BIM-based Damage Assessment and Scheduling for Post-Earthquake Building Rehabilitation

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An a-priori assessment of the post-earthquake condition of structures has long been a target of the Architectural, Engineering and Construction (AEC) industry, with recent efforts by the Pacific Earthquake Engineering Research (PEER) Center highlighting such goal. The aforementioned PEER efforts have developed an appropriate basis for seismic damage assessment, including cost estimation and scheduling for post-earthquake building rehabilitation, but visualization tools are notably absent from this framework. The methodology proposed herein relies on the integration of tools currently available to the AEC industry, such as Building Information Modeling (BIM), a fourth-generation programming language, a relational database management system and construction management tools, within the PEER Center framework. The proposed process is automated through the development of appropriate software, providing building information models with data about the building elements' damage state, 3D damage assessment visualizations, the expected rehabilitation cost and duration, for different levels of seismic intensity.

1 INTRODUCTION

1.1 *Overview & Scope*

In recent years, the scientific community has focused many of its efforts on understanding the behavior of structures under seismic loads, notwithstanding the uncertainty and difficulty in forecasting earthquakes and their consequences. 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. As a result, an 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 the building may experience. Instead of relying on 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.

The work presented herein aims the development and presentation of a practical computer-based approach for estimating and visualizing damages, costs and repair scheduling for post-earthquake building rehabilitation by use of Building Information Models. Within the proposed framework (Christodoulou et al. 2010), the geometric properties of a building's elements (i.e. of columns, beams, walls, doors and windows) are combined with the structural response of the building (obtained through a series of non-linear dynamic analyses for given ground motion sets scaled to specified levels of seismic intensity) and then visualized through its BIM.

1.2 *Performance-Based Earthquake Engineering Using BIM*

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 technology and its several incarnations have proven to be a particularly useful communication, planning, analysis and decision-making tool for designers, engineers and constructors. The benefits of BIM have been extensively researched and documented in literature.

PBEE allows the design of structures that can perform to a desired performance level under earthquake loads, 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. In recent years several guidelines that recognize such needs have been published, such as the FEMA-356 and ATC-40 guidelines (FEMA 2000, ATC 1996). A prominent example is the PEER Center methodology (Cornell & Krawinkler 2000) that has been developed to offer a comprehensive assessment of 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 is expressed by Equation 1.

$$\lambda[DV] = \int_{DM}\int_{EDP}\int_{IM} \begin{Bmatrix} G[DV \mid DM]\times \\ P[DM \mid EDP]\times \\ P[EDP \mid IM]\times \\ \left|\dfrac{d\lambda(IM)}{dIM}\right| \end{Bmatrix} dIM\ dEDP\ dDM \qquad (1)$$

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, inter-storey 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.

2 BIM-BASED DAMAGE ASSESSMENT AND SCHEDULING FOR POST-EARTHQUAKE BUILDING REHABILITATION

2.1 *Methodology*

The proposed method utilizes numerical simulations and a combination of the extracted probabilistic response distributions with the appropriate fragility curves, to evaluate all possible damage scenarios (Christodoulou et al. 2010). These numerical calculations provide repair cost estimation per element, element group, storey 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 & 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 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.

2.2 *Benchmark Building*

The benchmark building (Figures 1-2) is a two-storey 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's ground and first floor heights are 4.57m and 3.96m, respectively and each floor total area is 355m². Column dimensions are 55.9/55.9cm and beam dimensions are 45.7/55.9cm. The slab thickness is 20cm, outdoor and indoor wall thicknesses are 25cm and 10cm, respectively.

3 3D DAMAGE VISUALIZATIONS

The 3D model (Figure 3) 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 the elements' data inventory tool as it is 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.

