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A STATE OF THE ART REVIEW ON THE ANALYTICAL SIMULATION OF CEILING, PIPING AND PARTITIONS

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ABSTRACT

It is well understood from past earthquakes and experimental studies that non-structural systems suffer more damage and sustain greater losses when compared to structural members. Also, recent years have witnessed significant progress in analytical simulation of non-structural systems. Among these non-structural systems, acoustical lay-in suspended ceilings, fire sprinkler piping and light-gauge steel-frame gypsum partition walls were paid more attention as they contributed to the major construction effort inside a building and damage losses during past earthquakes. This state-of-the-art paper aims to make a comprehensive survey on the recent modelling techniques and sketches a vision for future analytical works that can help the community better assess and improve the seismic performance of acoustical lay-in suspended ceilings, fire sprinkler piping and non-structural light-gauge steel-frame gypsum partition walls.

INTRODUCTION

Damage to non-structural systems accounts for over 78% of the total estimated national annualized earthquake loss [1]. This is mainly because damage to non-structural components in a building is usually triggered at shake intensities much lower than those required to initiate structural damage [2]. Among these non-structural systems, suspended ceilings, fire sprinkler piping systems and partition walls are known as some of the main sources of loss after an earthquake [3].

Several failure modes such as the falling of ceiling panels, buckling of ceiling grid members, failure of ceiling grid connections, damage near the ceiling perimeter, leakage of pipe joints, impact of sprinkler heads and ceiling panels, gypsum cracking in partition walls, plastic hinge formation in partition studs, tearing of partition tracks, failure of supporting elements, and complete collapse were identified in sprinkler, ceiling, and partition wall systems. Nearly all of these damage mechanisms were observed in past earthquakes, such as the 1989 Loma Prieta Earthquake [4], 1994 Northridge Earthquake [5], 2006 Hawaii Earthquake [6], 2010 Chile Earthquake [7], 2010 Haiti Earthquake [1], and 2011 Christchurch (New Zealand) earthquake [8].

Seismic assessment of acoustical lay-in suspended ceilings were mainly made through experimental studies such as ANCO [9], Rihal *et al.* [10] and Yao [11]. In addition, several experimental studies were performed on ceiling systems, including some studies using shake tables [12-34]. Within these studies, the effect of using retainer clips, pop rivets, compression posts and perimeter seismic clips in ceiling systems was assessed. Various cyclic, quasi-static and shake table studies were carried out on light-gauge steel-frame gypsum partition walls [35-47] to better understand their performance under seismic events. A few system-level experiments [48-52] were performed on these walls to assess the integrating performance of these partition walls. The effect of loading protocols, top connection details, wall heights, framing thicknesses, openings and corner and T connection details were studied in these experiments. In order to evaluate and understand the dynamic response of piping systems, several experiments [53-60] were performed on pipe components. The major objective of these studies was to evaluate the failure modes associated with individual pipe components, without considering system performance. Besides the static tests, several shake table experiments [27, 50, 61-69] were carried out in piping systems in order to better understand their seismic performance. From these experiments, valuable observations and results such as leakage rotations, acceleration amplification factors, damage in supporting elements and damage in ceiling systems near sprinkler heads were provided.

Although the data obtained from past earthquakes and experiments are critically valuable, several restrictions (e.g., geometry limitations, number and intensity of input motions) are always associated with them. By using reliable analytical modelling techniques, many of these limitations can be eliminated, which will result in more comprehensive seismic assessment of ceiling-piping-partition systems. Therefore, this study aims to evaluate the strengths and weaknesses of current analytical models and suggest future paths for enhancing these analytical techniques. To do so, a brief description for each of the ceiling, piping and partition systems is provided. A detailed description of available modelling techniques for each of these non-structural systems is given. Finally, several recommendations are provided to enhance the capability of current analytical procedures for future numerical seismic assessment of ceiling-piping-partition systems. It should be noted that the scope of this paper is limited to the seismic performance of acoustical lay-in suspended ceilings, fire sprinkler piping and non-structural light-gauge steel-frame gypsum partition walls with details that are common in the United States construction practice.

BACKGROUND

A brief description for each of the acoustical lay-in suspended ceilings, fire sprinkler piping, and light-gauge steel-frame

