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Seismic retrofitting of buildings using Building Information Modeling

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Abstract. Building Information Modeling (BIM), in the last couple of decades, has emerged as a technology that can be used in combination with different methodologies in the fields of architecture, engineering, and construction industry as a digital model to facilitate the planning and design process, construction and maintenance. Using the tools of BIM, the stakeholders generate the digital models that can help them to identify the problems. A total of 24 conference papers, referenced journal articles, and other academic sources were analyzed based on their relevance and research focus areas. This article provides a review on the integration of building information modeling with different methodologies for seismic retrofitting of both structural and non-structural components of buildings. Pre-seismic and post-seismic applications of Building Information Modeling with the integration of different methodologies have been reviewed overbuilding life cycles with a view of addressing the challenges and recommending the future research perspectives. In the end, by stating the possibilities of integration of BIM tools with different methodologies mainly using Performance-Based Earthquake Engineering as a paradigm which is fully probabilistic, this paper concludes that the implication of the Building Information Modeling with the integration of different methodologies isn't merely the inclusion of the certain conditions, but also of the numerical integration of all the possible uncertainties.

Keywords: Architecture, Engineering & Construction Collection, Building Information Modelling, seismic retrofitting, building life cycle, project cost estimating, building maintenance cost optimization

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Сейсмическое переоснащение зданий с использованием информационного моделирования зданий

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Аннотация. В последние несколько десятилетий появилась технология информационного моделирования зданий (BIM), которая может использоваться в сочетании с различными методологиями в области архитектуры, проектирования и строительства в качестве цифровой модели для облегчения процесса планирования и проектирования, строительства и технического обслуживания. Используя инструменты, заинтересованные стороны генерируют цифровые модели, способствующие определению проблемы. Опираясь на актуальность и направление исследований были проанализированы в общей сложности 24 доклада конференций, ссылки на журнальные статьи и другие академические источники. Представлен обзор интеграции информационного моделирования зданий с различными методологиями сейсмического переоснащения как структурных, так и неструктурных компонентов зданий. Предсейсмические и постсейсмические приложения информационного моделирования зданий с интеграцией различных методологий были рассмотрены в течение жизненного цикла зданий с целью решения проблем и рекомендации будущих перспектив исследований. Предполагая возможность интеграции инструментов BIM с различными методологиями, в основном использующими основанную на производительности сейсмотехнику (PBEE) в качестве парадигмы, которая является полностью вероятностной, делается вывод о том, что следствием информационного моделирования зданий с интеграцией различных методологий является не только включение определенных условий, но и численное интегрирование всех возможных неопределенностей.

Ключевые слова: проектирование и строительство, информационное моделирование зданий, сейсмическое переоснащение, жизненный цикл здания, оценка стоимости проекта, оптимизация затрат на техническое обслуживание здания

Introduction

In the past, the seismic retrofit was done in order to achieve a specific public safety objective, but engineering solutions were often limited by economic and political considerations [1]. However, with the development of Performance-Based Earthquake Engineering (PBEE), several levels of performance objectives are gradually recognized [2]. As different studies are conducted in the area of structural design and retrofitting stakeholders visualized that in structural engineering the amount of damage, the economic loss, and the repair cost of structures were improperly high, even though those structures are designed with available seismic codes based on traditional design philosophy [3]. Consequently, Building Information Modeling (BIM) plays an important role to reduce the amount of damage and economic loss throughout the building life cycle. Building Information Modelling (BIM) is a digital representation of an entire construction process (design, construction, and manage-

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ment across the entire lifecycle) [4]. BIM design tools provide a new approach and can help rehabilitate and retrofit buildings. BIM helps users create highly detailed 3D structural and non-structural models of buildings and infrastructures to enable public, government, engineering, construction, and business communities to better understand the task holistically and plan alternatives. In addition, the BIM process can help identify, diagnose and even predict problems that buildings might experience in the future by simulating such seismic events and their impacts. Several studies have been focused on the acceptance and implementation of BIM in the sector [5–8].

