Damage Assessment, Cost Estimating, and Scheduling for Post-Earthquake Building Rehabilitation Using BIM

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ABSTRACT

A methodology is developed for integrated and automated seismic damage assessment, cost estimating, scheduling and three-dimensional (3D) visualizations for post-earthquake building rehabilitation. The proposed methodology relies on the development of software based on the integration of tools currently available to the Architectural, Engineering and Construction (AEC) industry such as Building Information Modeling (BIM), a fourth-generation programming language, a relational database management system and construction management tools within the framework for seismic damage assessment developed by the Pacific Earthquake Engineering Research (PEER) Center. This process provides automated generation of 3D damage assessment visualizations, cost estimation and schedule-of-work sequences for reinforced concrete moment-frame buildings, per element, element group, story and building, for specified levels of seismic intensity and given ground motion sets. Ultimately, BIM is enhanced with data about elements' damage state, the expected rehabilitation cost and duration in the aftermath of an earthquake. Hence, engineers and developers have the unique opportunity to create a holistic picture of any RC moment-frame building's seismic behavior, which is easily comprehensible by non-engineer owners, customers or shareholders.

INTRODUCTION

In recent years, intense interest is observed worldwide for comprehending the behavior of structures under seismic excitation. The uncertainty that makes the forecasting of earthquakes (and their consequences) impossible constitutes an important hindrance in understanding their effect on buildings in a specified area. The emergence of Performance Based Earthquake Engineering (PBEE, Cornell & Krawinkler 2000) is slowly pushing the study of major infrastructure projects away from the classic design of a code-conforming building (one design fits all models) to a structural design process that encompasses the growing need for specialized structures tailored to the requirements of each individual owner. Thus, the owner can now decide upon the level of performance (i.e. safety) that is desired for a certain building at each possible level of earthquake shaking that it may experience.

To enhance communication between engineers and owners, in place of engineering response parameters (e.g., shear, moment, drift) the PEER PBEE framework is based on the use of non-engineering quantities such as cost, downtime and casualties. Our aim is to present a practical computer-based approach for estimating and visualizing damages, costs and repair scheduling for post-earthquake building rehabilitation using Building Information Models (BIMs). A BIM provides 3D digital representation of a building's physical characteristics. The geometric properties of the building's elements, namely the columns, beams, walls, doors and windows are combined with the building structural response, resulting from a series of non-linear dynamic analyses for given ground motion sets scaled to specified levels of seismic intensity.

Through the combination of the extracted probabilistic response distributions with the appropriate fragility curves, all possible damage scenarios are simulated. These numerical calculations provide repair cost estimation per element, element group, story and building at different intensity levels. Considering the uncertainty in the unit prices, the complete repair cost distribution is determined rather than just its mean value. Additionally, through the design of an automated relational database and its interface with scheduling software, the building assemblies are classified according to their damage state in work breakdown structures (WBS) and assigned to specific repair activities of fixed productivity. As a result of the time scheduling, the rehabilitation time and hence loss-of-use cost is estimated.

Beyond estimation, visualization of damage is paramount. Without the proper visualization capability damage or cost values often become meaningless. For example, any significant debris on a hospital corridor could easily render a number of rooms useless or inaccessible. Such implications are impossible to decipher from the output of any existing structural analysis program, let alone explaining them to the client. Having PBEE analysis results available on the 3D level, offers the ability to engineers and clients to identify restricted areas, plan for possible routes for moving material and personnel and in general get a sense in real-time of what is happening without having to physically go and inspect the building.

To achieve this goal we propose combining current PBEE practice with Incremental Dynamic Analysis (IDA, Vamvatsikos and Cornell 2002), together with readily available visualization techniques in order to create 5D BIM - where downtime and rehabilitation cost become the fourth and fifth dimension, respectively. The resulting model can become the main communication tool between engineers and owners, offering a realistic and comprehensive assessment of the risk that the building owner will be asked to undertake in the aftermath of an earthquake. This tool can be implemented in any professional design office and easily form the basis for new structural analysis software.

