Canadian Conference - Pacific Conference on Earthquake Engineering 2023
Vancouver, British Columbia
June 25th – June 30th, 2023

Seismic Loss Assessment of Buildings using Building Information Modelling

Joaquin Acosta Reveco[1*], Oh-Sung Kwon[2], Siriwut Sasibut[3], Feng Rong[4].

[1]Ph.D. Candidate, Department of Civil & Mineral Engineering, University of Toronto – Toronto, ON, Canada.
[2]Ph.D., P.Eng., Professor, Department of Civil & Mineral Engineering, University of Toronto – Toronto, ON, Canada.
[3]Ph.D., P.Eng., Senior Software Developer, Altair Engineering Inc. – Troy, MI, United States.
[4]Ph.D., P.Eng., Senior Research Engineer, Altair Engineering Inc. – Troy, MI, United States.
[*]j.acosta@mail.utoronto.ca (Corresponding Author)

ABSTRACT

Despite the clear benefits of using advanced seismic assessment methods, like FEMA P-58, seismic performance assessment in this sense is not commonly applied in practice. This can be attributed to additional complexity and longer execution times involved when working with the nonlinear model of a real building, and to the extensive information needed to represent vulnerable contents within the building, which are required to obtain meaningful performance metrics. Although nonlinear analysis guidelines have appeared to support engineers, the building information issue has not been well addressed, leaving potential users of these methods to solve the problem by themselves. Considering this, recently, researchers have studied the use of Building Information Modelling (BIM) to enable automated and detailed assessments of performance for a specific building. Nonetheless, the few studies conducted so far developed applications scoped to specific BIM software, therefore not widely applicable. In this research, we developed a method to assess the seismic performance of a given building, using the FEMA P-58 Methodology, taking advantage of the BIM models used for the design of the building. The method uses open-source technologies and open BIM standards (the *Industry Foundation Classes* schema), so it can be applied to any BIM model, independently of the BIM software used. The method was tested on a realistic two-storey clinic building, with steel moment frames designed for a site in California. We show how the method significantly expedites the assessment process, with automatic creation of an inventory of vulnerable components. This inventory can be readily updated with the latest changes in the buildings' BIM models, and the consequent effect of these changes on the building's performance can be quickly evaluated. Practicing engineers can use this method to apply advanced seismic assessment more productively on real projects. Further research needs will also be discussed.

Keywords: seismic loss assessment, FEMA P-58, building information modelling, BIM, IFC.

INTRODUCTION

Buildings designed to meet current seismic design standards can usually avoid collapse during a major earthquake, but the structural system might still be damaged beyond what is economically feasible to repair [2]. Likewise, even if the structural system is slightly damaged in a strong earthquake, the nonstructural components and other contents of the building can experience severe damage. Examples of this can be seen, for instance, in the main airport in Santiago, Chile, after the 2010 Maule Earthquake, where the structure experienced minor damage, but the operations in the facility were interrupted nevertheless [3]. Healthcare facilities can also be heavily impacted by damage to nonstructural components, even if structural damage is not severe, as observed from the 2010 Darfield earthquake in New Zealand [4].

The consequences of these outcomes are human casualties and economic losses due to repair or demolition tasks, as well as downtime. These consequences, understood broadly as seismic losses, can be minimized by design, in principle, but current design methods established in building codes are not suitable for such task. Indeed, building codes worldwide have an implicit performance objective of protection of lives by avoiding collapse. The expectation is that a given design that complies with all the rules in the code will achieve the objective [5]. Thus, building codes alone cannot be used to design buildings with specific performance objectives, such as seismic loss minimization.

Conversely, modern *performance-based seismic design* (*PBSD*) methods have been developed to explicitly account for the potential losses in a given building, facilitating decision making using straightforward metrics of performance [2]. For instance, one of the most comprehensive and up-to-date methodologies for building performance assessment, the FEMA P-58 Methodology [1], can be used for a highly detailed quantification of building seismic performance in terms of probable economical losses due to future earthquakes, among other metrics. The results from this kind of seismic performance assessment constitute an objective criterion to select the most appropriate configuration of a building design among several alternatives.

In general terms, the FEMA P-58 Methodology is based on Monte Carlo simulation, and in each realization a set of structural building response parameters are used to assert damage states and corresponding repair costs for every component in the building, according to their fragility functions. Total repair costs are the summation of repair costs of all the components. The method considers variability in structural response, in component damage due to structural response, and in repair costs, among other source of uncertainty. A review of the methodology is outside the scope of this article, and relevant discussions can be found elsewhere (*e.g.*, [1], [25].)