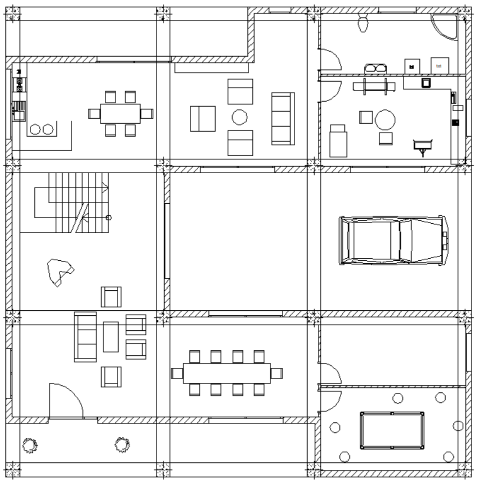

Figure 1. Building ground-floor plan.

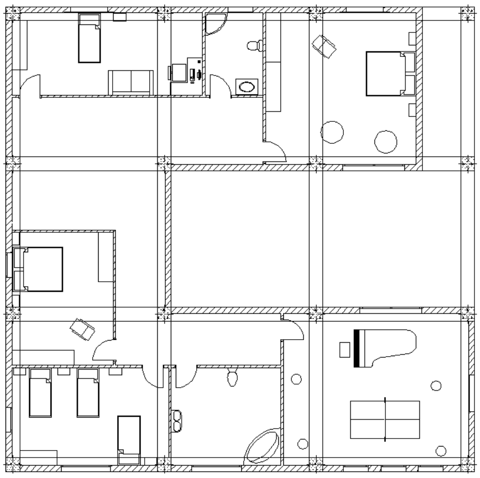

Figure 2. Building first-floor plan.

The 3D model and the element properties (from BIM) are then combined with deduced fragility curves to investigate 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 to 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 inter-storey drift ratio (IDR) of the storey on which they are located.

Figure 3. Building 3D model.

Once a structural assessment is made, a damage measure (DM) per building component is computed subject to the fragility curves associated with each component (EDP). 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 the corresponding elements 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 shown below, gray color is assigned to walls that collapse in order to distinguish them from doors and windows.

The aforementioned 3D-visualization of the building damage state by selectively coloring BIM 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 4, at 0.3g, ground floor columns and beams do not suffer any damage (white color), while walls, doors and windows suffer complete loss (black color). At 0.6g (Figure 5), columns suffer slight damage, some beams do not get damaged while other suffer slight damage. Walls, doors and windows collapse. At 0.9g (Figure 6), columns and beams suffer moderate and slight damage, respectively. At 1.2g (Figure 7), columns suffer moderate and severe damage, some beams suffer slight damage while other suffer moderate damage. At

1.8g (Figure 8), all columns and beams suffer severe and moderate damage, respectively. At 2.4g (Figure 9), columns suffer total loss.

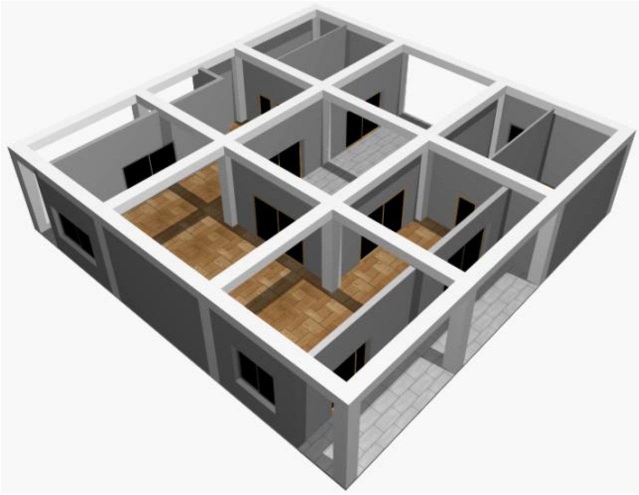

Figure 4. Ground floor 3D damage visualization at $S_a(T_1)$ =0.3g.

