A BIM-Based Framework for Forecasting and Visualizing Seismic Damage, Cost and Time to Repair

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ABSTRACT: A methodology is presented for integrated and automated forecasting of damage assessment, cost estimating, scheduling and of 3D/4D visualizations for post-earthquake building rehabilitation. The proposed methodology is based on the integration of Building Information Modeling (BIM) and Assembly-Based Vulnerability (ABV) techniques. ABV is a framework for evaluating the seismic vulnerability and performance of structures on a building-specific basis, utilizing seismic analysis techniques to determine the structural response of a building. The methodology used accounts for structural and non-structural building components and corresponding fragility curves, and subsequently applies BIM-based techniques to automate the generation of cost estimates, activity schedules as well as 3D/4D visualizations of the associated rehabilitation work.

1 INTRODUCTION

1.1 *Motivation*

The Architecture, Engineering and Construction (AEC) industry has long strived for improvements in the manner it develops and implements projects and, despite the strong inertia it has shown to adopting new technologies, it has embraced three-dimensional visualization in its quest to improve current practices within the industry. The premise has always been that the transition to BIM would offer considerable benefits in all stages of the AEC process.

A similar revolution in structural engineering has seen the rise of Performance-Based Earthquake Engineering (PBEE), where the profession is slowly moving away from the classic design of a code-conforming building (i.e. the one-design-fits-all model) to the production of improved designs tailor-made to fit the performance requirements of a particular building 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. Still, the communication between the owner and the engineer has always been troublesome, as the engineering descriptors of performance (e.g., inter-storey drift, plastic rotation or shear capacity) are typically meaningless outside the civil engineering profession. Recent attempts to quantify performance in more tangible terms, such as rehabilitation cost, casualties or time to repair (Miranda and Aslani 2003, Gouler et al. 2007) have greatly improved the situation but they still fail to provide a comprehensive understanding of the building's behavior to the average non-engineer. Therefore, it is only natural to couple PBEE with 3D/4D visualization techniques to facilitate the communication between the owner and engineer.

1.2 *Literature Review*

The benefits of BIM have been extensively researched and documented (Collier and Fischer 1996, Fischer 2000, Griffis and Sturts 2000, Christodoulou 2001, Akinci et al. 2002, Koo and Fischer 2000, Kamat and Martinez 2001). The technology and its several incarnations have proven to be a particularly useful communication, planning, and analysis tool for designers, engineers and constructors. At the core of these technologies lies the need to improve on the visual representation of the facility under design or construction. To that extent, the desired high level of visualization of architectural and engineering designs has been the primary driving force for developments in three-dimensional visualization in the AEC industry.

PBEE is the natural evolution of the structural design process to encompass the growing need for specialized structures tailored to the needs of each individual owner. It allows the design of structures that can withstand frequent or rarer earthquakes with the desired performance, for example 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 levels of shaking. Several guidelines that recognize such needs have appeared in recent years, e.g. SAC/FEMA-350/351, FEMA-356 and ATC-40 (SAC 2000a, SAC 2000b, 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 level of shaking and any desired limit-state by integrating the seismic hazard and the structural analysis results with dam-age and cost estimation to produce realistic estimates of the cost associated with any earthquake.

What has been missing is a way to visualize such results on an actual 3D structure using existing professional software as the means to facilitate the communication between client and engineer. Building owners rarely understand the technical language used by engineers and often fail to realize the differences between the design alternatives offered and their actual seismic performance. Improved performance typically means investing a higher initial construction cost that is expected to be more than paid off by the decreased damages experienced in the design life of the building.

Thus, proper communication of the implications of any design decision is essential, in order to facilitate the commitment of the necessary funds.

Unfortunately, current practice limits the information exchanged between owners and engineers to a handful of numbers, which are usually meaningless to the clients. Even when attempts are made to approximately estimate the actual repair cost and downtime in an earthquake scenario, such numbers carry a high uncertainty that is often in the order of 100% or more.

Furthermore, single numbers often fail to communicate an important feature that is a primary target of PBEE, namely the actual level of operability of the structure after any minor or major event. PBEE has been all about integrating structural damage (beams, columns) with non-structural (HVAC, doors, partitions) and building contents' damage. Without the proper visualization capability such numbers become mute. 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 simplifies understanding considerably. Clients are now able to identify restricted areas, plan for possible routes for moving material and personnel and in general gain a proper understanding of the post-earthquake capacity of the structure to function as intended. To achieve this goal we propose to couple current PBEE practice together with readily available visualization techniques that can be implemented in any professional design office.