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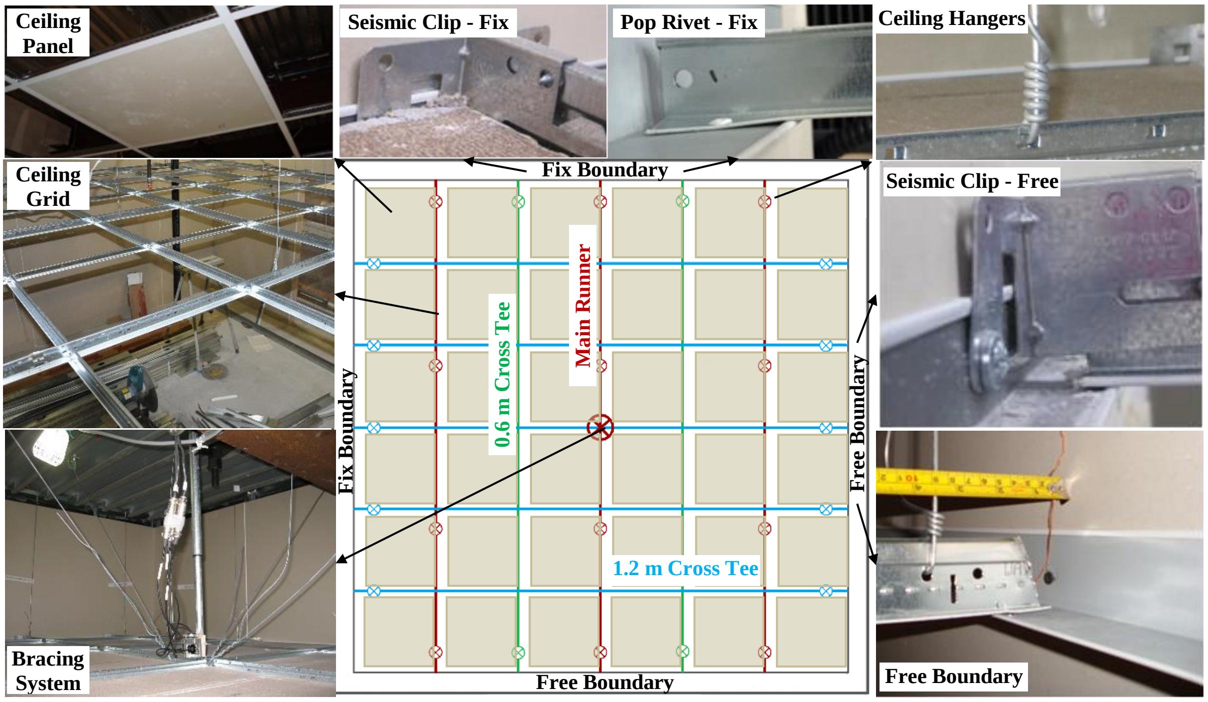

Figure 1: Typical layout and elements of an acoustical lay-in suspended ceiling system.

gypsum partition walls is provided in this section. The details presented below are obtained from current installation code requirements and common construction practices.

Acoustical Lay-in Suspended Ceilings

Suspended ceiling systems are a non-structural component installed within buildings to serve as an aesthetic barrier between electrical, mechanical, and piping systems and the living space below. The entire ceiling grid is hung from the structural floor above. A typical suspended ceiling system with acoustic tiles is composed of grid members, boundary wall angle, hanger splay wires and, if braced, splay wire braces and compression posts. The simplest tile geometry is a 0.61 m x 0.61 m square with a thickness ranging from 13 mm to 19 mm and a typical weight of 5 kg/m^2. The grid system of a suspended ceiling system consists of inverted main tee beams and inverted cross tee beams, made of light-gauge steel, that interlock at locations of intersection. The grid sits on light-gauged L-shaped wall angle at its perimeter that is screwed to the partition walls. A ceiling system in a low seismic zone has a minimum 10 mm grid wall angle clearance on all boundaries. The perimeter conditions of a seismically braced ceiling system are slightly different, with a minimum grid wall angle clearance of 20 mm on two adjacent boundaries and fixed to the wall along the other two boundaries.

Acoustic ceiling tiles are manufactured from a compressed high-density mineral fibre material and are available in many shapes and sizes. The simplest tile geometry is a 0.6 m x 0.6 m square with a thickness ranging from 13 mm to 19 mm. The acoustic tiles are placed within the tee beam grid system, simply resting on the flange of each tee beam. The tiles are not mechanically locked into place. Hanger wires are placed at 1.2 m intervals around the ceiling perimeter at no more than 200 mm from the wall. The compression post and splay wire bracing is installed at 3.6 m intervals beginning 1.8 m from the wall. A compression post is used in a bracing assembly to react against the vertical component of the splay wire braces. The hanger wires and splay wires of braced systems are made of 12-gauge wire that is looped through holes in the main tee beams and connected to the supporting floor deck above the ceiling. The typical layout and components of a ceiling system with two free and two fixed boundaries are presented in Figure 1.

Fire Sprinkler Piping System

A typical fire sprinkler piping system is composed of a water pressure tank, pipe runs, sprinkler heads, hangers, braces and restrainers. Pressure tanks provide enough pressure behind the water in a system. Sprinkler heads spray the pressurized water onto an area in case of fire or smoke. Pipe runs are composed of: 1) risers: vertical supply pipes; 2) main runs: pipes that supply branch line water; 3) branch lines: provide drop pipe water; and 4) drops: armover or straight drops that supply sprinkler head water. Hangers carry the dead weight of a piping system. Braces resist the seismic load of a piping system. Braces can be solid or tension-only (cable) braces. Wire restrainers limit the displacement movement of branch lines. The schematic of a typical fire sprinkler piping system is presented in Figure 2.

Light-Gauge Steel-Frame Gypsum Partition Walls

Typical construction of partition walls consists of C-shaped, cold-formed light-gauge steel studs nested in and screwed to C-shaped steel tracks at the top and bottom. The most commonly used studs and tracks are gauge 20 and gauge 25 with a web depth of 92 mm. The track is usually fastened to the structural slab with powder actuated fasteners (PAFs) and is used to align the vertical studs. The gypsum board, consisting of a rigid gypsum core sandwiched between paper layers, is attached to the studs and track with bugle-headed drywall screws placed at regular intervals. The two most commonly used gypsum thicknesses are 12 mm and 15 mm. It should be noted that many other configurations exist depending on the geometry limitations, seismic requirements, desired fire rating and sound isolation preferences. The schematic of a typical light-gauge steel-frame gypsum partition walls is presented in Figure 3.