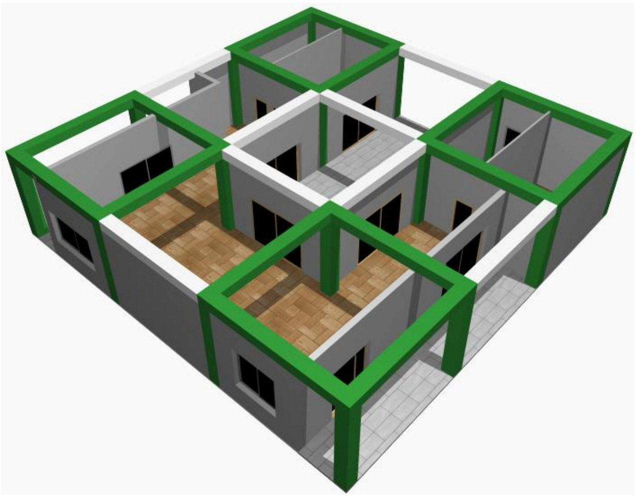

Figure 5. Ground floor 3D damage visualization at $S_a(T_1)$ =0.6g.

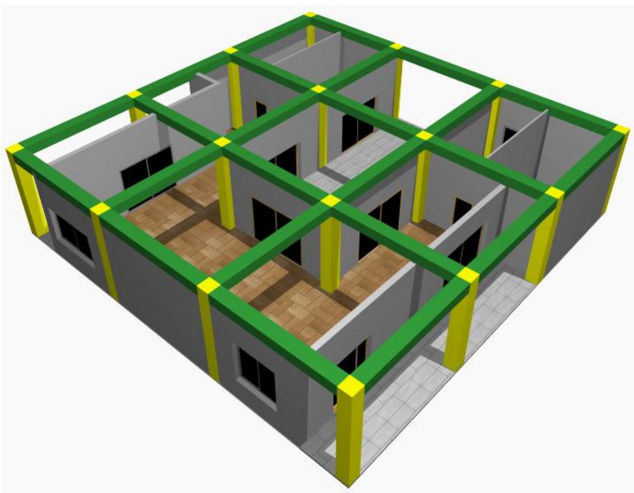

Figure 6. Ground floor 3D damage visualization at $S_a(T_1)$ =0.9g.

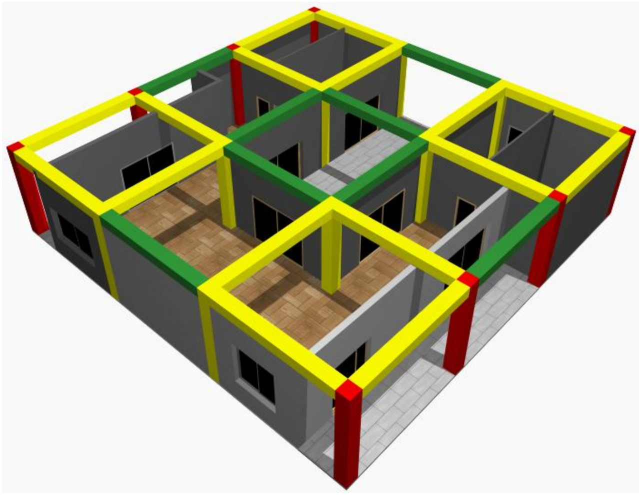

Figure 7. Ground floor 3D damage visualization at $S_a(T_1)$ =1.2g.

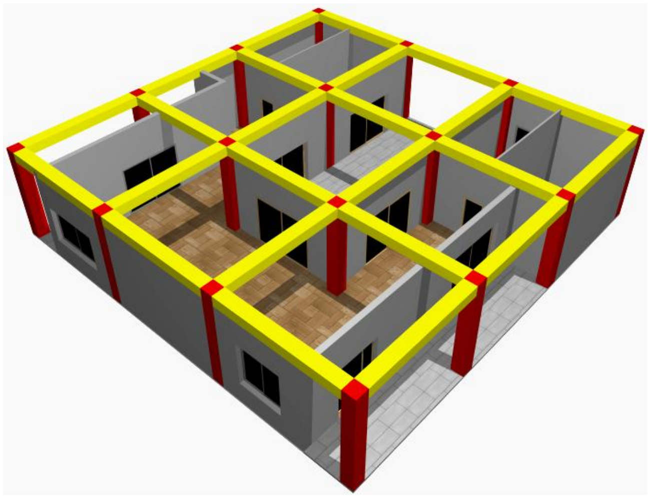

Figure 8. Ground floor 3D damage visualization at $S_a(T_1)$ =1.8g.

