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# Automated seismic design of non-structural elements with building information modelling

Daniele Perrone[a,*], Andre Filiatrault[a,b]

[a] University School for Advanced Studies IUSS Pavia, Italy
[b] State University of New York at Buffalo, USA

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ABSTRACT

The seismic performance of non-structural elements is nowadays recognized to be a key issue in performance-based earthquake engineering. The knowledge of construction details within a building is of paramount importance in order to reduce uncertainties and improve the quality of the analysis and design, particularly in regards to non-structural elements. The use of Building Information Modelling (BIM) could represent a new frontier in the seismic design of non-structural elements by increasing the reliability of the seismic design and/or assessment. This study discusses the effectiveness of using Building Information Models in seismic design of non-structural building elements. A simple tool has been developed to perform automatically the seismic design of sway braces for pressurized fire suppressant sprinkler piping systems based on information extracted from a Building Information Models. The effectiveness of the proposed procedure was validated via a case study.

## 1. Introduction

Non-structural elements represent all the systems and elements attached to the floors and walls of a building that are not part of the load-bearing structural system [1]. 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. The architectural elements include suspended ceilings, partition walls, window systems and all those elements that form part of the buildings. Mechanical and electrical equipment are built-in non-structural elements that include electrical equipment, HVAC equipment, cooling towers, and piping systems. Finally, building contents belong to the occupants of a building and include computer and communication equipment, bookshelves and filing cabinets. Fig. 1a shows a three-dimensional view of a portion of a building with common non-structural elements along with typical structural components. According to Miranda and Taghavi [2], non-structural elements represent most of the total investments in typical buildings. In hospital buildings, for example, the structures make up approximately only 8% of the total monetary investments (Fig. 1b).

The damage induced in non-structural elements during recent earthquakes demonstrated their vulnerability to accelerations and displacements that arise from the structure's seismic response. A significant part of the observed earthquake related losses in recent earthquakes worldwide has been attributed to the damage to non-structural elements. The non-structural elements without seismic design generally exhibit damage at low seismic intensities and can significantly affect the immediate functionality of buildings [4]. This issue is of paramount importance for strategic facilities, such as hospitals and schools that should remain operational in the post-earthquake emergency response [5]. During the recent 2010 Chile earthquake, the Santiago International Airport was closed for several days following the significant damage to the piping systems interacting with ceiling systems [6]. During the same earthquake, four hospitals completely lost their functionality and over 10 lost 75% of their functionality due to damage to fire sprinklers [6]. During the 2001 Nisqually earthquake in the Seattle region in the United States (US), considerable damage was observed to suspended ceiling systems and interior partition walls [7]. During the 2009 L'Aquila earthquake in Italy, one of the most common non-structural element failures was related to partition walls experiencing large in-plane inter-storey drifts [8,9]. Significant damage to non-structural elements has been also observed during the 2012 Emilia earthquake in Italy. In this seismic event, industrial facilities reported large economical losses often related to the failure of rack systems [10].

In the light of these considerations, the seismic performance of non-structural elements is nowadays recognized to be a key issue in performance-based earthquake engineering (PBEE) in order to ensure a desired structural system performance for a given intensity of seismic excitation [11]. The most developed guidelines for the application of PBEE are those included in the FEMA P-58 document [12] developed

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* Corresponding author at: University School for Advanced Studies IUSS Pavia, Palazzo del Broletto—Piazza della Vittoria, Pavia, Italy.
*E-mail address:* daniele.perrone@iusspavia.it (D. Perrone).

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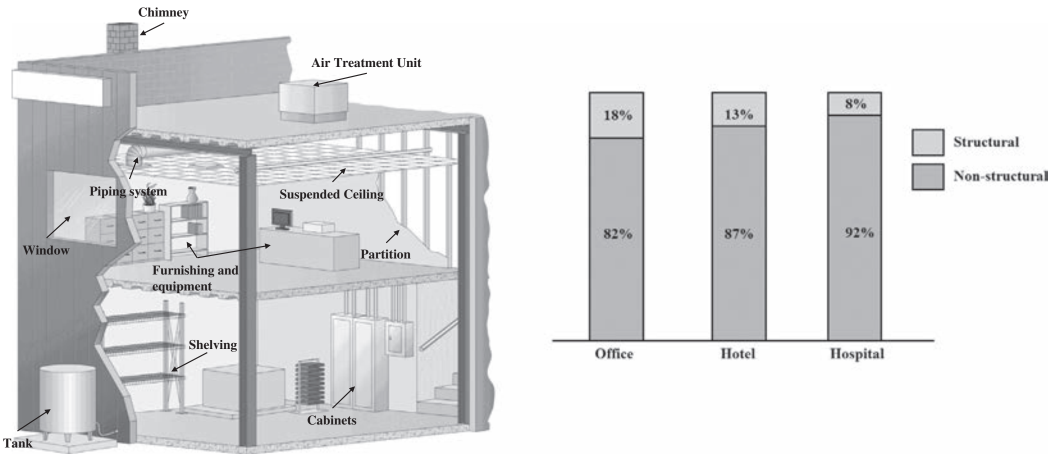

a) Typical non-structural elements, after [3]  b) Relative investments in typical buildings, after [2]

**Fig. 1.** Typical non-structural elements and economical investments.
a) Typical non-structural elements, after [3].
b) Relative investments in typical buildings, after [2].