Literature review

Building Information Modeling and its application. Technology can play a significant role in ensuring the quality of construction [9]. BIM technology can support multiple techniques such as the construction simulation, information statistics, the management of the various processes reflected in the contents of the visual, which can strengthen the management of control [9]. BIM is based on three-dimensional (3D) digital technology and integrates all of the information in the construction project lifecycle while providing a detailed expression of project-related information [10]. If the main affecting factors of the quality of the project, such as human, equipment, and materials can be well controlled, the quality of construction can be secured [11]. So, the use of BIM is mainly to play an effective role in controlling these factors starting from architectural design to project completion and further building life cycle control. In fact, BIM technology application on the construction site of different people, reasonable division of labor, so that everyone can play its greatest role in the process of construction and make their own analysis on the key and difficult work, to avoid the possible risks in the process of construction.

Benefits of Building Information Modeling for stake holders. The perspective of the key stakeholders regarding BIM is fundamental since they achieve direct benefits from its adoption. The approach BIM can remarkably improve the association among stakeholders bringing an added value to their business. Indeed, the collaboration among stakeholder can increase organizational capacities which enhance the performance of the project management during the design and construction process [12]. According to a survey conducted on the benefit of BIM [13], the firms that adopted BIM were asked to indicate benefits that they experienced. According to their responses the following top benefits (frequency rate 13% for each answer) emerge: a) improvement of the collective project understanding; b) improvement of the stakeholders' collaboration; c) improvement of the project quality. The other benefits are ranked just behind: a) reduction of errors and changes during the design phase (11%); b) reduction of errors and changes during the production and construction phase (11%). Referring to the analysis obtained from the survey [13], 50% of respondents (6 firms) state to use BIM in their professional activity, but only 3 firms are using it for all projects. The survey reveals a low and medium level of knowledge and ability to use BIM.

Building Information Modeling for existing buildings. According to a reviewed research on the application of BIM overbuilding life cycle [14], most of the BIM research focuses mainly on the preliminary and construction stages. However, in recent years significant investments were made in retrofitting of existing buildings with the aim to realize a strong functional, energy, and seismic refurbishment. BIM can play a vital role in retrofitting of existing buildings. Applying of BIM methodology to existing construction follows detailed documentation study and accurate analysis of the real state of the building [15].

Building Information Modeling as support of seismic design. In urban areas due to an increase in population the horizontal expansion of building has been changed to vertical rising. High rise buildings have become considered as urban infrastructures as bridges and highways. Design of this high-rise buildings need to be designed so that the buildings resist earthquake forces. Although BIM technology can be applied over the building lifecycle its importance in designing for seismic has a wide range. BIM integrates early earthquake safe design considerations that doesn't need design modifications during the construction phase. Fundamentally, with BIM, any elements of a building can be modeled and designs can also be validated using BIM [16].

BIM for Retrofitting of Earthquake affected structures. BIM not only assists engineers while working on designs from the beginning but also ensures that the structure is restored as it was before the earthquake [16]. In fact, BIM plays a vital role in the process of retrofitting of earthquake affected structures. BIM captures the reality of any structures with the help of point cloud information and converting it to 3D BIM models or photogrammetry. It is expected to analyze the captured information model using BIM structural software to check the displacements under the seismic loads through virtual simulation. Additionally, different information and data can be extracted for the retrofitting decisions.