There are many challenges when applying a method like FEMA P-58 in real building projects. One of them is the need to gather and manage very detailed information about a building's contents, their seismic damageability, and associated repair characteristics. For a structural design professional, processing all such information is cumbersome, prone to human errors, and time-consuming, thus not appealing in their practice. Moreover, the required information comes from all the disciplines in the building (*i.e.*, architectural, structural, mechanical, electrical, etc.), and is not static, since it is continually being developed throughout the design process.

To tackle this difficulty, recent research has explored the use of *Building Information Modelling* (*BIM*) in advanced seismic performance assessment. BIM is a design paradigm which is becoming the standard in the AEC/FM[1] industry to address the development and exchange of design information [6]. BIM is centred on the use of tridimensional models to manage all the information that is generated throughout the design and operation of a facility. As such, the BIM model of a building can provide a very detailed inventory, listing all relevant components and their properties, which can be used as input for a seismic loss assessment method.

In this research, we developed a framework for advanced seismic loss assessment of buildings using the BIM model of a building. A user of this framework could efficiently assess the probable seismic losses of a building whose design is documented in a BIM model, using the FEMA P-58 methodology. It is seen that it is possible to automate the generation of an inventory of building components as input for FEMA P-58, and that important differences can be observed in the estimated losses when compared to simpler but approximate methods are used to generate such inventory.

LITERATURE REVIEW

Building Information Modelling (BIM) can be thought of, in general terms, as a set of processes and computational tools used in the design, construction, and operation of facilities. It has become common practice in the AEC/FM industry. In more concrete terms, BIM revolves around using tridimensional (3D) representations of a facility, in which the components from all the subsystems of a building (*i.e.*, architectural, structural, and MEP[2]) can be represented geometrically and *semantically* (that is, by its function). To illustrate, the BIM model of a healthcare facility can be seen in Fig. 4, where the integration of all building disciplines can be appreciated. The BIM method has improved collaboration between the different disciplines involved in a building project thanks to digital workflows. For a thorough discussion on the multiple aspects of BIM, the reader can consult the works by Sacks *et al.* [6] and Borrmann *et al.* [7].

Although research on BIM has been mostly concerned with aspects of implementation to support efficient transfer of information during the development of a building project, there is an increasing interest in studying BIM for building performance [8]. Here, the term *building performance* is referred to in a broad sense, noting that *energy performance* and *thermal comfort* have been the primary focus of researchers in this area, and only recently BIM for seismic performance has drawn more attention.

In a conceptual study in 2014, Welch *et al.* [9] argue that BIM could help to reduce the uncertainty in seismic risk assessments. They reasoned that through BIM, a detailed inventory of a building can be obtained, comprising structural, architectural, and service components. Such inventory could then be used in a detailed seismic performance assessment procedure, such as the PEER-PBEE framework [10], reducing the uncertainty commonly present in such procedures. They further claim that manufacturer details in nonstructural components can allow for precise fragility assignment. Likewise, in a study about the

[1] Architecture, engineering, construction, and facility management.
[2] Mechanical, electrical, and piping systems.

application of FEMA P-58 on a realistic building, Yang *et al.* [11] indicated that collecting the building inventory was time-consuming and it needed coordination efforts. They did not used BIM but claim that doing so could be useful to obtain a detailed inventory including quantity, location, construction cost and time, and what they called ’seismic adequacy’ of structural, MEP, and architectural components, in order to reduce engineering effort in these activities.

Perrone and Filiatrault [12] demonstrated how BIM tools can be used for the seismic design of nonstructural components. Considering that losses due to damage in nonstructural components are significantly higher than those attributed to structural damage, they argue that detailed knowledge about nonstructural components is very important to reduce the uncertainty in the assessment of potential seismic economic losses. To this end, BIM technology could be very useful to conduct accurate assessments, given it is possible to develop a comprehensive inventory of nonstructural components, that includes connection details and accurate component quantities—aspects that are necessary for proper damage assessment and ensuing loss quantification. They proposed a design framework to help in the reduction of earthquake related losses, in which all the nonstructural components of a building are included, and their seismic details can be developed or verified by respective responsible parties, and then uploaded to a centralized BIM model. They illustrated with an example of seismic bracing design of a sprinkler piping system.