PERFORMANCE BASED EARTHQUAKE ENGINEERING USING BIMs

BIM is an innovative integrated design process involving the design, construction and management of digital representations of physical and functional characteristics of a facility. The benefits of BIM have been extensively researched and documented providing high quality information and helping to significantly reduce risks in all phases of a construction project (Griffis and Sturts 2000). The technology and its several incarnations have proven to be a particularly useful communication, planning, analysis and decision-making tool for designers, engineers and constructors.

PBEE allows the design of structures that can withstand frequent or rarer earthquakes with the desired performance, e.g., remaining fully operational for low intensity frequent earthquakes, sustaining low damage at less frequent events and perhaps needing heavy repairs or replacement but maintaining structural integrity at the rarer and most intense shaking levels. Several guidelines that recognize such needs have appeared in recent years, e.g., FEMA-356 and ATC-40 (FEMA 2000, ATC 1996). A prominent example is the PEER Center methodology (Cornell and Krawinkler 2000) that has been developed to offer a comprehensive assessment of the building performance at any intensity level and any desired limit-state by integrating the seismic hazard and the structural analysis results with damage and loss analysis to produce realistic estimates of the rehabilitation cost and duration associated with any earthquake. The probabilistic prediction of the building performance can be expressed through Equation 1.

$$\lambda[DV] = \int_{DM}\int_{EDP}\int_{IM} G[DV \mid DM]P[DM \mid EDP]P[EDP \mid IM]\left|\frac{d\lambda(IM)}{dIM}\right| dIM\; dEDP\; dDM \quad (1)$$

where,

DV: decision variable, e.g., repair cost and duration.

DM: damage measure, e.g., slight, moderate, severe damage or total loss.

EDP: engineering demand parameter e.g., plastic rotation, interstory drift ratio etc.

IM: intensity measure e.g., spectral acceleration at the first mode $S_a(T_1)$.

λ[·]: mean annual frequency of exceedance of the quantity in brackets.

G[·]:complementary cumulative distribution function (CCDF) of the quantity in brackets.

P[·]: probability density function (PDF) of the quantity in brackets.

BENCHMARK BUILDING DESIGN

The benchmark building (Figure 1) is a one-story reinforced concrete special-moment-resisting-frame structure designed by Haselton (2006). The building is symmetric in both orthogonal directions with equally spaced four-bay frames in each direction. The model contains only structural assemblies i.e. columns and beams. Thus, walls, doors and windows are added in order to achieve the best feasible building simulation in a real environment and analysis integration regarding the damages that may occur to all the building elements. The building height is 4.57m and its total area is 353m². Column dimensions are 55.9/55.9cm and beam dimensions are 76.2/76.2cm. The slab thickness is 20cm, outdoor and indoor wall thicknesses are 25cm and 10cm, respectively.

3D DAMAGE VISUALIZATIONS

The 3D model (Figure 2) is developed in ArchiCAD (Graphisoft 2013) and contains both structural (columns, beams, slabs) and nonstructural (walls, doors, windows, furnishings, etc.) building components. This model is used both as a digital visualization tool and as an information repository as it can be used to generate several item listings for quantity-takeoff. In particular, the geometric properties i.e., height, width, length, thickness, area, surface and volume of all columns, beams, walls, doors and windows are exported. The geometric properties are combined with the structural response resulting from a series of non-linear dynamic analyses, performed by Haselton (2006) in OpenSEES (PEER Center 2009), for thirty-nine given ground motion sets in twenty-two specified levels of seismic intensity $S_a(T_1)$ from 0 to 2.8g.

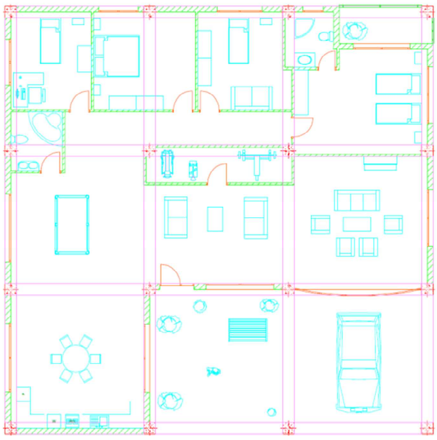

Figure 1. Building ground plan.

Figure 2. Building 3D model.

