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Towards generation of as-damaged BIM models using laser-scanning and as-built BIM: First estimate of as-damaged locations of reinforced concrete frame members in masonry infill structures

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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 their 'as-built' BIM models and scans of their 'as-damaged' states. This paper focuses on a crucial step: generating an initial 'best-guess' for the new locations of the façade structural members. The output serves as the seed for a recursive process in which the location and damage to each object is refined in turn. Locating the 'as-built' structural members in the 'as-damaged' scan is challenging because each member may have different displacement and damage. An algorithm was developed and tested for the case of reinforced concrete frames with masonry infill walls. It exploits the topology of the frames to map the original structural grid onto the damaged façade. The tests used synthetic datasets prepared from records of two earthquake-damaged buildings. In both cases, the results were sufficiently accurate to allow progress to the following step, assessment of the individual structural members.

1. Introduction

Structural engineering expertise is essential in search and rescue (S&R) and recovery operations in the aftermath of a major earthquake in an urban area. S&R teams need information about voids that may have formed in buildings that have sustained damage in order to plan efforts to reach any survivors safely. In the recovery phase, structural engineers gather information to assess the state of the buildings and the degree of damage they have suffered.

To be effective, the information must be gathered rapidly. Yet in post-disaster situations professional structural engineers are a scarce resource and gathering the information is, in and of itself, a difficult and potentially hazardous activity. Under the standard protocols of most countries, in the immediate post-earthquake phase structural engineers inspect each building and classify it as safe, unsafe or dangerous [1–3]. This is laborious, slow and provides little of the detailed information needed.

For these reasons, researchers have proposed the use of remote sensing techniques and sophisticated computing methods. One approach has been to provide surveyors on the scene with mobile applications for recording data, such as ROVER Ready [4] and Urban RAT [5]. These tools help surveyors record and transmit information, but they do not acquire information directly. Remote sensing technologies, such as laser scanning and photogrammetry, can be used to automate data acquisition and to rapidly provide point cloud and segmented geometry information describing the exterior forms of building components after an earthquake [7–9]. However, the point cloud and segmented face geometry cannot be analyzed in relation to the pre-existing building components without extensive interpretation and information about the building's original condition. Exterior scanning has two additional drawbacks: it lack the semantics needed for damage assessment of the exterior components and it provides no information at all concerning the interior components and spaces of the building.

However, much more detailed and useful information can be inferred if an 'as-built' model compiled using Building Information Modeling (BIM) [6] technology is used as the starting point for inference from the point cloud data. BIM models can provide the detailed information about buildings' 'as-built' states in the form of parametric object-oriented models with component, functional and other non-geometric information, and they can be used to

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store new information as it is acquired. This has been explored for the purposes of construction management, where systems attempt to estimate construction progress based on comparison of scan and image data with 'as-planned' BIM models [10,11].

The authors propose a framework of steps and a suite of algorithms to process information from these two sources to generate useful structural engineering information for post-earthquake S&R and recovery efforts. The overall method, described in Section 3 below, aims to generate an 'as-damaged' BIM model that contains both the external and internal components of a building, with both structural and building system components. The aim is to provide first responders with information that can guide their S&R efforts, akin to 'x-raying' the damaged building. The information can also be used directly to assess the damage, first for structural assessment and later for estimating the costs of repair and/or for planning the demolition.

The framework as a whole requires six main modules. Details for modules 1 and 6 can be found in [12]. This paper focuses on module 3 of the framework, dealing with the challenge of reconstructing the BIM model of the exterior facade of a damaged building from the point cloud data. The authors developed and tested a procedure that prepares an initial estimate of the locations of the 'as-damaged' structural frame members on each façade using information from the 'as-damaged' scan and the 'as-built' BIM. The algorithm presented is specific to the case of reinforced concrete framed buildings with unreinforced masonry (URM) walls.

2. Literature review

2.1. Remote sensing data acquisition for earthquake damage detection

Airborne laser scanning technology is useful in post-earthquake phase for general damage identification at the detail level of the structure as a whole [13,14]. Terrestrial Laser Scanning (TLS) can provide more detailed damage information at a much higher resolution than aerial scanning, making it applicable for damage assessment on building elements. Lindenbergh and Pietrzyk [15] discussed applications in change and deformation detection using static and mobile TLS. Both static and mobile TLS were able to document the spatial geometry of a bridge in high accuracy [16].