In recent years researchers have more explicitly focused on the benefits of BIM technology to manage building data as input for seismic loss assessments. Alirezaei *et al.* [13] proposed the concept for a semi-automated procedure for performance assessment, in which a BIM model of a structure was used to generate a structural analysis model for the OpenSees platform [14]. More recently, Xu *et al.* [15], [16] developed a method to apply the FEMA P-58 Methodology, using BIM to automate the creation of a structural analysis model and to manage all the information about vulnerable building components. They exploited the capabilities of the commercial BIM authoring tool Revit® [17], and its *application programming interface* to manage all the building information and to add other functionalities so the FEMA P-58 Methodology could be applied through the program’s graphical user interface (GUI). The authors emphasized that the application of FEMA P-58 with its original database of repair cost functions, which are based on costs in United States, to a building located elsewhere may lead to substantial errors. To overcome such limitation, Xu *et al.* [15] used a database of costs according to local practice in China for their framework. Through a case study application, they found that the results on probable building repair costs were consistent with existing data from actual repairs after earthquakes in China.

Despite all the progress, past research has focused on the development of tools that work with specific BIM software, as in the work by Xu *et al.* [15] where their implementation was a plug-in for Revit. Such approach narrows the scope of application to one in which all disciplines have been modelled using the same software. To improve on this aspect, and develop a method independent of commercial software vendors, it is possible to use the AEC/FM industry’s open standard for exchange of BIM information, namely the *Industry Foundation Classes* (IFC) data model [18]. All the major BIM software platforms can export a BIM model to an IFC format [19], hence, if the process uses IFC models as input, it can be broadly applicable.

BIM FRAMEWORK FOR SEISMIC LOSS ASSESSMENT

From the previous section it can be seen there is a clear interest in using BIM to generate a detailed inventory of building components for seismic loss assessment. Such an inventory can be used as input for a method like FEMA P-58. Although not explicitly mentioned in the literature review, an alternative to BIM would be simply to compute the quantities of the components of a building from design drawings or bills of materials and the like, which would be inefficient for a design practitioner, and not amenable for automation. The other alternative that is currently available is the *Normative Quantities* tool included with FEMA P-58 [20]. As stated in the documentation of the tool, it can provide an estimate of the quantities for all the typical components a building could have based on the building’s total area and occupancy type. The results that the tool provides are based on statistics from many buildings in the US, and for every quantity it can output median values and dispersions. The Normative Quantities approach offers a convenient way of producing a building inventory, but the type of components and quantities will only be a rough approximation, where the specifics of a building are not considered.

In this article we propose a BIM workflow to automatically generate a detailed inventory of a building based on the exchange of BIM data with an open data schema, IFC, instead of relying on specific commercial BIM software. In this way, we can conceive a general method to work with BIM data, that can be implemented by any researcher or practitioner and integrated into their assessment workflows.

The Industry Foundation Classes Schema

The Industry Foundation Classes (IFC) is a schema (or data model) developed and maintained by *buildingSMART International* [21] and formally defined in ISO 16739-1 [18]. It can be seen as an information exchange format for buildings, that attempts to be open and independent from BIM software tools. The schema is object-oriented, with a vast array of entities to represent building elements, such as beams and partition walls, to materials, space location, project actors and processes, and so on. A good review of IFC can be found in Borrmann *et al.* [7, Ch. 5] or in the documentation for the current version of the schema, IFC 4.3 [22].

The relevance of IFC stems from its adoption by BIM software vendors. Most of BIM authoring software can export a building model from its native data format to IFC, so it can be read by another program that supports IFC. There is more than one serialization format for IFC, but the most common one is *clear encoding*, which is a text format written with the *EXPRESS* modelling language [23].

To efficiently use the information stored in an IFC file—which can have several thousands of entities depending on the size of the building, knowledge of the IFC schema (hierarchy) is needed, but this is hardly a problem considering the growing number of open-source libraries for different programming languages that can be used to read and write IFC files. A list of such libraries can be found in the buildingSMART website [24], under the category *Development Tools*.

Proposed Framework

An overall workflow to use BIM for the seismic loss assessment of a given building is depicted in Fig. 1. We assume that the design of the building has been documented using BIM, and that the models from different design specialties are available in IFC format. A user of our method is thought to be a structural engineer, given that an understanding of the assessment process is still required. For the assessment itself, we are using the FEMA P-58 Methodology, which is state-of-the-art.