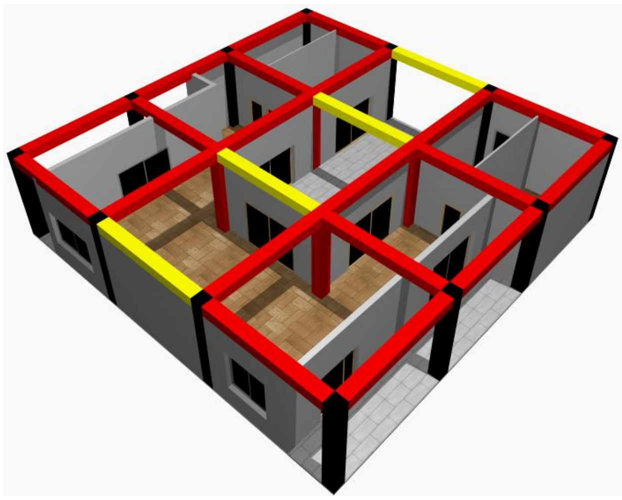

Figure 9. Ground floor 3D damage visualization at $S_a(T_1)$ =2.4g.

Similarly, at 0.3g first floor columns and beams do not suffer any damage, walls suffer moderate and severe damage, while doors and windows suffer moderate damage (as shown in Figure 10). At 0.6g

(Figure 11), columns and beams do not get damaged, while walls, doors and windows suffer complete loss. At 0.9g (Figure 12), columns suffer slight damage.

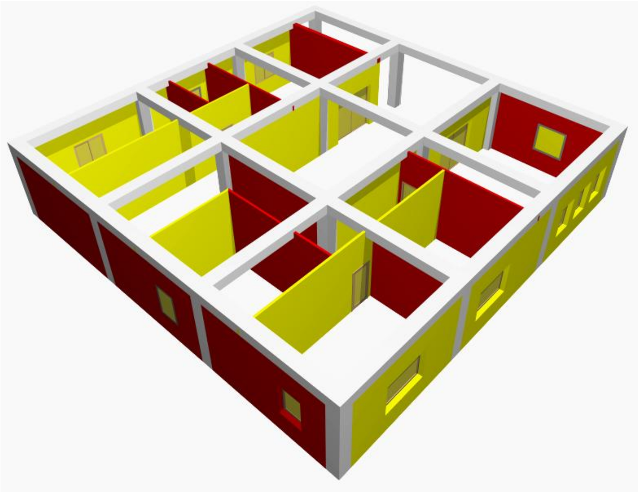

Figure 10. First floor 3D damage visualization at $S_a(T_1)$ =0.3g.

Figure 11. First floor 3D damage visualization at $S_a(T_1)$ =0.6g.

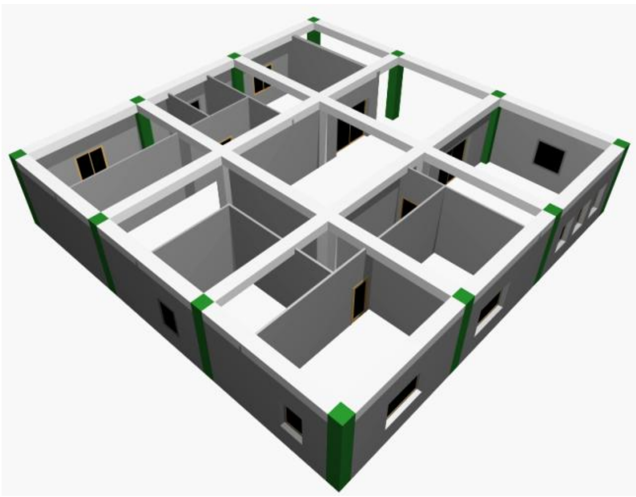

Figure 12. First floor 3D damage visualization at $S_a(T_1)$ =0.9g.