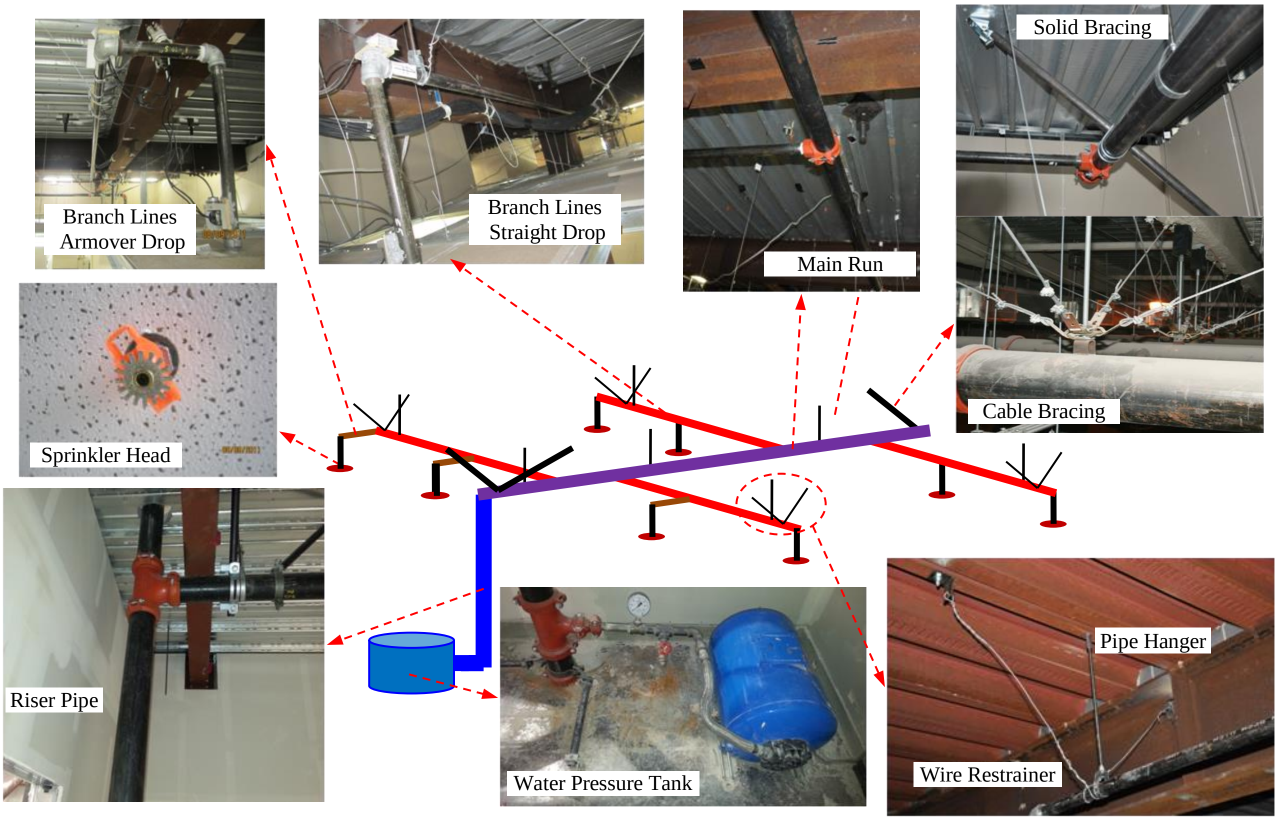

Figure 2: Typical layout and elements of a fire sprinkler piping system.

