Damage Quantification from Point Clouds for Finite Element Model Calibration

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ABSTRACT: This paper discusses the objective quantification of structural damage from a point cloud. In this case, point clouds are created by various methods including light detection and ranging (LiDAR) and/or computer vision techniques (e.g. structure-from-motion or SfM). The quantified damage data before and after a dynamic test series is used to calibrate a finite element model of a two-story building.

Test Structure and Measured Data

The focal point of this study is the building shown in Fig. 1, located in El Centro, California. The two-story building was built in the 1920s, has an overall length of 39 m in the north-south direction, 26.5 m in the east-west direction, and a maximum height of 11.8 m. The building comprises of six reinforced concrete structural frames in the north-south direction connected with reinforced concrete joists in the east-west direction which are connected via a one-way floor slab. The upper story walls are comprised of two single wythe independent masonry infills, while the first floor has three types of infill: reinforced concrete panels, unreinforced masonry panels, and the combination of these two construction styles. This building was subjected to four significant earthquakes. The most recent earthquake, the 2010 El Mayor – Cucapah Earthquake, caused significant structural damage to the building, which was subsequently red-tagged for demolition. The masonry infills of the north and west bays experienced significant shear cracking which led to damage of the RC columns. In addition, the infills in four out of five bays in the south wall partially or fully collapsed.

SHM Methodology and Results

A LiDAR scanner and an unmanned aerial vehicle were deployed to collect geometric characteristics of the structure in its current state. The LiDAR scanner utilized in this case study was the FARO Focus X130, which is a phase-based scanner with a maximum range of 130 m and an integrated camera to supplement color triplets for each vertex. In general, the accuracy of LiDAR scanners is a function of the equipment, scan resolution, and environment. For this study, the point cloud density was approximately 1 point per square centimeter. In addition, the unmanned aerial vehicle (UAV) platform consisted of a DJI Phantom 2 quadcopter with an onboard GoPro camera. The camera captured 598 images pre-test and 444 images post-test which were used to generate point clouds using a SfM platform.

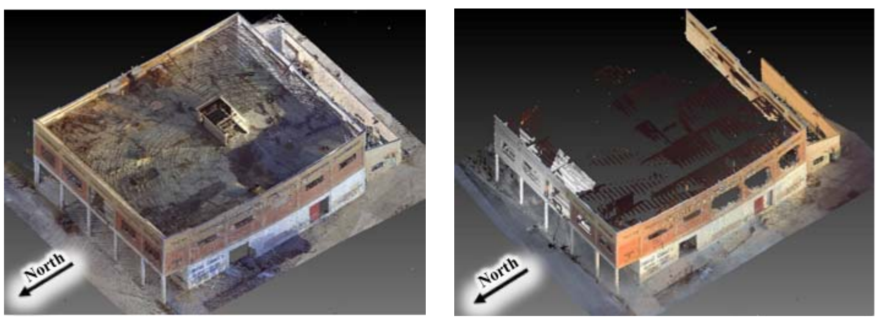
Dynamic testing was conducted using a 100-kip portable eccentric mass shaker owned and operated by the University of California, Los Angeles, to induce progressive structural damage and measure the dynamic properties of the buildings. The shaker was anchored on the second floor slab near the north-west corner and was used to produce harmonic excitation between 0-5.5 Hz. A total of 26 forced vibration tests and ambient vibration recordings were conducted before and after the demolition of the infill walls over a four-day period [1].

To characterize the pre- and post-test damage, LiDAR and UAV surveys were conducted to create pre- and post-test point clouds. The pretest point cloud consisted of eleven scans and nine UAV passes of the building's façade and roof. The post-test point cloud was generated by four LiDAR scans and six UAV passes. The post-test point cloud consisted only of the north, south, and west walls along with the roof level, due to site permission issues and also lack of damage in the east wall. Fig. 2 shows the pretest and post-test LiDAR point clouds. The point clouds obtained via LiDAR scans and SfM were registered together into a uniform coordinate system.

(a) northwest corner of the building

(b) visible damage at the south wall and undamaged east wall

Fig. 1 Imperial Cabinet building aerial views following the 2010 El Mayor-Cucapah earthquake.



(a) pretest

(b) post-test

Fig. 2 Imperial Cabinet building northwest aerial view LiDAR point clouds.

To quantify the potential surface damage of a structure, variations of the surface geometry proposed in the literature [e.g. 2, 3] are incorporated herein. In this study, surface damage and defects are quantified using an average weighted variation of the surface normals. To compute the normal vector for a point, n neighboring points are triangulated to form $n(n-1)/2$ regions. Then an average weighted normal vector is computed over this area. [4] To estimate the variation of these normals, the relative angle is computed with respect to a least squares regression reference plane for each wall. As the angle increases from zero, a greater variation in the surface geometry is indicated. It should be noted that the change in the surface geometry (where the angles differs from zero) can represent both surface damage of the structure as well as architectural features. An application example of this methodology is provided in Fig. 3b in which the vertices with the highest relative angle to the reference plane are highlighted in red. Referring to the colorized scan in Fig. 3a, the red points indicate surface damage including cracks, concrete spalling, and unstable bricks at the interface of the collapsed wall.

Linear Finite Element Model and Model Updating

The point cloud data provides high-resolution geometric data that is used to enhance the accuracy of the geometry within a linear elastic finite element model (FEM) in SAP2000. The model consists of continuous beam elements for beams and columns as well as thin shell elements for floor slabs and infill walls. Stiffness reduction factors are incorporated within the FEM to reflect damage; however, these are typically subjective and based on a visual inspection. In this case study, the identification of localized damage along certain exterior elements, as well as accurate measurements of the openings within the exterior infills guide a more objective selection of stiffness reduction factors. Specifically, one stiffness reduction factor accounts for the element-level damage based on the identification of localized defects within the point cloud (e.g. cracking and spalling). Likewise, a second stiffness reduction factor accounts for opening(s) in the infill wall (e.g. windows) that can be quantified from measurements within the point cloud [5].

(a) (b)

Fig. 3 Single bay of second floor at the west wall of the building after the test: (a) the colored point cloud and (b) detected damage shown by red (grey in black and white prints) color.

Lessons Learned

An advanced method for objective surface damage and defect detection and quantification from point clouds is applied on an actual structure. The quantified surface damage and accurate geometric measurements are used in the FEM calibration via the estimation of stiffness values for various damaged structural elements (beams, columns, and infill). The comparison between the model and the actual structures, indicates that the calibrated FE model can predict the dynamic properties of the building and its response to the induced vibrations during the tests.

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