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USE OF BUILDING INFORMATION MODELLING FOR THE SEISMIC DESIGN OF NON-STRUCTURAL ELEMENTS

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ABSTRACT

The damage observed during recent earthquakes demonstrated the high vulnerability of non-structural elements due to accelerations and displacements arising from the structure's seismic response. Non-structural elements that do not incorporate any seismic design generally exhibit damage at low seismic intensities and can significantly affect the immediate functionality of buildings. This issue is of paramount importance for strategic facilities, such as hospitals and schools that must remain operational in the post-earthquake emergency response. Nowadays some impediments still hinder the introduction of seismic design of non-structural elements into practice. The introduction of the Building Information Modelling (BIM) technology has significantly enhanced several aspects of the planning, design and construction processes along with numerous aspects of the project management. The capability of BIM to organize and export information to external software could greatly increase the feasibility of conducting comprehensive and automatic seismic design and risk assessment. The use of BIM could represent a new frontier in the seismic design of non-structural elements by increasing the reliability of the seismic design. In this study, the effectiveness of using Building Information Models for the seismic design of non-structural elements is demonstrated. A conceptual framework to perform the automatic seismic design of non-structural elements using information available in Building Information Models is presented. A simple Excel based tool has been developed in order to perform the automatic seismic design of sprinkler piping systems. The design tool extracts the piping layout from Building Information Models and performs automatically the seismic design of sway bracings according to the seismic provisions of the NFPA13 standard in the United States. The effectiveness of the proposed conceptual framework, as well as of the developed design tool, is investigated via an illustrative example.

Keywords: Seismic design, Non-structural elements, Building Information Modelling (BIM)

1. INTRODUCTION

Recent major earthquakes have demonstrated the strategic role of non-structural elements after a seismic event. Non-structural elements are not part of the load-bearing system, but are nonetheless subject to the same dynamic environment of a building during an earthquake. Modern building codes worldwide generally classify non-structural elements into three main categories: 1) architectural elements, 2) mechanical and electrical equipment and 3) building contents. Architectural elements, mechanical equipment as well as building contents must be designed to withstand the forces and displacements arising from the structure's seismic response. The damage observed during past earthquakes showed that damage in non-structural elements occur for seismic intensities much lower than those required to produce structural damage. Even if the non-structural elements are not part of the load-bearing system, they significantly affect the reparation costs and the immediate functionality of buildings after an earthquake. According to Miranda and Taghavi (2003), non-structural elements represent most of the total investments in typical buildings. In hospital buildings, for example, the structures make up

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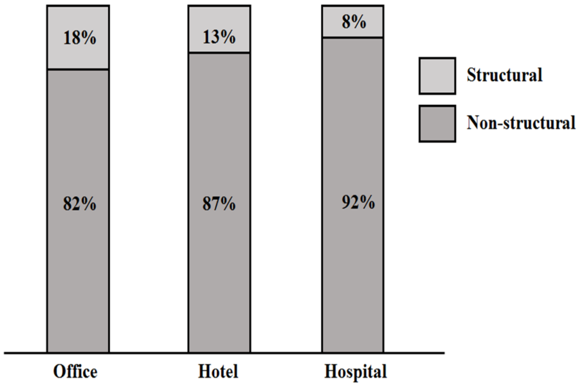
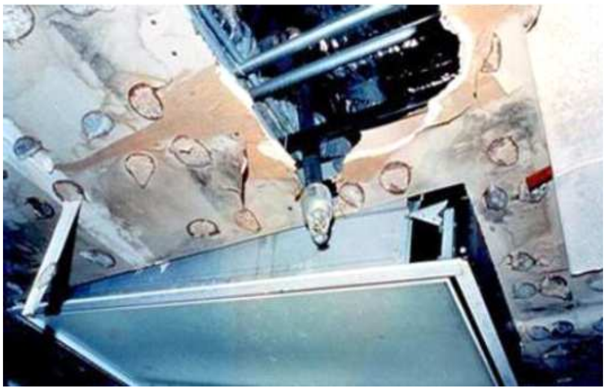
approximately only 8% of the total monetary investments (Figure 1a). Focusing, for example, on the damage to piping systems, observations from past earthquakes have demonstrated that the major damage in sprinkler piping systems is located at the joints, sprinkler heads, support hangers, and bracing systems (Figure 1b). After the 1994 Northridge Earthquake in California, many studies were conducted to assess the damage inside buildings and in particular in hospitals. Based on the surveys conducted respectively by Ayres and Phillips (1998) and Fleming (1998), damage data and information on piping systems in 13 hospitals were collected and described. Inside these buildings, water lines were broken, and most hospital buildings suffered from significant water damage due to failure of chilled water and hot water pipe lines. For example, the Olive View Hospital had no structural damage, but the hospital was closed because of water damage (Ayres and Phillips 1998). The February 27, 2010 Chile Earthquake, was one of the largest earthquakes in modern times; it was another demonstration of how non-structural damage affects the functionality of critical facilities. Four hospitals were closed, and 12 hospitals lost almost 75% of their functionalities due to failures of non-structural elements including fire sprinkler systems (Gupta and Ju 2011, Miranda *et al.* 2010).



a) Economical investments



b) Damage to sprinkler piping system (FEMA E-74 2011)

Figure 1. Typical non-structural elements damage and economical investments.