A novel application of TLS for assessing damage to buildings dealt with tornado damage in the US [17]. The authors used point cloud data (PCD) acquired before and after an earthquake to evaluate how much damage was caused to each building. They were also able to estimate the path direction and the wind speed of the tornado by combining data for multiple buildings. Despite the progress made in recognition of building objects within PCD for generic construction management applications [11,18], neither Kashani et al. nor others who have applied TLS to earthquake damage assessment have attempted to compile parametric building models.

In addition to laser scanning, terrestrial video and photogrammetry technologies can also generate dense 3D point clouds of a scene using approaches such as 'Structure-from-Motion' systems [19], Multi-view Stereo methods [20], and others. Some examples:

- German et al. [7] successfully designed and implemented an algorithm to identify the cracks in concrete columns using video recordings.
- Torok et al. [21] used images obtained from an unmanned robotic platform to similarly identify cracks in the main structural members.
- Yamazaki et al. [22] used photos collected by Unmanned Aerial Vehicles (UAV) to generate a 3D model of a district damaged in the 2015 Gorkha earthquake in Nepal.

Some other applications in condition assessment of civil infrastructures are reviewed in [23]. However, none of the above attempted to reconstruct parametric building models at the level of detail of individual building components.

2.2. Damage assessment and modeling

A number of studies have focused on identifying and evaluating structural damage to exterior members by analyzing observed cracks and spalling data. To assess the performance of damaged reinforced concrete structures, Farhidzadeh et al. [24] proposed a crack related damage index that is capable of estimating specimens' relative stiffness loss. Paal et al. [25] proposed identification of cracking and spalling of reinforced concrete columns. Their work was later extended to compute the residual drift capacity of such columns [26,27]. Lattanzi et al. [28] applied photogrammetry techniques to identify cracks on bridge columns in structural tests. The feature data of the identified defects were further used to build a prediction model for maximum column drift.

Damage to structures may have causes other than earthquakes, of course, and TLS has been proposed for tasks such as bridge health/damage evaluation [29]. Examples include measuring the thickness of corroded gusset plates of collapsed I-35W Highway Bridge in Minneapolis, Minnesota [30] and deformation measurement of a Hungarian bridge on the Danube during its load testing procedure [31]. Tang and Akinci [32] formalized the workflow of manual procedures of processing PCD for bridge inspection to enable automation.

These studies demonstrate that the TLS methods can detect damage with high accuracy, but that the process depends on scans of the pre-event state. In case of a disaster, it is unlikely that a pre-event scan of the studied area will be available so that the model might not be applicable in such circumstances. Furthermore, none of these efforts has attempted to reconstruct an 'as-damaged' BIM model.

2.3. Scan to BIM – challenges in semantic interpretation

The Scan-to-BIM process has been the subject of numerous studies. Tang et al. [33] surveyed techniques developed in civil engineering and computer science that can be utilized to automate the process of creating as-built BIMs. The authors sub-divided the overall process into three core operations: geometric modeling, object recognition, and object relationship modeling. They surveyed the state-of-the-art methods for each operation and discussed their potential application to automated as-built BIM creation. They also outlined the main methods used by these algorithms for representing knowledge about shape, identity, and relationships. Bosché et al. [34] explored the opportunity for frequent, detailed and semantically rich assessment of as-built status of MEP works in construction projects by joining three dimensional laser scanning and 3D/4D BIM models, and Sacks et al. [35] proposed an approach for semantic enrichment that supports object recognition and object relationship modeling.

Xiong et al. [36] presented a method to automatically identify and model the main visible building components of a scanned indoor environment (walls, floors, ceilings, windows, and doorways). The authors suggested extracting planar patches from a voxelized version of the raw point cloud. Their algorithm learns the unique features of different types of surfaces (vertical, horizontal, etc.) and the contextual relationships between them and uses this knowledge to automatically label patches as walls, ceilings, or floors. The authors also presented an opening detection algorithm to detect openings in building facades. They overcame the challenge of modeling partially occluded or occupied openings by