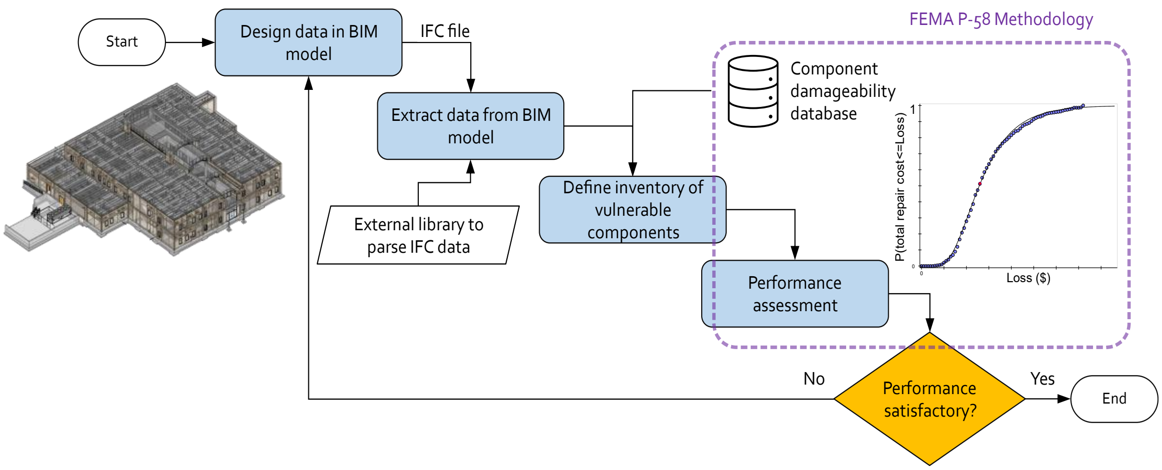


Figure 1. Overview of proposed framework for seismic loss assessment using Open BIM.

It should be noted that the IFC models must have relevant information about their elements' quantities. This requirement is easily satisfied by BIM software exporting their data info IFC, considering there is a standardized set of properties, or *IfcElementQuantity*, in the IFC schema, where relevant quantities such as component length or area are included. With this assumption, it is possible then to extract data from the BIM models and consolidate it in a database. The data extracted includes component location and its type, such as wall, duct, pipe, etc. An example showing how to traverse the IFC hierarchy to find the quantities required for an object in an IFC building model can be found in Fig. 2.

The following step is to define an inventory of seismically vulnerable components. The components in this inventory will need to be assigned a fragility function type and a *performance group* number according to the usage in FEMA P-58. This assignment process can be thought of as *classifying* BIM objects and is a common task in BIM workflows. As such, the IFC standard already considers classification codes as attributes that objects can have, according to different classification schemes. It is worth noting that the subject of classification in BIM is an independent research topic (*e.g.*, [26], [27]) and defining an automatic mechanism for it is beyond the scope of this study. For the purposes of the demonstration example included in the next section, we manually assigned fragility function codes to BIM objects based on their properties and engineering judgment.

Once having an inventory with fragilities and performance groups assigned, it is possible to prepare an input file for the PACT program, which is distributed with the supporting documentation of FEMA P-58 [20]. PACT can conduct all the calculations required for the loss assessment and display the results graphically. Although it supports input through a GUI, its internal file format is an XML file, which can be sourced in through a command line application included in PACT. Once the assessment is run, a user can review the results and decide on the adequacy of the performance or to improve some aspects of the design.

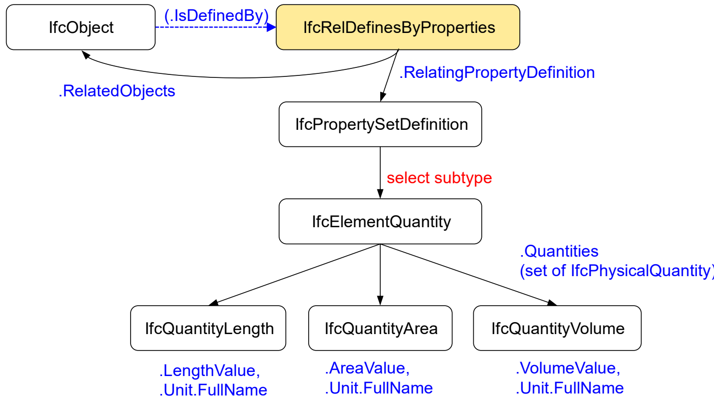


Figure 2. Example of traversing the IFC hierarchy to find building component properties.

