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Information modeling of earthquake-damaged reinforced concrete structures

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ABSTRACT

Accurate and reliable information about buildings can greatly improve post-earthquake responses, such as search and rescue, repair and recovery. Building Information Modeling (BIM), rapid scanning and other assessment technologies offer the opportunity not only to retrieve as-built information but also to compile as-damaged models. This research proposes an information model to facilitate the data flow for post-earthquake assessment of reinforced concrete structures. The schema development was based on typical damage modes and the existing Industry Foundation Class (IFC) schema. Two examples of damaged structures from recent earthquake events, compiled using an experimental damage modeling software, illustrate the use of the data model. The model introduces two new classes, one to represent segments of building elements and the other to model the relationships between segments and cracks. A unique feature is the ability to model the process of damage with a binary tree structure. Methods for exporting as-damaged instance models using IFC are also discussed.

1. Introduction

Earthquakes affect millions of people and cause extensive damage to buildings and other structures. In the United States alone, the average economic loss from earthquakes is approximately $4.4 billion a year [1]. Search and Rescue (S&R) operations begin immediately once an earthquake has occurred, and recovery, including repair and renovation or demolition of damaged buildings follows. Both require rapid assessment of the damage to great numbers of buildings [2], because clear and accurate information is needed to support decisions about search and rescue safety, habitability and repair of the buildings.

In planning S&R operations, the primary information needed is the location of 'air-pockets' in the building in which survivors may be trapped and any possible pathways to reach them [3]. The voids and pathways are defined by the geometry and the new placement of the building's components, including structural elements and nonstructural elements that might be relevant for S&R teams, such as major ducts and pipes, partitions and fixed furniture. Structural element information should include the configuration of the structural system and the type, detailing, connectivity, material strength and condition of its structural elements. Lack of information seriously hampers rescuers' ability to locate and reach survivors while time is of the essence. In current practice, as-built information of the building is at best available in 2D drawing sets.

In the recovery phase, buildings may be approved for occupation, slated for repair or condemned for demolition. The assessment and any planning for renovation require detailed comparison of building elements' status before and after the earthquake. The Federal Emergency Management Agency (FEMA) guide to earthquake damage assessment (FEMA 306) [4] details what information should be collected and how it should be obtained. The guide prescribes how the information should be documented, however, it does not consider any digital documentation, and it also requires preparation of 2D plans, sections and elevations.

Given the development of Building Information Modeling (BIM), cloud storage and various rapid data acquisition technologies, much of the needed information can be derived automatically or semi-automatically, stored and delivered using BIM tools. As-built information can already be provided in BIM formats using existing applications. Recent research efforts have proposed pre-installed data-storage devices to store digital as-built information [5] and the use of mobile devices for smart retrieval of information has been implemented and tested [6]. Damaged buildings can be surveyed by engineers using traditional methods, such as those prescribed in FEMA 306 [4], but methods are also being developed

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for acquisition of the damaged states of building façades using laser scanning [7,8] and photogrammetry [9,10] and for derivation of the full damaged state of structures using structural collapse simulation models and the façade data [11]. In addition, a reliable connection between as-built information and damage inspection records for conducting joint pre- and post-earthquake assessment studies also attracts fairly scientific interests [12].

Application of BIM to S&R and to recovery phase operations demands development of a data model to represent the necessary information. The schema of such a model must support parametric, semantic and interoperable representation of a building not only in an 'as-designed' or an 'as-built' state, but also in an 'as-damaged' state. This paper reports the development of the schema for the domain of reinforced concrete (RC) buildings. The data model is based on the existing IFC specification [13] due to its broad acceptance as an open international standard and its ability to fully represent the as-built state. The focus of the paper is therefore on the object classes, their properties, and their interrelationships that are all needed to represent the as-damaged state concepts such as segments of building elements, plastic hinges and cracks.