At 1.2g (Figure 13), some beams do not get damaged while other suffer slight damage. At 1.8g (Figure 14), all columns suffer moderate damage and beams suffer slight and moderate damage. At 2.4g (Figure 15), columns suffer severe damage, while beams suffer moderate and severe damage.

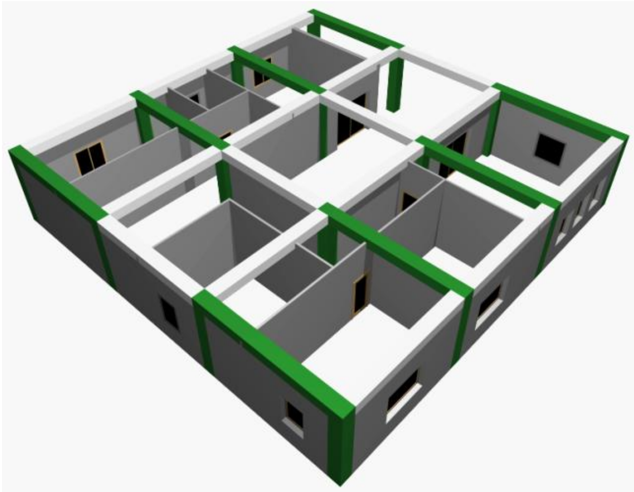

Figure 13. First floor 3D damage visualization at $S_a(T_1)$ =1.2g.

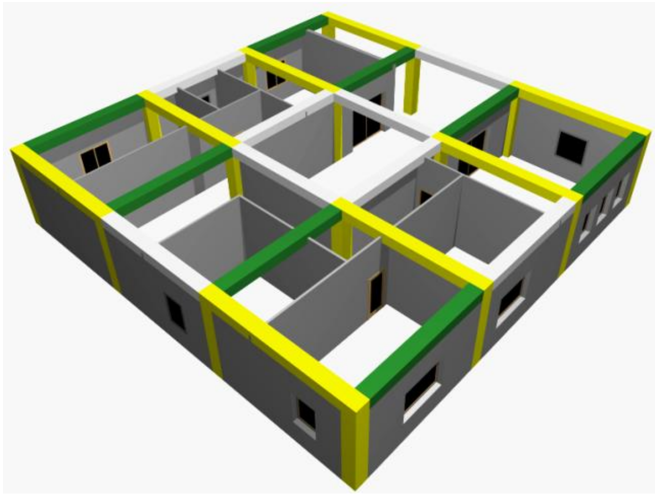

Figure 14. First floor 3D damage visualization at $S_a(T_1)$ =1.8g.

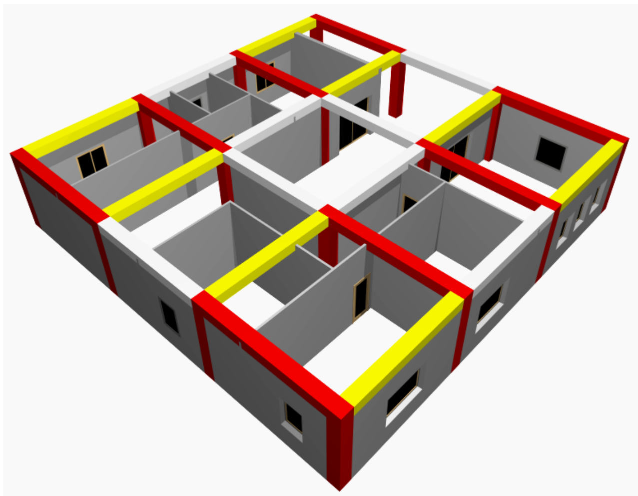

Figure 15. First floor 3D damage visualization at $S_a(T_1)$ =2.4g.

