A Study of the Effect of Infilled Brick Walls on the Behavior of Eccentrically Braced Frames

Saedi Daryan A[1], Ziaei M[2], Golafshar A[3], Pirmoz A[4]

[1,2,3,4] *Dept. of Civil Engineering , K.N.Toosi University of Technology, Tehran, Iran*
Email: Masoodz.z@gmail.com

ABSTRACT :

Eccentrically Braced Frames (EBFs) are usually infilled by masonry walls, but in common design, the stiffness and lateral resistance of these walls is ignored. In this study, a proper model is developed using explicit finite elements method to study the behavior of EBFs with infilled masonry wall. Because of complicated mechanical and geometrical properties of masonry walls and also because of the interaction between steel frame and masonry wall, this model is not easy to obtain. To ensure the ability of the model to precisely simulate the behavior of an EBF with infilled brick wall, initial models were made and the problems were solved comparing the results of experimental test and the results of these initial models. Material models and some basic principles of explicit finite element algorithm are used and three initial models were made: a model of a brick wall without EBF, a model of an EBF without infilled brick wall and finally a model of an EBF with infilled brick wall. Using these three initial models, constitutive model for masonry and steel material, and also the proper elements for modeling the behavior of mortar are obtained. Then the final model of an EBF with infilled brick wall is made and the influence of brick wall on the behavior of total frame is studied. In addition, shear strength and cracking pattern of masonry wall under static loading is studied.

KEYWORDS: Eccentrically braced frame, infilled brick wall, explicit finite element method

1. Introduction

In an eccentrically braced frame, axial forces induced in the braces are transferred either to a column or another brace through shear and bending in a segment of the beam called link beam. These link beams act to dissipate the large amount of input energy of a severe seismic event via material yielding.

These frames are usually infilled by masonry walls but in common design, the influence of these walls on the behavior of total frame is ignored. These infilled walls may have a significant influence on the stiffness and the strength of eccentrically braced frames. In a well designed EBF, inelastic action is limited just to the link beam and the other members remain in the elastic range during an earthquake. The existence of a masonry wall may influence the action of link beam, so the behavior of these frames should be studied considering the effects of infilled masonry walls. Although there are several studies about eccentrically braced frames and masonry walls, study about the eccentrically braced frame with infilled wall is rare.

Also experimental tests provide reliable data which can determine the real behavior of the frame with infilled wall, in many cased conducting experimental test is very expensive or impossible. Another disadvantage of experimental test is that mechanical and geometrical parameters are limited in the tests.

Because of the advances in numerical methods, simulation of complicated real structures became possible. Among the numerical methods, the explicit finite element method is a powerful method for studying and modeling an eccentrically braced frame with infilled masonry wall. In this article a finite element model for an eccentrically braced steel frame is made and compared to the same frame which has the infilled wall.

ABAQUS finite element program is used for parametric modeling of specimens. Firstly, the analysis of the frame without masonry wall was carried out by standard method and the model was verified using the results of experimental tests. Then the EBF model was made with and without infilled masonry wall and the analysis was done by explicit finite element method and the results were compared to the results of experimental tests to assure the ability of the explicit finite element method for simulating the complicated mechanical and geometrical properties and also the interaction between masonry and steel material in the frame. After verifying the models, final model was made to study the behavior of an eccentrically braced frame with infilled brick wall.

2.1 Details of Bruneau and Berman test

Bruneau and Berman in 2006 studied the effect of using box section as the link beam in eccentrically braced frames. In usual design, wide flange sections are used for link beams, but since it is impossible to provide lateral bracing in bridges to prevent lateral-torsion buckling, box section was used to eliminate the need for the lateral bracing, because box sections have significant torsional strength. This test was selected for verifying the finite element models. The test setup is shown in figure 1.