To demonstrate the use of this framework, we developed a WPF (Windows Presentation Foundation) application, using .NET Framework version 4.8 [28], [29], and the C# programming language [30]. To work with the IFC data we used the open source library Xbim Toolkit [31]. The overall architecture of the system is illustrated in Fig. 3. We started with an off-the-shelf open-source IFC viewer program, and we added features to process IFC data into an inventory of building components, which can be visualized, and then serialized into the XML format that PACT supports. The program is a work in progress and not all the features, like visualization of results, are presented in this paper.

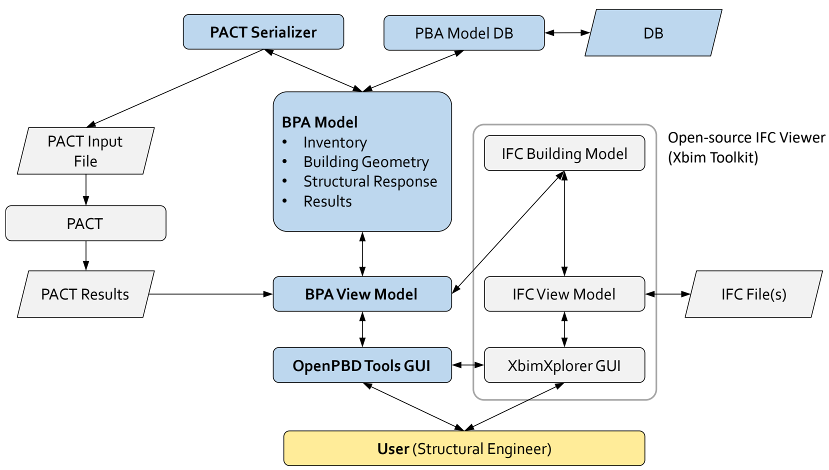


Figure 3. Proposed system architecture.

EXAMPLE APPLICATION

To demonstrate our developments, we used BIM data from a 2-storey clinic building that can be found online [32]. There are 3 models comprising architecture, structure, and MEP disciplines, and were published by the *Construction Engineering Research Laboratory*, *US Army Corps of Engineers* as part of a research project [33]. While the building is hypothetical, the models are realistic and very complete. A 3D view of the *federated model*[3] is shown in Fig. 4.

Building Setup

Despite the level of detail in the BIM models of the building, there was not structural design criteria available with which to set requirements for a seismic assessment. Thus, a site in California was assumed and a set of perimeter steel special moment frames (SMF) were designed according to ASCE 7 [34], AISC 360 [35], and AISC 341 [36]. The structural analysis model used for design was developed with Altair S-FRAME [37]. A 3D view of the model showing extruded members and a partial view of the SMF can be found in Fig. 6.

The design model was then used to automatically generate a 3D model for nonlinear analysis in OpenSees, using a set of Python routines previously developed by the authors [38]. Beams and columns in the SMF were modelled with plastic hinges using

[3] The term *federated model* or *federation* refers to a model obtained from a combination of different models of a building.

the Modified Ibarra-Medina-Krawinkler model [39], [40]; panel zones were modelled with Krawinkler's parallelogram model as per [41]. The nonlinear model was used to run nonlinear time-history analysis for a set of 11 ground motions at 8 levels of seismic intensity, as recommended in [25] for a time-based assessment. The ground motions were chosen according to a seismic disaggregation for the assumed site, but further details of the ground motion suite are not included for brevity. The structural analysis results are used to run three different assessment cases in which the quantities in performance groups are as follows:

I. Quantities from BIM inventory (assumed deterministic)
II. Normative Quantities with their respective dispersions (values will be treated as random variables in PACT)
III. Normative Quantities without dispersion (assumed deterministic)

These cases will enable us to compare the effect of having accurate quantities for the building components as opposed to approximate ones from statistical data. Case III was added to isolate the impact of the dispersion in the quantities from case II.