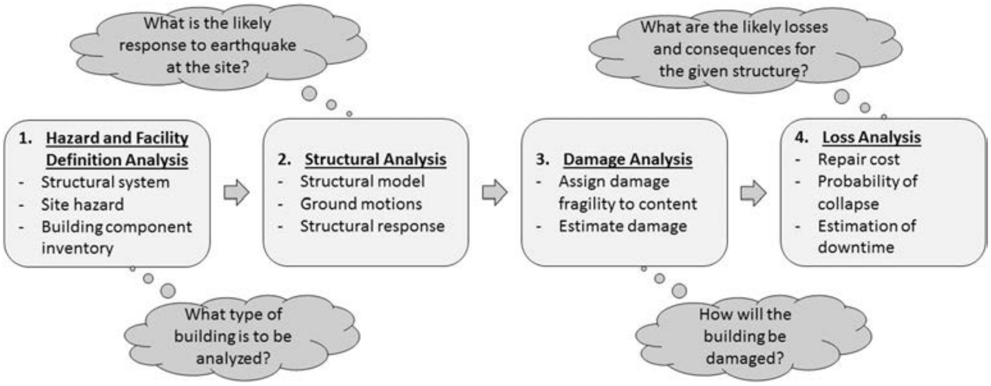

**Fig. 2.** Overview of the four stages of PEER PBEE framework, after [13].

largely based on research conducted by the Pacific Earthquake Engineering Research Center (PEER). The FEMA P-58 procedure allows the probabilistic seismic assessment of the building performance through a multi-stage process based on PEER's PBEE framework. As illustrated in Fig. 2, the PEER's PBEE framework involves four stages: 1) hazard and facility definition analysis, 2) structural analysis, 3) damage analysis and 4) loss analysis.

The first two stages represent the conventional steps in earthquake engineering analysis. In the facility definition stage, the structural configuration and the seismic hazard at the facility location are evaluated. During the structural analysis stage, a structural model of the building is subjected to seismic excitations of various intensities in order to evaluate the maximum response in terms of displacements, forces and accelerations. The third stage of the performance evaluation consists in the damage analysis, which establishes the probability that a certain element (structural or non-structural) in the building will exceed a certain damage state for a given intensity level (using the structural analysis results together with the element fragility functions) [14]. Given the numerous types of structural and non-structural elements that can be found in a building, the availability of element fragility functions depends on extensive experimental investigations [15–16]. Finally, the last stage of the procedure includes the computation of decision variables such as monetary loss due to repair costs, loss of use of facility (downtime) or the likelihood of injuries and/or fatalities. For each damage states defined during the analysis, the consequences for all elements over the range of possible intensity levels are established.

The importance of non-structural elements in the PBEE framework is evident, considering the non-structural damage observed during past earthquakes. The losses and consequences related to the damage of non-structural elements are much higher than those due to structural elements, in particular for low intensity seismic events. 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. Building Information modelling is defined by international standards as "*a shared digital representation of physical and functional characteristics of any built object which forms a reliable basis for decision*" [17]. BIM is a tool to manage accurate building information over the whole life cycle of a facility and is able to support data beyond the design and construction phases, such as the management, maintenance and deconstruction processes [18–19]. The detailing of all elements available in Building Information Models is essential in 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. This paper discusses how the information available in Building Information Models could be used for the seismic design of non-structural elements in order to reduce the seismic risk of new and existing buildings. A case study is presented on the automatic seismic design of pressurized fire suppressant sprinkler piping systems using BIM.

## 2. Impediments to incorporate non-structural design into practice: use of BIM in seismic design

The increasing complexity of new building designs due to ever more stringent requirements have resulted in design professionals becoming increasingly specialized, with each group focusing on a particular project aspect [17]. For this reason, it is of paramount importance that a close collaboration be maintained between the different stakeholders involved in a construction project. In order to ensure the energetic efficiency of buildings, for example, a close cooperation between architects and mechanical engineers is necessary. At the design stage, the architects evaluate the best materials and the building orientation in order to decrease the thermic dispersions and facilitate the work of the mechanical engineers. The same idea should be applied during the seismic design of buildings. As discussed in Section 1, the seismic design of a building is not only related to the structural safety but also to the achievement of adequate seismic performance of the non-structural elements. For this reason, the performance of structural and non-structural systems must be harmonized.

One of the impediments to incorporate seismic design in non-structural elements is the perception by investors and stakeholders that construction costs would increase. An estimation of the costs related to the seismic design of non-structural elements was conducted by the authors through a survey of some manufacturers of supporting piping systems. The results of the survey 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 [20]. Comparing only the costs related to the supporting system, the costs increase by about 17% if the supporting systems are seismically designed compared to those designed only for gravity loads. In the evaluation of the costs, the advantages related to reduced losses after an earthquake should be considered as well as the increased life safety. Note also that the seismic design of some typologies of non-structural elements is mandatory in some seismic active areas.

Close collaboration between architects and structural engineers understood to be highly desirable has now become practice within Europe and North America [21]. Unfortunately, this collaboration has not been successful for the design and installation of non-structural elements [22]. The seismic design and installation of non-structural elements remains a controversial issue in terms of expertise and responsibility. Often the question arises during the course of a construction project as to who should be responsible for the integration of structural and non-structural seismic designs and installations. Within current construction practices, the answer to this question is not always clear. The main stakeholders in a construction project that could be involved in the seismic design and proper installation of the non-structural elements are the building owner, the architect, the structural, mechanical and electrical engineers and a variety of specialty contractors. Looking at the specific competences of each stakeholder, one can argue that architects, mechanical and electrical engineers in many cases do not have sufficient specific knowledge to seismically design and properly install non-structural elements or are not sufficiently trained in that role. 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 and fee structures. The contractors often entrust the task to subcontractors that apply the codes and standards seismic prescriptions to the best of their abilities but often do not have adequate expertise, particularly if some engineering design calculations are required. It seems to be necessary that a new professional discipline of “non-structural coordinator” be introduced within the building professions to ensure that the non-structural elements achieve the level of system reliability in meeting the demands caused by a design earthquake [22]. 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 (MEP systems, furniture, architectural elements, etc.). The knowledge of the applicable codes and standards providing prescriptions for the seismic protection of non-structural elements as well as the ability to quantity and optimize the costs involved in the design process is also of paramount importance for a non-structural coordinator. The authors believe that structural engineers, familiar with the seismic provisions for the various typologies of non-structural elements, would be the most suited professionals to serve as non-structural coordinators in a construction project. The introduction of such a new profession also means increased fees to be paid by the owners. The owner's tendency to save fees during the contracts negotiations could be detrimental to safety during an earthquake and could lead to major economic losses due to the damages after the earthquake. Petak and Alesch [22] stated that “…*one approach to achieving greater systems integration and better building system performance at the same or lower cost within the seismic safety community is a combination of a systems perspective and performance based earthquake engineering*…”.