Methodology

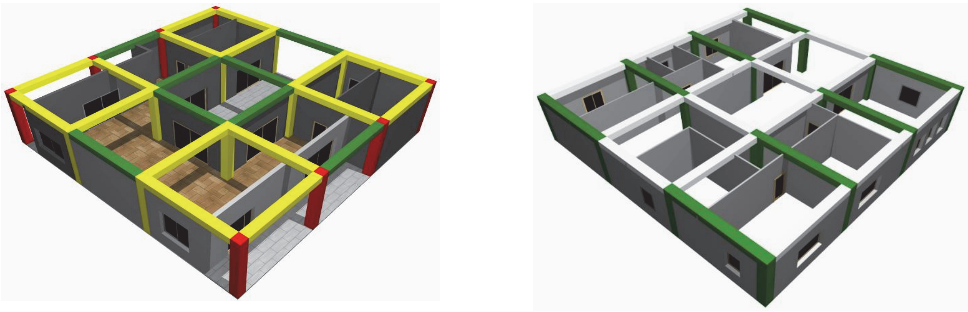
A literature search was carried out based on the title, abstract, and keywords. It was carried out as per journal publication search engine, i.e., Google Scholars, different databases, and other platforms. But the searching focus was on the Google search engine. Keywords were very crucial for the success of searching the literature. The key words applied in literature searching include ‘Architecture, Engineering, and Construction (AEC)’, ‘Building Information Modelling (BIM)’, ‘Seismic Retrofitting’, ‘Building Life Cycle’, ‘Project Cost Estimating’, ‘Building Lifecycle’, ‘Building Maintenance cost optimization’. Articles from journals, conference proceedings, published case studies, press releases, online articles, professional presentations and review papers were used. All the above-stated sources were published and publicized within the last two decades and the latest publication is published in 2020. A total of 31 papers were studied which specifically concentrating on retrofitting and Building Information Modeling (BIM). The journals used in this review search are journals of Engineering and construction: ‘Automation in Construction’, ‘The Open Construction and Building Technology’, ‘Advanced Engineering Informatics’, ‘International Association for the Seismic Performance of Non-Structural Elements’, ‘International Journal of Safety and Security Engineering’, ‘Building and Environment (B&E)’, and ‘Building Simulation (BS)’. The most cited journal was ‘Automation in Construction’. The reviewed papers were further classified based on two of five main stages of project lifecycle ‘repair and maintenance & operation and demolition’ of structural and non-structural elements of the building. It is important that the findings are not explained at each stage of the building life cycle, because the review is only concentrating on the application of BIM on seismic retrofitting of buildings and remedial action to be taken for further action. The literature review was carried to analyze the current trend of Building Information Modeling over seismic retrofitting. The details of the selected findings are discussed in the next section of this review.

Research findings

Seismic risk analysis consists of hazard, vulnerability, and exposure. Recently, research revealed that all retrofitting options with BIM are utilized Performance-Based Earthquake Engineering (PBEE) design as a paradigm which is fully probabilistic and consists of numerical integration of all the conditional probabilities, propagating the uncertainties from one level of analysis to the next [17]. Compatibly, BIM software has built-in cost estimating features in which material quantities are extracted automatically and can be updated when any changes are made in the whole model. As per conducted research the visualization of damages, scheduling, and cost estimation of retrofitting buildings are applied for both pre-seismic retrofitting and post-seismic retrofitting Using Building Information Modeling [4; 14; 18].

Building Information Modeling for 3D visulization damage state assessment of building. The assessment of the post-earthquake state of structures is a concern of Architectural, Engineering and Construction (AEC) industry, with the help of Pacific Earthquake Engineering Research (PEER) as a paradigm. PEER developed an appropriate basis for seismic damage assessment, cost estimation and scheduling for port-earthquake building retrofitting with lack of visualization tools in the platform. To integrate this visualization with PEER a two-storey reinforced concrete special-moment-resisting-frame structure designed by Haselton [19] has been used as model and a methodology has been proposed [20] which integrates Building Information Modeling (BIM) with the framework of PEER to provide 3D damage assessment visualization, the expected retrofitting cost and scheduling for different level of seismic intensity. In fact, time and cost estimation are a platform in the BIM and represented as four-dimensional (4D) and five-dimensional (5D) simulations respectively. The proposed method follows numerical simulations and a combination of the extracted probabilistic response distributions with appropriate fragility curves, to evaluate all possible damages scenarios [20]. The numerical calculations give repair cost estimation per element, element group, storey, and building at different intensity levels of the earthquake. Additionally, in an automated relation database and scheduling software, the building elements are classified according to their damage state in work breakdown structures (WBS) and assigned to specific repair activities of fixed productivity rate to estimate the time and cost of retrofitting. As per the simulation [20], the damage states vary and 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. By comparing building damages at various intensity levels as they are illustrated in Figures 1 and 2 for $Sa(T1)$ equal to 1.2 g, it is possible to understand the need to utilize this technology in PBEE. This research revealed that the possibility and importance of BIM technology in PBEE by comparing the building damage state at different levels ($Sa(T1)$ equal to 0.3, 0.6, 0.9, 1.2, 1.8, and 2.4 g). As shown in Figure 1 the 3D damage state of the following simulations are ground floor and first floor at intensity $Sa(T1)$ level 1.2 g. The proposed methodology and colors show the damage state of the building elements. In this sense, the colors black, red, yellow, green, and white describe collapsed, severely damaged, moderately damaged, slightly damaged, and not damaged state of the building elements respectively.