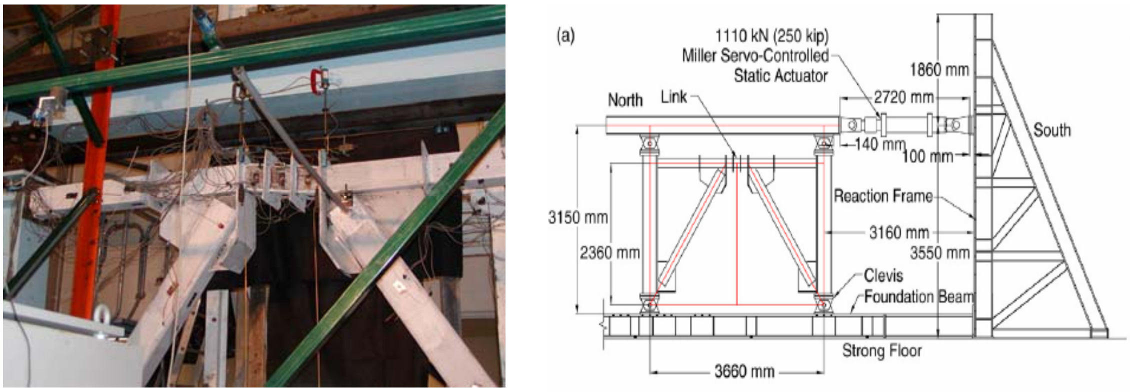

Figure 1: test setup used by Bruneau and Berman

2.2 Finite element model and material properties

Shell elements were used to make the frame model. As it can be seen in figure1, the frame is simply supported and the load is applied through a beam which is connected to the frame by a hinge. For simulating the base support condition and load applying method, the connection of columns to the base is modeled in a way to act like a hinge. The same condition is made at the top of the columns to simulate the exact load applying method used in the experimental test. The finite element model is shown in figure 2. To prevent local buckling, stiffeners are placed around the beam since box section is used as the beam in this frame. The model is analyzed using standard method.

Figure 2: Finite element model of the eccentrically braced frame

2.3 Verifying the model

A comparison is made between the results of the experimental test and the results of finite element model analysis which is shown in figure 3. As it can be seen, there is a good agreement between the results. Finite element model had the ability to predict the peak point and also the initial stiffness of the curve.

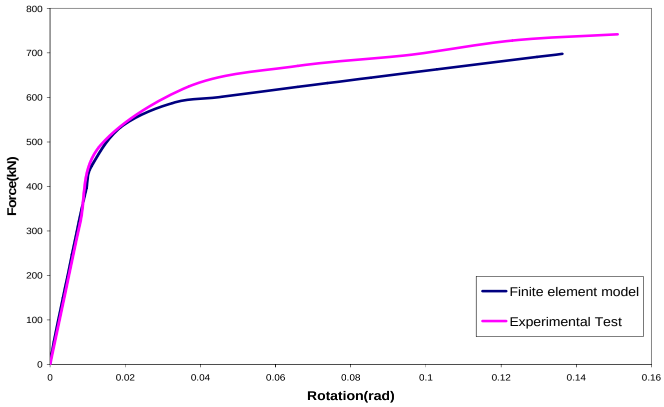

Figure 3: force-displacement obtained by experimental test and finite element model

3.1 Masonry panel

The complex mechanical behavior of masonry structures is the result of their non-homogenous and brittle material properties, as well as its geometric intricacy: masonry is composed of aligned, uniformly dispersed units connected by a regular array of bed and head mortar joints. These mortar joints are the weakness of the assembly and exhibit notable material nonlinearity and significantly influence the response of masonry. The nonlinear characteristics of the mortar joints initially result from the nonlinear deformation characteristics of the joints under shear and compression but are exaggerated by local failure, opening-closing, dilatancy and slip of the joints.

Two mechanical approaches, macro- and micro- modeling, have been adopted by researchers to formulate an appropriate constitutive description of masonry structures. The macro-modeling approach neglects the distinction between units and mortar joints by taking into account the effect of discrete joints in an average sense through homogenization techniques such as those presented by Dhanasekar et al. (1985) and Middleton et al. (1991).

Generally, this approach is recommended for the analysis of large masonry structures because of the inability to exert detailed stress analysis and capture the various failure mechanisms of masonry assemblages. Gambarotta et al. (1997 a/b) adopted a refined approach in which the wall was simulated as an equivalent stratified medium made up of layers representative of the mortar bed joints and of the units and head joints, respectively.