2 INTEGRATED DAMAGE ASSESSMENT AND 3D VISUALIZATION

2.1 *Real-Time Condition Assessment of Constructed Facilities*

Typical real-time monitoring systems consist of tens of wireless nodes placed at various locations in the structure being monitored, collecting and transmitting sensor data to a remote base-station. A multi-parameter visualization and decision-support system is then responsible for detecting and localizing any abnormalities in the structure and for producing early notifications and suggestions, which are then distributed to field engineers and maintenance technicians for their actions.

In the case, though, of constructed facilities (such as buildings) or hard-to-reach infrastructure (such as underground piping networks) the deployment of sensors is both costly and difficult (if not impossible sometimes). In such cases, post-construction sensor placement and data transmission capabilities are achieved by ad-hoc wireless networks (WSN).

2.2 *Computational Performance Assessment*

Sensors are useful when engineers are in need of seeing what really happened or maybe getting a sense, in real-time, of what is going on in a building after a quake without having to physically go and inspect the building (Naeim et al. 2006). On the other hand, using PBEE and in turn Incremental Dynamic Analysis (IDA) (Vamvatsikos and Cornell 2002) and Assembly-Based Vulnerability (ABV) (Porter et al. 2001) methodologies (that fit into the PBEE paradigm) engineers take a predictive approach, where they try to figure out what may happen in certain earthquake scenarios. ABV is a framework for evaluating the seismic vulnerability and performance of structures on a building-specific basis (Porter et el. 2001). The method utilizes seismic analysis techniques to determine the structural response of a building (e.g. IDA), accounts for structural and non-structural building components and corresponding fragility curves, and subsequently applies FIAPP-based techniques to automate the generation of cost estimates, activity schedules as well as 3D/4D visualizations of the associated rehabilitation work.

The ABV method (Porter et al. 2001) and similar methods by Miranda and Aslani (2003) make use of the simulated behavior of each assembly in a building and a corresponding fragility function to determine the probability that the assembly will be damaged and require repair or replacement. The probability is then used to simulate the damage state of each assembly in the building and to approximate the unit cost and duration to repair each such assembly.

Assemblies are based on either custom-defined work breakdown structures (WBS) or on industry-wide taxonomies such as the Construction Specifications Institute's (CII) Masterformat. The damage state of a particular assembly is considered to depend on the structural response to the load which it is subjected to, and the corresponding total cost for bringing the assembly back on-line is a combination of the repair cost and the loss-of-use cost. A definition of these costs as well as the time to repair each operational unit can be found in Porter et al. (2001).

3 INTEGRATED COST-ESTIMATING AND SCHEDULING FOR POST-EARTHQUAKE BUILDING REHABILITATION

The PEER methodology together with the ABV method is merged with BIM to generate a fully integrated and automated platform for visualizing all post-earthquake building rehabilitation functions (damage assessment, cost appraisal, work schedules, 3D visualizations, 4D sequencing). The process is depicted in Fig. 1.

At first, a 3D object-based model of a building is constructed in conformance with the BIM and IFC paradigms. The model, which was developed in Graphisoft's ArchiCAD software, contains both structural (beams, columns, slabs, etc.) and non-structural (walls, ductwork, furnishings, etc) building components and it is used both as a visualization tool and as an information repository. The model (a case-study three-storey concrete building) is used to generate several item listings for quantity-takeoff and cost-estimating purposes, or for structural-analysis purposes.

A relational database management system (RDBMS) is developed concurrently with the 3D model containing the project's WBS and underlying building assemblies, CSI codes, unit cost and production rates. The 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 BIM CAD object has a unique ID which is linked, through a mapping table, to a CSI code and through that to a crew code. The mappings can be of type "one-to-many" or "many-to-one", allowing the user to assign several BIM objects to one or several CSI codes as needed. For example, a "concrete column" object can be assigned to "formwork", "casting", "insulation" and "painting" CSI codes.