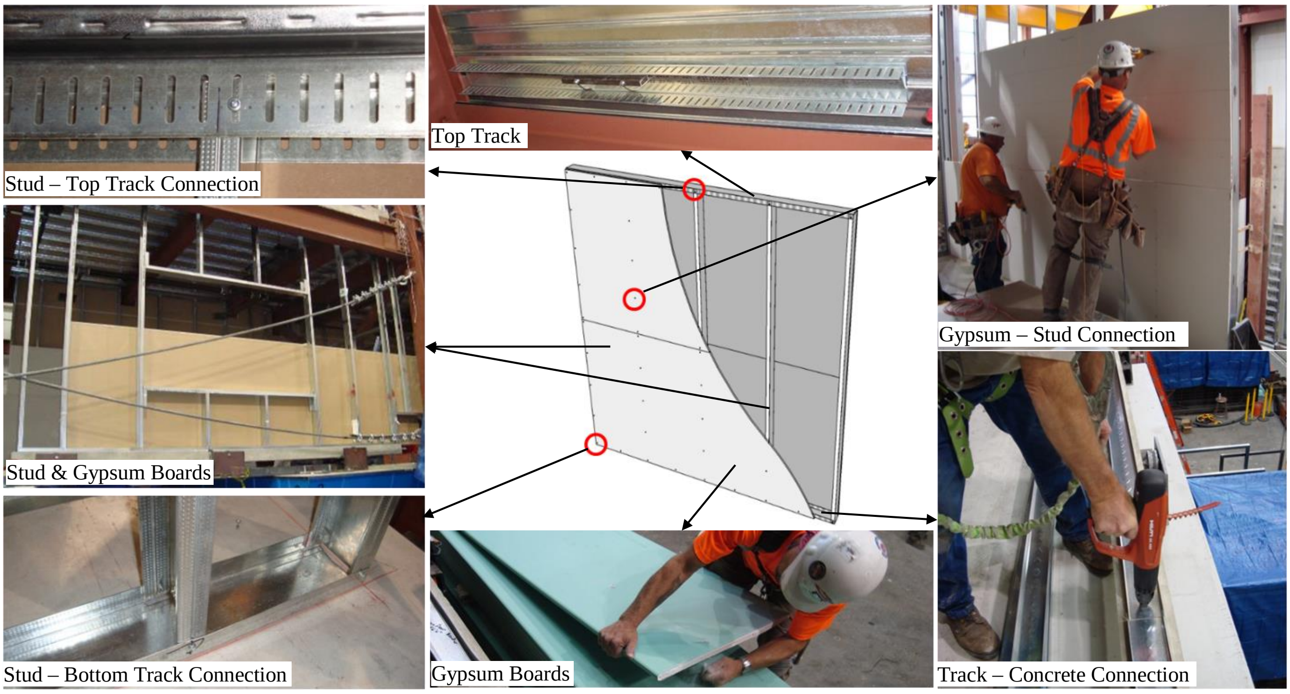

Figure 3: Typical layout and elements of a light-gauge steel-frame gypsum partition walls.

ANALYTICAL MODELS OF NON-STRUCTURAL SYSTEMS

In this section, a detailed description of available techniques on acoustical lay-in suspended ceilings, fire sprinkler piping, and light-gauge steel-frame gypsum partition walls are presented, respectively.

Acoustical Lay-in Suspended Ceilings

Suspended ceilings are one of the most difficult non-structural systems to be analytically modelled due to their heterogeneous and complex construction [24, 70]. As a result of such complexity, very few analytical analyses have been performed on ceiling systems.

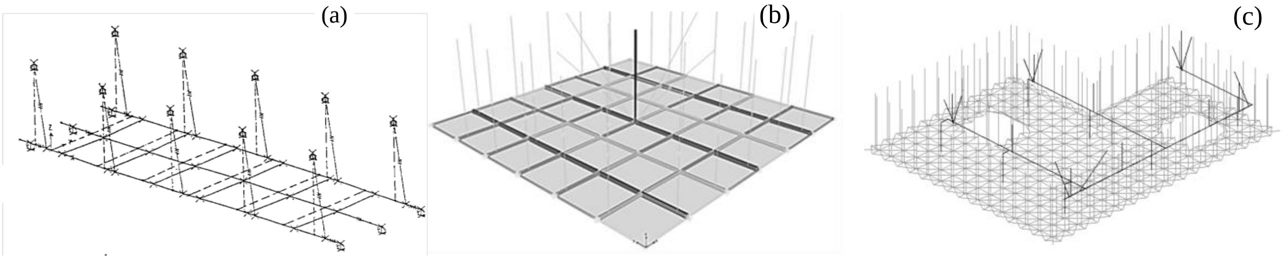

Figure 4: Typical layout and elements of a light-gauge steel-frame gypsum partition walls:(a) Yao [11], (b) Echevarria et al. [3], (c) Soroushian et al. [74].

A simplified model was developed by Yao [11] using the ANSYS [71] software (see Figure 4a). In their study, cable elements were chosen to simulate hanger wires. Frame elements were chosen to model the main runners. The cross tees were modelled with two pin-ends. Lay-in panels did not contribute any stiffness but their mass was included in the model. Roller connections were used at the boundaries to simulate perimeter connections. This simplified model was used to perform the eigen value analysis of a ceiling system.

A finite element model of suspended ceiling systems was developed using the Ruamoko [72] software. In this modelling methodology [73], beam elements were used to model the ceiling grid members, while contact elements were used to capture the sprinkler head-ceiling panel interactions. Seismic fragility curves of ceiling systems were further developed by comparing the analytical demand estimates with the component capacities obtained from the experiments.

In another study, simplified unidirectional analytical models were developed [74] to capture general dynamic behaviour of a ceiling system. In this modelling methodology, the suspended ceiling system, in the longitudinal direction, was considered as a multi-pendulum system interconnected by slip-lock springs, representing main runner splices. The oscillation of this system is resisted by perimeter (end connection) springs (e.g., pop rivet and wall angle series spring), and after the pop-rivets fail, the motion is restrained by end walls, whose effect can be represented by an external force. In the transverse direction, the ceiling system was modelled as a system that consists of beams and springs where beams represent main runners with distributed mass (e.g., of 1.2 m wide tributary area including ceiling tiles and cross tees) and springs represent cross tees and pop rivets. The analytical results using such simplified models were compared with experimental responses and showed reasonable agreement.

In a more sophisticated analytical model [3], a suspended ceiling system was created using SAP2000 [75] (see Figure 4b). In this modelling procedure, beam elements were used to model the grid elements. The main runners were assumed to be continuous, but the cross tees were pinned at each end. Ceiling panels were modelled with an x-shaped assembly with a lumped translational-rotational mass placed at the centre joint that is rigidly connected to four corner joints. Hanger and brace wires were modelled using the Hook Link to resist only tensile forces. The compression post was modelled as a frame element with the gross section properties of the member. Ceiling panels were placed in between grids by using two horizontal and one vertical T/C Friction Isolator Links at each corner of the ceiling panels. The horizontal links were assigned to have a construction gap, while no gap was considered for the vertical link. It should be mentioned that the uplift and pounding of ceiling panels to the grid system was simulated by using these T/C Friction Isolator Links. Similar types of isolator links with appropriate construction gaps were used to connect the end of the grid members to the wall angles at their free boundaries. At the fixed boundaries, T/C Friction Isolator Links were used in the horizontal directions and grids were rigidly connected to wall angles in the vertical direction. This model was used to generate the seismic fragility of 13 m^2 and 73 m^2 ceiling systems in the braced and unbraced condition.