Many efforts have been done in the last years to develop advanced or simplified methodologies in order to evaluate the earthquake related losses and to ensure a desired building performance for a given intensity of seismic excitation (Welch *et al.* 2014a). The FEMA P-58 (2012) methodology is probably the most developed procedure to perform the probabilistic seismic assessment of a building performance. Figure 2 illustrates the four steps required to perform the probabilistic seismic assessment according to the Performance-Based Earthquake Engineering (PBEE) framework (Calvi *et al.* 2014).

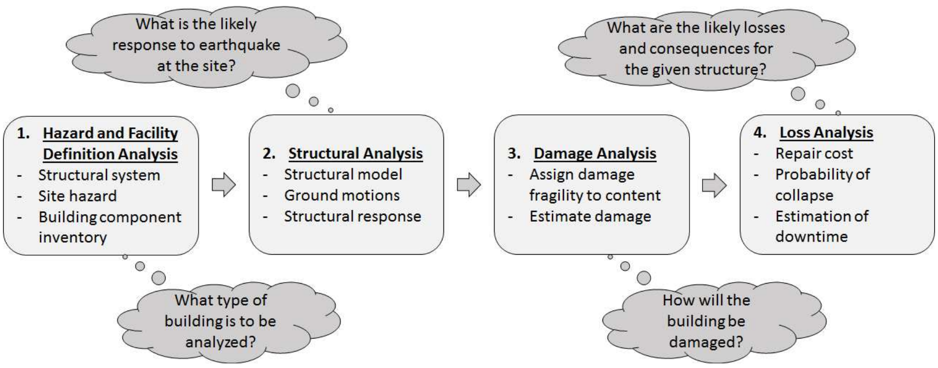


Figure 2. Overview of the four stages of PEER PBEE framework, after Calvi *et al.* 2014.

Within the PBEE framework the non-structural elements are of paramount importance, in particular in the damage (step 3) and loss analyses (step 4). During the damage analysis, the probability that a certain element (structural or non-structural) in the building will exceed a certain damage state for a given

intensity level is established. At this stage, the availability of fragility functions for both structural and non-structural elements is necessary. In the literature, few experimental investigations are available for non-structural elements. For this reason, many fragility functions are based on expert judgments.
The knowledge of details within a building is of paramount importance in order to reduce uncertainties and improve the quality of the analysis results, particularly in regards to non-structural elements. With this in mind, the use of Building Information Modelling (BIM) could significantly increase the accuracy of a seismic assessment (Welch *et al.* 2014b, Perrone and Filiatrault 2017). The use of BIM concentrates on preplanning, design, construction and integrated project delivery of buildings and infrastructure. Recently, research focus has shifted from earlier life cycle (LC) stages to maintenance, refurbishment, deconstruction and end-of-life considerations especially of complex structures (Volk *et al.* 2013). In this paper, the use of BIM to improve the seismic performance of non-structural elements is discussed demonstrating the effectiveness of the proposed approach through the development of a simple tool for the automated seismic design of sprinkler piping systems.

2. USE OF BIM IN SEISMIC DESIGN

Due to the increasing complexity in the design of new buildings a close collaboration between the different stakeholders involved in a construction project should be guaranteed. Nowadays the architectural design is devoted to ensure the functionality and the correct distribution of the space in the building as well as to facilitate the work of the mechanical engineers in terms of energetic efficiency. Similar considerations should be also applied to the seismic design of the buildings, with a close collaboration between the architects and the structural engineers. To obtain a desirable building performance the energetic and structural design should be harmonized looking at the seismic performance of the mechanical equipment required to create a safe and comfortable building environment. The same idea should be also applied to all architectural elements, such as partitions, ceilings and building contents, in order to achieve adequate seismic performance during seismic events. It is a common belief of investors and stakeholders that the seismic design of non-structural elements will significantly increase the costs of the building. Even if the tendency of the owners to go for the lowest fees in design contract negotiations could save money at the onset, it could significantly increase the repairing costs in the case of a damaging earthquake, particularly when improper attention is given to the design and installation of non-structural elements (Filiatrault and Sullivan 2014). The results of a recent study indicated that for piping systems installed in commercial buildings, the seismic design of the supporting system increase the costs by approximately 1% with respect to the overall cost of the piping system (Hilti 2016).
The second issue regarding the seismic design of non-structural elements is related to who should be responsible for the integration of structural and non-structural seismic design and installation. The answer to this question is not always clear because many professionals could be involved in this issue (i.e. architects, structural, mechanical and electrical engineers as well as the building owners). In terms of specific competencies, the only professional with expertise in the seismic design is usually the structural engineer. At the same time, structural engineers are often not interested in the design of non-structural elements and believe this issue is not inherent with their responsibility. Based on these considerations, it appears evident that a new profession called "non-structural coordinator" should be introduced within the building professions. The non-structural coordinator should be familiar with the basic principles of structural design and earthquake engineering. At the same time, a good background regarding the architectural aspects involved in the design process is required (mechanical, electrical and plumbing systems, furniture, architectural elements, etc.). In this context, the use of BIM could greatly enhance the integration between structural and non-structural engineering. The BIM process consists in creating digital files used for a 3D representation and management of the physical and functional characteristics of the building (Figure 3). BIM files can be seemingly exchanged or networked in real-time among the various building professionals who plan, design, construct, operate and manage the building. BIM could be very useful to identify performance targets both for structural and non-structural elements and to identify the more common typology and configuration of non-structural elements installed in the buildings. The detailing of all elements available in Building Information Models is essential to the PBEE assessment framework in order to properly attribute damage characteristics

(fragility functions), define the quantities (for the estimation of repair costs) and evaluate the repair time (Perrone and Filiatrault 2017). For this reason, the use of BIM could be considered a good solution to introduce in a more refined way the performance of non-structural element in the vulnerability analysis of buildings.