The physical properties of an object (mass, surface, length, volume) in conjunction with the production rates from the CSI codes assigned to it dictate the duration of the corresponding damage-rehabilitation activity. It should be noted that, since the goal is the creation of damage-assessment cost and time estimates which are as complete as possible, the 3D model also contains building contents (Fig. 2).

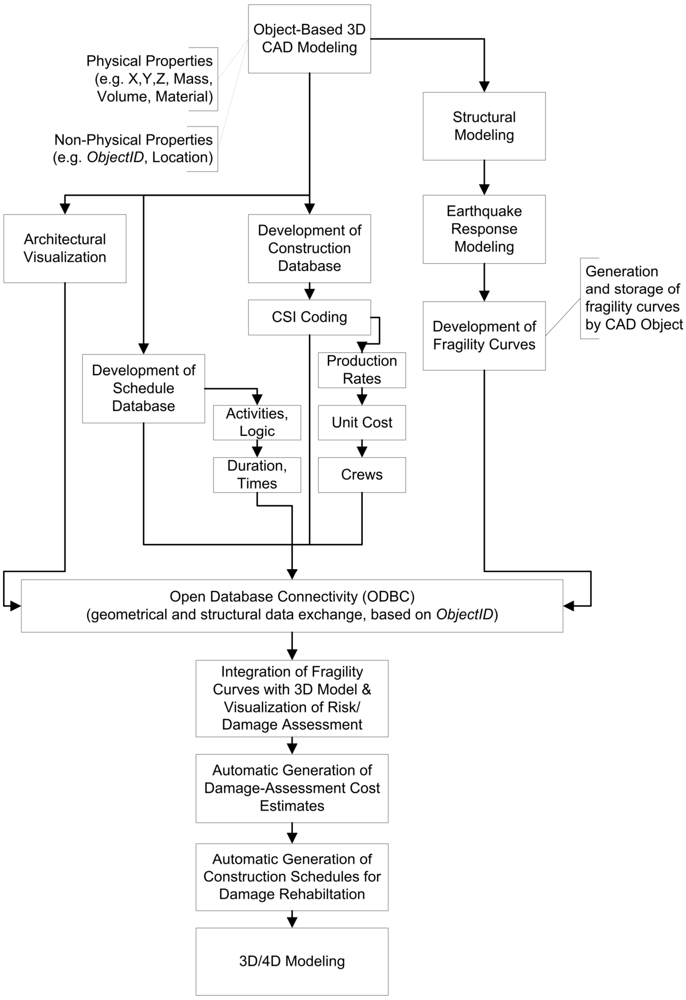

Figure 1. Flowchart of proposed post-earthquake damage assessment and visualization.

Figure 2. 3D BIM of case-study building floor with structural, non-structural components contents in undamaged state.

The RDBMS also contains construction-sequencing templates ("fragnets") addressing possible rehabilitation scenarios. The schedule fragnets include the relationships between the construction activities and typically follow the WBS/CSI structure (activities with lower CSI masterformat codes precede activities with higher CSI codes). The duration of each activity in a fragnet is computed based on the BIM objects included in the activity and the production rate of the crew assigned to them is based on the CSI code for each object (Fig. 3).

