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Finite Element Modeling of Masonry Infill Walls Equipped with Structural Fuse

Ali M. Memari and Mohammad Aliaari

Additional information is available at the end of the chapter

Abstract

Masonry infill walls in multi-story buildings are intended to function as envelope and partition walls, and without sufficient gaps between the infill and the frame, the infill tends to contribute to lateral seismic load resistance, which can lead to damage. By isolating the infill walls from the frame, vulnerability to damage will be reduced; however, the potential benefit from the strength and stiffness of the infill walls will be lost too. The compromise solution seems to be a controlled engagement of the masonry infill walls by employing a structural fuse concept. In this chapter, initially, a review of the literature on seismic performance of masonry infill walls is presented. This is then followed by explanation of the concept of the masonry infill structural fuse. Then a discussion on experimental tests carried out on different types of fuse elements as well as ¼ scale specimen of frame and infill walls with fuse elements is presented. Finally, the results of finite element computer modeling studies are discussed. The study has found that the concept of using structural fuse elements as sacrificial components in masonry construction is practical and can be given consideration for more refined design and detailing toward practical application.

Keywords: masonry, infill, seismic, fuse, modeling

1. Introduction

Masonry bearing wall systems were the predominant structural systems prior to the use of framed structures. Once steel and concrete framing systems replaced bearing wall systems, especially for multistory buildings, masonry walls were then used as infill walls (**Figure 1**) to provide the envelope and partition wall functions. Besides such functions, the role of masonry infill walls in seismic resistance of buildings has long been well recognized. In fact, because of

participation of masonry infill walls in resisting lateral seismic loads, infill walls and/or their framing systems can sustain damage with life-safety hazard potential [1, 2].

Traditionally, masonry infill walls are specified by architects as exterior envelope walls, backup walls for veneer systems, or interior partition walls. Such construction does not carry gravity load from floors and only carries its own weight. Depending on the details of joints between the edges of infill walls and infilled frames, the interaction between the infill wall and frame can adversely affect the seismic behavior of the structure (e.g., [3, 4]). In most cases, the small gaps between the infill wall and the structural frame are infilled with caulking and in some cases with mortar [5]. This tight-fit construction (**Figure 2**) engages the infill wall in in-plane lateral load resistance [6]. Depending on whether the wall is solid (complete infill) or the existence of large openings that make the infill wall partial infill, the wall's interaction with confining
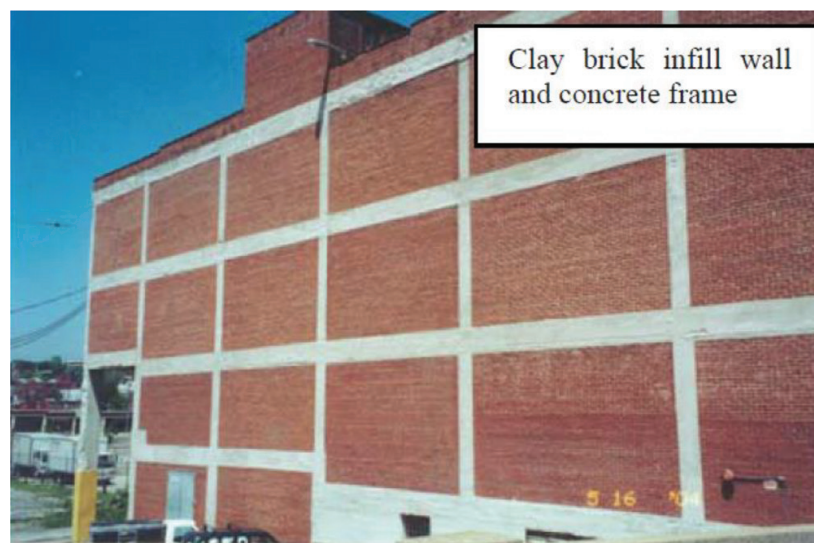

Figure 1. Examples of masonry infill wall in a reinforced concrete frame building [Photo by Ali M. Memari].
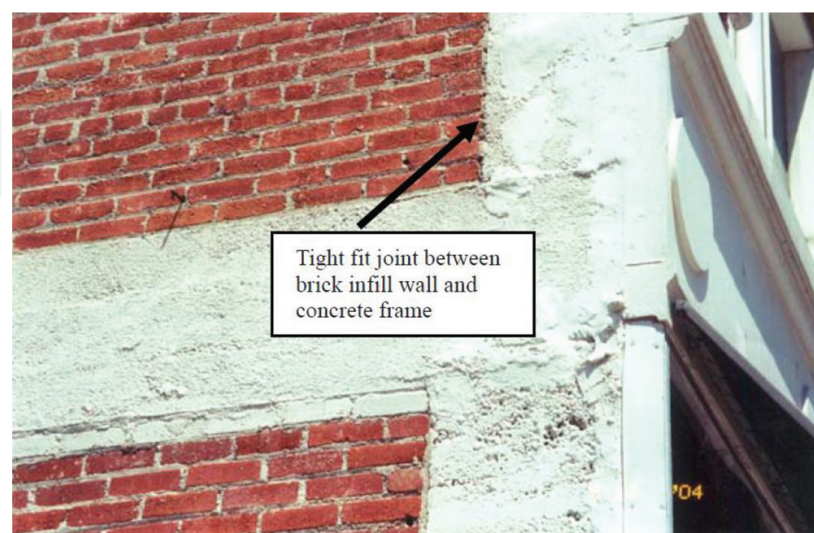

Figure 2. Example of a tight-fit masonry infill wall construction [Photo by Ali M. Memari].

frames could possibly lead to premature column failure as a result of short column effect or to increased levels of ductility demand in columns. Furthermore, because these tight-fit infill walls essentially behave as shear walls, their distribution in plan could increase torsional moments and create structural irregularities, if not placed symmetrically. The manner infill walls resist lateral loads is much like a compression brace, and the cyclic interaction of this effective brace with structural frame connection may lead to either the failure in the masonry and/or damage to the beam-column connection. Tight-fit construction of infill walls, whether of partial height or full height can lead to extensive damage to walls, columns, or beam-column joints. Besides the life-safety hazard that such damage will pose, in terms of financial loss, infill wall damage and subsequent repair/replacement work can seriously challenge building owners and tenants.

In order to avoid damage to infill walls, columns, or joints, the use of gaps between the infill wall and the frame is one alternative as shown in **Figures 3** and **4**. Providing gaps between the infill wall and the confining frame is a building code requirement (e.g., [7]) if the infill wall is not designed as part of the lateral force-resisting system, that is, if it is a nonparticipating infill. On the other hand, if the in-plane isolation joints are not large enough to satisfy the conditions

Figure 3. Example of partition infill wall isolated from the frame with small gaps: (a) beam-column joint area and (b) gap between column and infill wall [Photo by Ali M. Memari].
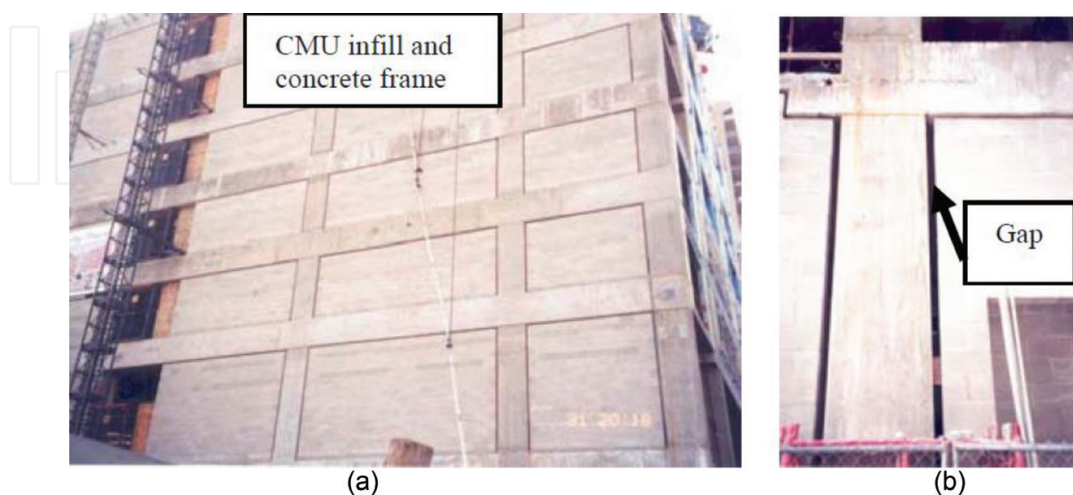

Figure 4. Use of large gaps between infill backup wall and frame in a Seattle building: (a) view of several stories of the building and (b) close-up view of gaps between column and infill walls [Photo by Ali M. Memari].

for nonparticipating infills, then the infill wall is considered as part of the primary lateral force-resisting system, that is, participating infill, and it must be designed as a shear wall, which complicates design and construction and is not typically desirable by designers. For isolation of infill walls, small gaps (e.g., 9.5 mm–12.7 mm) are usually provided, which are then filled with caulking or other deformable fillers. **Figure 3** shows an example of an infill wall construction with isolated joints from the frame with small gaps. In more seismically active areas, larger gaps are usually provided, as shown in the example of **Figure 4**, which shows a large gap between concrete masonry unit (CMU) infill wall and reinforced concrete frame. This particular infill wall was, however, intended to function as the backup wall for brick veneer exterior skin. In general, when such a gap is to be provided, the gap size should exceed the expected interstory drift, which is determined either by structural analysis, or as the maximum allowable value specified in the building code.

Providing large gaps for partition wall applications will cause its own challenging issues with respect to fire safety and sound transmission issues for which the architect and designers should recommend appropriate solutions. Providing small gaps in general will not have the scale of the problems of large gaps. However, under moderate-to-strong earthquakes, the gap openings will likely approach the upper limit for story drift ratios of building codes such as ASCE 7–16 [8]. For instance, for a Risk Category II building with allowable story drift ratio of 2%, the upper limit will be nearly 75 mm for a 3750 mm story height. In that case, once the gap opening is overcome by the frame story drift, the columns will then bear against the infill wall, and under cyclic-type oscillations, the infill wall and/or frame members can sustain damage. It is the responsibility of the designer to assure the sufficiency of the gap size, and if it is desirable to keep the gap size small, the designer will have to increase the size or number of frame members designated as part of the lateral-force-resisting system, which could translate to substantial increase in construction cost.

By isolating the infill wall from the frame and avoiding their interaction in buildings with moment-resisting frames as their primary lateral force-resisting system, damages to infilled frames, failure of infill walls, and potential life-safety hazards can be avoided. However, in that case, the building is deprived of the potential benefit from the strength and stiffness that masonry infill walls can offer even if they are not designed as shear walls. It should be noted that even unreinforced masonry walls inherently possess considerable stiffness that can be properly and advantageously employed in lateral force resistance.

One shortcoming of this isolation option is that the beneficial effects of the masonry infill in stiffening and strengthening the structural frame system will not be employed. In general, since the masonry infill walls are heavy and greatly increase the effective seismic weight of the building, it would be logical to engage them also in lateral load resistance. However, it is the potential damage to these brittle components that designers wish to avoid. The compromise solution seems to be a controlled engagement of the masonry infill walls by employing a structural fuse concept. Such an idea is based on desirability of employing beneficial effects of strength and stiffness of infill walls to reduce story drifts during seismic events up to certain controlled levels. Under strong shaking, when the interaction force between the infill wall and the frame exceeds a certain level, it is desirable to isolate the infill wall from the frame in order to avoid damage to the wall or the frame. This function is provided by using a structural fuse.

In this chapter, preliminary studies on this concept are reviewed. Initially, the concept of the masonry infill structural fuse is explained. This is followed by discussion of experimental tests on different types of fuse elements. Next, the pilot experimental studies employing a one-fourth scale frame and infill walls with fuse are reviewed. The results of computer-modeling studies are then presented followed by recommendations for additional follow-up studies that need to be undertaken.

2. Background and literature review

There has been over 60 years of research on infill walls. The following references are mentioned as chronological representative examples of the experimental and analytical studies done over the past six decades: [2, 5, 9–48]. Even after such extensive international efforts, there is still room for enhanced understanding and design considerations of masonry infill wall interaction with structural frame.