A comprehensive analytical model of suspended ceiling systems was developed [76] using the OpenSees platform [77] (see Figure 4c). In this modelling methodology, all ceiling grids were modelled with elastic Force-Based Beam-Column elements with gross section properties of the main runs and cross tees. The main runs were assumed to be continuous while inelastic axial, shear and bending models were used at each end of the cross tees. The nonlinear behaviour at the end of cross tees was developed and experimentally calibrated through a series of studies [29, 31, 78]. The ceiling panel was modelled with an x-shaped assembly with five lumped masses placed at the centre and four corners of this assembly. Ceiling hanger wires and braces were modelled truss elements with a tension only Elastic-Perfectly Plastic (EPP) Gap material. The nonlinear behaviour of these wires was developed and calibrated with the available experimental data [78]. Compression posts were modelled with elastic Force-Based Beam-Column elements with gross section properties of these members. The connections between each corner of the ceiling panels and grid intersections were modelled using three zeroLengthImpact3D elements. Two of these elements were oriented perpendicularly in a horizontal direction. These horizontal elements accounted for the inherent gap between the ceiling panels and grid boundaries if the panels are perfectly centred. The vertical element with no initial gap allows tile uplift relative to the grid plane. In the vertical direction, additional zeroLength elements with elastic uniaxial material were used between each corner of the ceiling panels and grid intersections or perimeters to capture the panel-grid vertical interaction [79]. Grid members are attached to the perimeters using the inelastic hinge model, which was generated and calibrated according to the series of experimental results. A horizontal zeroLengthImpact3D element with an initial construction gap value was used for connecting grids and wall angles in the sliding direction of unattached perimeters. In order to capture the progression of damage in ceiling systems during seismic excitations, the real-time element removal algorithm was incorporated in the response history analyses. The element removal algorithm enables the model to redistribute the forces after failure of an element using the remove element command in OpenSees platform [77]. Ceiling grid connections and their perimeter attachments as well as ceiling hangers and wire braces were removed during the response history analysis when they reached their predefined failure capacities. Ceiling panels were removed when the uplift of at least one tile corner reached the grid height and the horizontal gap at the uplifted corner was closed. When both ends of a 0.6 m cross tee reach their failure capacity, the corresponding grid and its supporting panels are then removed from the model. Four panels and two 0.6 m cross tees are removed from the model if similar failure mechanisms happen for a 1.2 m cross tee. In this modelling methodology, the interaction between the ceiling panels and sprinkler heads was modelled using one zeroLength element between each sprinkler head node and centre panel node. Two

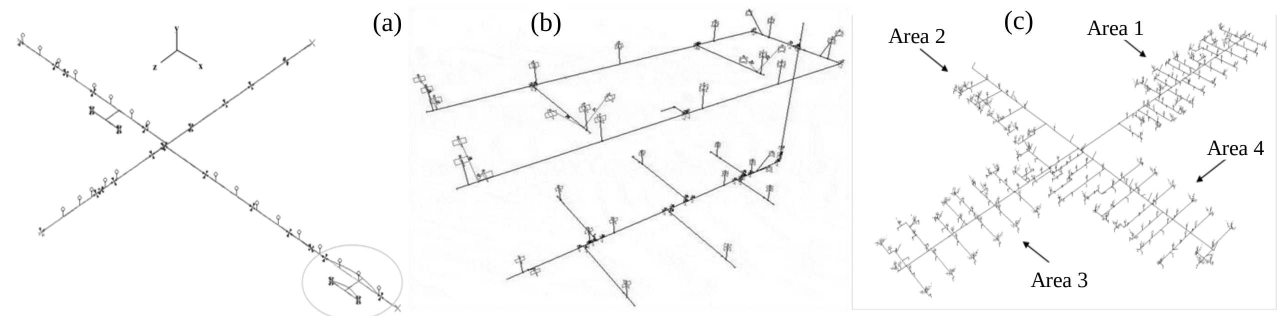

Figure 5: Examples of analytical studies on piping systems: (a) Ju and Gupta [87], (b) Tian et al. [89], (c) Soroushian [69].

parallel inelastic force-displacement models (one in tension and one in compression), developed and validated by Soroushian *et al.* [78] based on ceiling panel tearing tests, were assigned to the translational degrees of freedom at these elements. The analytical results obtained from this methodology were validated with an integrated ceiling-sprinkler assembly installed in a full-scale, five-storey, steel moment frame building.

