Figure 9. Each of the resulting polylines is then shifted up by the beam's height (which is known explicitly from the 'as-built' BIM) to determine the top levels of the beams. Where no voids exist in a cell, the polylines of neighbouring cells are extended, making the default assumption (for lack of any other information) that the earthquake damage has not caused any internal displacement of the beams in that cell.

The positions of beam-column joints are estimated based on the beam and column width from the 'as-built' BIM and on the position of the damaged beams in all the structural cells. According to the topology of URM infilled RC frame cells, the center axes of the left and right columns in each cell can be estimated by connecting these joints. The resulting first estimate of the structural grid of the damaged building is shown in Figure 10.

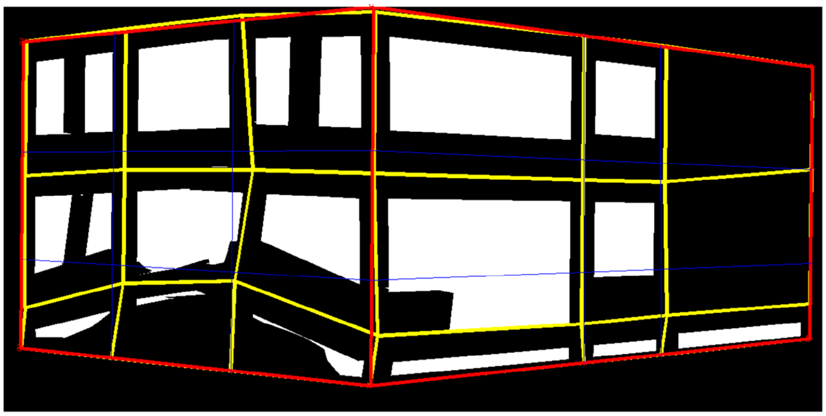


Figure 10. Refinement of the initial damaged skeleton. (Initial skeleton in blue, refined skeleton in yellow, facades boundaries in red)

The structural grid of the damaged building defines the 'as-damaged' structural cells. Since each 'as-damaged' cell is already associated with it corresponding 'as-built' cell, their inner components are also associated with the components from the 'as-built' BIM, and all the semantic property data are inherited respectively.

5 Conclusions

The development of a methodical procedure for this phase of reconstruction of semantically rich BIM models of damaged buildings using TLS reinforces the supposition that this is a promising approach to support structural analysis and planning of S&R operations after a natural disaster. Two major problems have been tackled in this solution: the lack of any semantic information in the scan and the difficulty of matching the initial structural objects with the final deformed objects due to damage.

A new systematic method, which serves as a module in a broader S&R support system, has been developed to overcome these problems. In this method, the 'as-built' BIM model is essential for providing the semantic information of building components. Also, a set of rational assumptions concerning the specific geometry, topology and behavior of URM infilled RC frame were necessary to facilitate the methods' steps. The steps include extracting voids from the scan, mapping the voids to the structural cells, and reconstruction of the structural grid of the damaged building.

Application of the proposed approach to a case study of a building damaged in the 2003 Bingol Earthquake showed good and satisfactory results. Visual inspection of the results (Figure 10) relatively to the photo of the damaged building (Figure 4), shows that 42 out of 45 structural components (93.3% of beams and columns) were identified correctly. Some elements, such as the corner columns on the first and second floors sheared and their resulting pieces are overlapped. Situations like this cannot be identified by the method because of the explicit simplifying assumption, within the current scope, of rigid body motion.

Damage modes like elements overlapping, out of plane damage of structural building elements, etc., must therefore be identified in module 4 of the overall system (presented in Figure 1), which uses local segmentation of the 'as-damaged' scan to identify cracks and breakages in individual elements. In this way the modules will be deployed recursively to refine the model of the damaged building façade. In addition, more cases of damaged buildings will need to be tested in the near future to seek evidence for robustness of the method for module 3 and of the system as a whole.

References

Aristidou, A. & Lasenby, J. (2010), Motion Capture with Constrained Inverse Kinematics for Real-Time Hand Tracking, IEEE, pp. 1–5.

