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Information requirements for earthquake damage assessment of structural walls

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ABSTRACT

The engineering analysis for determining the remaining seismic capacity of buildings following earthquakes requires performing structural calculations, observations of the actual damage, and applying extensive engineering judgment. Additionally, the analysis should often be performed under stringent time requirements. This study identifies the information requirements for representing the damage information and performing the visual damage assessment of structural walls. The damage descriptions for seven common damage modes of structural walls were studied by employing the affinity diagramming method. The study showed that the information required to represent the damaged conditions can be grouped under five broad categories and using seventeen damage parameters. A sensitivity analysis showed that the damage parameters have varying degrees of importance. The results of the study can be used to develop formal representation of damage information in information models and potentially allow better allocation of data collection time in the field.

1. Introduction

The earthquake regions around the world contain a large stock of buildings. For example, only in Los Angeles, CA, there is a stock of estimated 40,000 particularly vulnerable RC buildings, due to old design practices [1,2]. The total number of buildings, which will need to be assessed following a future earthquake is much higher given that it would be necessary to assess not just vulnerable RC buildings, but all buildings that got impacted from the earthquake. Historical evidence and research studies show that there is a pressing need to assess the damage severities of buildings objectively, accurately, and rapidly, and quantify the effects of the earthquake on the structural properties of the components [3,4].

Current methods for damage assessment are manual and rely heavily on the structural engineering expertise of the inspectors and their engineering judgment [5]. Inspectors are expected to have a good level of understanding and experience in assessing the effects of the ground motion on the seismic performance of components by observing the indications of damage, performing structural computations, and synthesizing the structural properties and construction details of a building [5].

Manual approaches for evaluating structures have been criticized for being error-prone, slow, and subjective [6–9]. Therefore, several researchers have been studying ways to automate the damage assessment process [9–28]. Studies on computer vision techniques show promising advancements for capturing and identifying damage indicators, such as cracking, spalling, and displacements, using machine vision methods [9,14,16–22,26,29–33]. On the other hand, automation of the actual damage assessment procedures using the captured damage indicators is not a well-studied subject. The studies on automating the damage assessment procedures include using augmented reality along with the residual story drift as the damage metric, and using damage indicators (e.g., cracking, spalling) in a fragility analysis to identify the aftershock vulnerability of buildings [10,11]. To the best knowledge of the authors, however, none of the previous studies address the automation of the engineering analyses for damage assessment, based on the FEMA 306 guideline, which practicing engineers have to follow [34].

This study focuses on the FEMA 306 manual for "Evaluation of Earthquake Damaged Concrete and Masonry Wall Buildings" [34]. We picked this guideline to focus on for three reasons. First, it is the standard document, which the engineers have to follow when

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assessing the performance of damaged buildings [34]. FEMA 306 is referenced by the latest version of ASCE/SEI 41-13 (2013) for the evaluation and repair of earthquake damage, component type identification, visual condition assessment, and non-destructive testing. Second, the guideline builds on a thorough investigation of existing body of research and presents a procedure that can used for a wide variety of damage modes and component types [34]. Finally, it is being adopted by countries, such as New Zealand, thus reaching wider application [35].

According to FEMA 306, engineering analyses are performed on those earthquake damaged buildings, which are tagged for further analysis after a rapid assessment [34]. The current practice of damage assessment requires the quantification of the degrading effects of the earthquake by determining the damage modes and damage severities of structural components, which is called the engineering analysis [34]. The damage mode is the dominant behavior of a structural component (e.g., ductile flexure, shear, etc.) and the damage severity is a measure of how much the damage has progressed in the dominant mode. The damage mode and severity determines the reduction in strength, stiffness, and displacement as a result of earthquake damage.

The damage modes and damage severities of structural components are identified using a combination of strength calculations and visual assessment. In strength calculations, the lateral forces which would generate particular damage modes are calculated using strength equations. The actual damage behavior of components can differ from theoretical behavior determined by strength calculations, due to several reasons, such as differences in material strengths between design and actual, and interactions between building components and loading conditions. The visual observations allow the engineer to determine the actual damage mode of the components by assessing how the damage indicators are formed (e.g., cracking, spalling, crushing, rebar damage, and residual displacements). However, the visual assessment is not adequate alone to determine the damage mode and severity. Therefore, a combination of strength analysis and visual assessment is employed. FEMA 306 presents a very detailed analysis of the visual damage indicators for different damage modes.