Fire Sprinkler Piping

Seismic evaluation of fire sprinkler piping systems were also evaluated through analytical studies for more than a decade [80-82]. In more recent analytical models, ABAQUS [83] software was used to validate the static and dynamic analysis of the piping system with grooved couplings by Martinez and Hodgson [84]. This finite element model (FEM) was able to predict approximately 70% of the acceleration obtained from the experiment. However, this FEM model was not able to capture the pipe and bracing strain in an acceptable range. In another study [85], the FEM model of threaded connections was generated by using ABAQUS software [83]. The analytical model showed good agreement with a four-point bending test strain results. Research was conducted [86] on one of the four sections of the UCSF Hospital fire sprinkler system by using the OpenSees platform [77]. While the piping model used in this study was entirely linear, the floor motions considered in this study accounted for the nonlinearity of the supporting building.

In a more elaborate analytical study by Ju and Gupta [87], a 51 mm diameter black iron threaded joint model was developed and calibrated with a series of component level experiments at University at Buffalo [88] by using the OpenSees platform [77]. In this study, a piping segment of the UCSF Hospital was modelled by considering rigid connections at pipe joints (Figure 5a). The existing 51 mm diameter threaded joint model was then incorporated at three critical locations of the UCSF piping model. This modelling methodology was then used to develop fragility curves under several ground and floor motions, including the floor responses of two low-rise, five-storey and high-rise, 20-storey buildings.

In a comprehensive study by Tim *et al.* [89], nonlinear hinge models were developed and calibrated, with experimental results obtained at the University at Buffalo [88], for threaded, grooved and thermoplastic (CPVC) with cement joints for various pipe diameters. These hinge models were developed by using a generic bilinear model in MATLAB software [90], multi-linear Pivot model in SAP2000 [75] and Pinching4 and Hysteretic model in the OpenSees platform [77]. Further, in their research analytical models were developed in SAP2000 to simulate and validate the modelling methodology with the seismic response of a two-storey, full-scale fire sprinkler piping system [60, 89] (Figure 5b). In this modelling methodology, all pipes, including main lines, branch lines and vertical risers, were modelled in SAP2000 with the use of frame elements. The frame section properties were calculated automatically and assigned to each member using as input the pipe's outside diameter and wall thickness. Distributed mass was assigned to each member considering the weight of the wet pipes. Pipe joints were modelled using the calibrated parameters of bilinear pivot models with the zero-length link element in the rotational DOFs. All vertical steel rod hangers were simulated as bilinear steel members and were assumed to have a pin connection to the pipes and a fixed boundary condition at the top with the floor slabs to which they were anchored. Both longitudinal and lateral braces were modelled using frame elements with elastic section properties and were assumed to have fixed boundaries at both ends. As the wire restraints only had resistance in tension, cable sections were adopted to simulate the wire restrainers with pin connections for both ends. This modelling methodology was then used to develop fragility curves under floor motions obtained from floor responses of a four-storey hospital building.

In another study [69], the analytical model of the entire UCSF piping system was developed in the OpenSees platform [77] (Figure 5c). The pipes, including the main runs, branch lines, and sprinkler drops, were modelled with ForceBased Beam-Column [77] elements using the elastic gross section properties of the pipes and an elastic material with steel material properties. Grooved- and threaded-fit pipe joints were modelled using one zeroLength element on either end of the pipe elements with the Pinching4 parameters. These joint models were generated and calibrated with experimental results obtained at the University at Buffalo [88]. To accommodate flexural yielding of the hanger bars, they were modelled using Force-Based Beam-Column elements with a nonlinear fibre-section consisting of the Giuffre-Menegotto-Pinto steel material [91]. This material is implemented in OpenSees as the Steel02 material model. These hangers were pinned to the pipes and were fixed at their far end. The wire restrainers were modelled using truss elements, coupled with a tension only Elastic-Perfectly Plastic (EPP) Gap material. The rigid seismic braces were modelled with Force-Based Beam-Column elements using their elastic section properties. The connection of the solid braces was assumed to be rigid at both ends. The mass of the piping system was determined using the wet weight of the pipes with an additional mass at sprinkler head locations. The mass and weight of the system were concentrated at the nodal points. A real-time element removal algorithm was then incorporated in the analyses to capture the progression of damage to the piping system during seismic excitations by using the remove element command in the OpenSees platform [77]. This algorithm was set to remove the pipe hangers, solid braces, and wire restrainers after reaching their failure capacity. It should be mentioned that this modelling methodology was validated with the results of four different experiments [69]. Also, various component and system-level fragility curves were obtained by using this modelling procedure [92-94].

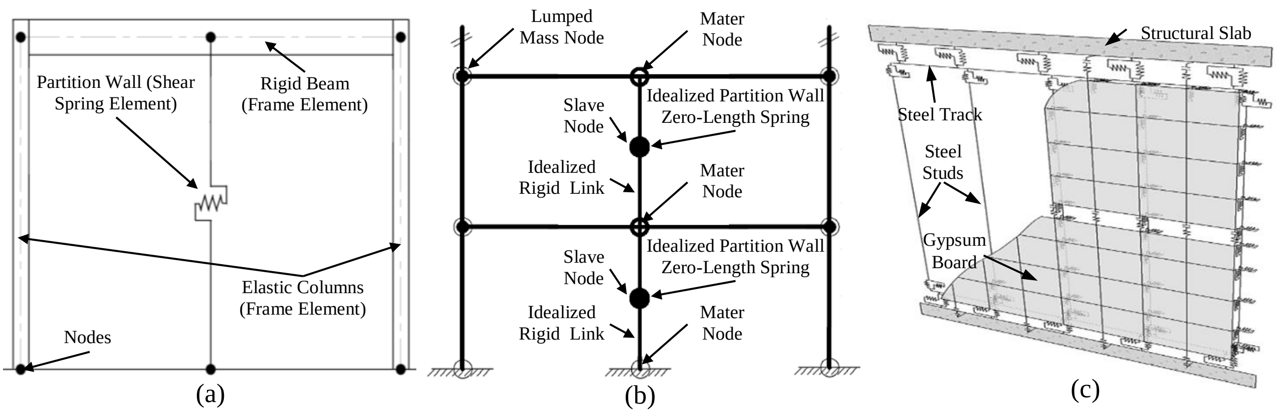

Figure 6: Examples of analytical studies on partition systems: (a) Davies et al. [40], (b) Wood et al. [94], (c) Rahmanishamsi et al. [95].