Alternately, the micro-modeling approach is a computationally intensive approach. A large number of elements are required because the masonry structure is modeled as a discontinuous assembly of blocks connected by appropriate discrete joints. The joints are simulated by appropriate constitutive interface elements so that considerations such as the initiation of fracture, propagation of cracks and sliding at interfaces with different levels of refinement of the assemblage can be taken into account. Therefore, a more realistic and rigorous analysis can be expected since it allows locating exact joint positions and adopting appropriate constitutive models for the blocks and interfaces. *Ali et al*. (1988), Anand *et al.* (1990) and *Rots* (1991) adopted a refined approach in which both the masonry units and the mortar joints are discretely modeled with continuum elements. The significant computational intensity of this level of refined analysis restricts its application to small laboratory specimens. In a less-refined approach, Arya et al. (1978), *Page* (1978), and *Gambarotta et al.* (1997a) modeled mortar joints with zero thickness interface elements and masonry units with enlarged continuum elements to account for the space formerly occupied by mortar joints. The approach with this level of refinement is also computationally intensive for the analysis of large masonry structures. Furthermore, *Formica et al.* (2002) pointed out that the interface elements are only suitable for a small displacement field as a result of their inability to provide easy remeshing to update existing contacts and/or to create new ones when the motion is large.

Considering the above concepts and the accuracy needed in this study for simulating the initiation of failure, crack propagation and slippage in different surfaced, the micro method was selected for modeling the behavior of infilled brick wall.

Masonry shear walls are generally tested in the lab using quasi-static loading history in order to gain better understanding of the failure pattern and deformation characteristics including measure of ductility. As such they are modeled using static perturbation finite element modeling techniques based on implicit methods. Such finite element analyses of masonry walls in general, although have provided much insight into the behavior of masonry shear walls, have been regarded as too cumbersome and inefficient in terms of the time taken for the analysis as well as the complexities of the modeling strategies. These conventional implicit techniques require solution of equilibrium equations containing full stiffness matrix of the structure; as such they are very time consuming. Furthermore, as the masonry cracks the stiffness matrix tend to become ill conditioned posing a convergence problem. This paper presents a computationally efficient explicit finite element modeling technique that is capable of simulating highly nonlinear events. The explicit finite element modeling technique never requires a fully assembled system stiffness matrix; rather it solves for the internal variables using the theory of dynamic wave propagation in solids. Although explicit technique is more suitable for high dynamic events such as impact, quasi-static load tests could also be simulated if due care is taken to minimize the kinetic energy due to rapid cracking/load shedding. As iterations are not performed, much smaller increments of the applied load are required for the explicit technique to provide acceptable results. Converged solutions obtained from this technique are based on satisfaction of the global energy equilibrium equations; as such it is suitable where the global structural behavior, such as the deformation and failure characteristics, is of prime importance.

3.2Critical time increment

In time integration methods, choosing a proper time increment is definitely important. Small time steps are necessary to obtain accurate and stable responses.

ABAQUS/EXPLICIT generally requires 10,000–1,000,000 increments to achieve converged solutions, but the computational cost per increment is generally relatively small. For accuracy, the time increment was kept quite small. Maximum time increment used by the explicit solver related to the stability limit of the structure globally is calculated from the natural frequency corresponding mode shapes of a dynamic system. The loading time was increased up to 100 times the period of the lowest mode. By artificially increasing the step time the velocities and the kinetic energy were minimized.

In the followings, to verify the masonry infilled wall models, the experimental tests carried out by Vitorino et al. were selected and the finite element models were made according to the specimens tested in this experimental study and the models were analyzed using explicit finite element method.

To construct the wall specimens in the experimental test, a layer of mortar was poured on the slab at first and then the wall is constructed. Then a concrete beam is installed on the wall and finally measuring instruments were installed on the wall.

The walls were tested after drying. The vertical compression load is applied by a 1000 KN capacity hydraulic actuator using force control method. The rate of loading was 1 KN per second. When the vertical load reached to the specific value, it is kept constant and the lateral load is applied to the specimens by applying small displacements.

3.4 finite element model and material properties

Two kinds of elements were used to model masonry panels, eight-node solid elements were used to model the bricks and contact elements were used to simulate the mortar. It was assumed that the panel behaves nonlinearly under applied displacement. The mortar was modeled using interaction element in ABAQUS which allows for small relative slippage in the contact surface. The properties of this element are defined according to the properties of mortar in the experimental test. In the following figure finite element model and sub-structures are shown. The model meshing was fine enough to obtain accurate results. Material properties used in the test are tabulated in table 1.