The advancements in BIM technology have significantly enhanced several aspects of the planning, design and construction processes along with numerous aspects of the project management [22]. To assess building performance in the early design stage, access to a comprehensive set of data regarding a building's geometry, contents, use, and mechanical equipment allows improving the accuracy of information to be incorporated throughout the design process [23]. The combination of sustainable design strategies (i.e. performance-based seismic design) and BIM technology has the potential to change the traditional design practices and to efficiently produce a high-performance facility design. 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 [24]. The development of seismic assessment/design software for specific non-structural element typologies that are able to read the data provided by Building Information Models and provide output files that can be uploaded in the original Building Information Models could represent a new frontier in the seismic design of non-structural elements (Fig. 3).

Building Information Models could be very useful in the seismic design of buildings to identify performance targets both, for structural and non-structural elements. The integration of structural and non-structural elements in Building Information Models would allow identifying optimum seismic design solutions. Non-structural elements can be sensitive to story drifts and/or floor accelerations. By increasing the strength of the structure, the story drift demand may be decreased but, at the same time, the floor accelerations along the height of the building may be increased. The integration of the structural and non-structural elements in the same Building Information Model and the clear understanding of all elements present in the building are very useful in order to improve the seismic performance of the building. The seismic design can be optimized in order to limit drift or acceleration based on the non-structural elements intended for the building [21]. A correct application of performance-based seismic design by integrating structural and non-structural elements not only allows the definition of a single serviceability limit state, but the assessment of various performance levels. This strategy permits to take into account a range of possible seismic demands and to investigate the damage consequences related to structural and non-structural elements for various limit states. The accuracy of Building Information Models in terms of details and quantities is also of paramount importance to perform accurate seismic loss estimation analyses (PBEE) or to develop detailed models in external software in order to perform more sophisticated analyses (e.g. nonlinear dynamic response analyses of sprinkler piping systems) [25]. The non-structural coordinator in collaboration with BIM software developers could be responsible to verify the accuracy of Building Information Models. If the details required for the analysis of non-structural elements are not available in the Building Information Models, the non-structural coordinator should ask the particular BIM software

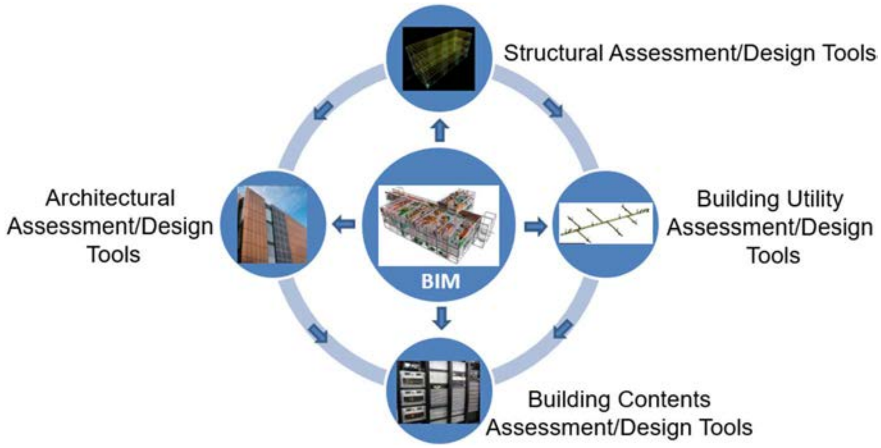

**Fig. 3.** Seismic design of non-structural elements using BIM and seismic assessment/design software.

developer to improve their models or should be able to directly improve the Building Information Model by introducing the information that are considered essential for the seismic analysis.

## 3. Purpose of the study, scope and methodology

The seismic performance of non-structural elements is nowadays recognized to be a key issue in the performance based earthquake engineering. Despite this, the seismic design of non-structural elements is still not incorporated into practice. As highlighted in the previous sections, the use of Building Information Modelling (BIM) could represent a new frontier in the seismic design of non-structural elements by increasing the reliability of the seismic design and/or assessment. The general objective of this study is to demonstrate the effectiveness of using Building Information Models for the seismic design of non-structural elements. For this purpose, the study focuses on the automatic seismic design of pressurized fire suppressant sprinkler piping systems that are very common in important facilities, such as schools and hospitals. The two specific objectives of the study are to:

1. Develop a conceptual framework to perform the automatic seismic design of non-structural elements using information available in Building Information Models.
2. Illustrate the above framework through a proof-of-concept case study on the automatic seismic design of sway braces for pressurized fire suppressant sprinkler piping systems using a Building Information Model.

To achieve the first specific objective, the possible exchange of information using .IFC file format has been studied focusing on the extraction and organization of all the information available in Building Information Models on non-structural elements. The second specific objective was achieved through the development of a simple software tool to perform automatically the seismic design of sway braces for pressurized fire suppressant sprinkler piping systems according to the seismic provisions of the NFPA13 standard [26] in the United States and based on information extracted from a Building Information Model. The effectiveness of the proposed conceptual framework and of the software tool has been demonstrated via a case study.

## 4. Conceptual framework for using BIM in seismic design

A Building Information Model simulates the construction project in a virtual environment over the whole life cycle of the facility [27]. BIM is typically realized with object-oriented software and consists of parametric objects representing building elements [28]. The simple exchange of information allowed by the use of the same file format helps to introduce multi-disciplinary information in the models and to create an opportunity for sustainability measures to be incorporated throughout the design process [23]. Industry Foundation Classes (IFC) is the most popular format for information exchange in BIM technology. The IFC format is a structured data model, a system of classification and description that refers to not only the physical elements of the building such as walls, doors, floors, etc. or their physical quantities but also to abstract concepts such as quantity, cost, time sequences of operations. The IFC format defines a single object-oriented data model of the building; it is a format of open data, public and independent from any software manufacturer and, therefore, it is possible to exchange the building information by simply exchanging files in ".ifc" format between various software tools. The use of IFC for data sharing in the construction and facility management fields is normed by the ISO 16739:2013 Standard [29] that specifies a conceptual data schema and an exchange file format for BIM data.