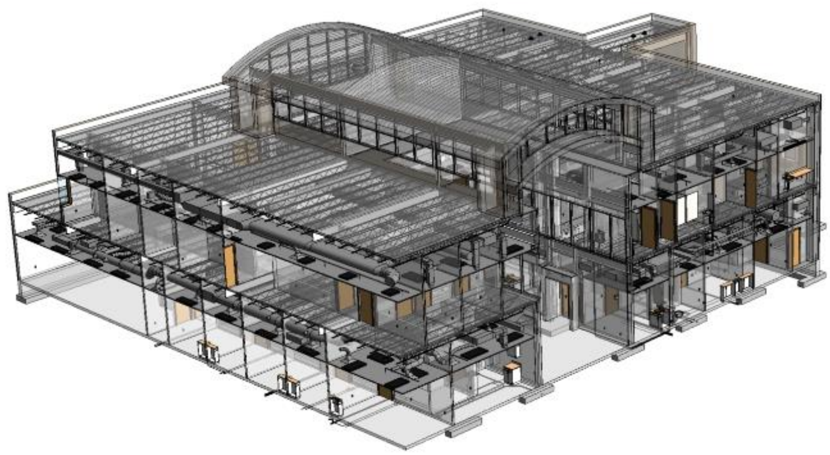


Figure 4. Section of BIM mode of a 2-story healthcare facility, displaying all disciplines. Model by NIBS [32].

Application and Results

As it was mentioned before, to create an inventory of vulnerable components, a mapping between BIM objects in the models and fragility functions and performance groups is necessary. For this example, the mapping was created manually using Revit 2023 and the original models before exporting the model to IFC format. Since classification is a common task in BIM, the tools available in Revit were used directly to assign a fragility code to every component, as shown in Fig. 5, for the case of an external wall assigned with the code *B2011.001b*, corresponding to a fragility function titled *Exterior Wall - Cold formed steel walls with wood structural panel sheathing, exterior - stucco one side*. It is important to mention that the practice of BIM is not uniform across the industry, and models can vary widely in their quality and amount of detail, thus it is not always possible to assign a fragility function precisely to a component based exclusively on the component properties in the model. Furthermore, for some components there might not be any appropriate fragility available in the FEMA P-58 database or custom database. We applied engineering judgment to complete the classification tasks for this example.

The prototype program developed to test our framework, applied to the current example, can be seen in the screenshot in Fig. 7. The figure shows a visualization of the architectural IFC model of the clinic building, and a tabular view of the respective inventory. Even though it is possible to consider the exact location of each component for the loss assessment, it was decided to lump the quantities of every fragility group according to storey level and direction. This simplification is a first approximation done to assess the effect of accurate quantities in the loss calculation, as compared to what would be obtained if using the *Normative Quantities* tool included with FEMA P-58 [20] (case I vs II and III).

A sample of the results can be seen in Fig. 8, where the total repair cost distribution for a seismic intensity with annual frequency of exceedance $\lambda = 4.04 \times 10^{-4}$ (return period $T_r = 2475$ years) is compared for the three cases described. There is a significant difference in the distribution of loss between case I and cases II and III. The median loss of the total repair cost in the assessments using Normative Quantities is approximately 50% larger than in the assessment with BIM quantities. Observing that the loss distribution curves in cases II and III are very similar, it can be argued that the big difference observed is due almost entirely to differences in the inventories from BIM and from the Normative Quantities tool, and to a lesser extent is due to randomness in the quantities. Considering this last observation, it is important to note that the inventories not only differ in the quantities associated to each building component, but also in the type of components in each one of them. A small fraction of components that appear in the Normative Quantities inventory is not present in the BIM inventory, because those components were not in the models, and vice versa. On one hand, the BIM inventory should be seen as the reference case, since the BIM models represent the specific building being studied, but on the other hand, the BIM models do not represent the *as-built* condition of the building, whereas the Normative Quantities statistics seem to be more complete in that regard. More research is necessary to clarify the effects of these factors.