A case study of research conducted on 5D simulation for post-seismic retrofitting [21] which is an RC frame structure with 6 floors and a total height of 25.6 m, an area of 921 m^2 with a length of 33.6 m and a width of 25.2 m assist that, BIM is a platform which extensively integrates PBEE for seismic rehabilitation of the building. A structural and architectural model which is followed by the proposed methodology for 5D simulation (time scheduling) in the research is shown in Figure 3.



a *b*

Figure 1. Ground floor (*a*) and first floor (*b*) 3D damage visualization at $Sa(T1)$ = 1.2 g [20]

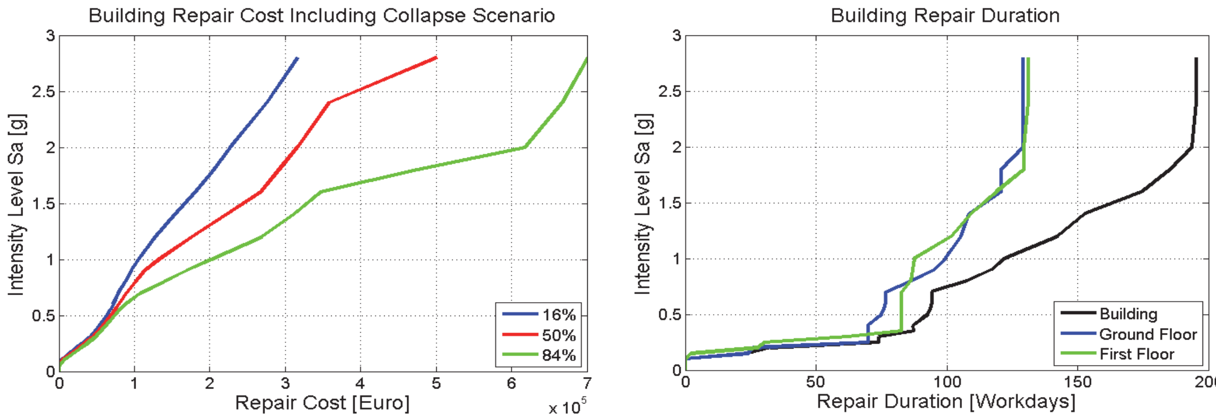


Figure 2. Building repair cost and duration distribution per intensity level $Sa(T1)$ [20]

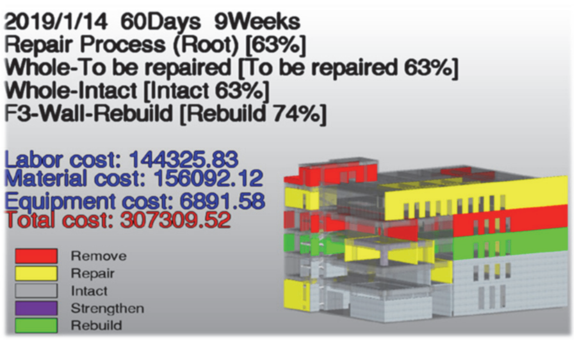


Figure. 3. 5D simulation of post-earthquake repair process [22]

Building Information Modeling and Assembly-Based Vulnerability. Researches are integrating different methodology with Building Information Modeling to visualize post-earthquake rehabilitation, but as mentioned in the previous section of this review PEER is serving as a paradigm for all conducted researches related to the thematic area. Here, BIM is integrated with PEER and Assembly-Based Vulnerability (ABV) [22].

Combining the PEER methodology with the ABV method and BIM to achieve an integrated and automated platform for visualizing all scenarios (damage assessment, cost appraisal, work schedules, 3D visualizations, 4D sequencing). ABV is a platform in which seismic vulnerability and performance of structures on a building evaluated [23]. The method is used to determine the structural and non-structural response of buildings by utilizing seismic analysis techniques and corresponding fragility curves to visualize 3D/4D simulations for retrofitting work. Graphisoft's ArchiCAD has been used for modeling the 3D structural and non-structural building elements with work breakdown structures and simultaneously a relational database management system (RDBMS) is developed which provide a link between the BIM objects and the other database, i.e., one-to-many or many-to-one mapping table to CSI code then to a crew code (e.g., 'concrete column' can be assigned to 'formwork', 'casting', 'insulation' and 'painting' CSI code).