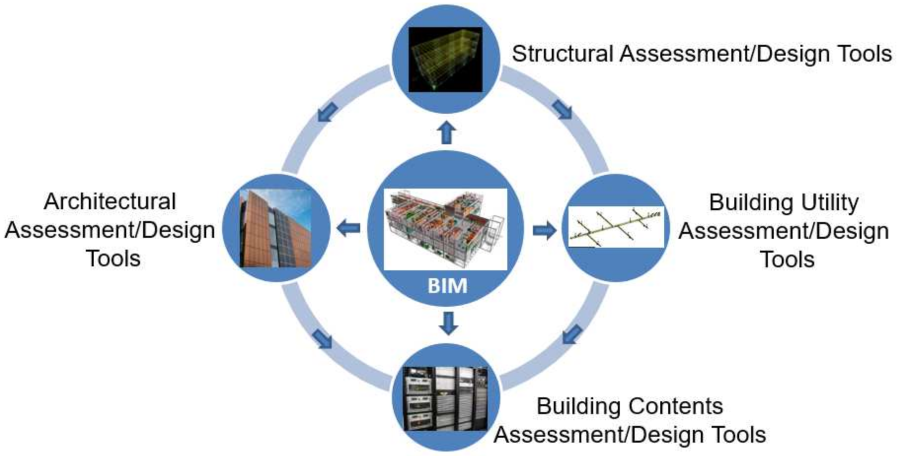


Figure 3. Seismic design of non-structural elements using BIM and seismic assessment/design software (Welch *et al.* 2014b)

The Building Information Models are traditionally used for clash detection, planning and scheduling (Ma et al. 2005, Jongeling and Olofsson 2007) without exploiting the great capability of the IFC format conventionally used in a BIM platform. The Industry Foundation Classes (IFC) data model is an open file format intended to describe building and construction industry data and normed by the International Standard ISO 16739:2013 (ISO 2013). The implementation of the information available in the Building Information Models in specific seismic design oriented tools through IFC file format could significantly improve the design of buildings. To date, some software solutions are able to perform the structural design of the building and export IFC files on BIM platforms. However, similar software are not available for non-structural elements. The development of a platform in which are collected all the information about the different typologies of non-structural elements installed in the buildings using the capabilities of the IFC format could allow the seismic design of non-structural elements and the achievement of desirable seismic performance not only from a structural point of view but for the entire building environment. The platform would classify the non-structural typologies in different categories in order to define the non-structural elements that require specialized design tools and those for which is required the application of code prescriptions (Figure 4). Once the seismic design is performed, the information on seismically designed non-structural elements could be uploaded to update the original Building Information Model.

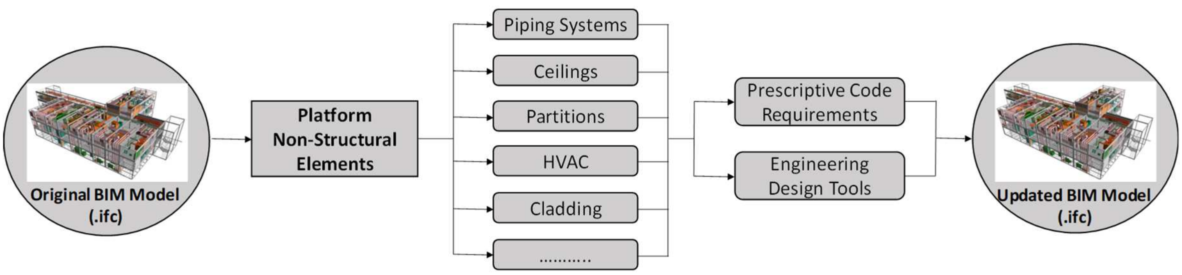


Figure. 4. Framework for the automatic seismic design of non-structural elements using Building Information Models

3. AUTOMATIC SEISMIC DESIGN OF SPRINKLER PIPING SYSTEMS

In order to demonstrate the effectiveness of the logical framework proposed in Figure 4 for the seismic design of non-structural elements using BIM, an illustrative example is presented and discussed. The illustrative example consists in the seismic design of the lateral supporting system for the sprinkler piping system in a building. Figure 5 shows all steps of the proposed procedure. Once the layout of the piping system is extracted by the Building Information Model, it can be uploaded in any CAD platform in order to obtain the coordinates of all piping elements. The seismic design of the sway bracing system is performed through a specialized tool called “Seismic Analysis of Piping System for BIM application” or “SAPIS-BIM”. This tool was developed in Microsoft Excel using Visual Basic for Application (Office VBA 2016). When the design of the bracing system is finalized, the coordinates of all elements of this system are used to update the original Building Information Model thanks to the versatility of the .IFC file format.