Table 1: material properties of the specimens used in Vitorino tests

Material	Poisson ratio	Ultimate stress (N/mm2)	Modulus of elasticity (N/mm2)
Block	0.2	57	15500

3.5 verification of the model

Force-displacement curves and cracking pattern of masonry panels obtained by finite element model is compared to those obtained by the experimental test. Figure 4 shows a comparison between the cracking pattern obtained by finite element model and experimental test. Failure modes show the relation between vertical load and crack pattern. In the specimens with fewer vertical loads, the failure of wall is in the form of cracks in the seams and no fracture occurred in the blocks. But in the specimens with higher vertical loads, diagonal cracks appeared and there were some fractures in the blocks. In general, it can be concluded that failure mechanism in wall is in the form of diagonal cracks and fracture of some panels and when the vertical load is increased the probability of block fracture increases. Force-displacement response obtained by finite element modeling and experimental tests is shown in figure 5. It can be observed that force-displacement respond curves have good agreement both in elastic and plastic ranges. This agreement shows the ability of explicit finite element to accurately predict the behavior of masonry panels. .The difference between the results of modeling and experimental test in nonlinear range is due to several parameters such as simplifications used in finite element model, defects in experimental tests, residual stress and especially nonlinear constitutive laws used in finite element modeling.

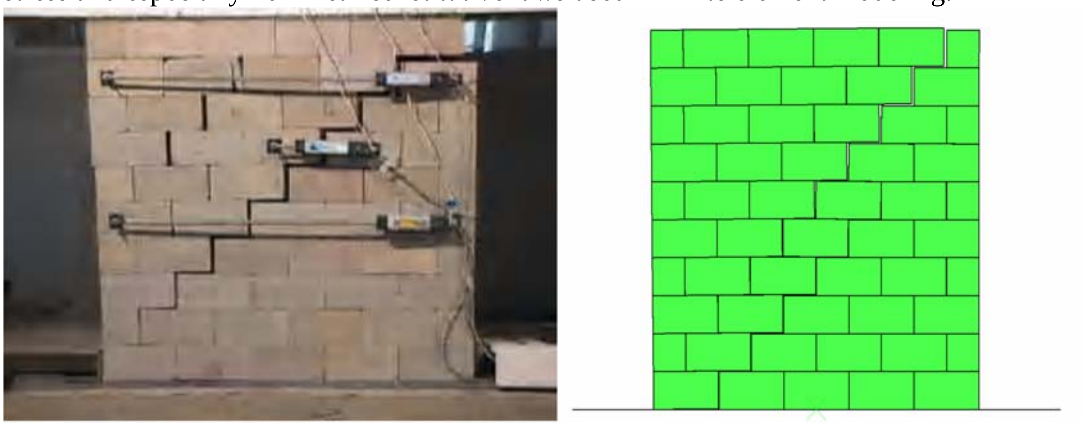

Figure 4: crack pattern in brick panel

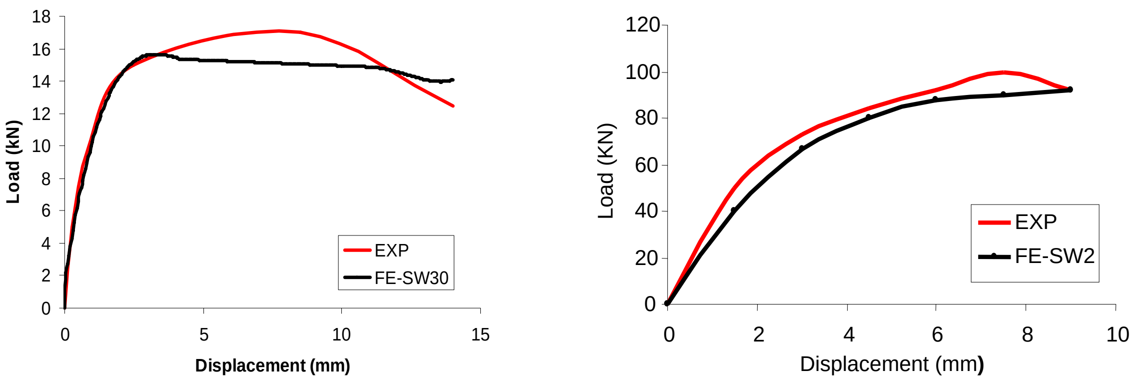

Figure 5: force-displacement curve of the tests carried out by Vitorino

4. Steel frame with infilled brick wall

Considering the prevalent application of masonry material in structures and their determinant role in stiffness and strength of structures, many studies have been carried in this field. In some of these studies, masonry panels are investigated separately and in some others, masonry materials are studied as infilled walls surrounded by steel frame(like the real situation of masonry panels in structures). The latter studies present more realistic results and applied forces and cracking pattern are closer to the real behavior of structural frames. In recent years this method of study is more used. For example, experimental tests have been carried out by Moghaddam et al. on steel frames infilled by masonry and concrete walls. In this study, the results of this experimental test are used to verify the finite element models. These models are analyzed using explicit finite element method.