Building Information Models can be used in a passive mode for clash detection, construction planning [30] or scheduling [31–32]. A more active use of Building Information Models involves implementing the information available in the Building Information Models in engineering analysis tools in order to improve the design process [33–34]. Some software currently available on the market are able to import .IFC files from Building Information Models and to export the same file format including useful information that are not introduced in the original Building Information Models. Some software devoted to the structural analysis perform the seismic analysis and export .IFC files in which all the seismic details of the structures are introduced; this can significantly improve the Building Information Models. Similar software are also available for non-structural elements but, in this case, the seismic design is generally not included in the software's capabilities. For example, CYPECAD MEP is a software for the design of the envelope, distribution and services of the buildings using 3D model with the various elements of the building [35]. The composition of non-structural elements such as partitions (conductivity properties of each layer, position of the vapour barrier, thermal bridges, etc.) is not usually specified during the design process of the building. The software incorporates an IFC format model import assistant, which allows users to automatically assign the properties of some typologies of non-structural elements. Despite these capabilities, the seismic design of non-structural elements is not included in the software.

Fig. 4 illustrates a general conceptual framework for the automatic design of non-structural elements using BIM in seismic prone regions. In this framework, the specific tool to be used for the seismic design varies depending on the typology of the non-structural element. Some non-structural elements only require adequate prescriptive restraints/braces/anchorage to the structural elements while in more complex cases, an engineering design of the supporting systems is necessary. The definition of a unique platform in which all non-structural elements available in the building are directly introduced using the information

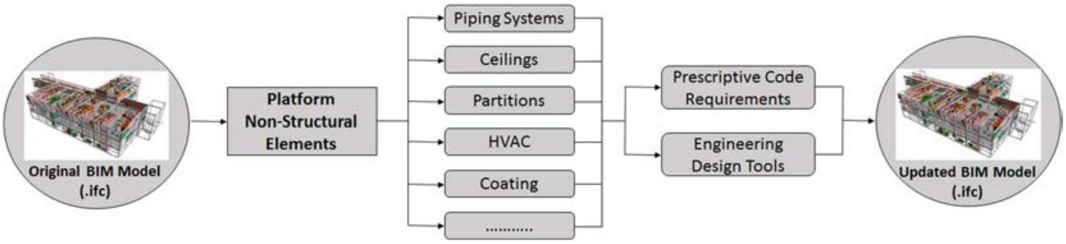

**Fig. 4.** Framework for the automatic seismic design of non-structural elements using Building Information Models.

available in Building Information Models could be an efficient solution to deal with the problems related to the seismic design/verification of specific non-structural element typologies. The platform could distinguish between the non-structural elements that require a seismic design from those requiring only prescriptive code requirements. Specialized external design tools would need to be developed and used to conduct the automatic seismic design of specific non-structural element typologies (e.g. piping systems, ceilings, partitions, HVAC systems etc.). At the end of the process, the new information on seismically designed non-structural elements could be uploaded back to the updated Building Information Model.

## 5. Automatic seismic design of sprinkler piping system

In this study, the effectiveness of the proposed framework illustrated in Fig. 4 is explored through an illustrative case study of the automatic seismic design of pressurized fire suppressant sprinkler piping systems. The extension of the methodology for the complete design of all typologies of non-structural elements will require the definition of a common platform in which all the non-structural elements are stored and addressed by different design tools. Fig. 5 shows the flowchart of the methodology utilized in order to conduct the automatic seismic design of pressurized fire suppressant sprinkler piping systems using the information provided by Building Information Models. The first step consists in the extraction of the sprinkler piping system layout from the original Building Information Model. The layout can be uploaded to any CAD platform thanks to the versatility of the .IFC format. The CAD model is used to evaluate and extract the geometric coordinates of each pipe joint of the system. These pipe joint coordinates are then automatically uploaded in an automatic seismic design tool for sprinkler piping systems developed in Microsoft Excel using Visual Basic for Applications [36]. The seismic design tool developed in this study is referred to as “Seismic Analysis of Piping Systems for BIM Application” or “SAPIS-BIM”. The design tool was developed in order to satisfy all the seismic design requirements for sway braces prescribed in Chapter 9 of the National Fire Protection Association NFPA 13: Standard for the Installation of Sprinkler Systems [26], as described below.

Once the layout of the piping systems has been upload in the SAPIS-BIM tool, a primary layout of the transverse and longitudinal sway braces is automatically established based on the prescriptive requirements of NFPA13. This primary layout of sway braces is then finalized and the dimensions of each brace cross-section are obtained using one of the three seismic analysis procedures available in NFPA13. In order to perform the seismic analysis of the piping systems, the accuracy of the Building Information Models is of paramount importance. All details regarding the pipe diameters, typologies and connections to the structure should be available in the models. Once all the seismic requirements are satisfied, and the optimum design of the sway braces has been achieved, the properties of the sway braces along with their coordinate locations are uploaded in the updated Building Information Model using the same CAD tool. In the next sections, all the steps of the automatic seismic design of sprinkler piping systems using BIM data are illustrated quantitatively through a case study.

### 5.1. NFPA13 seismic protection requirements

NFPA13 [26] provides the minimum requirements for the design and installation of automatic fire sprinkler systems in the United States. The lessons gained from previous seismic events in California (specially the 1971 San Fernando and 1994 Northridge earthquakes), led to numerous updates in order to improve the seismic requirements provided in the standard. 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 the water-based fire protection systems. Fig. 6 summarizes all sections of NFPA13 related to seismic design by rule prescriptions.