The 3D model and BIM element properties concurrently with the use of fragility curves are used in the investigation of the building response to earthquake loads in order to simulate all possible damage scenarios. Fragility curves represent the probabilistic expression of the strength of each component and relate structural response with various levels of damage, producing the probability of a component reaching or exceeding a particular damage state. The fragility curves for columns and beams are determined for their maximum plastic rotation, while for walls, doors and windows are determined based on the maximum interstory drift ratio (IDR) of the story in which they are located.

Once a structural assessment is made, a damage measure (DM) per building component is computed subject to the fragility curves associated with each component. This damage measure is discretized in *n* damage states (DS), depending on the component. The damage states vary, but typically they are classified as “no damage” - no action needed, “slight damage” - repairable (low-cost repairs), “moderate damage” -

repairable (repairs are cost-effective), “severe damage” - needs replacement (repairs are not cost-effective), and “collapse” - total loss. Therefore, the damage state for each building assembly can be used as a general “damage descriptor” that can in turn be visualized by use of appropriately coloring in the 3D model. i.e., white color for no damage, green for slight damage, yellow for moderate damage, red for severe damage and black for collapse. In the figures, gray color is assigned to walls that collapse in order to discern them from doors and windows.

The 3D-visualization of the building damage state by selectively coloring 3D objects based on their damage level, offers the ability to engineers and owners to understand the actual building operability after a seismic event. By comparing building damages at various intensity levels as they are illustrated in Figures 3 to 8 for $S_a(T_1)$ equal to 0.3g, 0.6g, 0.9g, 1.2g, 1.8g and 2.4g, respectively, it is possible to understand the need to utilize this technology in PBEE. As shown in Figure 3, at 0.3g, columns and beams do not suffer any damage (white color), walls suffer slight damage (green color), while doors and windows suffer moderate damage (yellow color). At 0.6g (Figure 4), columns and beams do not suffer any damage (white color), while walls, doors and windows suffer complete loss (black color). At 0.9g (Figure 5), columns suffer slight damage, some beams do not get damaged while other suffer slight damage. Walls, doors and windows collapse. At 1.2g (Figure 6), columns suffer moderate damage, at 1.8g (Figure 7), severe damage (red color), and at 2.4g (Figure 8), total loss.

BUILDING REHABILITATION COST

The building repair cost distribution is calculated by Monte Carlo simulation and specifically the Latin Hypercube Sampling (LHS) stratified technique for *N* possible damage scenarios. The method of calculating the building repair cost is applied to *K* elements and *N* possible damage scenarios and is performed for *R* ground motion sets in each one of the *L* intensity levels. At any intensity level, the expected repair cost of each component is the mean value of a vector containing *RxN* possible repair cost values, where *N* are the repair cost values obtained from each *EDP* generated by each ground motion set, separately. Similarly, the expected building repair cost is the mean value of the vector containing *RxN* possible repair cost values, where *N* is the sum of the individual element repair cost values in each damage scenario. Additionally, the variance, the standard deviation, and the coefficient of variation of the building total repair cost can be calculated (Georgiou 2013). The whole procedure is performed by software developed in Matlab (MathWorks 2009).

In the case a ground motion causes collapse of the building, the distribution of the building repair cost is replaced by *N* possible values as they occur from the building replacement cost distribution. Additionally, by choosing the analysis to be performed for particular elements, it is possible to calculate the expected repair cost per floor and per element category. Figure 9 illustrates the building repair cost distribution per intensity level, in the form of the median (50%) value as well as the standard deviation of the total repair cost (16% and 84% of the distribution).

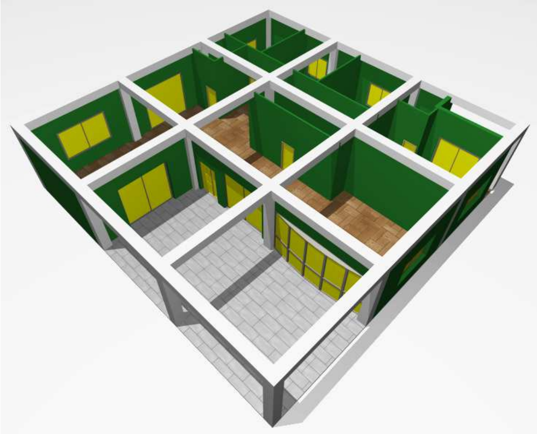

Figure 3. 3D damage visualization at $S_a(T_1) = 0.3g$.