The developed RDBMS [23] additionally consists of construction sequencing templates (fragnets) that address possible retrofitting scenarios which is the same simulation as stated in the previous section of this paper [20]. The schedule fragnets include the relationships between the construction activities and typically follow the WBS/CSI structure (activities with lower CSI master format codes precede activities with higher CSI codes) [22]. BIM objects and the production rate of the crew assigned based on the CSI code of each object helps to compute the duration of each activity as shown in Figure 4.

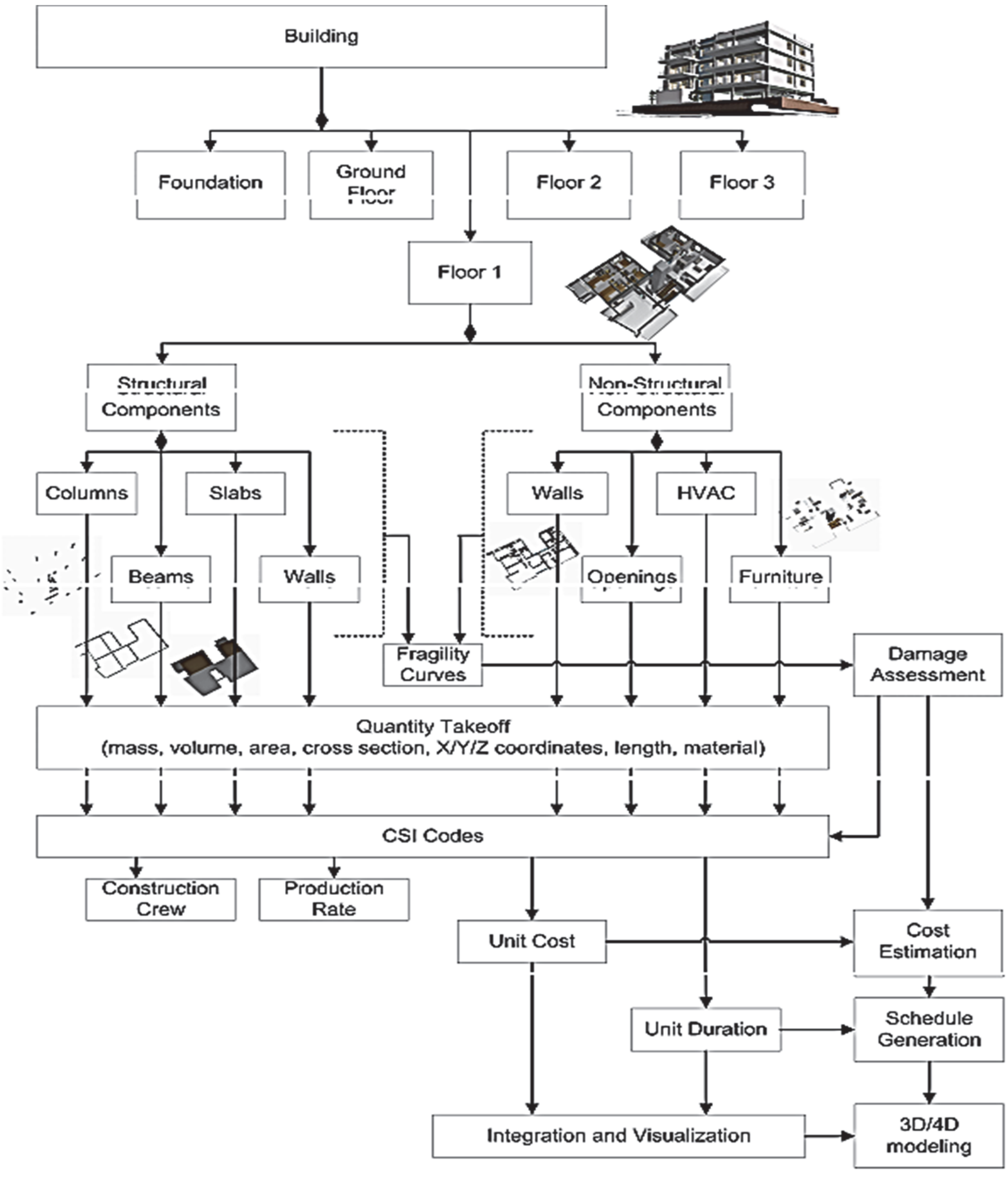


Figure 4. Schematic of BIM/ABV/Cost/Schedule/4D integration [23]