The next section reviews the possible modes of damage for RC structures, the ways in which they develop in structural components and the information required for post-earthquake response. This review provided the basis for information analysis to derive the new information to be modeled. The following section describes the analysis and details the derived building model schema. Examples of instantiation of as-damaged models are illustrated. The section on IFC outlines what extensions would be necessary to support as-damaged modeling of buildings.

2. Information requirements in post-earthquake responses

2.1. Damage modes of RC structures and their components

Reinforced concrete frames are the predominant construction method for residential, commercial and public buildings taller than two stories worldwide, and are therefore of primary interest in the context of earthquake recovery. At the level of detail of structures as a whole, their damage and collapse modes have been classified in general terms that are commonly used for buildings with other construction methods types as well. At the component level, reinforced concrete structures have specific modes of behavior and sustain damage in ways that are determined by the interaction of concrete and reinforcing steel.

At the least detailed level, damage classification is limited by the methods of data collection (satellite imagery, aerial photogrammetry or LiDAR scanning) [14]. At a resolution of meters or coarser, the seismic damage can only be detected and classified at the building level [14]. Table 1 outlines whole structure damage modes based on the 15 categories defined by Schweier and Markus [15]. The geometric measures needed to determine the damage mode of the whole building, and to evaluate the severity of a particular damage mode, include the orientation of the structure, the total height reduction at various points, the overall volume reduction, and the integrity of the external facades.

At 1 m resolution or less, which can be measured using terrestrial laser scanning or photogrammetry, detection and identification of damage to building components becomes possible. The as-damaged shape and condition of a damaged component depends on the sequence in which local sections of the structural member sustain displacement, cracking and eventually failure. The development of damage at any given section is dependent on the development of damage at other sections, because the reinforcement yields, the concrete is cracked or crushed at those locations where the stresses applied exceed capacity, and the component behavior changes from the original structural design intent.

(1) Surface cracking

In general, cracks are the precursor and sign of structural damage. Until cracks are sufficiently developed to split building components into pieces of concrete, they only appear as texture on the surfaces of building components.

(2) Spalling and delamination

Spalling or delamination occur as a result of the development of cracks, which form parallel to the principal compression stresses [4]. Due to the concrete's characteristic of brittleness and the containment effect of reinforcement, spalling usually occurs up to the cover depth of the RC components. Pieces or regions of concrete consequently become separated from the surface of a building element and fallen away revealing the reinforcement. Delamination usually occurs if the components are plastered or have a stone/brick cladding, where the layers of the decorative materials separate and fall away.

(3) Bending and buckling

Flexural cracks typically initiate at the extreme fiber of a section and propagate toward the section's neutral axis. Opposing flexural cracks in both directions often join with each other to form a relatively straight crack through the entire section [4]. Bending usually occurs in beams and slabs, while buckling usually occurs in columns. Both manifest as a curvature of the neutral axis of a longitudinal element or as a curvature along the surface of a plate element.

(4) Shearing and breaking

Associated with high bending moments, high shear demand produces cracks perpendicular to the neutral axis of the underlying components. The cracks further result in component shearing or breaking. Both of the two damage modes split the component into distinct segments. Rebar remains continuous, albeit ductile, across the two resulting segments in the case of shearing, while the segments are completely disconnected in the case of breaking. The separation of segments is highlighted in this damaged mode.

Modeling of the damage sustained by building components depends to a large extent on the identification of significant cracks on components and on the geometric features of the resulting segments, including the reduced volume shapes and their relative location and orientation. The damage modes of whole buildings can in turn be derived from the state of their components.

2.2. Use cases for compilation of as-damaged building models

How would a digital as-damaged building model be compiled and how would it be used? The possible information 'use-cases' have bearing on the level of detail required for geometry and properties. The following three modes may be used independently or in combination with one another.

The first mode of acquisition is large-scale damage assessment of the affected region. Emerging applications of aerial imaging techniques are making it possible to rapidly acquire point-cloud and image data describing damaged buildings [16,17]. As a macroscopic solution, these techniques can only provide general damage at building block level [15,18].

The second mode considered is on-site assessment using a portable tablet computer, in which an as-damaged model would be

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