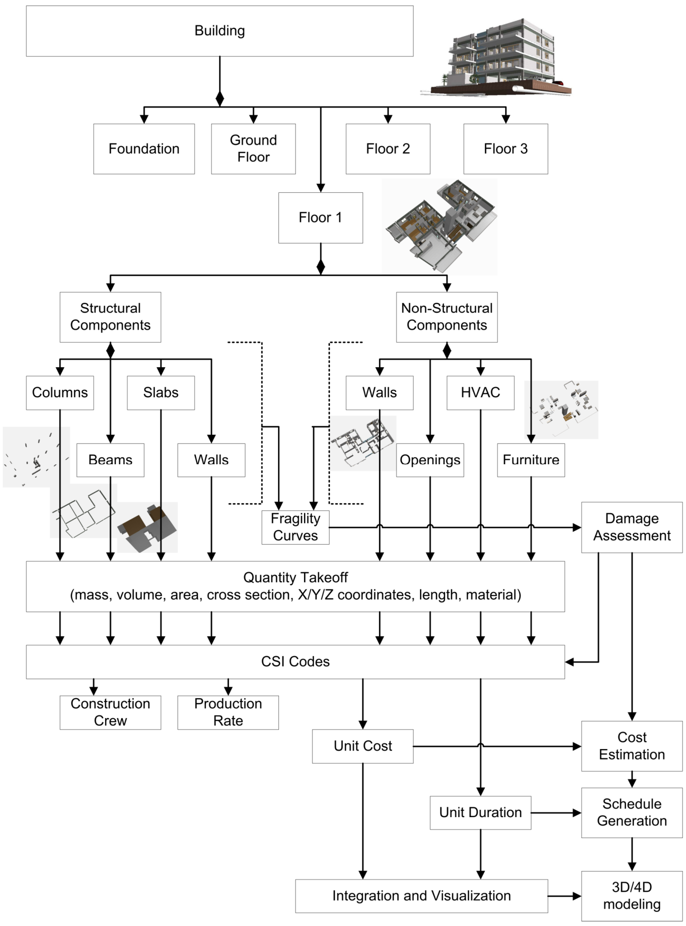

Figure 3. Schematic of BIM/ABV/Cost/Schedule/4D integration.

The 3D model and BIM information (object attributes) are used in the structural analysis of the building and in the investigation of the response to earthquake loads, by utilizing predefined assembly-based libraries and fragility curves. Once a structural assessment is made, a "damage measure" per building component is computed subject to the fragility curves associated with each component. Fragility curves relate structural response with various levels of damage, producing the probability of a structure (or structural component) reaching or exceeding a particular damage level. The gradients of damage vary, but typically they are classified as "zero, or slight", "moderate", "severe" and "total" damage.

Therefore, the damage measure and damage state produced by the structural analysis and the fragility curves for each building assembly can be jointly used as general "damage descriptors" that can in turn be visualized by use of appropriately coloring a 3D BIM model. In the case-study 3D BIM, the variables visualized are: (i) the damage state, (ii) the repair cost, and (iii) the repair time. The damage measure can be either a continuous variable in the range [0, 1] (with "0" indicating no damage and "1" indicating collapse), or a discrete variable, appropriately colored: (i) Green - slight or no damage, no action needed, (ii) Yellow - moderate damage, repairable, (iii) Red - severe damage, needs replacement (repairs are not cost-effective), and (iv) Black - total loss. Cost and time are represented as continuous variables and can be colored as in a typical contour plot. Progressive damage/collapse is currently not taken into account.

The cross-referencing of fragility curves with BIM objects and CSI codes generates the recommended action ("rehabilitate or replace" dilemma), the cost-to-rehabilitate and the associated duration (snapshots shown in Tables 1 and 2. Furthermore, the damage-assessment information is related back to the 3D model by means of an ODBC conduit that passes to the BIM the damage state of each assembly object as an attribute of it. This enables the 3D-visualization of the building damage state by selectively coloring 3D objects based on their damage level (Fig. 4).

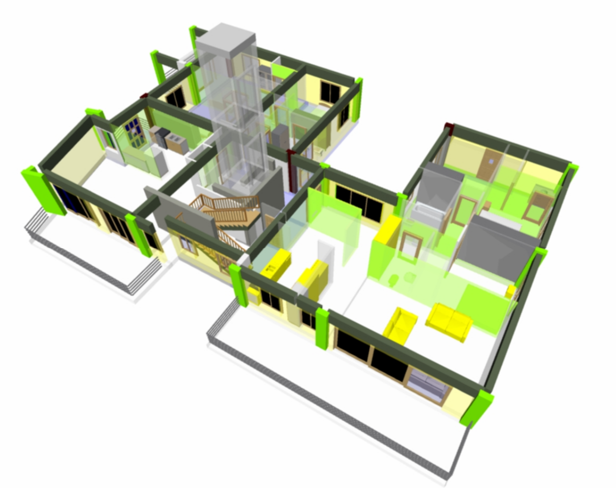

Figure 4. BIM/ABV integration – 3D rendering of building floor showing floor's damage state (darker colors indicate greater damage).

The case depicted herein corresponds to a post-earthquake scenario involving slight damages in the top floor of the building and some moderate damages in the first floor. The scenario further asserts "strong column, weak beam" behavior which confines the structural damage to the beams only. The collateral damage includes the windows of the first and fourth floor (all flagged as "severe damage"), the interior and exterior walls above which the beams suffered moderate to severe damage, and the floor contents in proximity of walls that suffered moderate or severe damage.