After the structural assessment is made damage measure per building elements computed that is subjected to the fragility curves. Fragility curves relate structural response with various levels of damage. The gradients of damage vary, but typically they are classified as "zero, or slight", "moderate", "severe" and "total" damage [23]. Therefore, the damage measure and damage state produced by the structural analysis and the fragility curves for each element of the building can be visualized by appropriately coloring a 3D BIM model. In the case study [23] (Figure 5) 3D BIM, the variables visualized are: (i) the damage state, (ii) the repair cost, and (iii) the repair time. The damage measures are expressed in a continuous variable ranging [0,1] indicating no damage and collapse respectively. In discrete variable, it is expressed with appropriate coloring in the 3D model as green, yellow, red, and black describing 'slight or no damage with no action needed', 'moderate damage as repairable', 'severe damage as it needs replacement' and 'total losses respectively. Cost and time are represented as continuous variables and colored as in a typical contour plot. In this case study progressive damage/collapse is not taken into account.

From the case study it is possible that by integrating PBEE, BIM (i.e., 3D, 4D and 5D) simulation and ABV to retrofit an existing building post-seismic and the results are shown below in Table.

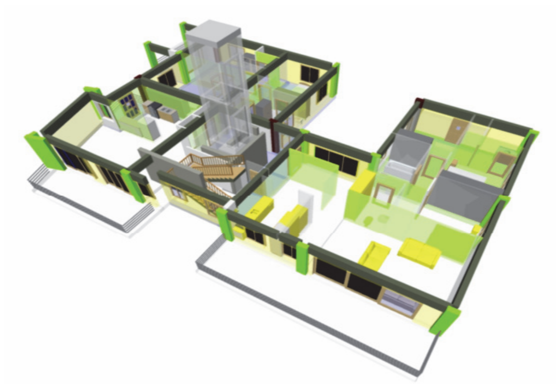


Figure 5. BIM/ABV integration – 3D rendering of building floor showing floor's damage state (darker colors indicate greater damage) [23]

Table

Damage assessment of building assemblies (excerpt) based on fragility curves [23]

WBS/Assembly component				Fragility/Structural analysis			Fragnet ref. code	Total cost, $	Total dur, *d*
Floor	Room	Object type	Object ID	Damage measure	Damage state	Action			
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

Semi-probabilistic approach in a BIM model. As mentioned in the previous section of this paper, seismic assessment is currently performed in the research field by means of Performance-Based Earthquake Engineering (PBEE) which is a fully probabilistic methodology. Engineering practitioners rarely adopt a fully probabilistic approach to assessing the seismic hazard at a construction site and performing economic loss assessments [4]. Indeed, a semi-probabilistic method that is integrated with BIM [4] allows security checks to be performed with a probabilistic value, even though the assessment is carried out in a deterministic method. Under this proposed method the randomness of materials is taken into account and characteristic values of material resistance and safety coefficients are assumed for the estimation of structural components capacity.

Recently, methodologies related to the optimal strategy for building seismic retrofit interventions are rarely applicable. However, the life cycle cost (LCC) analysis can be an efficient tool with a simplified methodology to optimize seismic retrofit interventions by considering both safety and economic features [4].

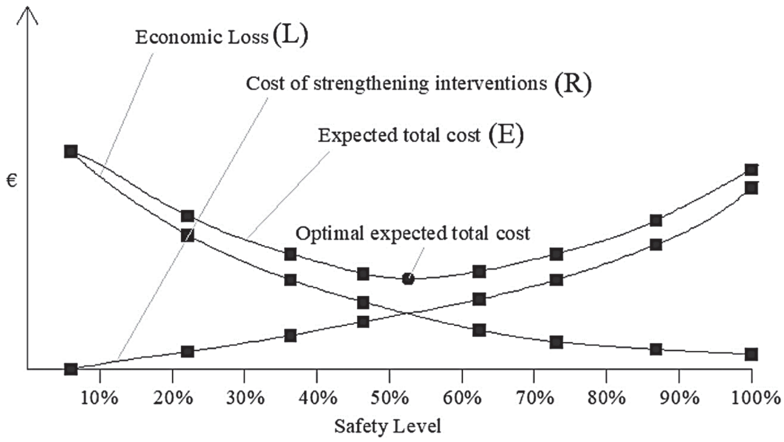


Figure 6. Procedure for the strengthening optimization [4]