Light-Gauge Steel-Frame Gypsum Partition Walls

Available analytical research on steel stud partition walls includes a study by Fülöp and Dubina [35], which was validated by the experimental results of fifteen wall specimens. In their model, using DRAIN-3DX software, a full nonlinear fibre hinge within a single degree-of-freedom bar captured the behaviour of wall panels. In another study by Restrepo and Lang [49], a four-line piecewise linear backbone response was developed based on experimental results of a test by Restrepo and Bersofsky [41]. It was mentioned that the analytical model application is only limited to the variables used in their test programme.

In a more comprehensive analytical study [40, 44], the mechanical behaviour of light-gauge steel-frame gypsum partition walls was modelled using the RUAUMOKO [95] software (Figure 6a). In this modelling methodology, three different elements, two frame type members and one nonlinear shear spring, were used. Frame elements were set to represent structural columns and beams. The beam was set to be rigid by using the rigid links on each end of the beam extending to the centre of the member and the columns were set to remain elastic. The shear spring was then used to resemble the partition walls. The Wayne Stewart Hysteretic model was assigned to the spring element in the in-plane direction of partition walls. Various parameters such as initial stiffness, yield force, post-yield stiffness factor, capping force, post capping stiffness factor, unloading stiffness factor, intercept force, softening factor and pinching factor of this hysteretic model was calibrated with experimental results of experimental results obtained at the University at Buffalo [40, 44]. This calibration of parameters was performed for six wall categories: commercial slip track, commercial full connection, institutional slip track, institutional full connection, partial height and improved detail construction.

In a similar study by Wood *et al.* [96], a partition wall was characterized as a spring and placed at mid-height of a floor using the OpenSees platform [77] (Figure 6b). This uniaxial spring was implemented only in the longitudinal direction with slaved degrees-of-freedom or rigid links extending from floor to floor (Figure 6b). To calibrate the analytical models with experimental results from the University at Buffalo [40, 44], the pinching4 material was used in a parallel configuration to provide better control of the unload and reload response of the material. Several characteristics, including backbone points, unloading and reloading behavior and total half-cycle hysteretic energy, were optimized to calibrate the partition models for each subgroup (e.g., commercial slip track, institutional full connection). A normalized partition model was also developed in this study, whose definition only requires wall length and building occupancy (commercial or institutional). This normalized partition model facilitates analytical studies of partition walls with geometries other than those used in the calibration process. This modelling methodology was then used in conjunction with nine buildings with floor number varying from 2 to 20. Several sensitivity analyses, such as studying the effect of structural period or mass participation change, due to the installation of partition walls, were investigated.

In a comprehensive study by Rahmanishamsi *et al.* [97], a detailed and computationally efficient analytical model for cold-formed steel-framed gypsum partition walls was developed in the OpenSees platform [77] (Figure 6c). In this modelling methodology, studs and tracks were modelled using nonlinear Force-Based Beam-Column elements with a fibre-section consisting of the Giuffre-Menegotto-Pinto steel material [91]. The gypsum boards were simulated by ShellMITC4 four-node elements with the ElasticMembranePlate-Section. The shell and frame elements are meshed into a number of sub-elements in order to provide nodes at locations of gypsum-to-stud/track connections and increase the accuracy of modelling. The mass of stud and track elements are concentrated at the nodal points, while the mass of gypsum boards were assigned as the unit mass to the section. The nonlinear behaviour of partition wall connections, namely the gypsum board-to-stud/track, stud-to-track and track-to-concrete connections, were represented by using the Pinching4 material along with twoNodeLink elements. The parameters of the “Pinching4” material have been calibrated using the component-level experimental data [45-47]. The contacts between the gypsum boards and the top and bottom concrete slabs were modelled utilizing two parallel zeroLengthContact3D elements, each in series with an additional twoNodeLink element with EPPG material. The contacts between the adjacent gypsum boards were represented by a single zeroLengthContact3D element between every two gypsum board nodes. The analytical results obtained from this methodology were validated with full-scale partition wall assemblies, tested at the University at Buffalo.

FUTURE DIRECTIONS

In this section, a summary of limitations that exist in each of the ceiling, piping and partition systems is described, followed by recommendations to improve the analytical modelling capability of these systems. While this section lists the required steps that results in more complex and advanced modelling methodology, it may not result in the most accurate results if more unreliable parameters and/or uncertain input values are incorporated. Also, as these modelling techniques are computationally expensive, they should only be used in the cases where high levels of performance details are required. It should also be mentioned that the knowledge related to the demands (e.g., seismic) on non-structural systems imposed by the structures (e.g., floor acceleration, inter-storey drift) is a standalone topic and is out of the scope of this study.