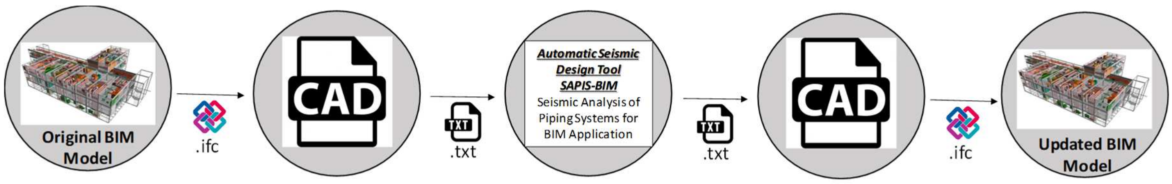


Figure 5. Seismic design of sprinkler piping systems using BIM data

3.1 Description of SAPIS-BIM Tool

SAPIS-BIM (Seismic Analysis of PIping Systems for BIM Applications) is a seismic design tool developed to demonstrate the effectiveness of using BIM in performance based seismic design of pressurized fire suppressant sprinkler piping systems that are very common in important facilities, such as schools and hospitals. SAPIS-BIM was developed to automatically perform the seismic design of the lateral supporting systems of sprinkler piping systems according to the seismic provisions included in the NFPA13 standard (2016) based on information extracted from the Building Information Models. NFPA13 (2016) provides the minimum requirements for the design and installation of automatic fire sprinkler systems in the United States. Chapter 9 of NFPA13 provides the seismic protection requirements in terms of hanging, bracing and restraints of piping systems. In particular, Section 9.3 describes the requirements to protect against damage from earthquakes water-based fire protection systems. The flowchart illustrated in Figure 6 summarizes the steps to be performed during the procedure implemented in SAPIS-BIM.

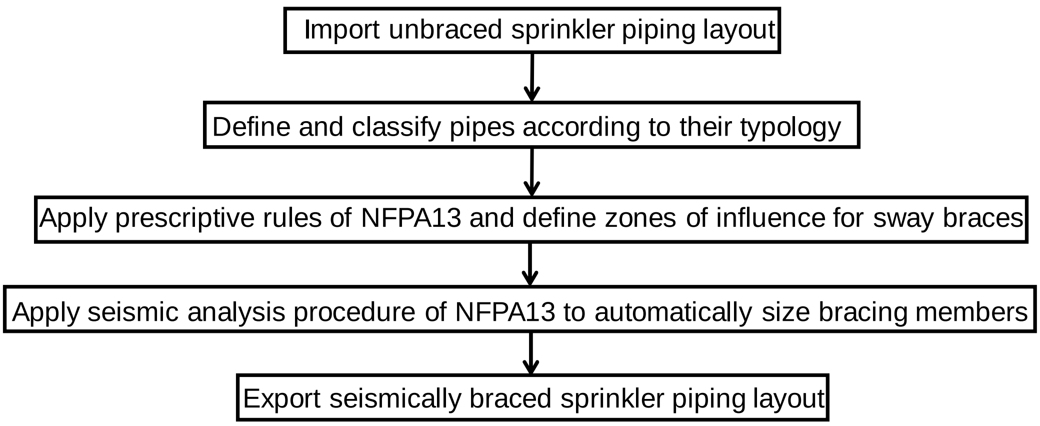


Figure 6. Flowchart of the procedure implemented in SAPIS-BIM

In order to import the unbraced sprinkler piping layout in SAPIS-BIM, it is required to create a .txt file in which the coordinates of the piping joints are listed. The tools available in CAD Applications could be used to automatically create the .txt file. Once the coordinates are correctly uploaded in SAPIS-BIM, a graphical representation of the piping layout is automatically sketched in a dedicated spreadsheet in order to verify if some inconsistencies arose during the uploading of the data. For each pipe, the typology (Main/Branch Line) and the diameter must be defined, NFPA 13 provides different prescriptive requirements as function of the pipe's typology, diameter and bracing direction. SAPIS-BIM automatically stores each pipe in a different spreadsheet according to its typology. The zones of influence are evaluated in terms of length of pipes and are used to calculate the seismic demand on the sway braces. The minimum number and the distance between transverse and longitudinal sway braces according to NFPA13 is automatically calculated for each pipe. The primary layout of sway braces is then finalized using various procedures available in NFPA13 to evaluate the seismic design forces and the dimensions of the brace sections. The three methodologies proposed by NFPA13 in order to evaluate the seismic design force have been implemented in the procedure. According to NFPA13, the horizontal force acting on the brace shall be permitted to be determined in accordance with Section 13.3.1 of SEI/ASCE 7-10 (2010) multiplied by 0.7 to convert to allowable stress design. Two simplified approaches are also permitted. In the first simplified procedure, the horizontal force acting on the brace shall be taken as $F_{pw} = C_pW_p$, where C_p is a tabulated seismic coefficient function only of the short period response parameter (S_s) at the building's site, while W_p is the weight of the piping system being braced (it is taken 1.15 times the weight of the water-filled piping). If data for determining C_p are not available, the horizontal seismic force acting on the braces shall be determined assuming $C_p = 0.5$. Once the seismic demand is evaluated, it is necessary to define the section and the size of the braces along with their geometrical configuration (height from the ceiling and angle of inclination). The slenderness ratio of the sway brace member is automatically evaluated and verified. NFPA13 includes capacity tables only for specific values of brace slenderness ratio (100, 200 and 300). SAPIS-BIM automatically performs the seismic verification of the braces. If the braces are not adequate, the user must change the size of the braces in order to finalize and optimize the design. Finally, the coordinates of the sway braces can be automatically exported in the CAD application using a .txt file created by SAPIS-BIM and then it is possible to update the Building Information Model using the versatility of the .IFC file format.