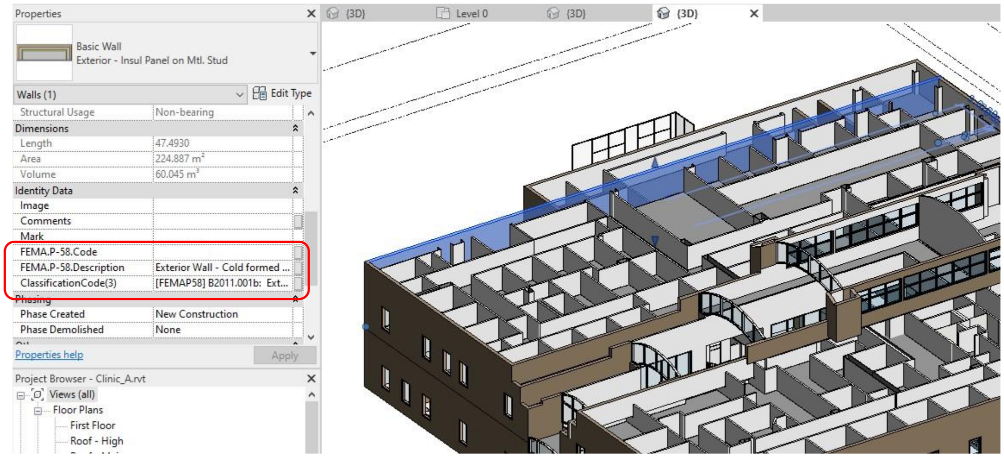
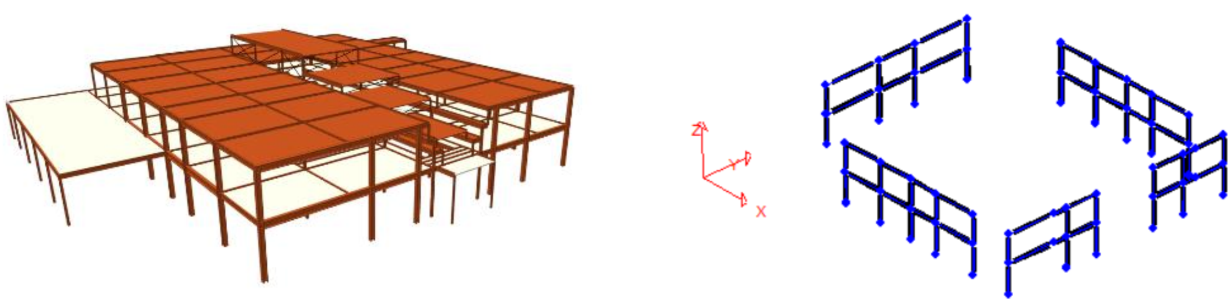


Figure 5. Classification of BIM objects in architectural Revit model according to fragility database codes.



(a) 3D overview of the complete model. *(b) Special steel moment frames only.*

Figure 6. Structural analysis and design model made in S-FRAME.