According to NFPA13, flexible couplings shall be provided to allow differential movements between the piping and the sections of the building to which they are attached. Specific indications related to the locations where the flexible couplings should be installed are provided in Section 9.3.2. Sections 9.3.3 and 9.3.4 provide requirements for the installation of seismic separation assemblies where piping crosses building seismic separation joints and the clearances that shall be provided to the sprinkler pipes passing through platforms, foundations, walls or floors. The diameter of a clearance varies depending on the pipe diameter. NFPA13 also describes all cases in which clearances are not required (e.g. horizontal piping passing perpendicularly through successive studs or joints that form a wall or floor/ceiling assembly). The bracing system that shall be installed in a sprinkler piping system varies depending on the pipe's typology. In order to resist horizontal seismic loads and to prevent vertical motions. Sections 9.3.5 to 9.3.7 of NFPA13 describe the types of braces and restraints that shall be used. Section 9.3.5 provides detailed prescriptions of the longitudinal and lateral sway bracing that shall be used in order to counteract the horizontal seismic design forces in the two main perpendicular directions of the piping systems. The resistance provided by restraints is considered to be lower than that supplied by braces. For this reason, Section 9.3.6 of NFPA13 states that restraints can be used only for branch lines in order to resist vertical movements (if braces are not required). Finally, Section 9.3.7 lists technical prescriptions related to C-type clamps used to attach hangers to the building structure.

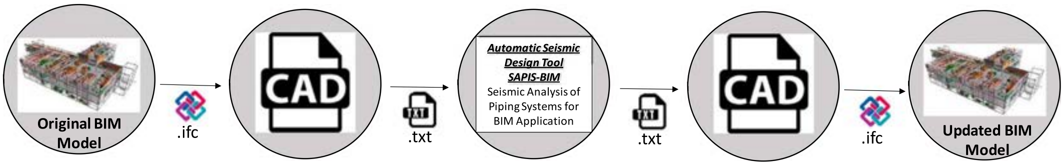

**Fig. 5.** Seismic design of sprinkler piping systems using BIM data.

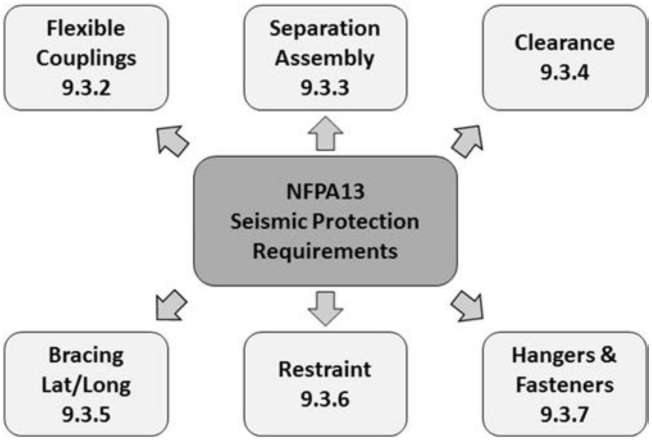

**Fig. 6.** Summary of NFPA13 seismic design by rule prescriptions.

The illustrative case study considered in this paper addresses only the seismic design of transverse and longitudinal sway braces and restraints. The longitudinal and transverse sway bracing are required for all sizes feed main and cross main pipes and for branch lines with a diameter equal to or larger than 65 mm. The sway bracing must be generally designed for both tension and compression and the slenderness ratio shall be lower than 300. The spacing between lateral and longitudinal braces shall not exceed a maximum of 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.

According to NFPA13, the horizontal seismic design force acting on a sway brace shall be permitted to be determined in accordance with Section 13.3.1 of the SEI/ASCE 7 standard in the United States [37] multiplied by 0.7 to convert to allowable stress design. Two simplified approaches are also permitted. In the first simplified approach, the horizontal force acting on the brace can be taken as $F_{pw} = C_pW_p$. The factor $C_p$ is the seismic coefficient. The values of $C_p$ are listed in Table 9.3.5.9.3 of NFPA 13 as a function of the short period (0.2 s) spectral response parameter ($S_{DS}$) at the building site. The factor $W_p$ is the weight of the system being braced (taken 1.15 times the weight of the water-filled piping). If data for determining $C_p$ are not available at the design stage, the horizontal seismic force acting on the braces can also be determined assuming a default value of $C_p = 0.5$. If the simplified approach is followed in order to evaluated the horizontal force acting on a sway brace, the importance factor proposed in the equation suggested by SEI/ASCE 7 Standard is automatically taken into account in the seismic coefficient ($C_p$). In order to evaluate the weight acting on each brace, a zone of influence for each bracing member must be determined. The zone of influence is the portion of the sprinkler piping system that the brace is intended to protect against inertia forces. The zone of influence for a lateral sway brace includes both the tributary weight of branch and main lines, while the zone of influence for a longitudinal sway brace shall include only the tributary weight of the main lines. The seismic design horizontal forces are compared to the allowable resistance of the braces. The maximum horizontal resisting capacities for sway braces are tabulated in NFPA13 for different shape, size, inclination angle and slenderness of the brace.

### 5.2. Description of SAPIS-BIM tool

In this section, the conceptual framework illustrated in Fig. 5 is described in detail through an illustrative case study. In order to make the SAPIS-BIM tool user friendly, the seismic design procedure was implemented in Microsoft Excel using Visual Basic for Application [36]. The Building Information Models for this illustrative case study was created using the freeware Tekla BIMsight software [38], while the sprinkler piping system layout was uploaded in SAPIS-BIM using the student version of AutoCAD [39]. The flowchart shown in Fig. 7 list the steps required for the automatic seismic design of the fire sprinkler piping system in SAPIS-BIM. Each step is briefly described in the following sections.

### 5.3. Description of the case study

The layout of a black iron threaded sprinkler piping system installed in each floor of a six-storey steel frame building structure is considered for this illustrative case study. The building is rectangular in shape and is braced in both principal directions direction by two exterior moment-resisting frames, as shown in Figs. 8 and 9. The building is assumed to be located in the United States on a site class B according to the soil classification contained in ASCE 7-10 [37], for which the short period design spectral acceleration $S_{DS}$ is 1.0 g.

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. Figs. 10 and 11 show the layout of the piping system for each floor of the building and the Building Information Models developed in the Tekla BIMsight software, respectively. The Building Information Model includes only the main structural elements and the fire sprinkler piping system, the architectural elements and utility systems are not included in the model to simplify this illustrative case study.