4.1 Details of the selected experimental test

Moghaddam et al. tested 11 steel frame specimens infilled by masonry and concrete walls under cyclic loading. One of these specimens which is a steel frame with masonry wall is selected to verify finite element models.

4.2 Finite element model and material properties

Brick panel is modeled using eight-node solid elements and contact elements are used to model the mortar. It is assumed that the panel behaves nonlinear under applied displacement. The mortar between the bricks is modeled using interaction element in ABAQUS which allows for little relative slippage in the contact surface. The properties of this element are defined according to the properties of mortar in the test specimens. Steel frame modeling is done using shell elements. To obtain accurate results, the meshing of finite element model was fine enough.

4.3 finite element verification

Force-displacement curves obtained by experimental test and finite element model are compared in figure 6. Initial stiffness and ultimate load in the two curves are close to each other which verify that explicit finite element method is precisely capable of simulate the behavior of masonry walls. Crack pattern in the finite element model is diagonal which is similar to those observed in experimental test carried out by Moghaddam et al.

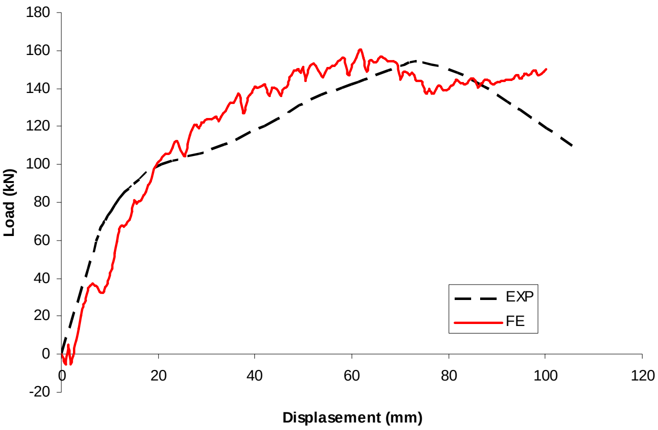

Figure 6: force-displacement obtained by experimental test carried out by Moghaddam et al.

5. Final finite element models

Using the initial finite element models, the capability and the accuracy of explicit finite element method to precisely simulate the behavior of steel frames with masonry wall is verified. Then six eccentrically braced frame finite element models are made and the analysis results of EBF with and without masonry wall are compared. It should be noted that large span frame models are analyzed in two cases. In the first case, the masonry wall is not braced in out of plane direction (SML3.4 ,SML2.8). In the second case, the brick wall is braced in out of plane direction, as it is required in seismic provisions (SML3.4*, SML2.8*).

6. present the results obtained from analysis of the models

The results obtained from the analysis of the models are shown in figure7 as force-displacement curves. In this figure, force-displacement curves are shown for some frame model with and without masonry wall.

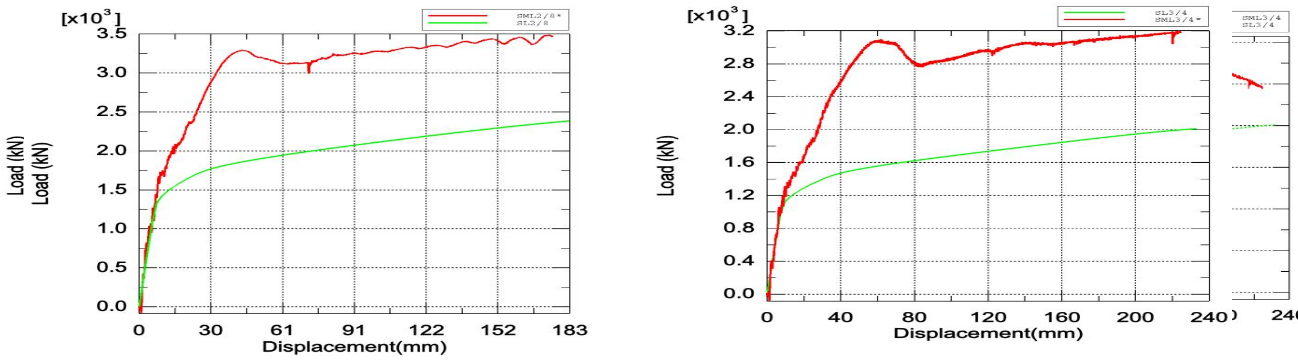

Figure 7: a comparison between force-displacement curves of frames with and without masonry wall