3.2 Illustrative Example

The case study building selected for illustrating the capabilities of the SAPIS-BIM tool is a four-storey reinforced concrete (RC) structure. Figures 7 and 8 show the main geometrical dimensions of the building. The building is assumed located in Cassino, Italy on a soil class A according to the soil classification proposed in Eurocode 8 (CEN 2004). This site is characterized by a design peak ground accelerations on stiff soil equal to 0.21g for a 10% probability of exceedance in 50 years and it is representative of a medium-high seismic hazard in Italy. The 2% in 50 years spectral acceleration value at a period of 0.2 s (equivalent to S_s in ASCE7) for the building's site is equal to 0.90g.

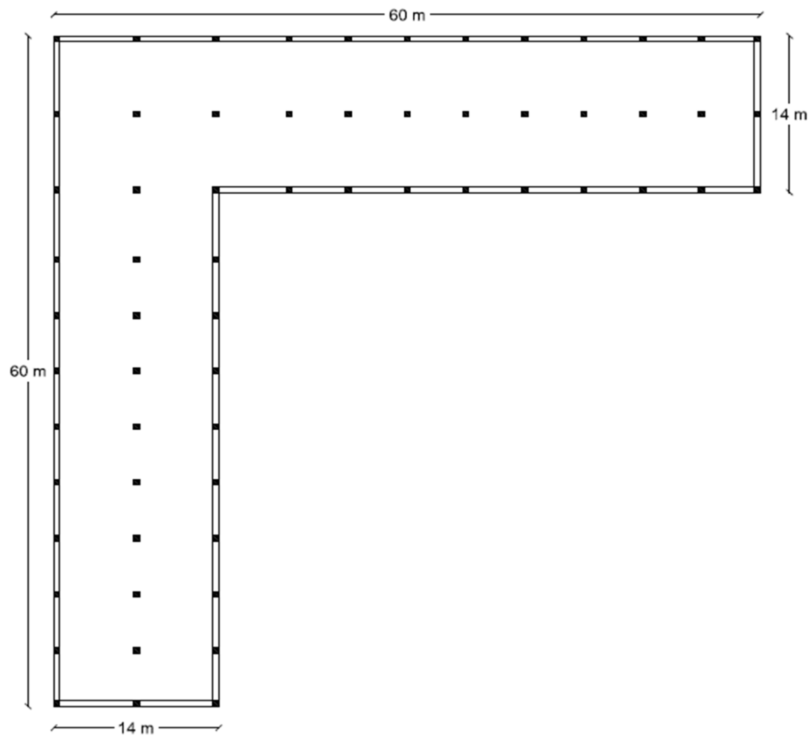


Figure 7. Plan view of the case study building

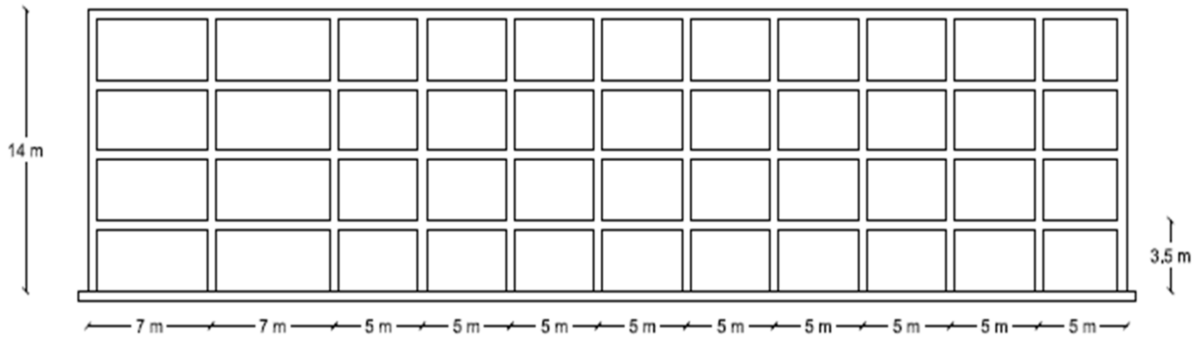


Figure 8. In elevation view of the case study building

A black iron threaded sprinkler piping system is installed in the case study building (Figure 9). The layout of the sprinkler piping system is composed of two main lines that run along the longest dimensions of the building and 15 branch lines orthogonal to the main lines. The main lines of the sprinkler piping system are made of 89 mm (3.5 in.) schedule 10 pipes, while the branch lines are made of 32 mm (1.25 in.) schedule 10 pipes. The same configuration is assumed at all floors of the case study building. A riser line with a diameter equal to 89 mm connects the sprinkler piping systems installed at each floor.