Table 1. Damage assessment of building assemblies (excerpt) based on fragility curves.

WBS/Assembly Component				Fragility/Structural Analysis			Fragnet	Total	Total
Floor	Room	Object Type	Object ID	Damage Measure	Damage State	Action	Ref. Code	Cost ($)	Dur (d)
1	101	Beam	BMR-001	0.22	Moderate	Rehab	BMR-RHB	10,000	10
1	101	Beam	BMR-002	0.32	Moderate	Rehab	BMR-RHB	10,000	10
1	101	Beam	BMR-003	0.25	Moderate	Rehab	BMR-RHB	10,000	10
1	101	Beam	BMR-004	0.28	Moderate	Rehab	BMR-RHB	10,000	10
1	101	Column	CLM-001	0.04	Slight	None	-	0	0
1	101	Column	CLM-002	0.05	Slight	None	-	0	0
1	101	Column	CLM-003	0.08	Slight	None	-	0	0
1	101	Column	CLM-004	0.02	Slight	None	-	0	0
1	101	Ext. Wall	EWL-001	0.15	Moderate	Rehab	EWL-RHB	2,000	4
1	101	Ext. Wall	EWL-002	0.17	Moderate	Rehab	EWL-RHB	2,000	4
1	101	Int. Wall	PRT-001	0.05	Slight	Rehab	PRT-RHB	1,000	1
1	101	Int. Wall	PRT-002	0.03	Slight	Rehab	PRT-RHB	1,000	1
1	101	Window	WND-001	0.60	Severe	Replace	WND-RPL	1,500	1
1	101	Window	WND-002	0.45	Severe	Replace	WND-RPL	1,500	1
1	101	Window	WND-003	0.62	Severe	Replace	WND-RPL	1,500	1
1	101	Door	DOR-001	0.65	Severe	Replace	DOR-RPL	1,000	1
1	101	Wardrobe	FRN-001	0.16	Moderate	Replace	FRN-RPL	350	0.5
1	101	Bed	FRN-002	0.21	Moderate	Replace	FRN-RPL	250	0.5
1	101	Desk	FRN-003	0.15	Moderate	Replace	FRN-RPL	150	0.5

Table 2. Cost and duration (excerpt) for post-earthquake damage rehabilitation.

Fragnet Ref. Code	Activity ID	Description	CSI Code	Quantity To Use	Unit Cost ($)	Unit Duration (d)
BMR-RHB	1	Remove debris	017419	Volume	50.00	0.5
BMR-RHB	2	Reinforce	032000	Volume	150.00	1.0
BMR-RHB	3	Formwork	031113	Area	120.00	1.0
BMR-RHB	4	Concrete pour	033000	Volume	150.00	0.5
BMR-RHB	5	Concrete curing	033900	Each	10.00	0.5
BMR-RHB	6	Interior painting	099123	Area	50.00	7.0
WND-RPL	1	Remove window frame	017419	Area	50.00	0.5
WND-RPL	2	Rehab. wall opening	064800	Area	75.00	0.5
WND-RPL	3	Concrete pour and curing	033900	Volume	150.00	0.5
WND-RPL	4	Install new window frame	064613	Area	75.00	0.5
WND-RPL	5	Exterior painting	099913	Area	50.00	0.5

4 CONCLUSIONS

The paper presents an integrated approach to assessing and visualizing post-earthquake building damages, by means of integrating a building information model with relational databases, 3D/4D computer-aided models and assembly-based vulnerability paradigms. 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/4D visualizations of buildings for the purpose of holistic damage assessments in the aftermath of an earthquake. The methodology can also be considered a "first-responder" approach to mediating the effects of earthquake-induced building damages, since it allows for hierarchical analyses of the damages of building components and subsequently the cost and time estimation for the rehabilitation of such damages, in a visual manner that is easily comprehensible by the stakeholders of each structure under investigation.

5 ACKNOWLEDGEMENTS

This report is based partially upon work funded by the Cyprus Research Promotion Foundation, under Grants No. ERYAN/0506/09 and CY-SLO/407/04.

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