The consensus among researchers is that it is wise to use the beneficial properties of the infills in design if their strength and stiffness characteristics can be relied on. The masonry design code, ACI 530–13/ASCE 5–13/TMS 402–13 [7], provides design guidelines for infill walls
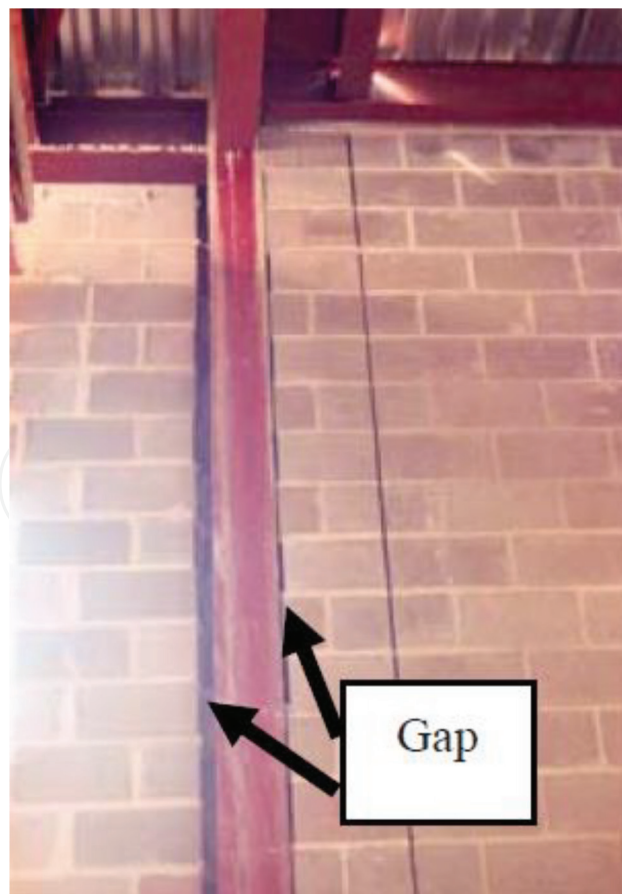

Figure 5. Use of different size gaps in a building [Photo by Ali M. Memari].

in Appendix B. The current code offers two sets of prescriptive design guidelines, one for masonry walls not considered participating in lateral force-resistance, and the other for walls that are expected to take part in lateral force resistance. For the latter group, masonry standards joint committee (MSJC) 2013 code requires these walls to be designed as shear walls, which necessitates use of sufficient reinforcement and detailing to satisfy in-plane and out-of-plane flexural and shear effects. According to the code, for the former group *B2.1.1: In-plane isolation joints shall be designed between the infill and the sides and top of the bounding frame., B2.1.2: In-plane isolation joints shall be specified to be at least 3/8 in. (9.5 mm) wide in the plane of the infill, and shall be sized to accommodate the design displacements of the bounding frame., B2.1.3: In-plane isolation joints shall be free of mortar to contain resilient material, provided that the compressibility of that material is considered in establishing the required size of the joint.* In practice, sometimes gaps of different sizes are provided (most likely not by design but because of construction issues) between the infill and the frame as shown in **Figure 5** in a building.

3. Development of a fuse element for masonry infill walls

In search of ways to find an alternative solution so that the infill wall can participate in lateral load resistance and provide additional stiffness for wind loading and low-to-moderate seismic events, but to disengage (be isolated) under major events, a fuse concept was introduced [49]. **Figure 6** shows the concept of a structural fuse placed between the infill wall and
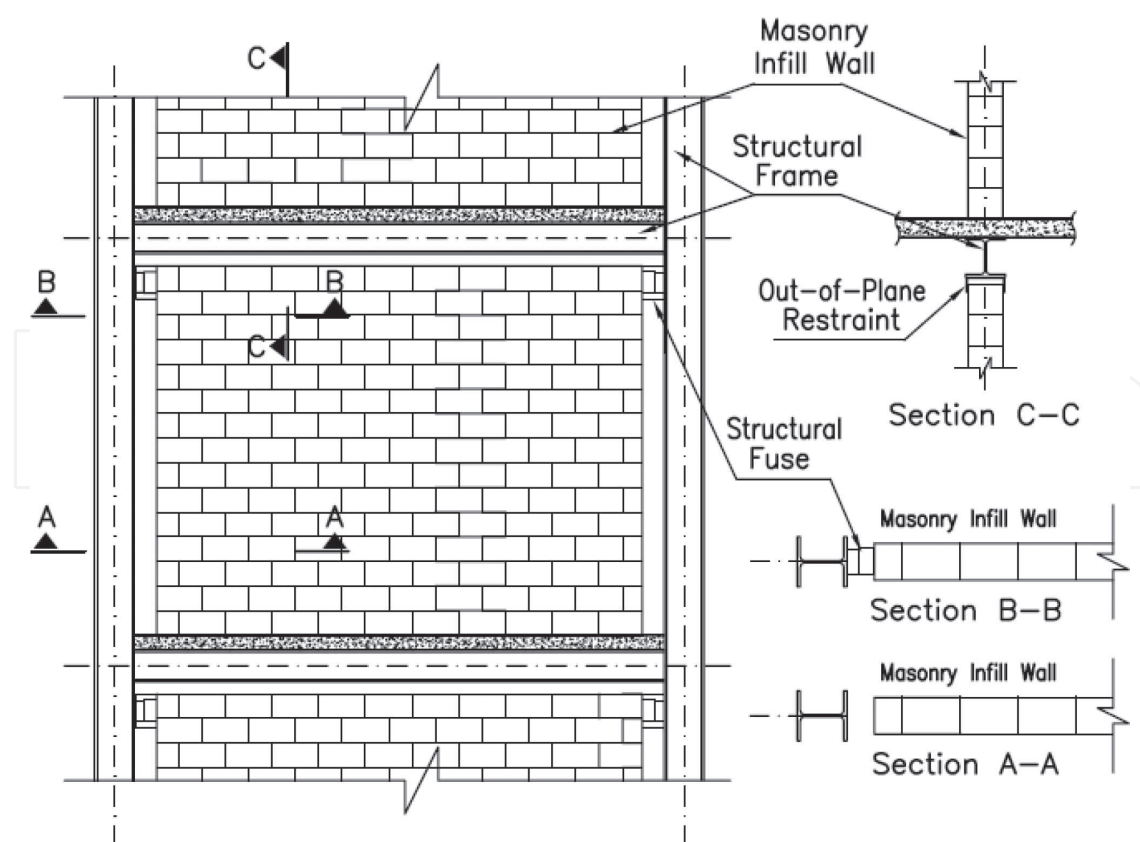

Figure 6. Schematic representation of fuse elements in a masonry infill wall [53].

structural frame. The fuse element is placed as a masonry unit (or part of it). Depending on the fuse element material and mechanism design, it can have stiffness and damping properties and it could be a single rigid-brittle element or a rigid-ductile element.

Pilot tests were carried out to investigate the concept and the feasibility of using such a fuse for infill walls [50–52]. A few different materials and mechanisms were studied to develop a potentially acceptable fuse element. The concept of a disk and a punching or penetrating rod was developed. In this concept, a disk of concrete or wood will be used as the breakable fuse element as shown in **Figure 7**. The fuse element types shown in **Figure 7** perform in a rigid manner up to their punching capacity, beyond which the interaction between the frame and the infill wall stops. In other words, when the fuse is installed between the top of the infill wall and the frame columns, the infill wall is engaged in lateral load resistance, but when the fuse breaks at the threshold design load of the fuse, the infill wall no longer offers resistance to lateral movement of the frame.

Another pilot study used rigid wood disks on a one-fourth scale three-story two-bay frame as shown in **Figure 8**. The pilot study investigated a rigid fuse element that worked only under compression. **Figure 8** shows how a wood disk breaks when its ultimate capacity is reached. The size of the gap between the infill walls and the frame shown in **Figure 8** was chosen for convenience of experimental study. For real applications in buildings, the fuse-holding mechanism will be placed in the location of an edge masonry unit, and therefore, normal gap
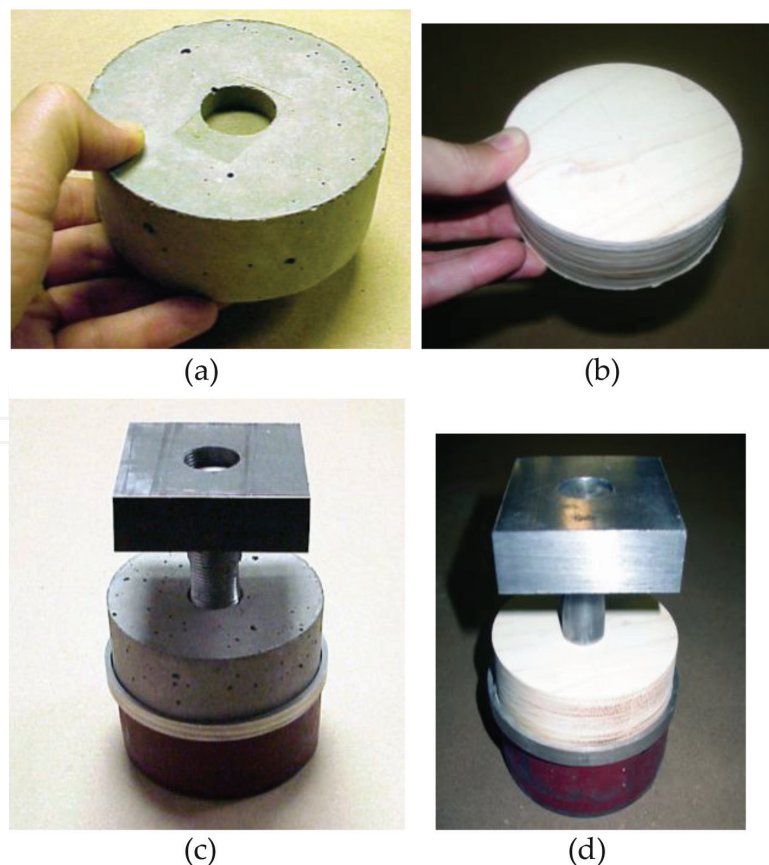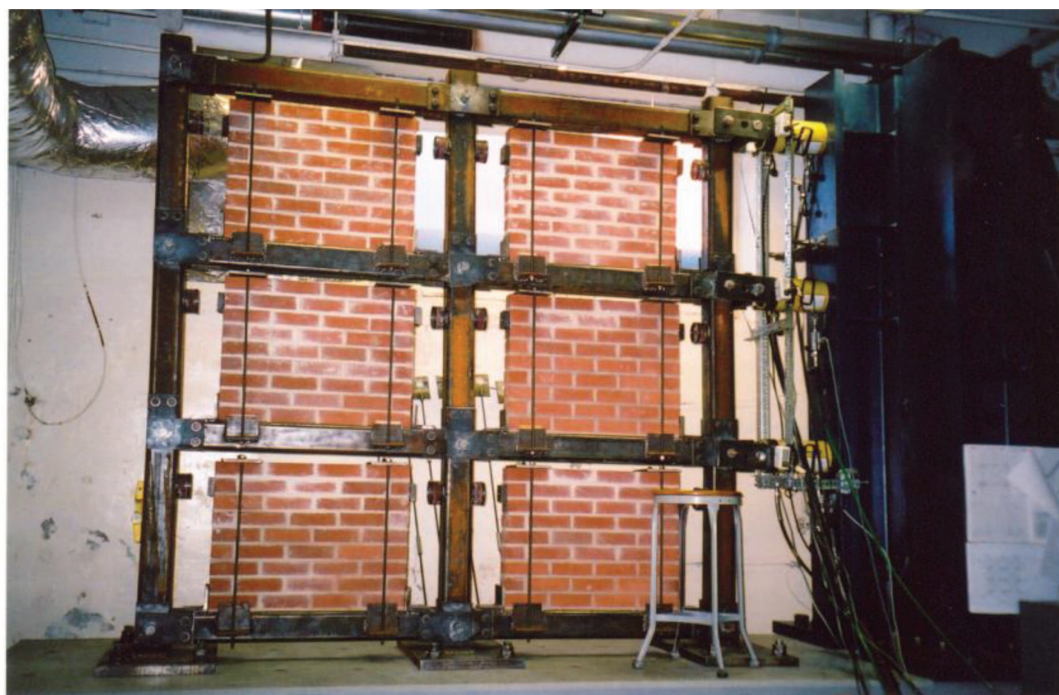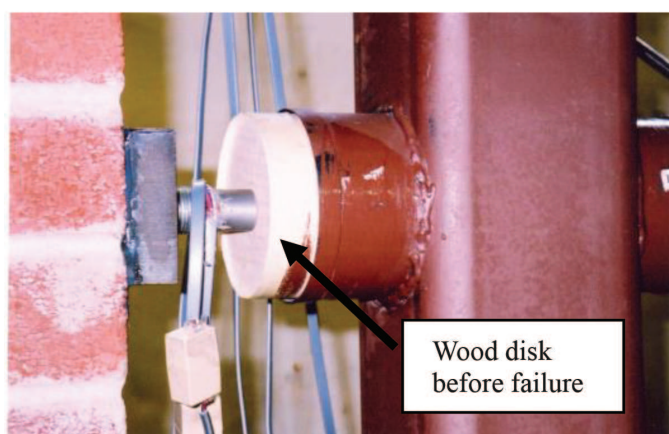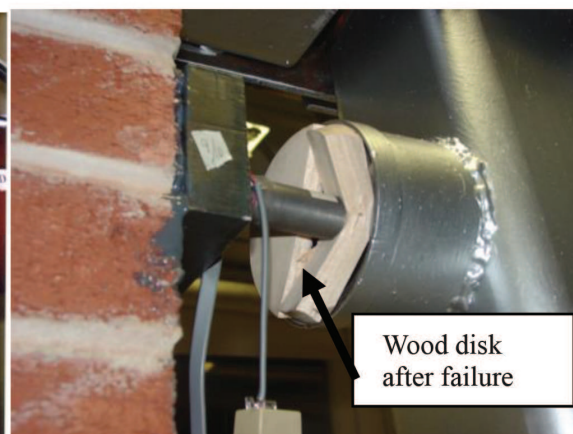

(a)   (b)

(c)   (d)

Figure 7. Rigid fuse element with concrete and wood disk alternatives: (a) concrete disk; (b) wood disk; (c) engagement of steel rod on concrete disk; (d) engagement of steel rod on wood disk [53].