### 5.4. Transfer of unbraced sprinkler piping layout and definition of piping typology

The first step of the procedure consists in the transfer of the unbraced sprinkler piping system layout from the Building Information Model into SAPIS-BIM. For this purpose, the .ifc file model of the fire sprinkler piping system is uploaded in AutoCAD. The coordinates of all pipe joints (T-joints or Elbows) are automatically extracted and written in a txt file using the CAD application. Once the coordinates are correctly uploaded in SAPIS-BIM, a graphical representation of the piping layout is automatically sketched in a dedicated spreadsheet. The

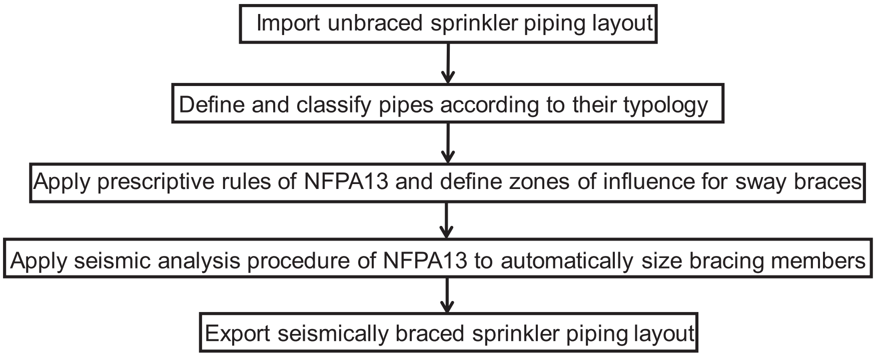

**Fig. 7.** Flowchart of the procedure implemented in SAPIS-BIM.

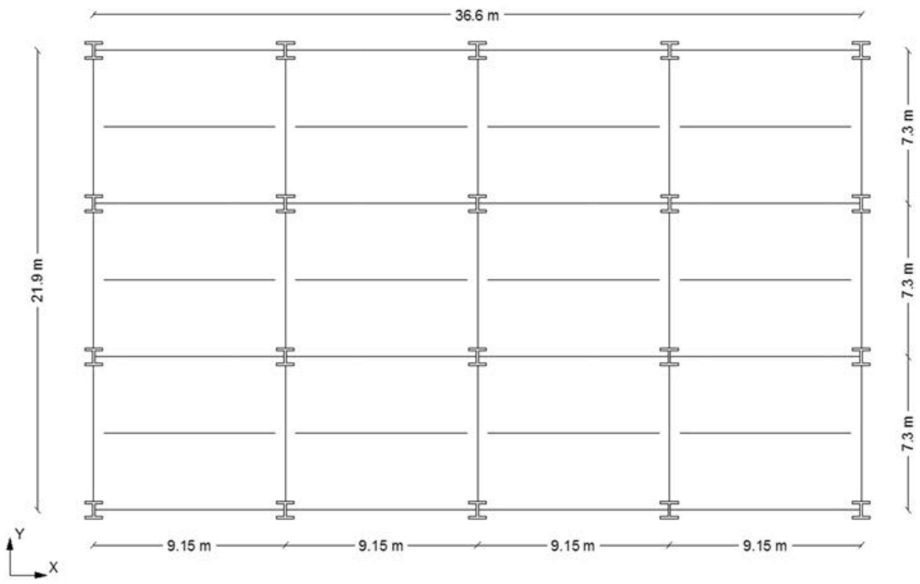

**Fig. 8.** Plan view of the case study building structure.

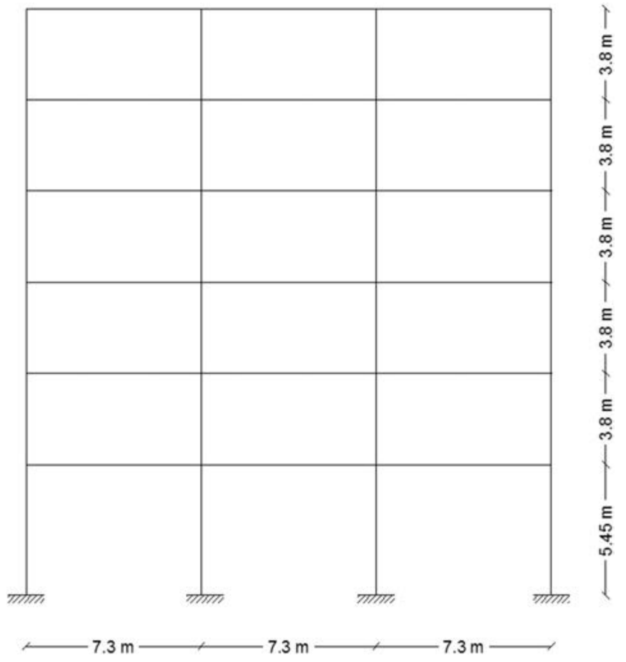

**Fig. 9.** In elevation view of the case study building structure.

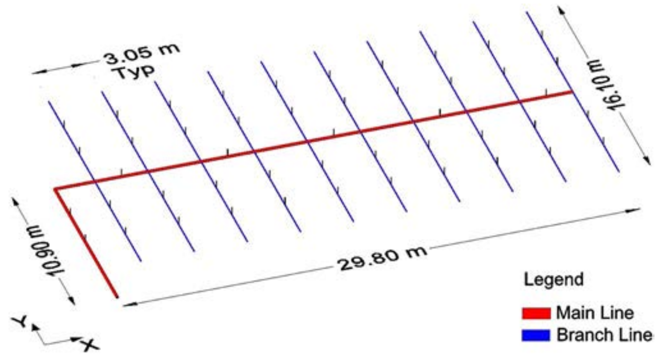

**Fig. 10.** Layout of the black iron threaded fire sprinkler piping system.

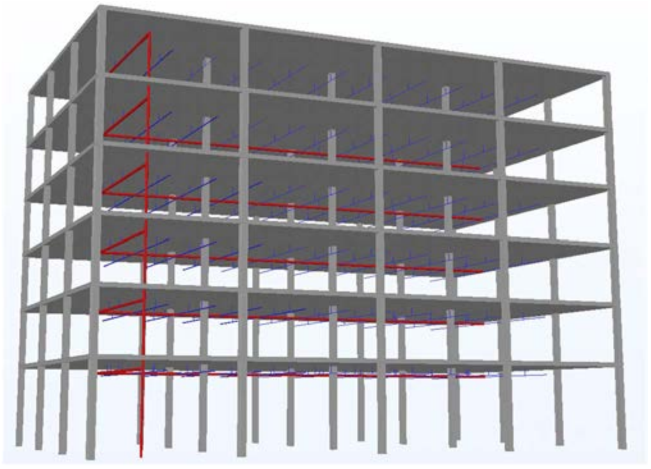

**Fig. 11.** Building Information Model developed in Tekla BIMsight software.

graphical output helps in avoiding mistakes during the pipe's classification. The user must then enter the typology (main or branch line) and the diameter of each pipe into the SAPIS-BIM. For this illustrative case study, two main lines and 20 branch lines are identified. The pipe diameters are equal to 89 and 32 mm for the main and the branch lines, respectively (Fig. 12).

### 5.5. Application of NFPA 13 prescriptive rules and definition of zones of influence for sway braces

According to NFPA13, the piping system shall be braced to resist both lateral and longitudinal seismic loads. The requirements provided by NFPA13 vary as a function of the pipe's typology, diameter and bracing direction. The main prescriptive requirements of the standard have been briefly discussed in Section 5.1. In order to satisfy the NFPA13 design by rule prescriptions, SAPIS-BIM automatically creates a spreadsheet for