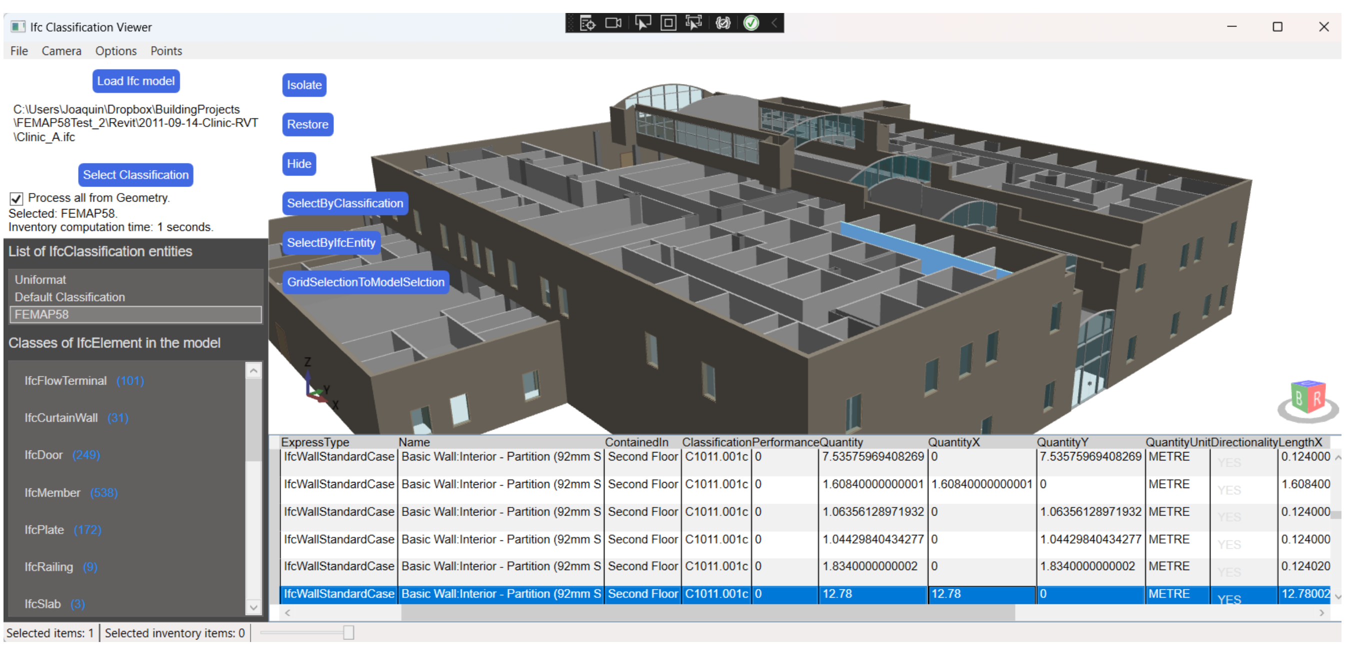


Figure 7. View of prototype desktop application, with a visual of an IFC model and respective inventory.

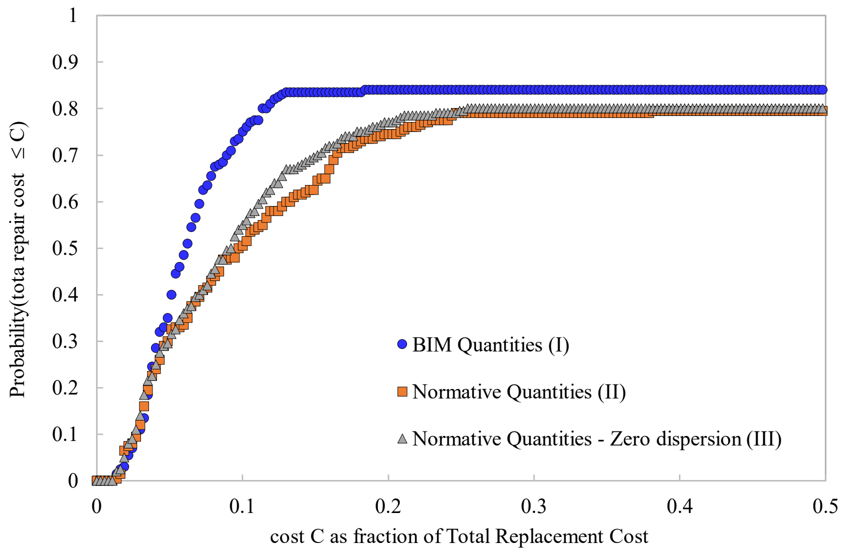


Figure 8. Comparison of loss distribution curves using an inventory from Normative Quantities and from BIM.

CONCLUSIONS

In this paper a method to generate the inventory of seismically vulnerable components of a building from BIM models was presented. The method is independent of BIM software used since it is based on the open data mode IFC. The resulting inventory can be used as input for the FEMA P-58 Methodology, and thus it can greatly expedite the assessment of seismic losses of a real-world building.

It was found that BIM technology is very suitable to automate and produce the information needed for seismic loss assessment according to FEMA P-58. The existing data abstractions present in BIM native formats and in IFC are sufficient to store and retrieve the data necessary to assign fragility functions to the components of a building, provided the detail of the BIM models used is high enough. The models used for illustration purposes in this paper were reasonably complete, but still an engineering judgement was required to assign fragility functions to certain components.

Assigning fragility functions to BIM objects is a crucial step that needs more research to automate it. This is a topic of ongoing research by the authors. More research is also required to establish minimum information requirements for BIM models, such that the loss calculations include all the components that typically contribute the most to seismic losses.

Through an application example it was observed that using quantities from BIM can have a significant impact in the total repair cost distributions when compared to approximate methods such as the Normative Quantities tools in PACT. It is acknowledged that more research is needed to thoroughly assess the effects of accurate quantities from BIM in loss estimates, considering that BIM models do not necessarily include all the information regarding a real building. Application of the method to a larger set of realistic building models is of interest to the authors as well. However, the presented method can clearly be used to automate cumbersome and time-consuming aspects of the assessment process, leaving more time for practitioners to deal with other important tasks, such as interpreting and using the results of a loss assessment to inform decision-making in real projects.

ACKNOWLEDGMENTS

The authors acknowledge the support of the Natural Sciences and Engineering Research Council of Canada (NSERC) and industry collaborator S-FRAME, part of Altair Inc. The first author gratefully acknowledges the funding of his doctoral studies provided by Agencia Nacional de Investigación y Desarrollo (ANID/PFCHA Becas Chile Doctorado 2019) [fellowship number 72200302].

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