Figure 8. Test results on one-fourth scale frame and infill wall with wood disk fuses: (a) one-fourth scale experimental setup; (b) steel rod tightened against wood fuse; and (c) steel rod puncturing wood fuse [53].

sizes can be used. Furthermore, the out-of-plane movement of the infill wall can be restricted using different available mechanisms as appropriate to a given design.

The process of pilot study leading to the test specimen shown in **Figure 8** consisted of initially developing load-deformation relations for isolated disk element to obtain the average capacities. Then isolated masonry walls were tested under in-plane shear loading to determine their capacities. Finally, the fuse disks were chosen such that they will break prior to masonry infill shear capacity. The detail of the experimental study is explained in Ref. [53]. In this chapter, only the computer-modeling aspect of masonry infill walls equipped with rigid-brittle structural fuse elements is presented. The objective of this chapter is to discuss development of a finite element model for the system (infill-fuse-frame) and validate it by using the results of tests on masonry infill walls (without fuse) available in the literature. In the process of developing the

finite element modeling, initially a single-bay, single-story steel frame with tightly fitted infill wall that has been studied by others was modeled. Once the single-bay, single-story model was validated using existing literature results, the model was subjected to monotonic push-over loading as well as cyclic loading under different load-control and displacement-control parameters. The presentation also includes discussion of a parametric study. Practical design approaches and guidelines for masonry infill walls equipped with the proposed structural fuse element and variation of masonry type for the fuse concept are presented in Refs. [54, 52].

4. Development of the finite element model for fuse-equipped infill wall

In the finite element model, material nonlinearities were considered because of nonlinear moment-rotation and force-deformation responses of steel frame connections, equivalent infill wall struts, tie-down anchors, and the fuse element. Large deformation and geometrical nonlinearities existed due to movements and contact between infill wall and frame. In this study, ANSYS finite element analysis program [55] was employed. Five different finite element types from ANSYS element library were used for modeling. The uniaxial BEAM3 element with compression, tension, and bending modeling capabilities was used to model the frame members. PLAIN42 element was used to model the masonry infill wall. CONTACT12 element was employed to model the interaction between infill and frame, and COMBIN39 spring element was considered to model the diagonal strut representing the masonry infill and rotational spring representing beam-column joint. Finally, COMBIN40 element was used to model the proposed structural fuse component.

To model a bare steel frame, BEAM3 element with three degrees of freedom (two translations and one rotation) at each node was used. PLAIN42 element with four nodes and two translational degrees of freedom per node was used as a plane stress element to model the infill wall. COMBIN39 element with two nodes and with up to three translational degrees of freedom per node can be used as a unidirectional element (e.g., uniaxial compression-tension element or purely rotational spring). The longitudinal option with two degrees of freedom per node was used to model the diagonal struts to represent effective infill and also tie-down rebars. The rotational option was used to represent the frame's beam-column connection. CONTACT12 element with two nodes and two translational degrees of freedom at each node was considered to model a gap between two surfaces, which can be in compression contact or at no contact and may also slide relative to each other considering Coulomb friction. This element was used to model the interaction between infill wall and frame when equipped with fuse. When there is interaction between the two surfaces, the normal stiffness and tangential (shear) stiffness may be active. A negative normal force represents contact between the two surfaces through a linear spring, while a positive normal force means lack of contact. On the other hand, when there is a negative force and the tangential force is less than the product of the normal force and friction coefficient, the two surfaces do not slide freely and are governed by the tangential spring stiffness. However, the two surfaces slide when the tangential force equals that product. COMBIN40 element is a special element to provide stiffness and damping to one side of a gap modeled in series. This two-node element with one degree of freedom per node (e.g., translational or rotational) can be

specialized for different applications by appropriate assignment of values for spring stiffness coefficients, damping coefficient, mass value, gap size, and a limiting sliding force.

From the result of a comprehensive review of experimental and analytical studies on infill wall systems [22], an appropriate specimen was chosen for development of finite element modeling in this work. The approach for finite element model validation consisted of initially modeling the bare steel frame, then adding brace elements following methods in Refs. [56] (single-diagonal strut model) and [57] (three-diagonal strut model). The last step in developing the model was to add fuse elements.

One of the specimens in the tests in Ref. [58] on single-bay, single-story steel frame with CMU infill walls (labeled WD7) was chosen for finite element modeling. The specimens selected are described in detail in Ref. [22]. Lateral load was applied to the frame at the top. Specimen WD7 [58] included CMU infill wall with standard horizontal bed joint reinforcement constructed without any gaps between the infill and the steel frame. Load-deflection diagram for the specimen is shown in **Figure 9** including the bare frame and infilled frame tests. The figure also shows analysis results discussed subsequently.

The bare frame was modeled as shown in **Figure 10(a)** using the finite elements as explained in the previous section. The trilinear moment-rotation relationship proposed in Ref. [57] was
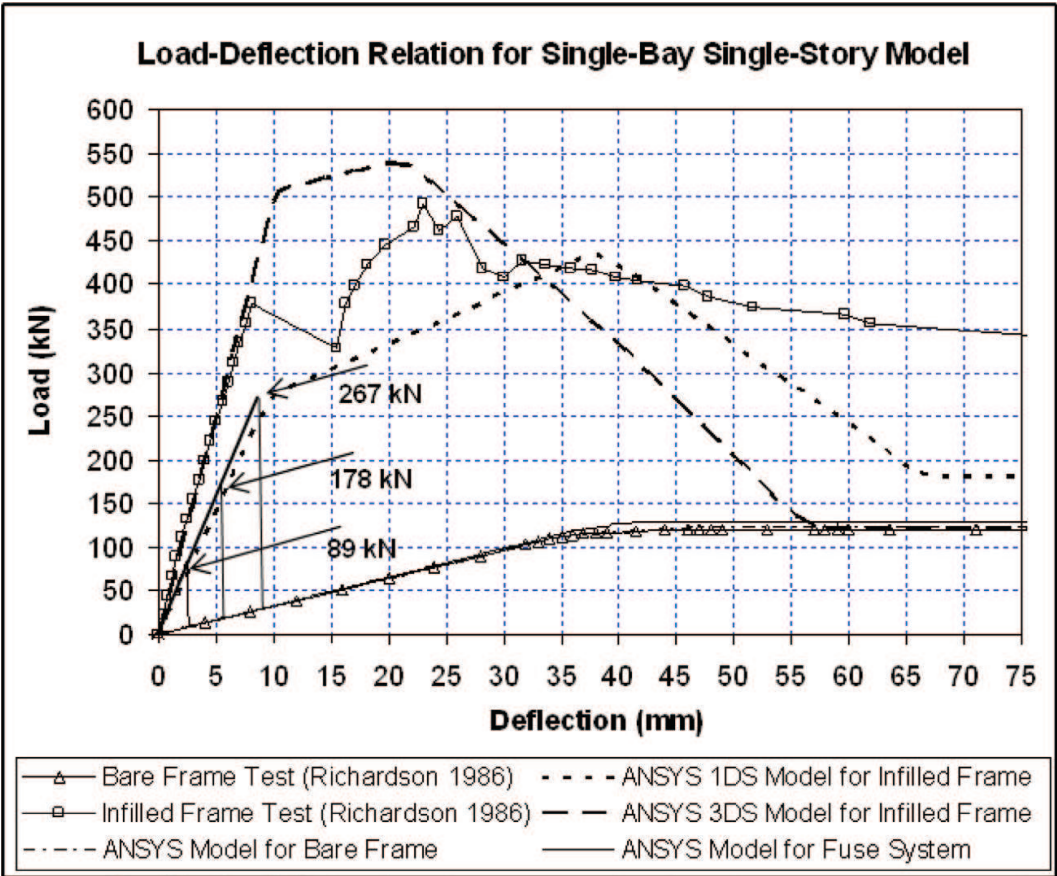

Figure 9. Load-deflection relation for single-bay, single-story system [53].

used for the beam-column joints. The load–displacement diagram for the model when sub-jected to monotonically increasing displacement was quite close to the experimental results. The bare frame showed to have an initial stiffness of about 3.22 kN/m. The failure mechanism consisted of formation of four plastic hinges in the four beam-column connections, which are represented by rotational springs in the model (**Figure 10(a)**).

The infill wall was modeled initially using the single-diagonal strut model [56] shown in **Figure 10(b)**. This was accomplished by adding a nonlinear diagonal compression strut to the bare frame model. However, the nonlinear rotational springs at the beam-column joint were substituted by frictionless hinges, in order for the diagonal strut to take the entire lateral load. The force-deformation model [56] was used for the strut representing the infill wall. The three-diagonal compression strut [57] shown in **Figure 10(c)** was also used as a second alternative for infill model. The force-deformation models were developed based on equations in Ref. [57] using the geometry and material properties of the modeled specimen (WD7). The infilled
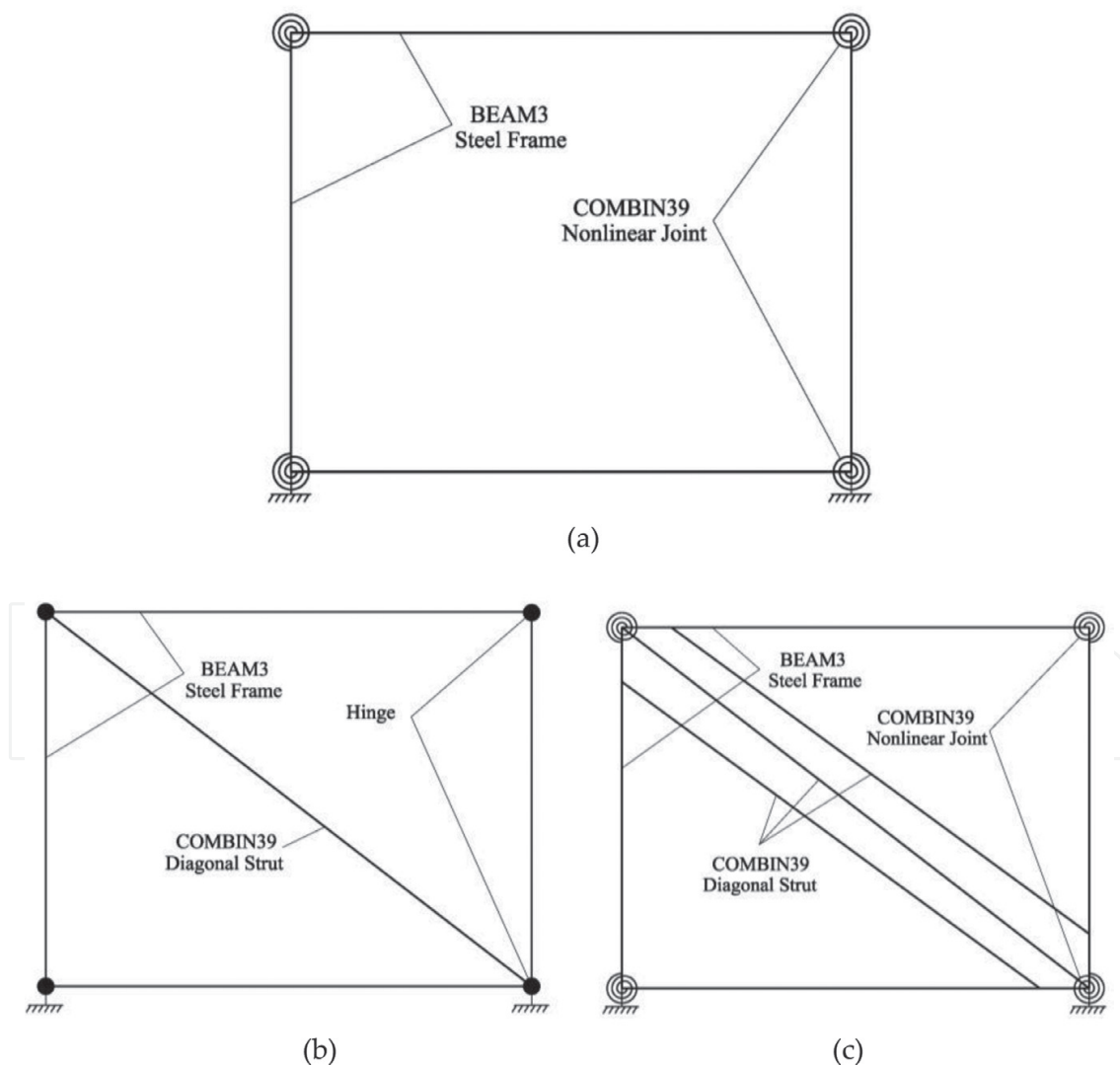

Figure 10. ANSYS models for (a) bare frame; (b) infilled steel frame with single-diagonal strut model; and (c) infilled steel frame with three-diagonal strut model [53].

frame models with the two types of strut models were subjected to monotonically increasing displacement with load-deflection plots compared to the experimental test results shown in **Figure 9**. The results of the two strut models show notable differences which is due to the assumptions made for force-deformation properties of the strut element. The three-diagonal strut model shows closer analytical results to the experimental test results.