4 REHABILITATION COST

The building repair cost distribution is calculated by Monte Carlo simulation (Latin Hypercube Sampling, LHS), stratified for N possible damage scenarios. The method 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 in Matlab using custom-developed algorithms.

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 16 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).

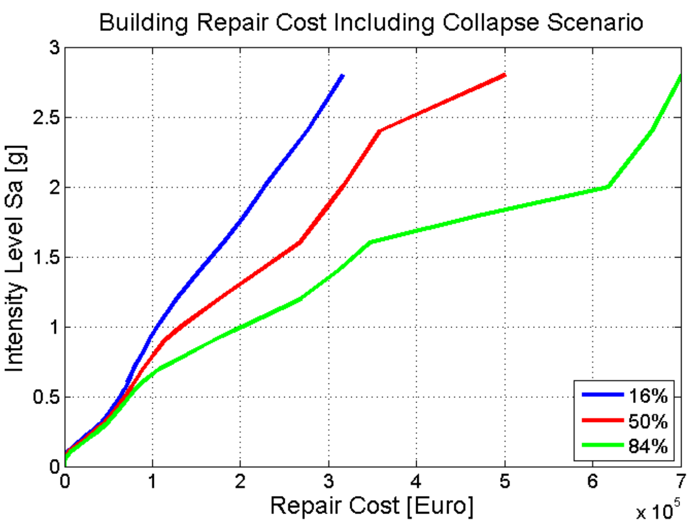

Figure 16. Building repair cost distribution per intensity level $S_a(T_1)$.

5 REHABILITATION DURATION

A custom-developed relational database management system (RDBMS) is then used to record the building elements in appropriate work breakdown structures (WBS), classified according to their damage state. 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.), as they are generated from the BIM, 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, the rehabilitation time and hence loss-of-use cost after each earthquake scenario is estimated (Georgiou 2013). Figure 17 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*.

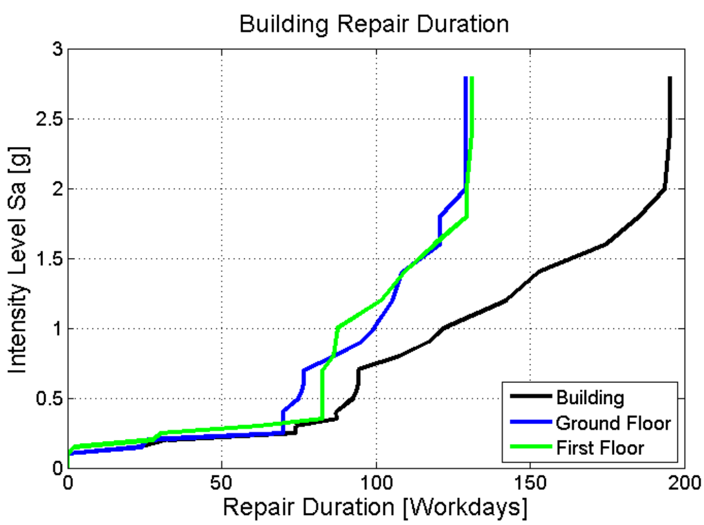

Figure 17. Building repair duration distribution per intensity level $S_a(T_1)$.

6 CONCLUSIONS

Described herein is a proposed integrated approach for post-earthquake building damage assessment and 3D visualizations, by means of integrating building information models with structural and construction engineering principles. The proposed method 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. The method enables a visually-delivered holistic approach to damage assessment, cost and time estimation for the rehabilitation of seismic damages, and offers a comprehensive assessment of the risk that the building owner will be asked to undertake in the aftermath of an earthquake.

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