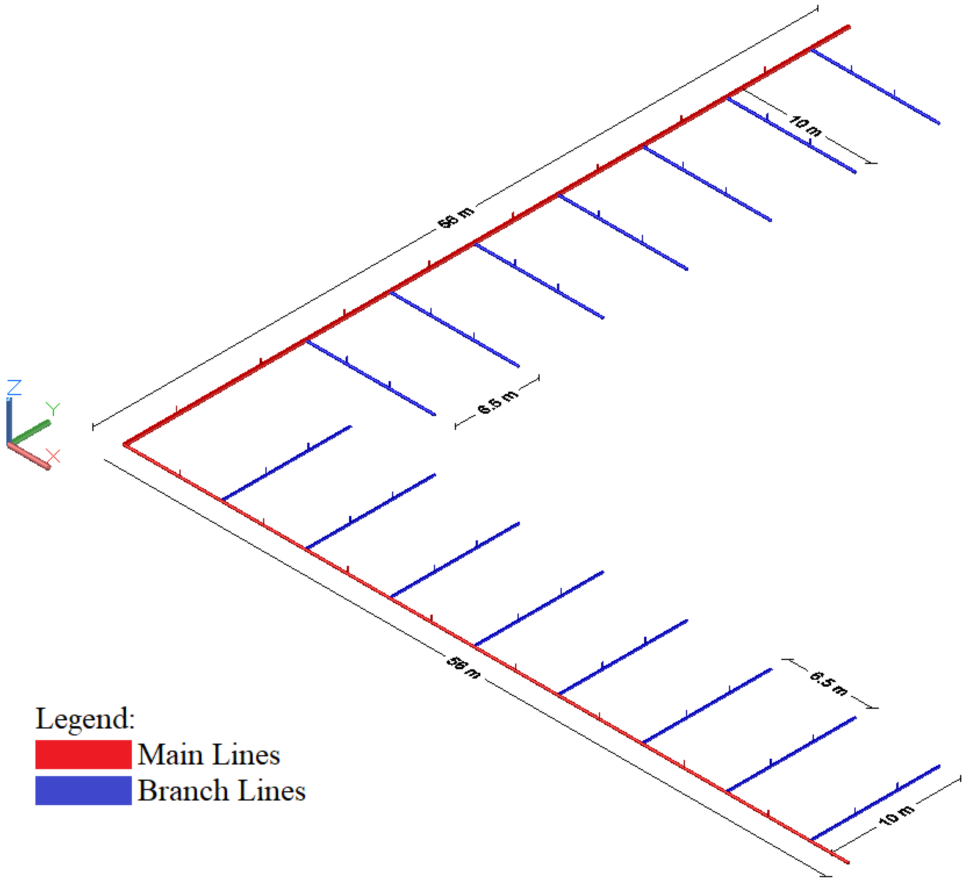


Figure 9. Layout of the sprinkler piping system

A simplified Building Information Model of the building was developed using Tekla BIMsight software (2016). In the Building Information Model, only the information required for this illustrative example (Figure 10) was included.

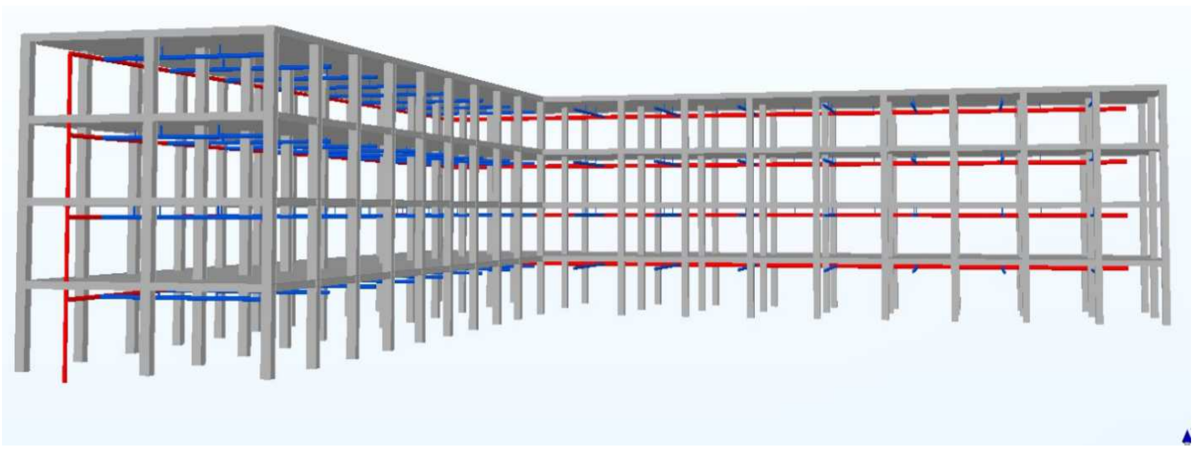


Figure 10. Building Information Model of the case study building with unbraced sprinkler piping system

3.3 Seismic design of bracing members

The first step in the seismic design of the lateral supports for the sprinkler piping system using SAPIS-BIM consists in the evaluation of the minimum number of braces (lateral and longitudinal). According to NPFA13 the maximum spacing between lateral and longitudinal braces shall not exceed 12 m and 24 m, respectively. Specific prescriptions are provided regarding the location of lateral and longitudinal sway braces near the end of pipe runs and near the changes in direction of the piping. For example, the first lateral sway brace should be located at a maximum 1.8 m from the end of the pipes not connected with other elements. For the sprinkler piping systems analyzed in this study, SAPIS-BIM automatically identified the two main lines (1-X and 1-Y) and the 15 branch lines. For each of them, the minimum number and distance between transverse and longitudinal sway braces are calculated along with the zone of influence applied on each sway brace, as reported in Table 1.