The next step in completing the finite element model (shown in **Figure 11**) was to add appropriate fuse elements and hold-down elements. At the location of the fuse element on the columns, two nonlinear rotational springs were added. The final steel frame model shown in **Figure 11** had a total of 33 BEAM3 elements and 6 COMBIN39 elements. The masonry infill wall was, then, modeled with PLAIN42 elements. To model the contact between infill wall and steel frame, CONTACT12 elements were added at top and bottom at each side. The model presented also shows vertical steel rebar hold-downs modeled with COMBIN39 elements with tension force-deformation properties shown in **Figure 12**. The bottom corners of the infill
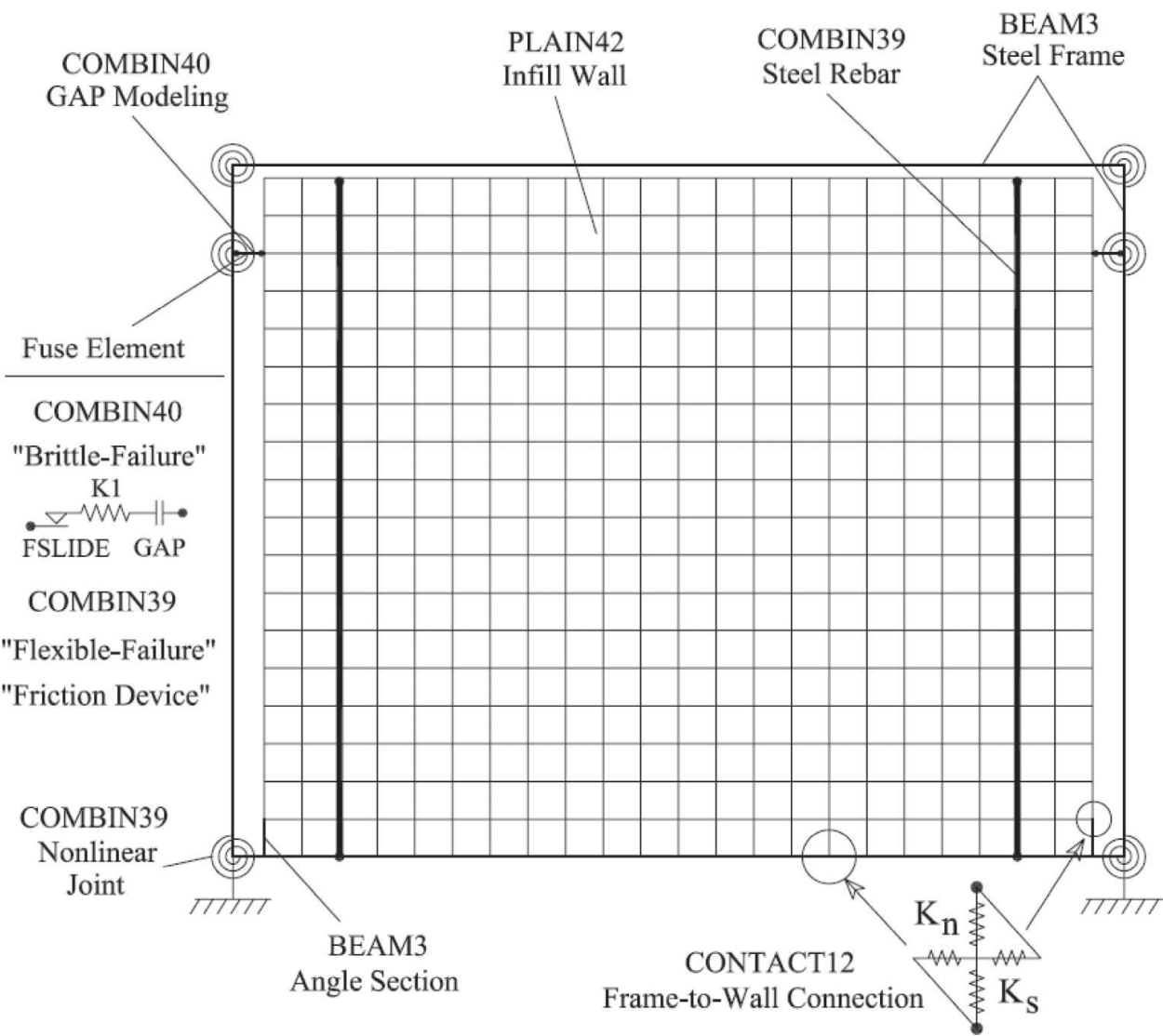

Figure 11. ANSYS model for infilled steel frame with fuse elements [53].

wall were assumed to be in tight fit connection with the columns to provide shear transfer. The micro infill wall modeling required 396 PLAIN42 elements, 27 CONTACT12 elements, and 2 COMBIN39 elements.

The fuse element used in the model is intended to simulate an elastic behavior up to failure or breakage of the element as shown in **Figure 13**. Once the fuse element breaks, there is no force transfer through the fuse element. COMBIN40 element provides the required property, which is transfer of force only in compression. To provide for such behavior, a very small value (0.0025 mm) was assumed for the GAP specification in the element property data. The spring K1 in the COMBIN40 element was determined considering the force-deformation results of the fuse elements pilot tests. COMBIN40 element features "break-away" property appropriate
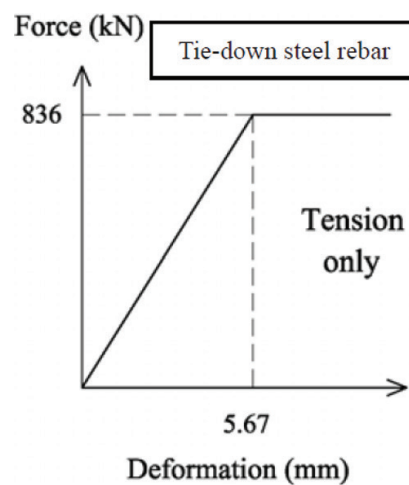

Figure 12. Force-deformation responses for tie-down steel rebar [53].
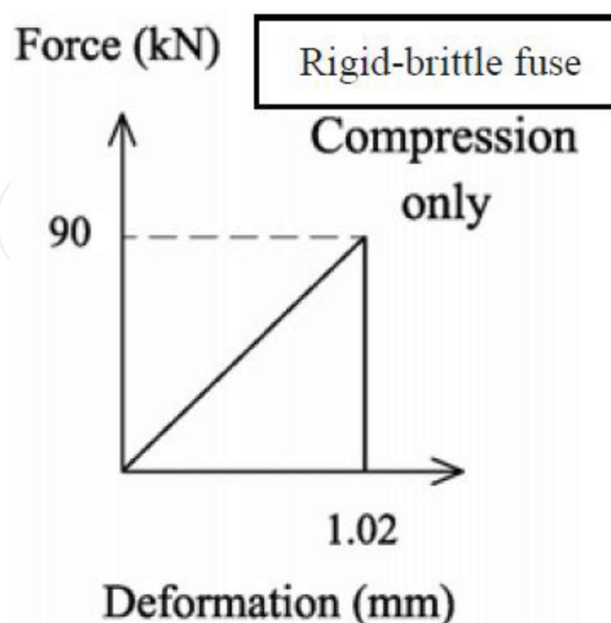

Figure 13. Force-deformation responses for the rigid-brittle fuse element [53].

to simulate the condition of fuse breakage with subsequent zero force in the element, once the fuse capacity is reached. The fuse capacity is a function of the masonry infill wall shear strength. According to test results in Ref. [56], the infill wall had a capacity of 383 kN, which with a factor of safety of 4.0, yields a fuse capacity of 89 kN for the model. This value was used to specify FSLIDE, for which a negative value results in a drop to zero when the force in the element reaches the specified capacity (89 kN), while a positive value represents yielding or constant force equal to the capacity. In this case, only negative value was assigned.

5. Discussion of the single-bay, single-story model analysis results

Pushover analysis of single-bay, single-story infilled frame with fuse element model was carried out to compare the response with infilled frame without fuse element. The results of this analysis are shown in **Figure 9** along with the results from the experimental study of the bare frame and infilled frame. For better clarity, **Figure 14** shows the plot of the initial deflection portions with larger scale. The effect of varying the fuse capacity on the system response is illustrated in **Figure 9** with three different values for the fuse capacity (i.e., 89 kN, 178 kN,
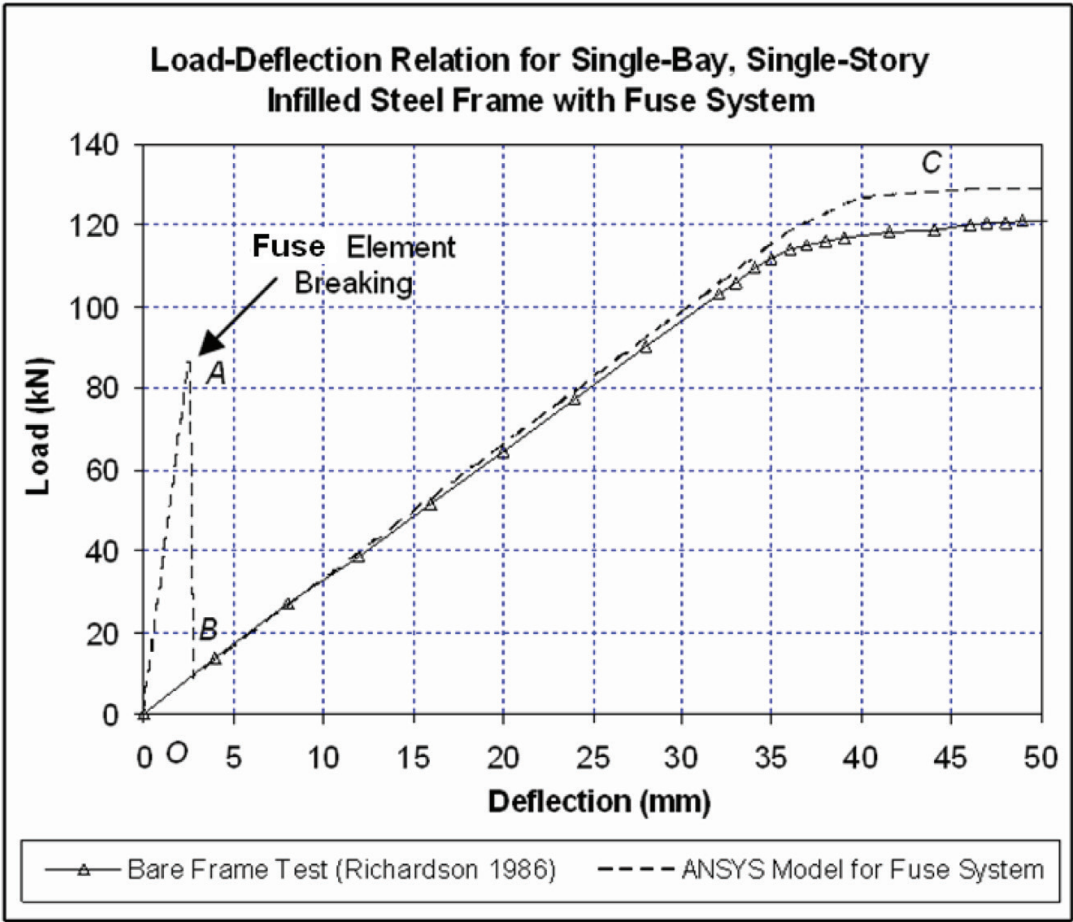

Figure 14. Load-deflection relation for single-bay, single-story model with "brittle-failure" fuse element [53].

and 267 kN). The figure shows two stages of response consisting of (a) prior to breakage of the fuse and (b) after breakage. During the first stage shown by line OA in **Figure 14**, the fuse transfers lateral loads from the frame to the infill wall and as such, the slope of the line OA represents the combined larger stiffness of the steel frame and the masonry infill wall. Upon breakage of the fuse at point A (capacity of fuse), there is sudden drop in the force level, line AB, followed by load-deflection relation along BC, which represents the response of the bare frame. This means that the infill wall is disengaged from the steel frame and only the bare frame is resisting the total load.

Comparison of the response of the model having fuse element with those of the bare frame and infilled frame in **Figure 9** shows that the stiffness of the system with fuse element is slightly smaller than that resulting from tested infilled frame (about 75% of the infilled frame). This, however, is about ten times the stiffness of the bare frame. Although as shown in **Figure 9**, higher strength fuse elements increase the strength capacity of the system, but it should be noted that the objective is to prevent failure of the wall. For example, based on the test results (shown on the figure), the tightly fitted masonry infill wall cracks around a lateral load of 378 kN. The smaller the fuse capacity, the larger will be the margin of safety against cracking.