Brilakis, I., Lourakis, M., Sacks, R., Savarese, S., Christodoulou, S., Teizer, J. & Makhmalbaf, A. (2010), Toward Automated Generation of Parametric Bims Based on Hybrid Video and Laser Scanning Data, Advanced Engineering Informatics, 24(4), 456-465.

Eastman, C., Teicholz, P., Sacks, R. & Liston, K. (2008), Bim Handbook, John Wiley & Sons, Inc.

EERI. (2015), Turkey School Bldgs - Moment Frames, Earthquake Engineering Research Institute.

German, S., Jeon, J. S., Zhu, Z. H., Bearman, C., Brilakis, I., DesRoches, R. & Lowes, L. (2013), Machine Vision-Enhanced Postearthquake Inspection, Journal of Computing in Civil Engineering, 27(6), 622-634.

Haldar, P., Singh, Y. & Paul, D. K. (2013), Identification of Seismic Failure Modes of Urm Infilled Rc Frame Buildings, Engineering Failure Analysis, 33, 97-118.

Kashani, A., Crawford, P., Biswas, S., Graettinger, A. & Grau, D. (2014), Automated Tornado Damage Assessment and Wind Speed Estimation Based on Terrestrial Laser Scanning, Journal of Computing in Civil Engineering, 04014051.

Liel, A. B. & Lynch, K. P. (2012), Vulnerability of Reinforced-Concrete-Frame Buildings and Their Occupants in the 2009 L'aquila, Italy, Earthquake, Natural hazards review, 13(1), 11-23.

Ma, L., Sacks, R. & Zeibak-Shini, R. (2015), Information Modeling of Earthquake-Damaged Reinforced Concrete Structures, Advanced Engineering Informatics.

Ma, L., Sacks, R., Zeibak-Shini, R., Aryal, A. & Filin, S. (2015), Preparation of Synthetic as-Damaged Models for Post-Earthquake Bim Reconstruction Research, Journal of Computing in Civil Engineering.

Smeets, D., Keustermans, J., Hermans, J., Vandermeulen, D. & Suetens, P. (2012), Feature-Based Piecewise Rigid Registration in 2-D Medical Images, 2012 9th IEEE International Symposium on Biomedical Imaging (ISBI), pp. 696-699.

Stoll, C., Karni, Z., Rössl, C., Yamauchi, H. & Seidel, H.-P. (2006), Template Deformation for Point Cloud Fitting, Proceedings of the 3rd Eurographics/IEEE VGTC conference on Point-Based Graphics, Eurographics Association, pp. 27-35.

Tang, P., Huber, D., Akinci, B., Lipman, R. & Lytle, A. (2010), Automatic Reconstruction of as-Built Building Information Models from Laser-Scanned Point Clouds: A Review of Related Techniques, Automation in Construction, 19(7), 829-843.

Torok, M. M., Golparvar-Fard, M. & Kochersberger, K. B. (2014), Image-Based Automated 3d Crack Detection for Post-Disaster Building Assessment, Journal of Computing in Civil Engineering, 28(5), A4014004.

Xiong, X., Adan, A., Akinci, B. & Huber, D. (2013), Automatic Creation of Semantically Rich 3d Building Models from Laser Scanner Data, Automation in Construction, 31, 325–337.

Yeh, I.-C., Lin, C.-H., Sorkine, O. & Lee, T.-Y. (2011), Template-Based 3d Model Fitting Using Dual-Domain Relaxation, Visualization and Computer Graphics, IEEE Transactions on, 17(8), 1178-1190.

Zeibak, R. & Filin, S. (2012), Detecting Changes in Urban Environments Using Terrestrial Laser Scanning, Surveying and Land Information Science, 72(1), 29-36.

Zeibak-Shini, R., Sacks, R. & Filin, S. (2012), Toward Generation of a Building Information Model of a Deformed Structure Using Laser Scanning Technology, 14th International Conference on Computing in Civil and Building Engineering (ICCCBE).