Table 1. Minimum requirements according to NFPA13

Typology	Direction	ID Pipe	Transverse Sway Braces		Longitudinal Sway Braces	
			ID Brace	Zone of Influence (mm)	ID Brace	Zone of Influence (mm)
Main Line	X	1-X	T-1	2203	L-1	3950
			T-2	3205	L-2	4900
			T-3	3205	L-3	4750
			T-4	3205	N/A	N/A
			T-5	1783	N/A	N/A
	Y	1-Y	T-1	1203	L-1	2950
			T-2	3205	L-2	4900
			T-3	3205	L-3	4750
			T-4	3205	N/A	N/A
			T-5	1783	N/A	N/A

N/A: Not Applicable

Five transverse sway braces and three longitudinal sway braces are required for both main lines (1-X and 1-Y). The branch lines do not require longitudinal nor transverse sway braces because the pipe diameter is smaller than 65 mm per NFPA13 provisions.
The seismic demand on the sway braces were calculated using the zone of influence provided in Table 1 and according to the simplified procedure allowed by NFPA 13 using only S_s = 0.90 g. Based on this approach the value of the seismic coefficient C_p is equal to 0.48. Table 2 lists the horizontal design seismic force on each sway brace calculated by SAPIS-BIM.

Table 2. Horizontal Seismic Demand on each sway brace in the main lines

Typology	Direction	ID Pipe	Transverse Sway Braces		Longitudinal Sway Braces	
			ID Brace	Horizontal Seismic Demand (kN)	ID Brace	Horizontal Seismic Demand (kN)
Main Line	X	1-X	T-1	1.15	L-1	0.93
			T-2	1.35	L-2	0.90
			T-3	1.35	L-3	0.83
			T-4	1.35	N/A	N/A
			T-5	0.82	N/A	N/A
	Y	1-Y	T-1	0.95	L-1	1.25
			T-2	1.35	L-2	1.22
			T-3	1.35	L-3	1.12
			T-4	1.35	N/A	N/A
			T-5	0.82	N/A	N/A

N/A: Not Applicable

To perform the verification of the sway braces, it is required to select the typology and dimension of the braces as well as the installation angle and vertical clearance of the sprinkler piping system. For this illustrative example, the vertical clearance was assumed equal to 1000 mm while the installation angle was taken as 45°. SAPIS-BIM automatically evaluates the maximum capacity and performs the verification in terms of capacity and slenderness ratio.
By changing the typology and section of the braces, it is possible to perform the optimization of the design in order to reduce the retrofit costs. In this case study, the maximum seismic demand on the braces is equal to 1.35 kN, a Pipe Schedule 40 with a diameter equal to 25 mm was selected for all sway

braces (Table 3). The allowable strength of the selected brace section is equal to 5.82 kN. Despite that capacity/demand ratio is quite high (4.3), this brace section was selected since is the smallest available to meet the maximum slenderness ratio requirement of 300. Even if for the branch lines do not required a specific design, NFPA13 prescribes that some restraints shall be installed.

Table 3. Braces typology in the main lines

Typology	Direction	ID Pipe	Transverse Sway Braces			Longitudinal Sway Braces		
			ID Brace	**Type**	**Diameter (mm)**	**ID Brace**	**Type**	**Diameter (mm)**
Main Line	X	1-X	T-1	Pipe Schedule 40	25	L-1	Pipe Schedule 40	25
			T-2	Pipe Schedule 40	25	L-2	Pipe Schedule 40	25
			T-3	Pipe Schedule 40	25	L-3	Pipe Schedule 40	25
			T-4	Pipe Schedule 40	25	N/A	N/A	N/A
			T-5	Pipe Schedule 40	25	N/A	N/A	N/A
	Y	1-Y	T-1	Pipe Schedule 40	25	L-1	Pipe Schedule 40	25
			T-2	Pipe Schedule 40	25	L-2	Pipe Schedule 40	25
			T-3	Pipe Schedule 40	25	L-3	Pipe Schedule 40	25
			T-4	Pipe Schedule 40	25	N/A	N/A	N/A
			T-5	Pipe Schedule 40	25	N/A	N/A	N/A

SAPIS-BIM then automatically determines the required restraints for each branch line. For this illustrative example, No. 12, 44 lb (1.96 kN) wires installed at 45° from the vertical and anchored on both sides of the pipe were selected. The wires are installed at mid-span of the branch lines. According to NFPA13, for branch lines with a diameter equal to 32 mm the maximum spacing between wires should not exceed 14 m (for $C_p < 0.5$). Figure 11 shows a three-dimensional rendering of the sprinkler piping system including the transverse and longitudinal sway braces as well as of the wire restraints installed in the branch lines.