The fuse element model shown in **Figure 13** describes a condition where upon breakage of the fuse, the force transfer across the fuse becomes zero. Since this could imply a shock-type response, but which is more like cracking of reinforced concrete or masonry system, it is possible to develop fuse elements that show more ductile response. For example, if the fuse element can be described by the trilinear or multilinear models shown in **Figure 15**, the corresponding load deflection plots for the infilled frame will be those shown in **Figures 16** and **17**, which show a more gradual drop of the force across the fuse and a smoother transition to the bare frame condition. It should be noted that depending on the mechanism of failure or design function of the fuse, different types of infilled frame response can be obtained. Examples of such mechanisms could include friction damper mechanism for energy dissipation and enhanced seismic response of the structure.
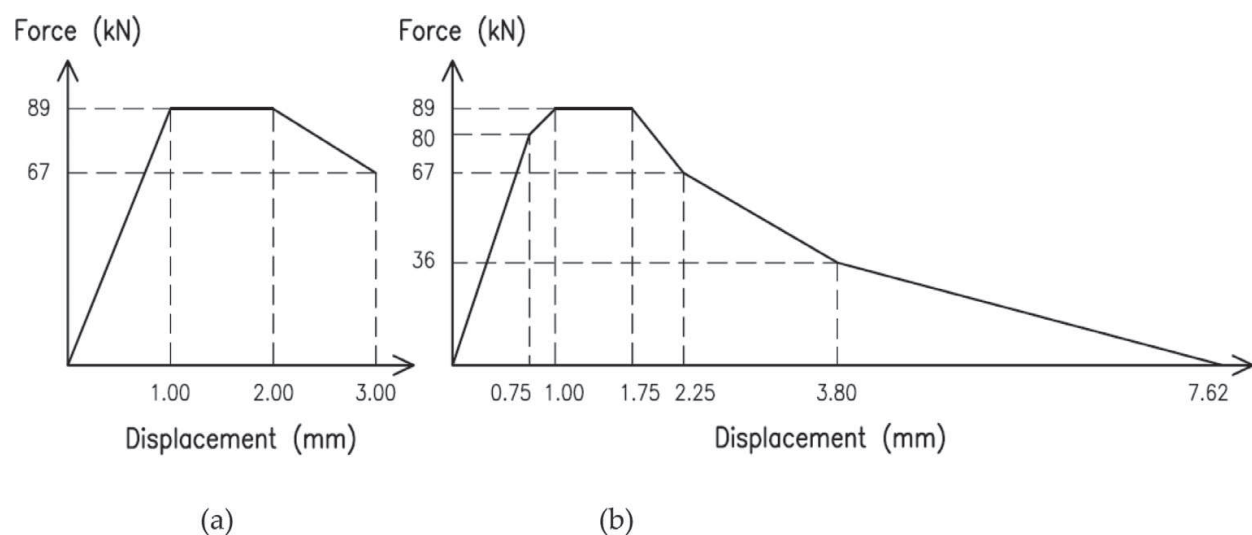

Figure 15. Assumed force-deformation responses for fuse element (a) "trilinear" and (b) "multilinear" [53].
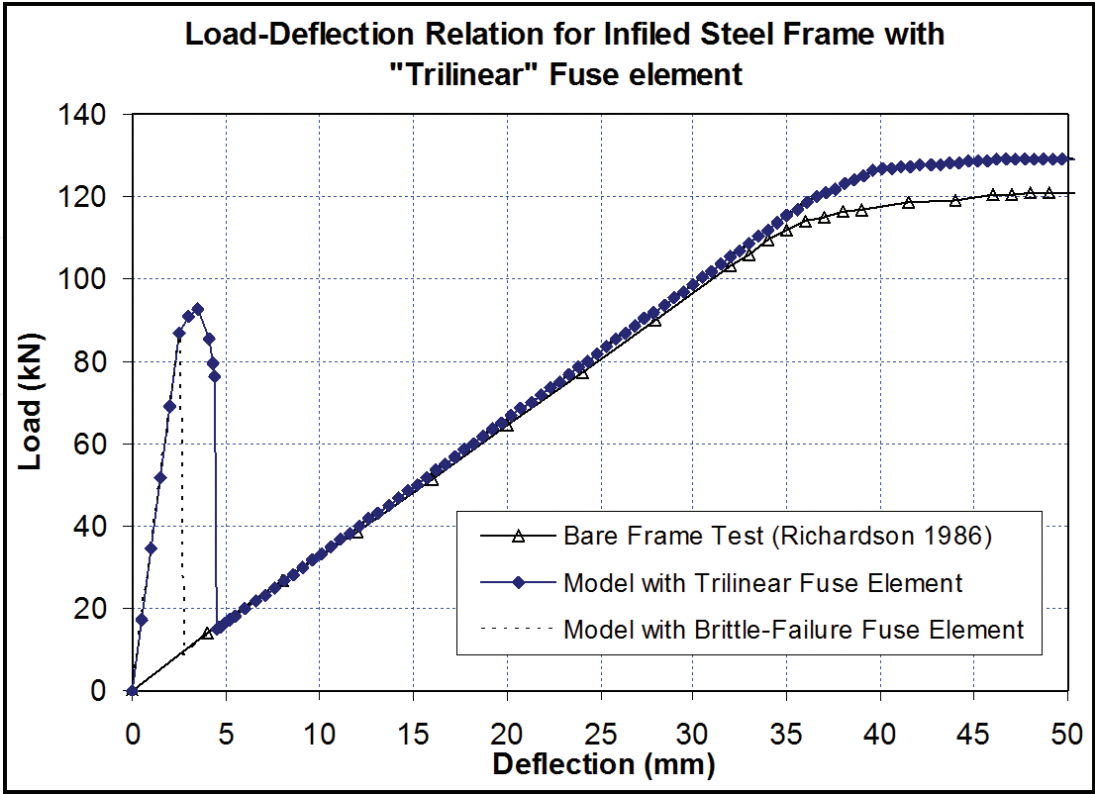
Figure 16. Load-deflection relation for single-bay, single-story case study with "trilinear" response for fuse element [53].
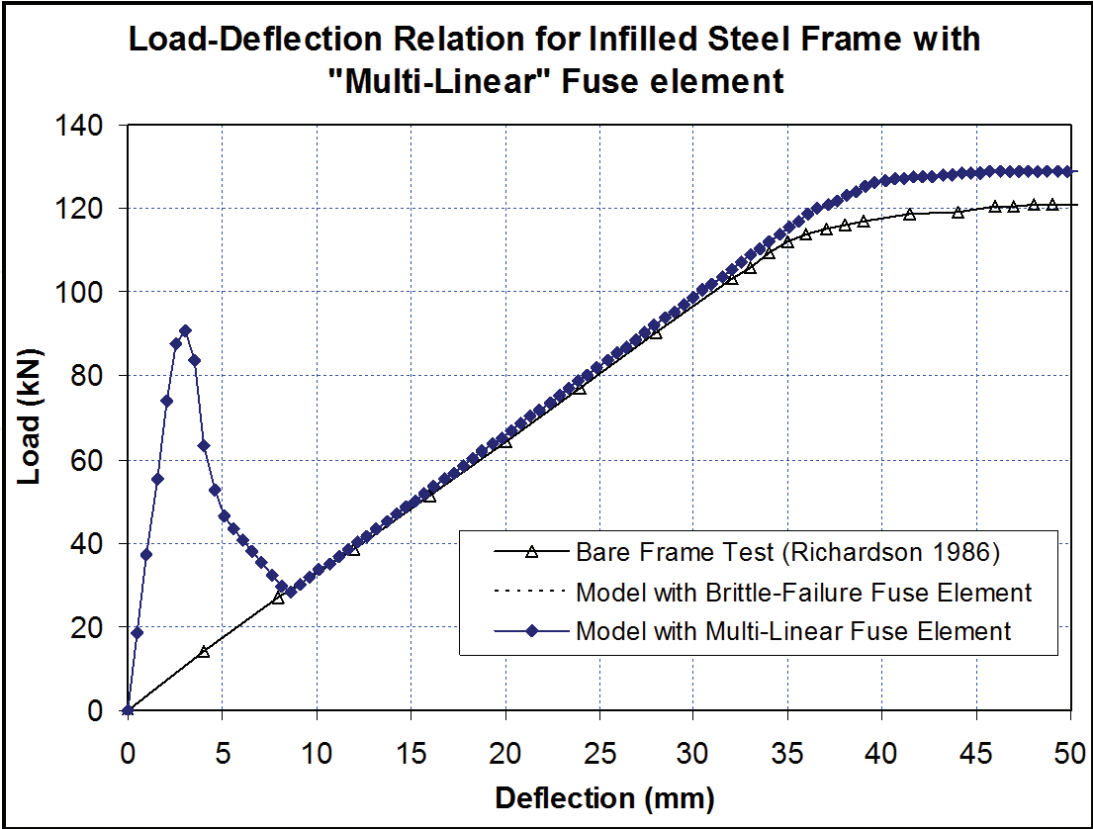

Figure 17. Load-deflection relation for single-bay, single-story case study with "multilinear" response for fuse element [53].

6. Discussion of the two-bay, three-story model analysis results

With the finite element model validated based on the performance of a single-bay, single-story infilled frame, the modeling approach can next be applied to a multi-bay, multistory system. The same modeling features presented in previous sections were used to model the two-bay, three-story frame shown in **Figure 18**. The panel dimensions and material properties were the same as those for the single-bay, single-story case. The steel frame members,
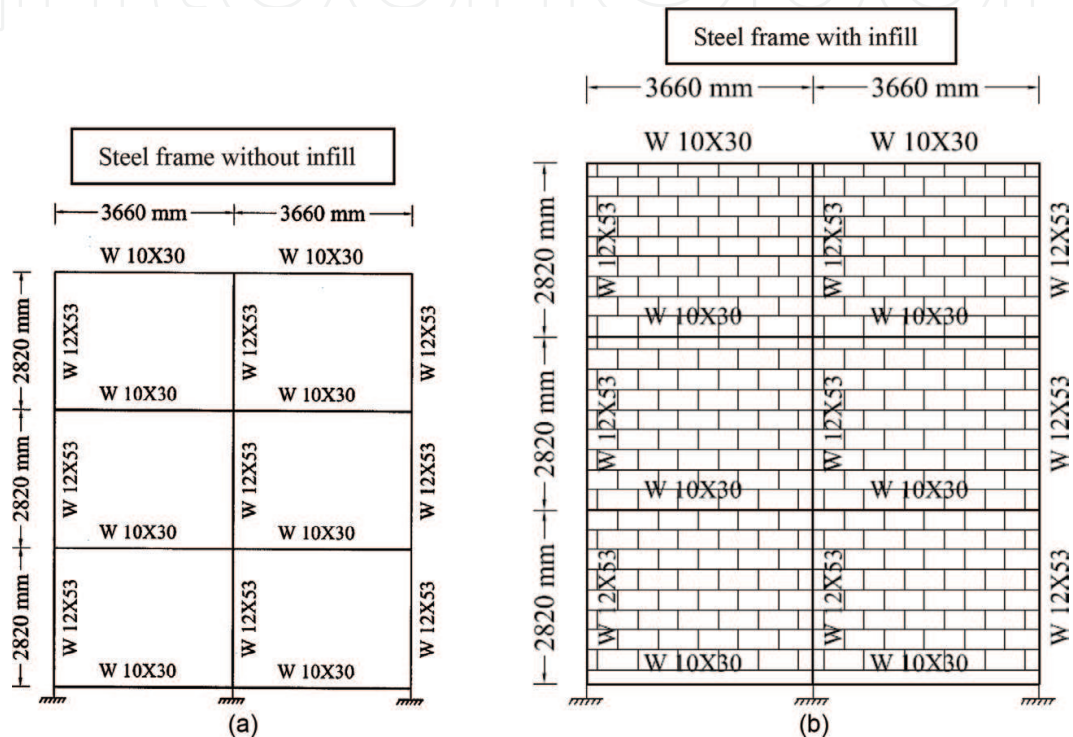

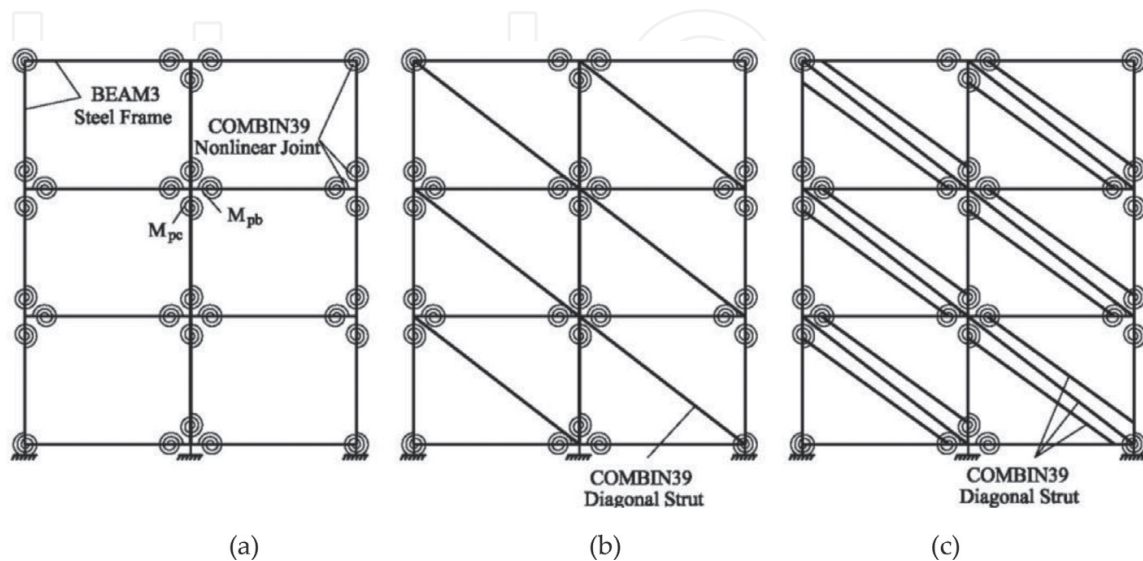**Figure 18.** Two-bay, three-story model description [53].