Acoustical Lay-in Suspended Ceilings

According to the available analytical models for suspended ceilings, linear elastic elements were used as representative of ceiling grids. However, during past studies [8, 28], damage in ceiling grids other than at end connections (e.g., buckling of grid members) were frequently reported. In addition, splice connections between the main run members were not modelled in any of the previous studies. Therefore, the use of more elaborate nonlinear elements for grid elements and splice models in main run connections may facilitate future analytical models to be able to capture various failure models in grid members.

Simplified modelling concepts such as mass only or rigid x-shaped assembly were used for the modelling of ceiling panels. However, as ceiling panels contribute to the in-plane stiffness and the extent of damage in ceiling systems, more accurate models with realistic properties of ceiling panels can enhance the modelling capability of ceiling systems. It should be mentioned that the previously defined mechanisms to capture the movement and failure of ceiling panels should be carefully examined in future studies.

The connection capacity of supporting elements (e.g., hangers, braces) to the deck and ceiling grid was not considered in previous studies. However, failure of these connections was reported in previous studies [25, 28]. The connection capacity of these elements needs to be determined at grid level and based on different base material properties and deck level.

Fire Sprinkler Piping

During past analytical studies on fire sprinkler piping systems, several approaches were used to simulate the bending behaviour of pipe joints. However, the torsional behaviour of these pipe joints was never considered in previous studies. Accounting for realistic torsional behaviour of pipe joints will enable future analytical models to capture system failures [25] due to the excessive torsional demands in pipe joints.

The accuracy of previous modelling methodologies for fire sprinkler piping systems should be investigated under vertical excitations. Vertical excitations were found [50] to be one of the main sources of damage to piping systems (e.g. failure of hanger clips due to uplift and pounding of pipe runs). Therefore, precise modelling of piping systems under vertical excitation can significantly improve the capabilities of future analytical models to better predict the seismic performance of piping systems.

Similar to ceiling systems, connections of pipe-supporting elements (e.g. sway braces, wire restrainers) were not specifically modelled in previous studies. Failures of these connections were reported several times during past studies [50, 27]. Therefore, accurate modelling of these connections will enhance future modelling techniques to better capture the propagation of damage in piping systems.

Light-Gauge Steel-Frame Gypsum Partition Walls

Cracking of gypsum boards is known as one of the most frequent type of failures in partition walls based on past earthquakes and experimental studies [1]. While available analytical tools may be able to capture the complete separation of gypsum boards from the studs, they cannot capture the initial cracking and its propagation in gypsum boards. Development of an elaborated analytical model for gypsum boards, in which the crack mechanism is accounted for, will enable future analytical models to estimate the extent of cracking damage in gypsum boards.

Excessive bending and plastic rotation of partition studs under large inter-storey drifts is the main cause of extensive damage in partition walls. However, current analytical models cannot accurately predict the behaviour of studs and the occurrence of their plastic hinge formation as a consequence. An experimentally validated analytical model for the bending response of partition studs can help engineers better estimate the level of damage in partition walls.

Almost all of the previous analytical studies were focused on the in-plane performance of partition walls. However, knowing the out-of-plane movement of partition walls is important as it provides the supporting perimeter for suspended ceiling systems. In addition, damage to the partitions in their out-of-plane direction due to the attached contents (e.g. bookshelves) is reported in previous studies [40]. Moreover, the performance of returning partition walls under the out-of-plane inter-storey drift is a topic of concern. Therefore, a systematic modelling procedure for future numerical studies will provide valuable information for investigating the out-of-plane performance of partition walls.

Corner and T connections of partition walls were not modelled in previous analytical studies. However, due to the differential movement of longitudinal and returning walls, several types of damage at the corner and T connections of partitions were observed during past studies. Thus, the detailed modelling of these connections will enable a full seismic risk assessment of partition walls.

Integrated Systems

In common constructions, a non-structural system generally has interaction with two or more other systems. These interactions can be within different non-structural systems, between non-structural system(s) and their supporting structures, or between non-structural system(s) and room contents. Therefore, while studying a non-structural system as an isolated subsystem provides vital information, it should be considered as an integrated system to represent the actual construction. Consequently, integrated simulation of non-structural systems will also provide more accurate tools for seismic assessment of non-structural systems.

SUMMARY AND CONCLUSIONS

In this study, a brief overview of acoustical lay-in suspended ceilings, fire sprinkler piping and light-gauge steel-frame gypsum partition walls was presented. Detailed descriptions of available modelling techniques for each of these systems were discussed. Finally, several recommendations were provided for future analytical simulations to better perform the seismic assessment of these systems. A summary of these are as follows:

- The use of elaborate nonlinear elements for grid elements, reliable splice models in main run connections, accurate models with realistic properties of ceiling panels, and a precise connection model of supporting elements can significantly improve the capability of future ceiling analytical models.
- Analytical simulation of piping systems can be enhanced by considering the torsional behaviour of pipe joints, connection capacity of supporting elements and accuracy of proposed modelling methodologies under vertical excitations.
- The numerical modelling capacity of partition walls can significantly be improved by including realistic gypsum board models, experimentally validated analytical models for the bending response of partition studs, out-of-plane

behaviour of partitions and detailed models for T and corner connection of partition walls.

- Integrated modelling of non-structural systems can result in more accurate and realistic seismic assessment of non-structural systems.

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