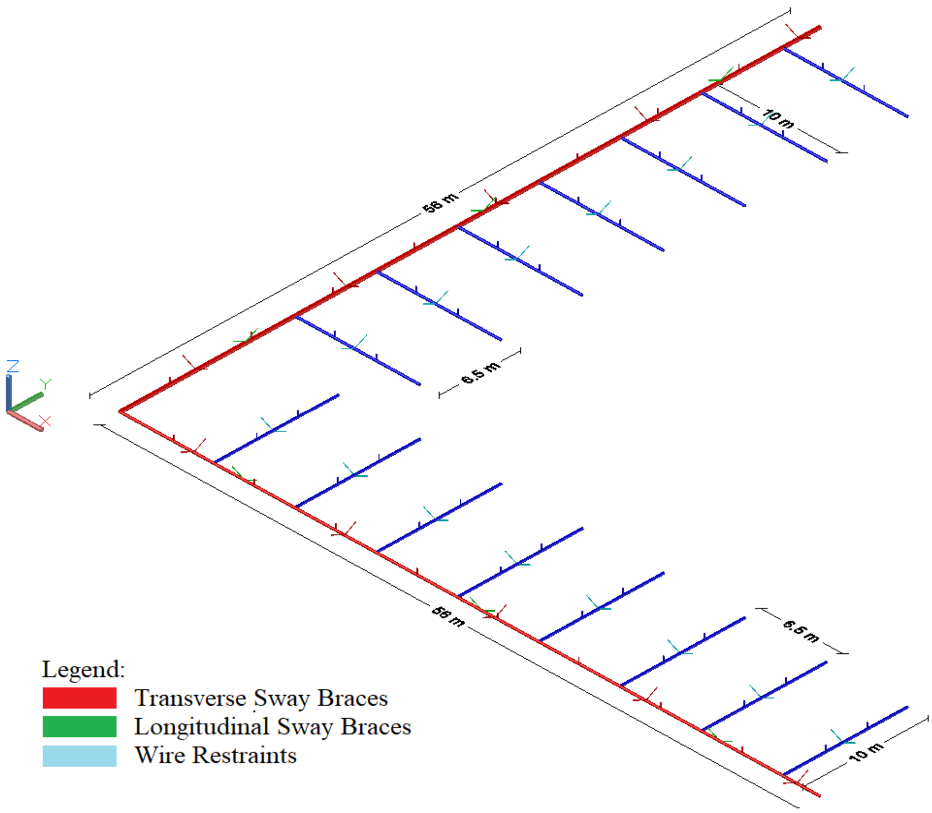


Figure 11. Layout of the sprinkler piping system seismically braced

The output file generated by SAPIS-BIM was used to export the coordinates of the bracing elements in the CAD application and to update the Building Information Model using the .IFC file (Figure 12).

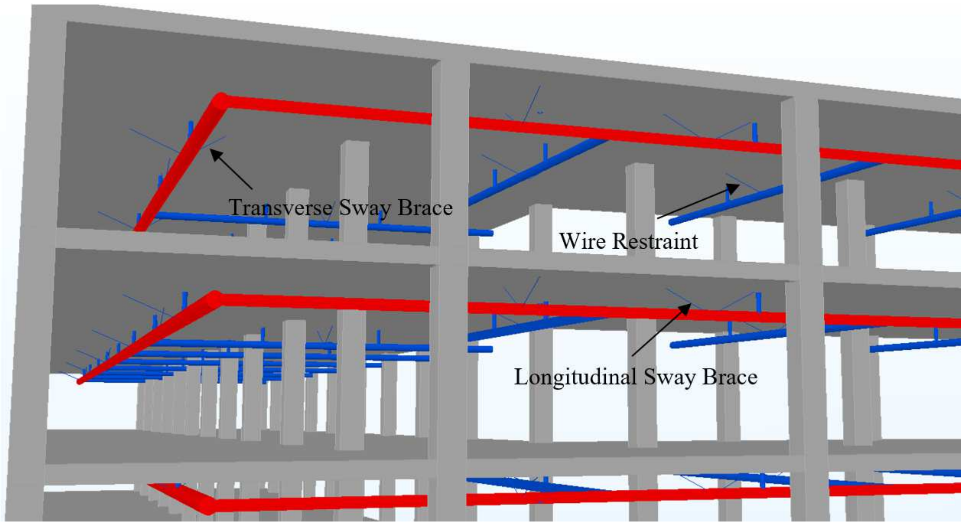


Figure 12. Updated Building Information Model with seismically braced sprinkler piping system (detailed view of sway braces and restraints in the top two floors of the case study building)

4. CONCLUSIONS

The results of the post-earthquake reconnaissance highlighted the high vulnerability of non-structural elements. Specific seismic regulations devoted to improving the seismic performance of non-structural elements and to reduce the associated economic losses, loss of functionality, and potential threats to life safety need to be introduced around the world. An effective method to improve the seismic performance of non-structural elements could be the implementation of performance-based seismic design coupled with the utilization Building Information Modelling (BIM) technology. In this study, a conceptual framework to use BIM for the seismic design of non-structural elements has been proposed. The effectiveness of the proposed methodology has been demonstrated through an illustrative example in which the seismic design of a sprinkler piping system was conducted automatically based on the information contained in a Building Information Model. In order to perform the automated seismic design, a simple Excel based tool (SAPIS-BIM) has been developed. The information available in the Building Information Model was easily implemented in SAPIS-BIM to perform the seismic design of the sprinkler piping system according to the NPFA 13 seismic provision. Based on the results obtained, the authors believe that the proposed methodology could be extended to different typologies of non-structural elements in order to create a unique platform in which all the non-structural elements available in a building could be classified and designed/verified. The introduction of this methodology, as well as of a new professional field referred to as “non-structural coordinator”, could significantly help lifting some of the impediments to incorporating non-structural seismic design into practice and in reducing earthquake related losses.

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