Figure 19. ANSYS models for two-bay, three-story case study: (a) bare steel frame; (b) single-diagonal strut method; and (c) three-diagonal strut method [53].

however, were modified to make them appropriate for a three-story structure. The masonry infill walls were assumed to be conventional CMU blocks (200 mm x 200 mm × 400 mm).

Models were developed for two-bay, three-story systems for three cases of bare frame, infilled frame without fuse, and infilled frame with fuse elements. The bare frame model shown in **Figure 19(a)** employed nonlinear beam-column joints shown in the figure by COMBIN39 elements. The model with masonry infill without fuse shown in **Figure 19(b and c)** consisted of two cases of single-diagonal strut and three-diagonal strut representation of the infill wall. **Figure 20** shows the moment-rotation section behavior assumed for beam and column sections. For the single-strut case, the force-deformation behavior model shown in **Figure 21** was used, while for the three-strut case, the models proposed in Ref. [57] were considered. The finite element model for the infilled frame with fuse elements is shown in **Figure 22**, where
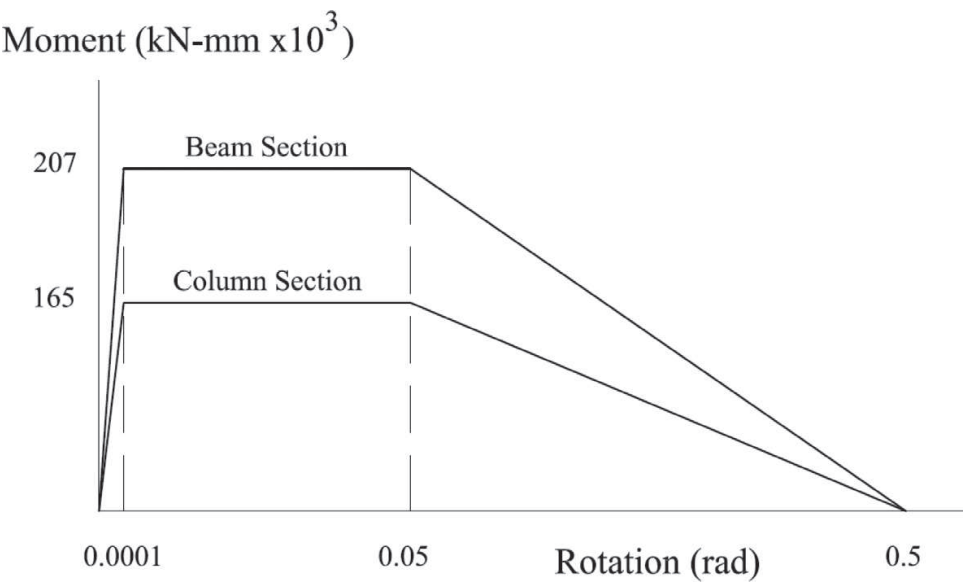

Figure 20. Moment-rotation response for joints [53].
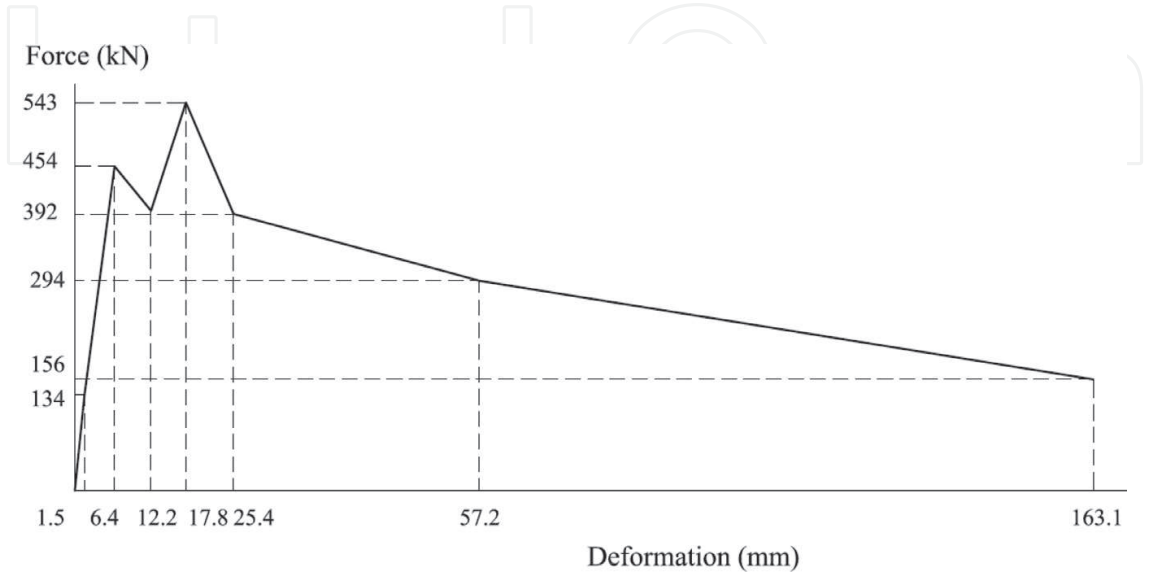

Figure 21. Force-deformation response for diagonal strut of single-diagonal strut model [53].

the elements used consist of 110 BEAM3 elements for the frame, 50 COMBIN30 elements for nonlinear joints, 606 PLAIN42 elements for masonry infill, 108 CONTACT12 elements for wall and frame connections, 12 COMBIN39/40 elements for fuse, 12 COMBIN40 elements for gap modeling, and 12 COMBIN39 elements for tie-downs.

The loading applied to the four models described consisted of imposing incremental horizontal in-plane displacement at the third floor level in a displacement-controlled mode. The resulting load-deflection diagrams for all four models are plotted in **Figure 23**. The results
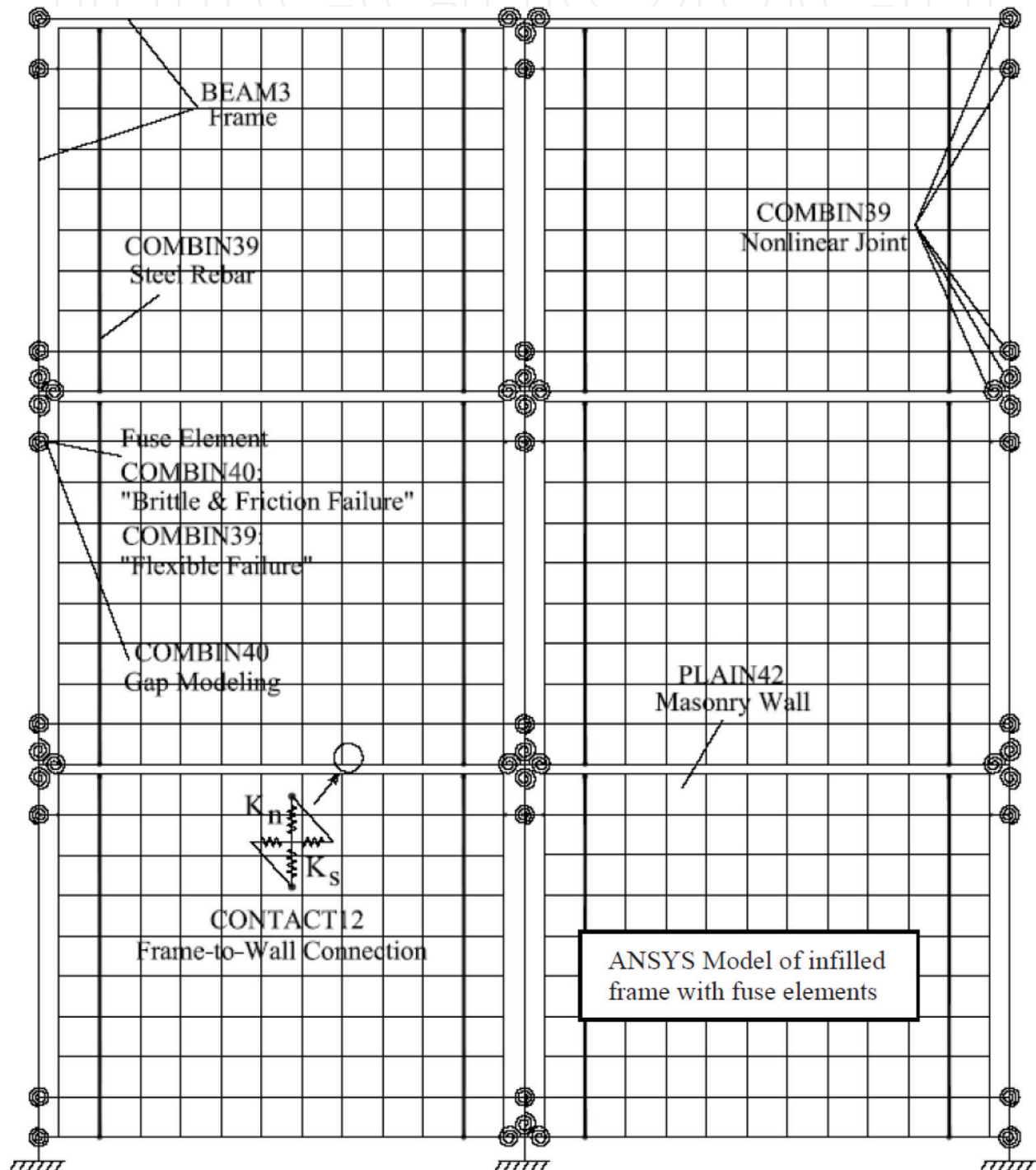

Figure 22. ANSYS model for two-bay, three-story infilled frame with fuse elements [53].
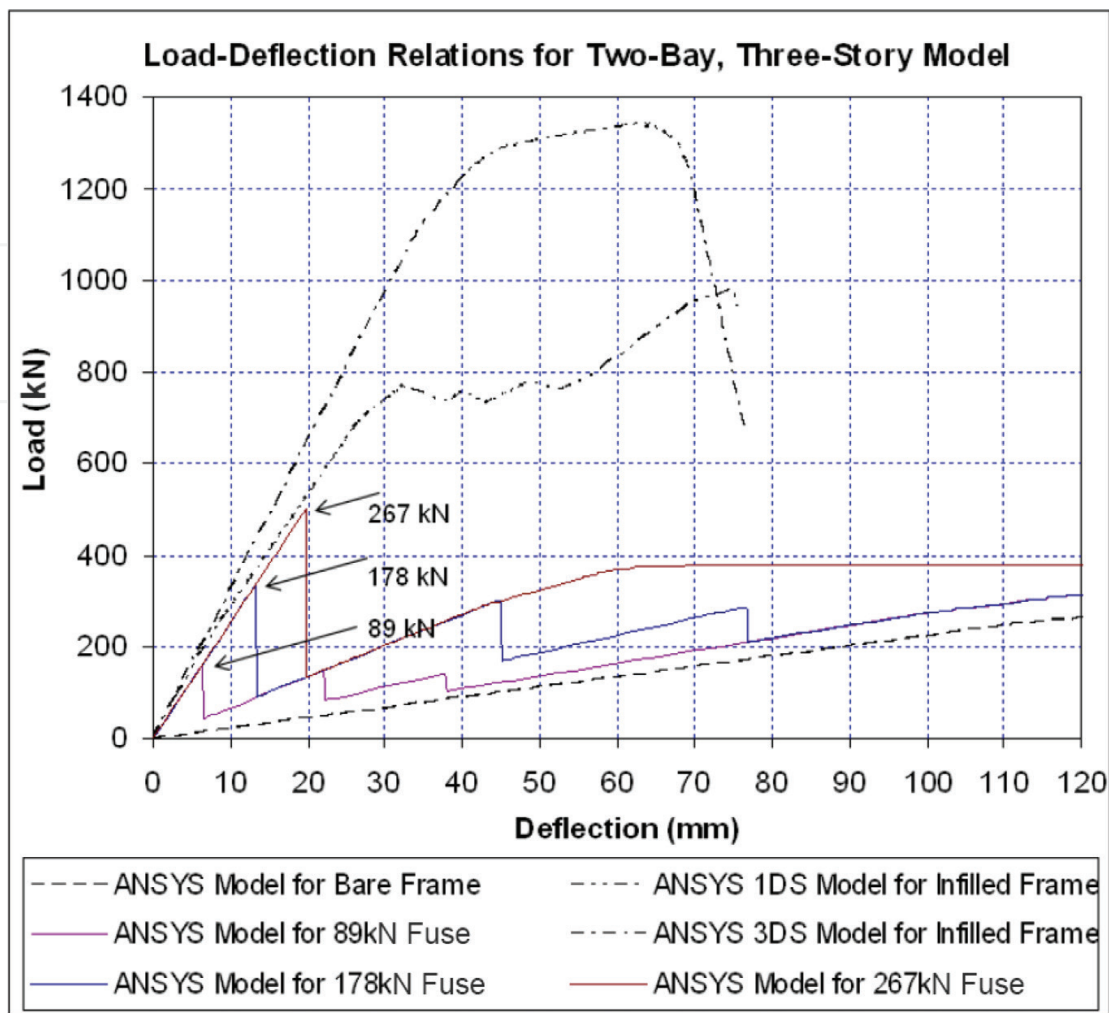
Figure 23. Load-deflection relation for single-bay, single-story system [53].