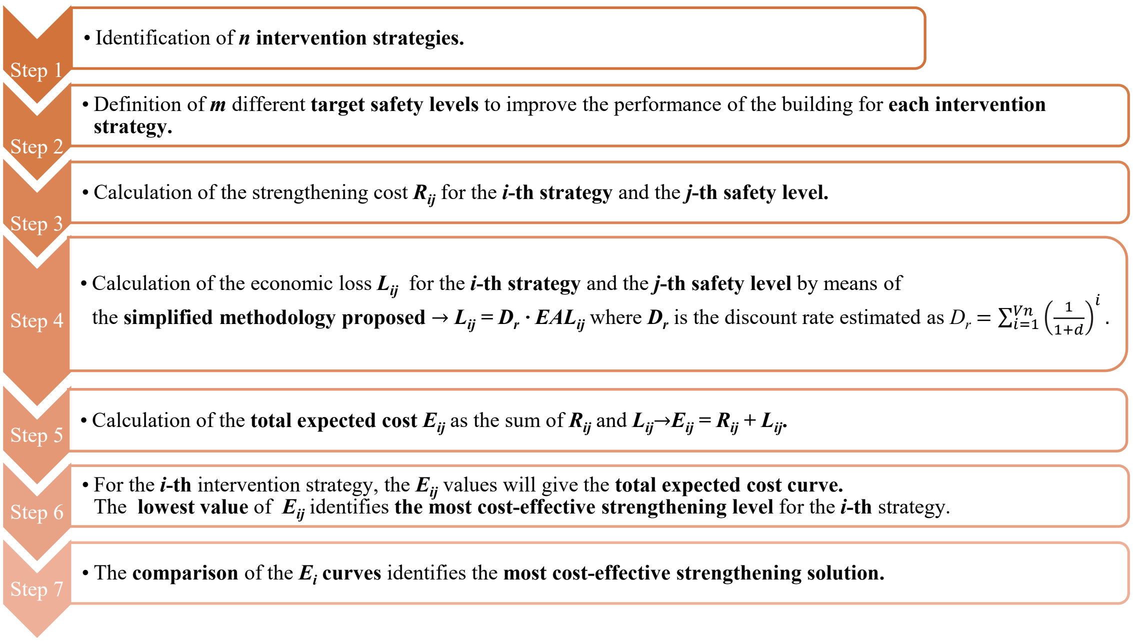


Figure 7. Flowchart of proposed procedure to optimize seismic retrofit interventions [4]

The optimization methodology goal is to point out the most cost-effective strengthening strategies and strengthening levels of existing structures throughout their structural lifetime. The retrofitting intervention strategy is very important to estimate the most cost-effective strengthening solution and economic losses at different intensities of retrofit intervention. According to the proposed methodology, the procedures and expected goal are expressed in Figure 6 and the first curve is ‘economic loss’ which identifies the loss related to different safety level; 'cost of the strengthening intervention' curve which reveals the costs needed to obtain a given safety level; and 'expected total cost' curve which is the sum of the previous curves for each safety level. The most cost-effective solution will be the lowest value of the expected total cost and the corresponding safety level. Based on the PEER approach the paths to follow from both a theoretical point of view and in terms of practical implementation in the BIM environment are shown in Figure 7.

The case study [4] was conducted by assuming the location in the city of Naples and is an academic example of a typical Italian facility built in the 1970s with no seismic provision and the proposed methodology has been implemented in a BIM model containing both structural (columns, beams and slabs) and non-structural components (partition walls, windows, and doors) as shown in Figure 8.