each pipe's typology. The pipes are also distinguished based on their two main orthogonal directions (X and Y). For the fire sprinkler piping system analyzed in this illustrative case study, the following pipes were identified by SAPIS-BIM: one cross main line in the X direction (1-X), one feed main line in the Y direction (1-Y), 20 branch lines in the Y direction (1Br-Y to 20Br-Y). For each pipe, the minimum number and distance between transverse and longitudinal sway braces are automatically calculated. The area of influence for each

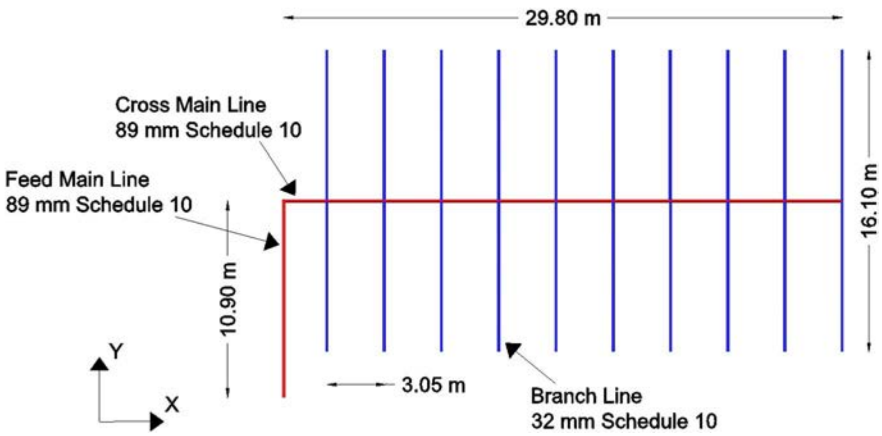

**Fig. 12.** Identification of the pipe's typology.

**Table 1**
Minimum requirements according to NFPA13.

| Typology | Direction | ID pipe | Transverse sway braces | | Longitudinal sway braces | |
|---|---|---|---|---|---|---|
| | | | ID brace | Area of influence (mm) | ID brace | Area of influence (mm) |
| Main line | X | 1-X | T-1 | 75,970 | L-1 | 96,480 |
| | | | T-2 | 59,340 | L-2 | 78,360 |
| | | | T-3 | 39,530 | N/A | N/A |
| | Y | 1-Y | T-1 | 5450 | N/A | N/A |
| | | | T-2 | 5450 | N/A | N/A |

N/A: Not Applicable.

**Table 2**
Horizontal seismic demand on each 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 | 2.350 | L-1 | 1.330 |
| | | | T-2 | 1.960 | L-2 | 1.160 |
| | | | T-3 | 1.310 | N/A | N/A |
| | Y | 1-Y | T-1 | 0.460 | N/A | N/A |
| | | | T-2 | 0.460 | N/A | N/A |

N/A: Not Applicable.

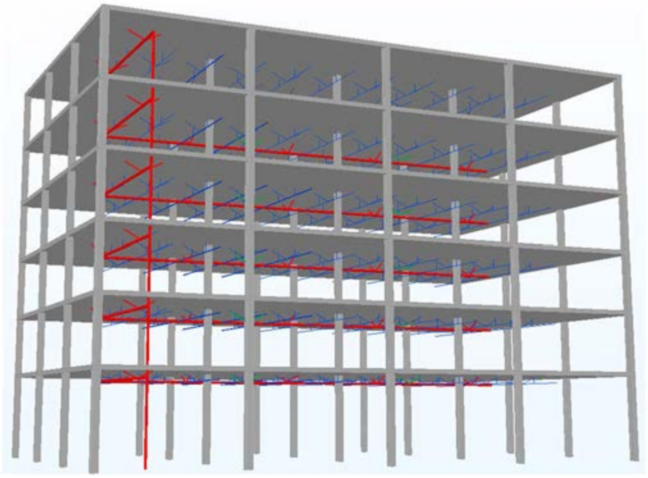

**Fig. 13.** Updated building information model with seismically braced piping layout.

sway brace is also evaluated. Table 1 resumes the results provided by SAPIS-BIM for the main lines.

The areas of influence are evaluated in terms of length of pipes and are used to calculate the seismic demand on the sway braces. For this case study, NFPA13 requires that the cross main line in the X direction be braced by at least three transverse sway braces and two longitudinal sway braces, while two transverse sway braces are required for the feed main line in the Y direction. A sway brace is not required for each branch line because the pipe diameter is smaller than 65 mm.