shown are consistent with the type of response observed for the single-bay, single-story in **Figure 9**. The results for the infilled frame with fuse element are also shown with three different fuse capacities. **Figure 24** shows the enlarged plot of the fuse-equipped system compared to the bare frame model, while **Figure 25** shows the sequence of fuse breakages. As expected, the load-deflection diagram for the system with fuse shows that after the breakage of the last fuse, the response closely follows the bare frame diagram. It should be added that such deflection will continue until the clearance between the frame and the infill wall is overcome, at which point the frame will directly bear against the infill wall, and the overall system will again experience high stiffness due to re-engagement and participation of infill wall.

The displacement-controlled load application is useful to understand the behavior of the system as each fuse breaks, and in general for experimental tests studies to collect detailed data at each displacement increment. To simulate more realistic earthquake loading conditions and also for design purposes, however, load-controlled application can be a better choice. The two-bay, three-story model of the infilled frame with fuse elements was subjected to such a load-controlled case. Consistent with the first-mode deflection and story lateral loads, in-plane loads of F/2, F/3, and F/6 were considered at the third, second, and first floor levels, respectively, and
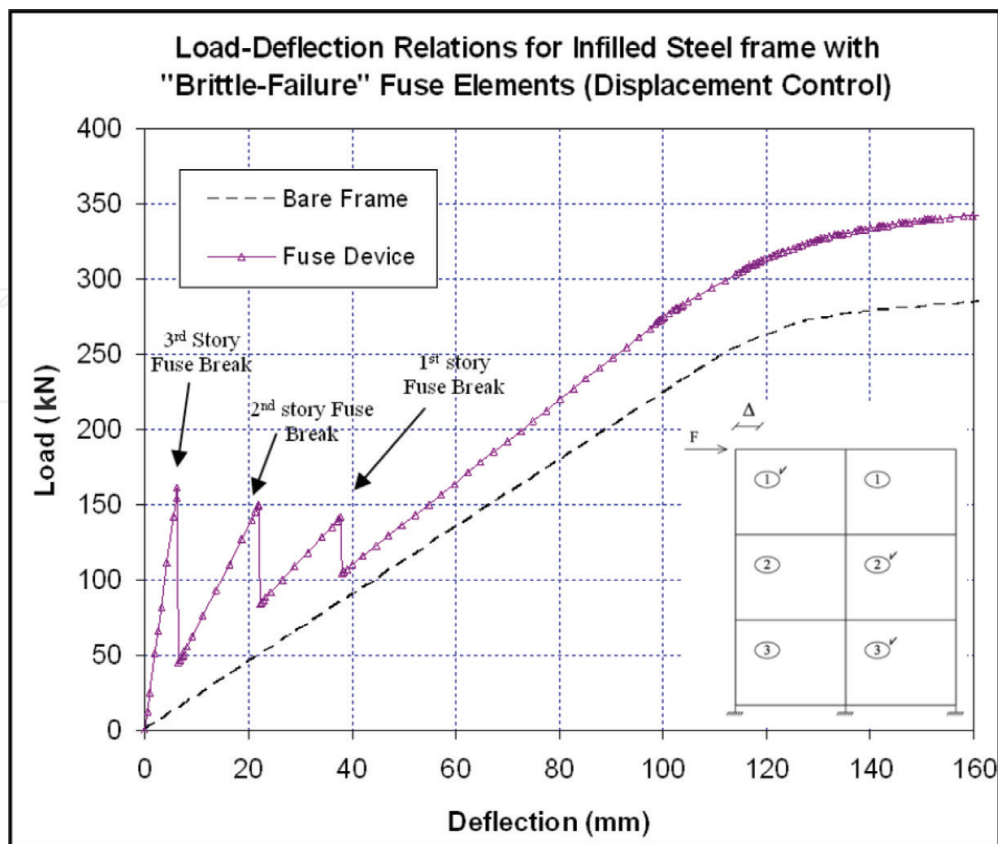
Figure 24. Load-deflection relation for two-bay, three-story infilled steel frame with "brittle-failure" fuse elements [53].
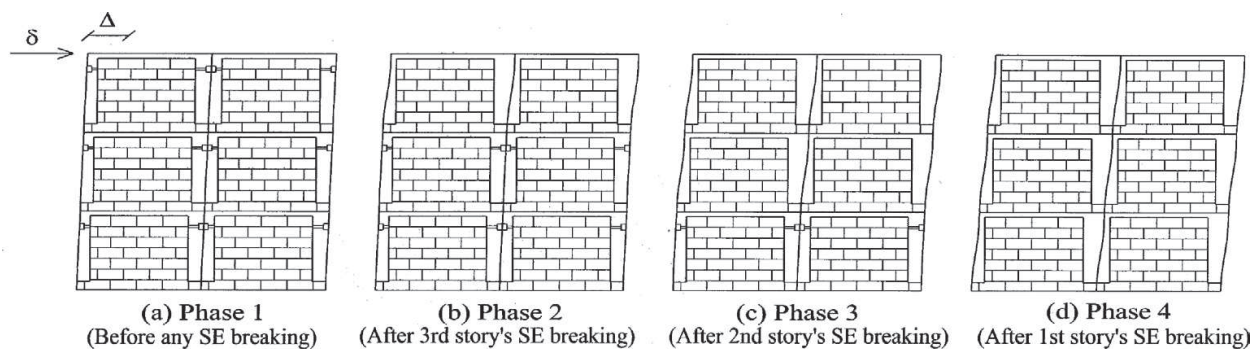

Figure 25. Behavior and failure mechanism of two-bay, three-story infilled steel frame with fuse system [53].

applied incrementally. The resulting load-deflection diagram is shown in **Figure 26** and the sequence of fuse breakage is graphically shown in **Figure 27**. **Figure 26** shows that upon the breakage of the last fuse (third story), the response follows that of the bare frame. The results in **Figure 26** show the beneficial effects of using fuse on increasing the stiffness and thus reducing in-plane deflection. Desirable sequence of fuse failure can be obtained by appropriate distribution of fuses with predetermined varying capacities over the height.

In addition to described analytical studies, parametric studies were conducted to determine the effect of varying the structural frame joint rigidities, member strengths, as well as the
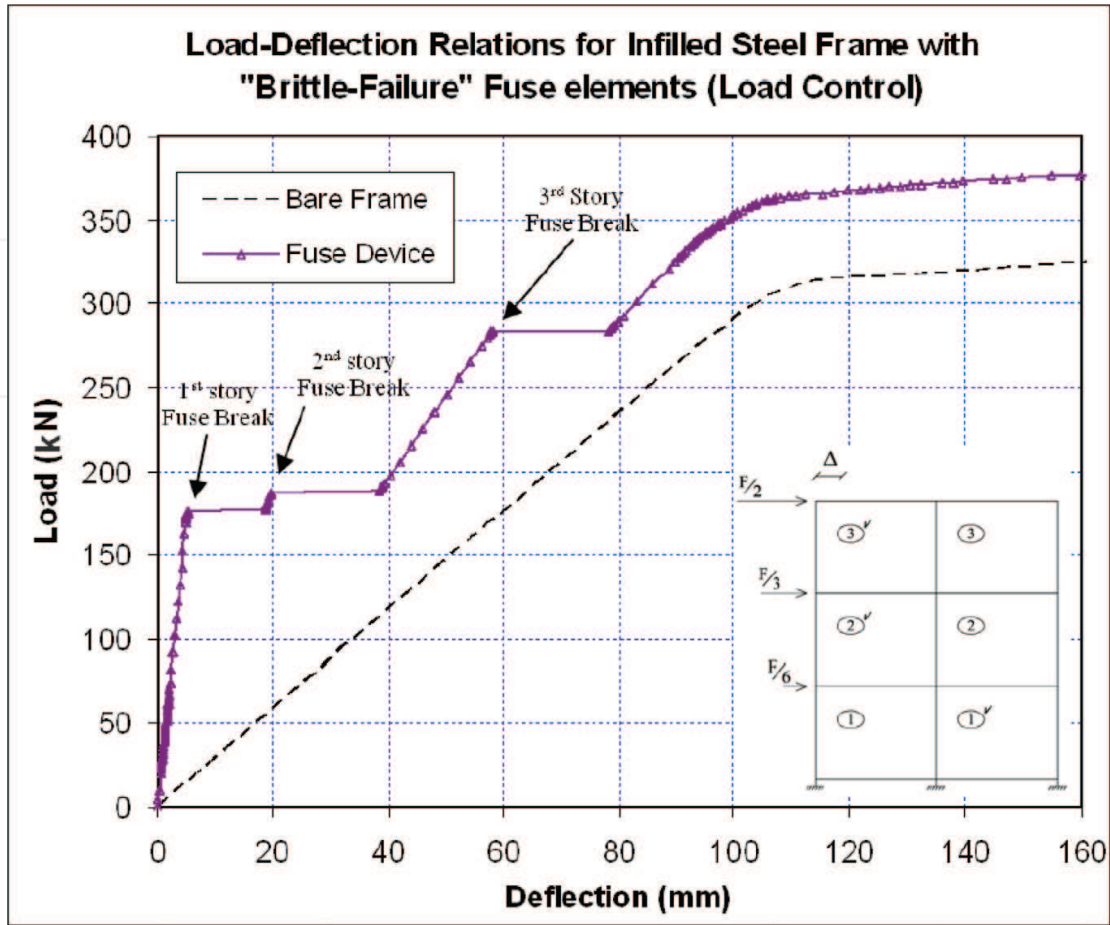
Figure 26. Load-deflection relation for two-bay, three-story infilled steel frame with "brittle-failure" fuse elements (load control) [53].

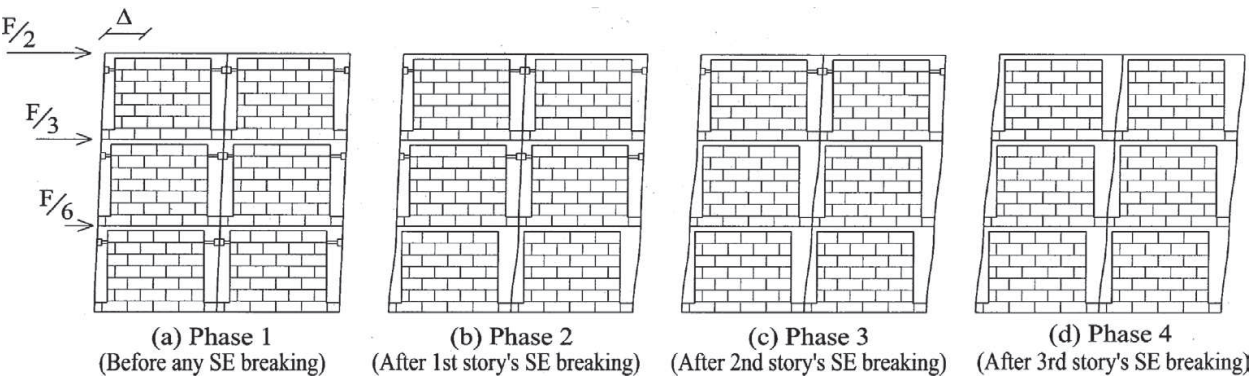| (a) Phase 1 | (b) Phase 2 | (c) Phase 3 | (d) Phase 4 |
| (Before any SE breaking) | (After 1st story's SE breaking) | (After 2nd story's SE breaking) | (After 3rd story's SE breaking) |

Figure 27. Behavior and failure mechanism of two-bay, three-story infilled steel frame with fuse system (load control) [53].

location and stiffness of fuse elements. The moment-rotation model used for beam-column connection is shown in **Figure 28**, where the initial stiffness is $K_j = M_{pl}/\phi_{el}$. By varying the rotation ϕ_{el} values from 0.0001 rad for a rigid frame to 100 rad for a pinned frame, the effects of joint stiffness on the response were evaluated. The results of the analysis for the two-bay, three-story frame are shown in **Figure 29**, which shows that by reducing the stiffness of the joints, the frame becomes more flexible. However, the effect on fuse performance is minor.