From the case study, the proposed methodology successfully integrated with BIM tools and the approach is apparently equivalent to the IN2 method proposed by Dolsek and Fajfar [24]. The expected actualized loss curve and the cost curve, plotted against the safety level, are shown in Figure 9. The summation of the economic loss and strengthening curves plotted against the safety level, produces the total expected cost. Generally, the most cost-effective safety level shows that the most cost-effective safety level for the FRP-based retrofit strategy is about 55% as shown in Figure 9.

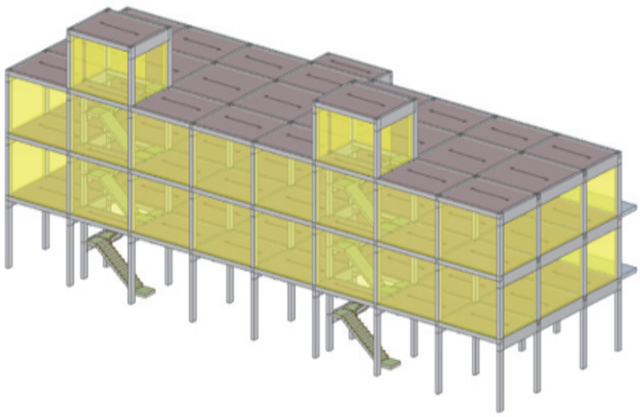


Figure 8. Structural model of the facility [4]

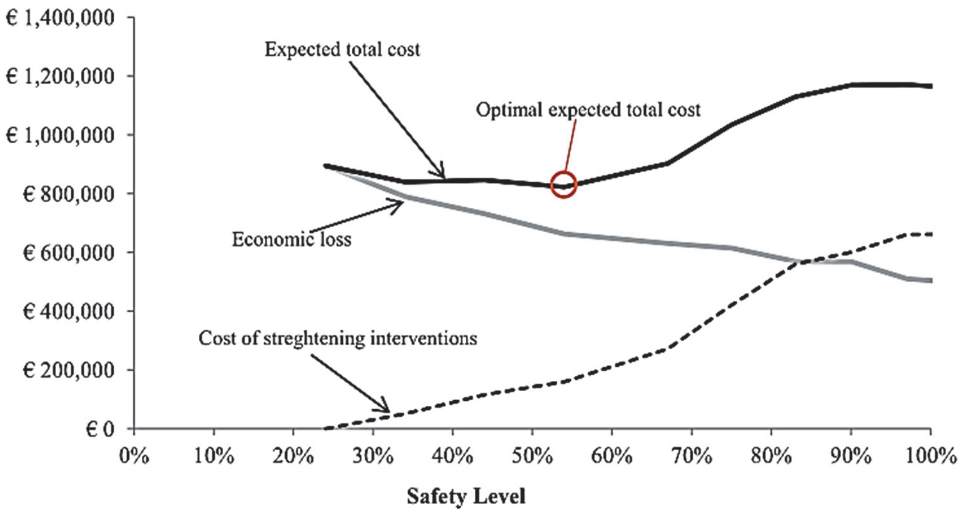


Figure 9. Strengthening optimization procedure in the case study [4]

Conclusions

Results show that Building Information Modeling can be integrated with different proposed methodologies for valuable seismic retrofitting of buildings. In the last two decades, researches on earthquake engineering have focused on the vulnerability and the exposure of different structure subjected to earthquake. Indeed, vulnerability is described by probabilistic curves, named fragility curves, which allow observing specific damage levels of both the structural and non-structural components of buildings probability which is a function of Engineering Demand Parameter (EPD). The case studies in the reviewed researches are disclosed the proposed methodologies under integrated approaches of BIM with different seismic retrofitting paradigms. Building Information Modeling components 3D, 4D, and 5D simulations are specifically integrated for damage visualization, scheduling for retrofitting and cost estimation respectively. This research also reveals the benefits of the BIM-based platforms in the evaluation of the economic losses for new and existing buildings and the optimization of the seismic retrofits to existing structures from an economic standpoint. The literature explicitly suggests that lack of expertise is the major barrier in the implementation of BIM for the building life cycle which includes the retrofitting of buildings. It is conceived that the AEC industry through continuous training and increasing awareness the maximum profit of BIM will be achieved. The future of BIM is radiant because the benefit of full implementation of BIM is gradually increasing as several studies are conducted. However, BIM implementation needs more studies in the AEC industry.

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