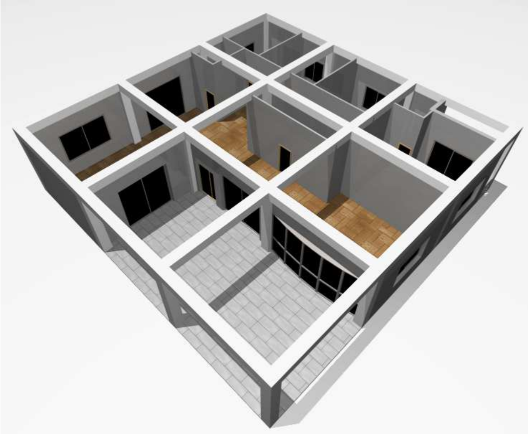

Figure 4. 3D damage visualization at $S_a(T_1) = 0.6g$.

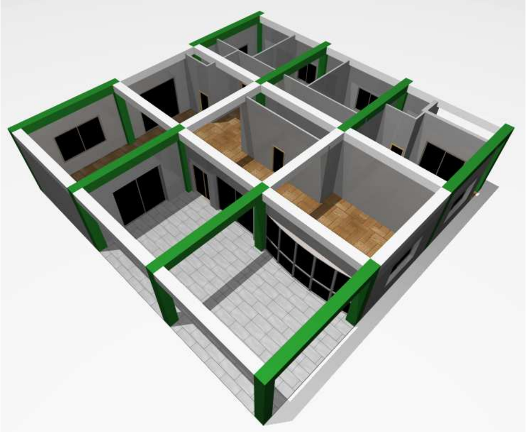

Figure 5. 3D damage visualization at $S_a(T_1) = 0.9g$.

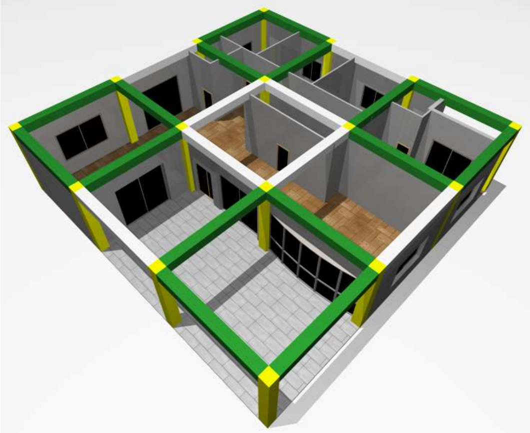

Figure 6. 3D damage visualization at $S_a(T_1) = 1.2g$.

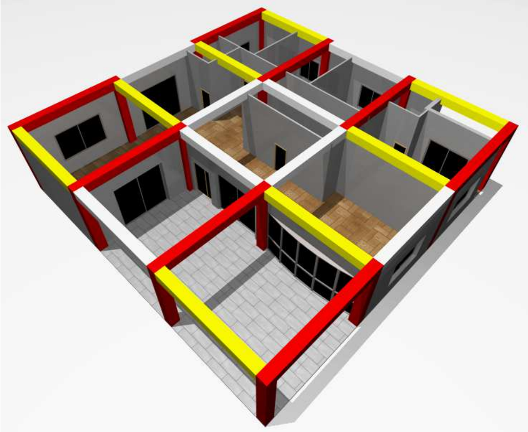

Figure 7. 3D damage visualization at $S_a(T_1) = 1.8g$.

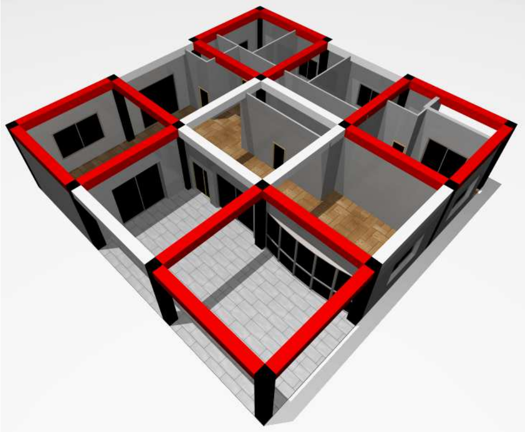

Figure 8. 3D damage visualization at $S_a(T_1) = 2.4g$.