Next, by changing the size of the frame members, for a rigid frame, the member size effect on fuse equipped infilled frame performance were studied. Such behavior for the two-bay, three-story frame with different member sizes is shown in **Figure 30**. The initial design consisted of W12x53 for columns and W10x30 for beams, and the variation includes two cases of heavier and two cases of lighter sections. The results of the analysis show that heavier frame members provide stiffer and stronger system as a whole and that with stronger frames, fuse breaks at lower displacements. The results also show that the strength of the fuse elements should be consistent with that of frame, that is, a frame with higher ultimate load capacity should be used with fuse elements with larger capacity.
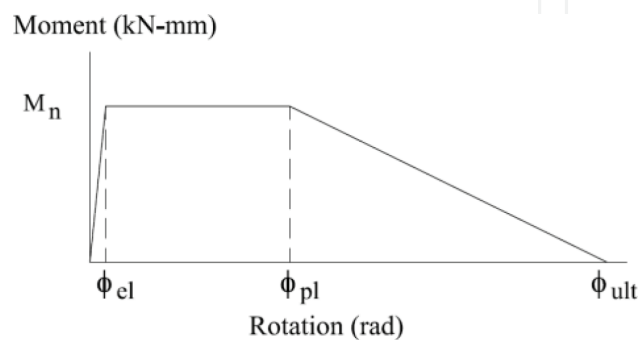
Figure 28. Three-linear moment-rotation response for joints [53].

Figure 29. Load-deflection relation for two-bay, three-story infilled steel frame with fuse system with different connection rigidity (stiffness) [53].

Figure 30. Load-deflection relation for two-bay, three-story infilled steel frame with fuse system with different frame Strengths [53].

Figure 31. Load-deflection relation for two-bay, three-story infilled steel frame with fuse system with varying location for fuse element [53].

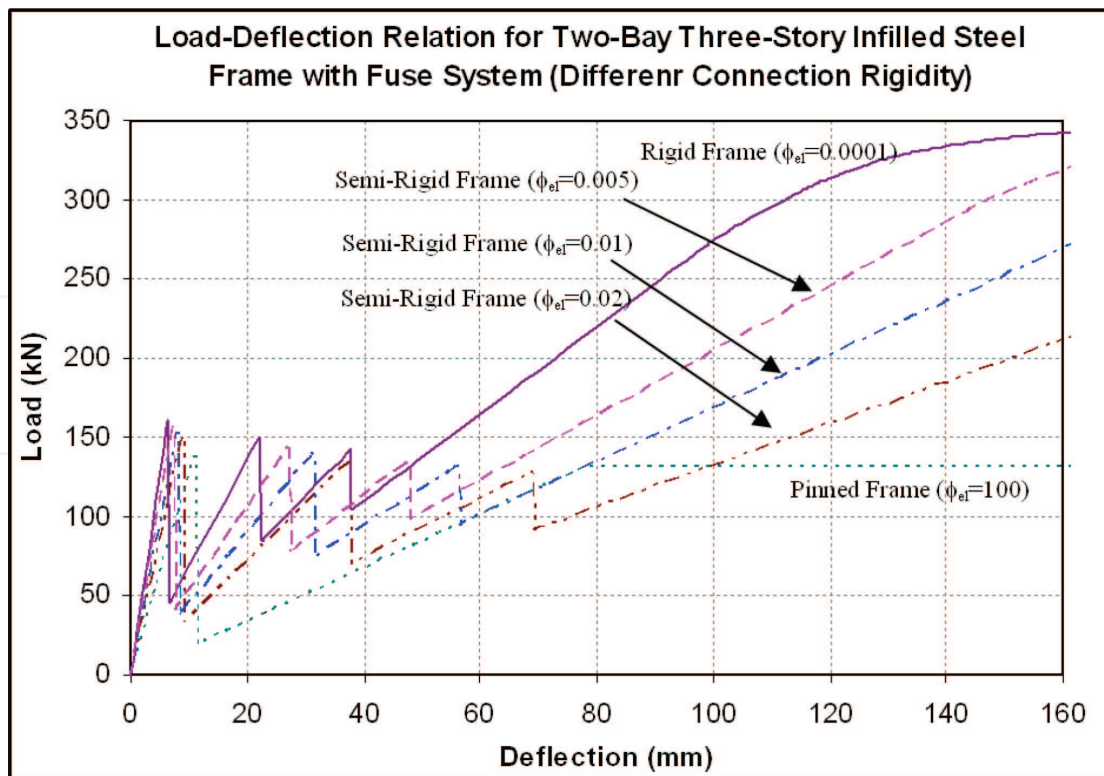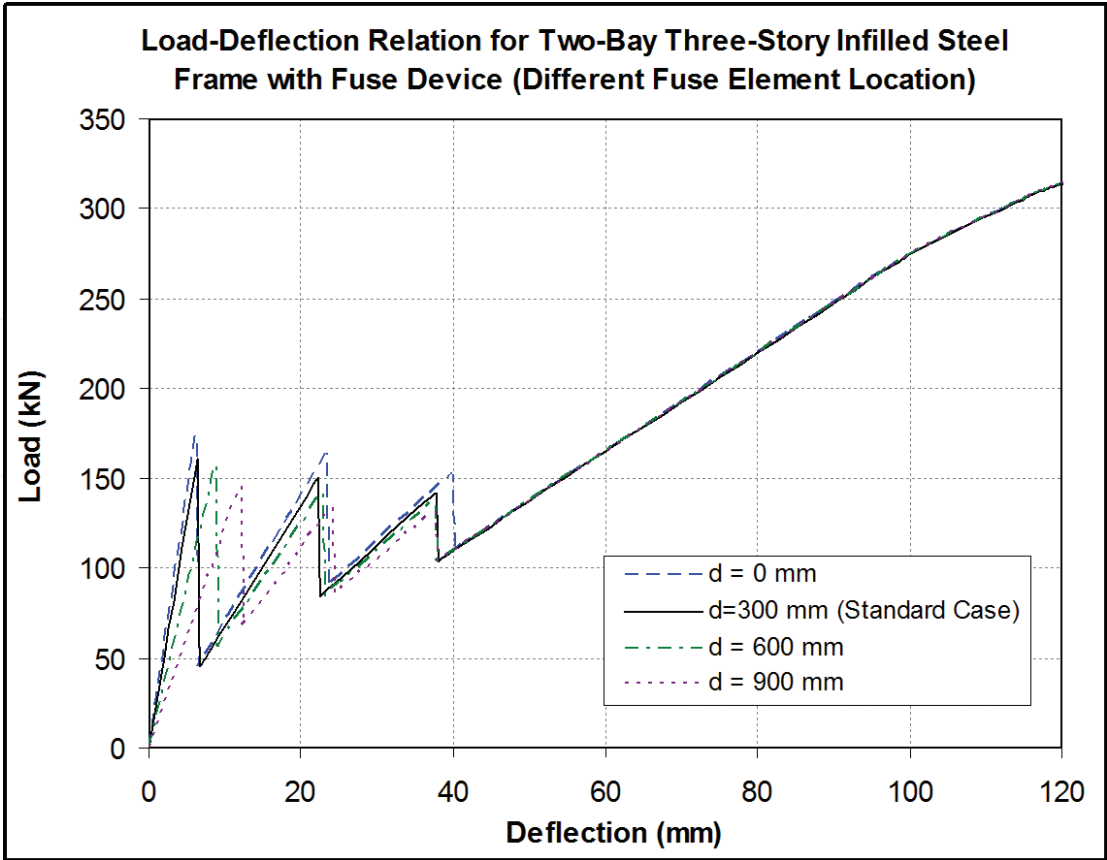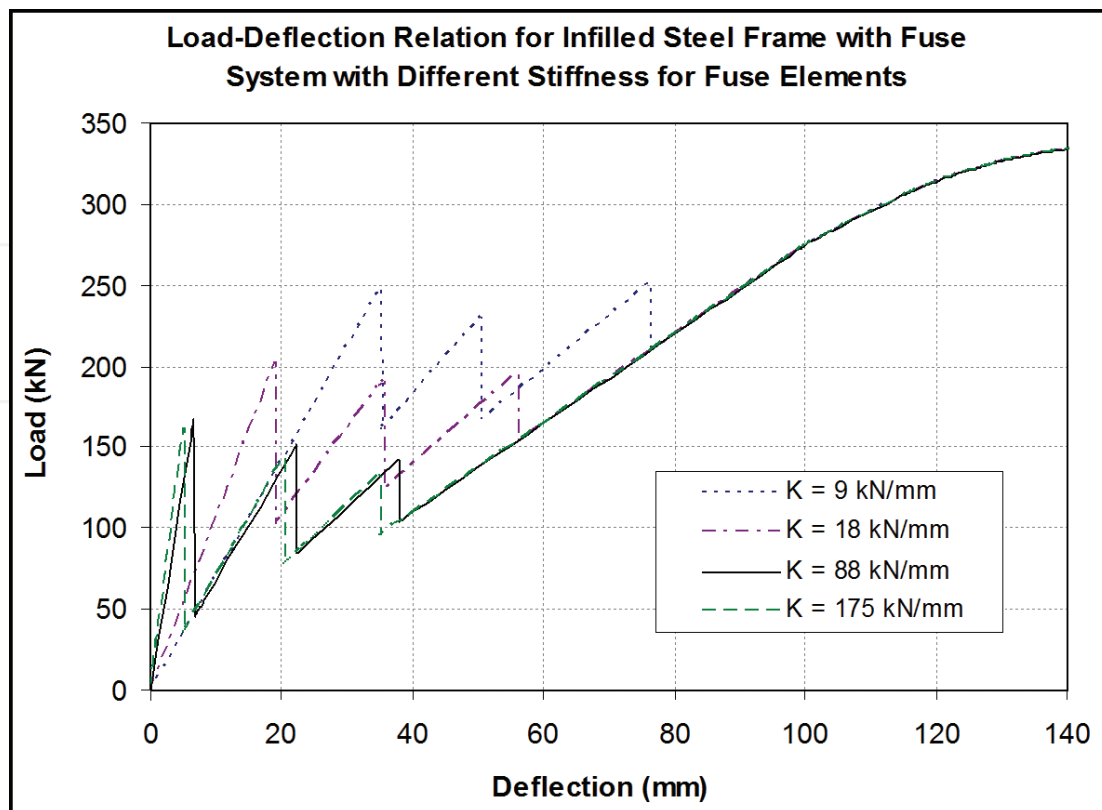**Figure 32.** Load-deflection relation for two-bay, three-story infilled steel frame with fuse system with different stiffness for fuse elements [53].

The effect of varying the vertical position of fuse elements with respect to the top of the wall was also examined. Four positions consisting of the wall top corner, 300 mm, 600 mm, and 900 mm below the top corner were chosen. The results of the analysis of the two-bay, three-story frame are illustrated in **Figure 31**, which show that the lower the position of fuse element, the larger the frame drift at fuse breakage points. The results also show that by lowering the position of the fuse, the initial stiffness of the entire system will be reduced and the fuse breaks at larger deflection. It can be concluded that higher positions enhances the effectiveness of the fuse function. Finally, in order to examine the effect of the fuse stiffness on the overall response, four different stiffness values were chosen for fuse elements and the results of the analysis of the two-bay, three-story frame are shown in **Figure 32**, which show that for fuse with lower stiffness, the load and deflection at fuse breakage increases. It can therefore be concluded that the stiffness of the fuse element can have a notable effect on the response of infilled frame.

7. Concluding remarks

The study presented has shown that existing commercial software (such as ANSYS or other similar software) can be used to effectively model complex use of masonry walls. The study has shown how various finite elements can be used to model masonry, structural fuse, as well as infilled frame for analysis under in-plane lateral loading. The available library of finite elements seems to be well-developed for this purpose. Aside from concluding the appropriateness of existing of modeling capabilities to capture various behavioral aspects of masonry

infills used in conjunction with fuse elements, some conclusions and remarks can also be mentioned related to the proposed use of fuse concept to mitigate damage to masonry infill walls and/or infilled frames. The concept of using structural fuse elements as sacrificial components in masonry construction is practical and should be given consideration for follow-up R&D studies and more refined design and detailing for practical application. The use of finite element modeling for parametric study of the proposed concept has shown that the effect of frame joint stiffness on the overall mode of behavior is not as much as the stiffness of the frame members. The latter affects the design of the fuse capacity, and for a given frame stiffness, the overall behavior will be sensitive to the fuse capacity. The finite element model analysis also showed that higher positions of the fuse element add efficiency to fuse element performance. While the presented study focused on proof of the concept for masonry infill within steel frames, the concept is equally applicable for concrete frames as well. In fact, variations of the presented concept can be expanded to develop energy dissipating fuse systems for application to steel and concrete frames as well as light frame construction infilled with other materials than masonry.

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