Previous research has found seven common damage modes for reinforced concrete wall components (i.e., piers and spandrels), including ductile flexure, pre-emptive shear, diagonal compression, boundary compression, sliding shear, and pier rocking [34]. Reinforced concrete frames generally exhibit either flexure or shear type of failure. Compared to RC frames, distinguishing between damage modes can be especially challenging for wall components, considering that the damage modes can look alike at low severities and calculations are required to determine the governing mode [34]. Therefore, this study focuses on structural walls.

Building Information Models (BIM) can potentially support representing the damaged conditions of the buildings for visual assessment and structural information for engineering analysis, such as the configuration, reinforcement details, and finite element models [12,36–40]. Hence, BIMs can be used to support the engineering analyses for strength analysis and visual assessment [36,38]. However, current BIMs are not developed to represent damaged conditions of buildings [12,32,41]. Therefore, representing the damage information in BIMs need to be investigated further. This study focuses on the visual assessment aspect of the analysis and develops the information requirements of visual assessment. The results of this study is combined with a formalization of the strength analysis for a complete engineering analysis in [42]

A representation requires abstraction of information, which depicts the common structure of all of the features required for damage assessment [43]. The abstraction should also support all of the details of individual damage modes. Through this way, the abstraction process can support all of the damage modes for reinforced concrete walls. This, in fact, requires bottom-to-top discovery of the hierarchical structure of information requirements. Therefore, we need a structured way of studying the damage assessment guidelines, sort them into hierarchies of damage information, and determine the abstraction of damage information. Using the results of such an information requirement identification study, a representation to support various tasks associated with damage assessment can be developed.

This paper studies the information items regarding all of the damage parameters, such as cracking, spalling, crushing, reinforcement bar damage, and residual displacements. The identified information requirements will be used for developing a BIM schema for representing damage conditions and for automatically assessing the damage modes and severities of RC walls in a future study. The proposed approach builds on the FEMA 306 guideline for the "Evaluation of Earthquake Damaged Concrete and Masonry Wall Buildings" in identifying the information requirements associated with the damage parameters stated above.

The research approach utilizes affinity-diagramming method for identifying the overarching patterns of information requirements for the visual assessment and groups the information requirements [44]. The affinity diagrams suggested an initial list of eighteen parameters. A sensitivity analysis was performed to validate the results and analyze the relative importance of the damage parameters. The sensitivity analysis showed that damage parameters that occur at high levels of damage and those that are specific to certain types of damage behavior has more impact on the assessment results. Given the fact that engineers have only a limited amount of time to collect data in the field, the results of the sensitivity analysis can potentially be used to prioritize collecting damage parameters.

2. Damage assessment procedures based on FEMA 306

Following earthquakes, a three-step procedure is applied [34,45,46]. First, within few days after an earthquake, experts perform rapid assessment to classify whether the buildings in the impacted area are safe, unsafe, or require restrictions in their usage [45]. Safe buildings can be used without any restrictions. Unsafe buildings should not be entered under any circumstance. Some restrictions on the usage of a building can be time limits or by the location. For example, an inspector might restrict the access to certain parts of a building, which contain potential hazards. Engineers generally have less than 30 min to perform a rapid assessment per building [45]. Second, a detailed assessment is performed on those buildings that were tagged for restricted usage [46]. Detailed assessment is similar to the rapid assessment in execution and function, but it is more thorough. Finally, within the weeks after an earthquake, engineering analyses are performed on safe and restricted buildings, in order to quantify possible effects of damage on the structural properties of structural components and to design retrofitting measures [34]. In all of these stages, collection of the damage data and analysis of the visual damage information using engineering knowledge are key factors for accurate assessment of the damage levels [34].

The engineering analysis has more complex requirements than rapid and detailed assessments. The goal of an engineering analysis is to determine the remaining strength, stiffness, and displacement capacity of structural components [34]. In order to determine the remaining capacities of damaged components, the source of the current damage and its nonlinear mechanism must be determined. This is not a straightforward task since the loads on the components and the relative stiffness of connected components influence the damage mode and severity.