### 5.6. Application of NFPA13 seismic analysis procedure for automatic sizing of bracing members

The most important step in the seismic design of a fire sprinkler piping system consists in the evaluation of the seismic demand. In SAPIS-BIM, a specific spreadsheet evaluates the seismic demand on each brace and optimizes the design process. The user can decide on using one of the three methodologies proposed by NFPA13 to evaluate the horizontal seismic force. For this illustrative case study, the horizontal force acting on the braces was calculated according to the simplified approach based on the $S_{DS}$ (1.0 g) for the building site. The resulting value of $C_p$ is equal to 0.51. Table 2 lists the horizontal design

**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 | N/A | N/A | N/A |
| | Y | 1-Y | T-1 | Pipe schedule 40 | 25 | N/A | N/A | N/A |
| | | | T-2 | Pipe schedule 40 | 25 | N/A | N/A | N/A |

N/A: Not Applicable.

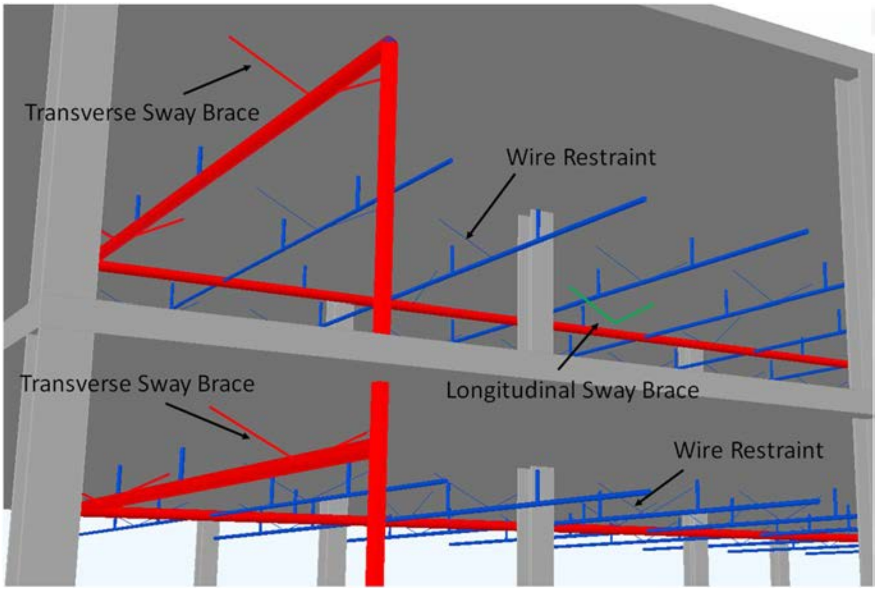

**Fig. 14.** Detailed view of sway braces and restraints.

forces on the transverse and longitudinal sway braces automatically calculated by SAPIS-BIM.

Once the vertical clearance of the piping system (800 mm) and the installation angle of the braces (45°) are provided by the user, the maximum horizontal load capacity and the slenderness ratio for each bracing member are automatically calculated and verified for a selected piping section. The capacity-to-demand ratio is automatically calculated. If the capacity is not adequate, the typology and the number of braces can be modified. An optimization of the brace sizes can be also performed. Table 3 shows the characteristics of the bracing system designed by SAPIS-BIM for the illustrative case study.

According to NFPA13, if the branch lines are not fitted with lateral sway bracing, restraints shall be installed. SAPIS-BIM automatically determine the required restraints for the branch lines. For the case study considered, each branch line is provided with No. 12, 44 lb (1.96 kN) wire installed at 45° from the vertical and anchored on both sides of the pipe. The restraints are installed at mid-length of each branch line.

The results of the seismic design performed using SAPIS-BIM have been verified by hand-calculations on several sprinkler piping system layouts.

### *5.7. Export of seismically braced sprinkler piping layout into updated building information models*

A graphical output of the seismically braced sprinkler piping layout is provided in SAPIS-BIM as final result of the design process. The coordinates of the sway braces are automatically exported in the CAD application using a .txt file created by SAPIS-BIM. Finally, the seismically braced piping layout is exported in Tekla BIMsight using an .ifc file in order to update the Building Information Model (Figs. 13–14). The representation of the sway braces in the model developed using Tekla BIMsight and shown in Figs. 13 and 14 is quite rudimentary. A more sophisticated representation, with all the details of the sway braces including their connectors, could be incorporated in more advanced High Definition (HD) BIM software.

## 6. Conclusion

The seismic performance of non-structural elements is nowadays recognized to be a key issue in performance-based earthquake engineering in order to ensure a desired structural system performance. The combination of sustainable design strategies (i.e. performance-based seismic design) and BIM technology has the potential to change the traditional design practices and to produce efficiently a high-performance facility design. The effectiveness of using Building Information Models in seismic design of non-structural elements has been discussed and illustrated through a sprinkler piping system case study. In this study, a conceptual framework for the seismic design of non-structural elements using the Building Information Models has been proposed and a simple Excel based tool (SAPIS-BIM) has been created for the automatic seismic design of sprinkler piping systems.

The results of the case study demonstrated that the information available in Building Information Models can be easily implemented in SAPIS BIM to perform the automatic seismic design of non-structural elements. SAPIS BIM is able to automatically perform the seismic design of sprinkler piping systems according to the NFPA13 Standard in the United States, as verified by hand-calculation for the case study considered in this paper. The simple Excel based tool proposed in this study for the seismic design of sprinkler piping systems showed that all the steps proposed in the conceptual framework for the seismic design of the non-structural elements can be easily achieved.

The results of this study suggest the need to extend this research through the development of similar BIM compatible tools for the automatic seismic design of other typologies of non-structural elements to help lift some of the impediments to incorporating non-structural seismic design into practice. The future extension of the proposed methodology to other non-structural elements could allow to define a unique platform in which all the non-structural elements available in a building are automatically seismically designed/verified. This could lead to a great advance in the reduction of earthquake related losses.

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