BUILDING REHABILITATION DURATION

Through the design of a relational database management system (RDBMS), developed in MS Access (Microsoft 2010), the building elements are classified according to their damage state in work breakdown structures (WBS). This RDBMS provides links between the BIM objects and the rest of the database tables archived in it, through the primary keys of each database table. For example, each element has a unique ID which is linked, through a mapping table, to a CSI code and through that to a crew code. As a result each element is assigned with specific repair activities, unit cost and production rates. The physical properties of the element (surface, volume etc.) in conjunction with the production rates from the CSI codes assigned to it dictate the duration "T" of the corresponding damage rehabilitation activity, as shown in Equation 2. As a result of the time scheduling performed in MS Project (Microsoft 2010), the rehabilitation time and hence loss-of-use cost after each earthquake scenario is estimated (Georgiou 2013). Figure 10 illustrates the distribution of the mean building repair duration per intensity level.

$$T_{i,c,j,ds,m} = \frac{Q_{j,ds,m} \cdot t_c}{n_{c,j,ds,m} \cdot P_{c,j,ds,m}} \qquad (2)$$

where,

$T_{i,c,j,ds,m}$: duration of the activity *i*, expressed in work-hours.
$Q_{j,ds,m}$: total quantity of all elements of type *j*, in terms of volume, surface or area.
t_c: total hours worked by crew *c* in a day. 8 hours work per work-day is adopted.
$n_{c,j,ds,m}$: number of available crews *c*.
$P_{c,j,ds,m}$: productivity per day of the crew *c*.

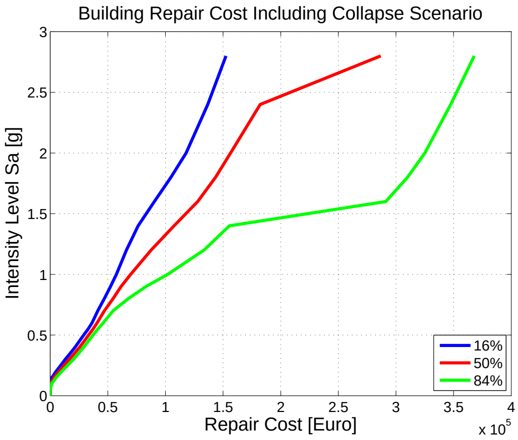

Figure 9. Building repair cost distribution per intensity level $S_a(T_1)$.

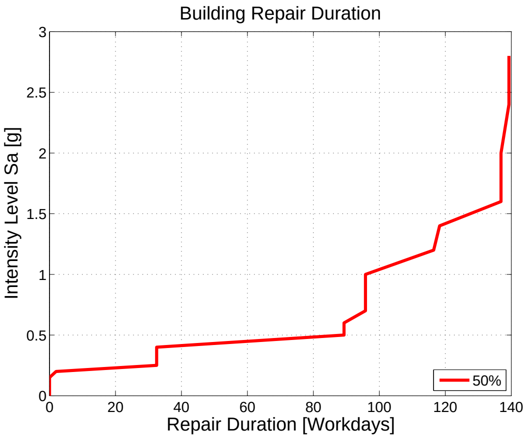

Figure 10. Building repair duration distribution per intensity level $S_a(T_1)$.

CONCLUSIONS

This manuscript presents an integrated approach for post-earthquake building damage assessment and 3D visualizations, by means of integrating a BIM with a programming language, a relational database management system and construction management tools. The resulting approach is a valuable tool for AEC industry participants, for it allows the automation of structural, cost and scheduling analyses and their integration with 3D visualizations of buildings for the purpose of holistic damage assessments and subsequently cost and time estimation for the rehabilitation of such damages, in a visual manner that is easily comprehensible even by non-engineers. This proposed new practice offers a realistic and comprehensive assessment of the risk that the building owner will be asked to undertake in the aftermath of an earthquake.

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