If the collapse limit of the structures is assumed to be the drift equal to 2% of structure height, as it is obvious from the figures, the masonry wall significantly affects the behavior of EBF. When the masonry wall does not exist, the frame dissipates a little part of input energy in elastic range and most of it in plastic range and so the frame has a full ductile behavior. But the behavior of the frames changes when the infilled brick wall exists. The presence of masonry wall affects both strength and lateral displacement of eccentrically braced frame. The stiffness and the strength of frame in elastic range increase significantly, but when the total system enters in plastic mode, after a little increase, the strength of frame decreases significantly due to fragile behavior of masonry wall. Because of principle cracking of masonry wall or sometimes collapse of it, steel frame and masonry wall do not behave as a united system and the increase in strength observed after the mentioned fall is only because of steel frame. To compare the results of steel frames with and without masonry wall, it should be said that in the case where masonry wall exists the displacement in which the total system yields is higher, but since the plastic range in force-displacement force is decreased significantly, the total displacement capacity of the frame is decreased.

The rotation capacity of the frame with brick wall is significantly decreased compared to the rotation capacity in bare steel frame. Except two frames, the fracture of masonry wall occurred before the link beam can reach the required rotation capacity of shear link beams (0.08 rad) and this shows that the frames are not ductile enough.

It should be noted that deformed shape of SMS and SMI specimens are similar and deformed SML specimens are similar to each others.

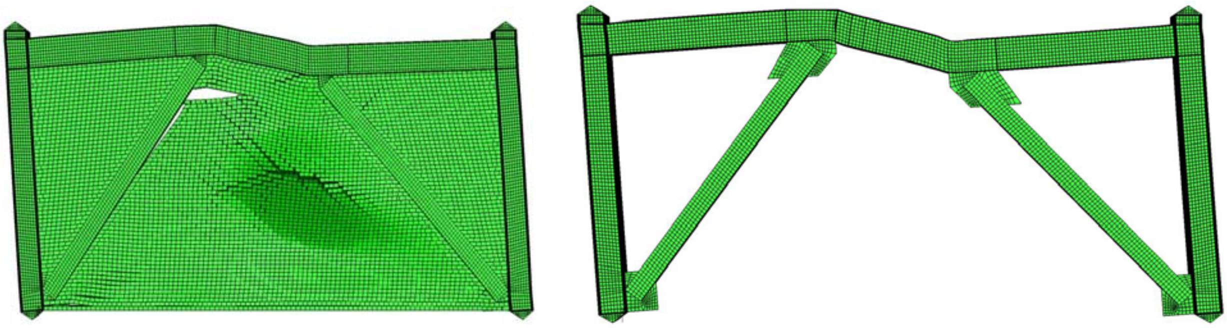

Figure 8: Deformed shapes of specimens SL3.4 and SML3.

As it can be seen in figure 8, the presence of bracings prevented the occurrence of diagonal cracks which usually occur in masonry walls. At the top of the space formed between two braces, horizontal cracks were observed in all specimens who were the main cause of wall fracture in small and medium and out of plane braced large span frames. In large span frames without out of plane bracing, the wall has displacement in out of plane direction in middle part which is the main failure mode of the wall.

7. conclusion

In this study, explicit finite element method is proposed for modeling and analyzing eccentrically braced frames with masonry infilled walls.

Firstly, the model of single brick wall and model of EBF with infilled wall were made and these models were analyzed by explicit finite element method. Comparing the results of these models and the results of experimental tests, good agreement was observed and the ability of models to precisely simulate the behavior of EBFs is verified. Then the ability of explicit finite element method to present mechanical behavior and complicated geometry of masonry materials and to simulate the interaction between steel frame and masonry wall was assured. The study confirmed that such models can be used to predict crack pattern, failure modes, initial stiffness and ultimate load. In addition, explicit finite element model present rational stress distribution at critical points such as wall heel and central part of the wall. After verifying the finite element models, the influence of masonry infilled wall on the behavior of eccentrically braced frames is studied. This investigation showed that in general, the presence of masonry wall increases the yield strength and the elastic range in the force-displacement curves. But the plastic behavior of the frame is deteriorated and due to fragile behavior of masonry materials, the total system of steel frame and masonry wall has a significant strength fall when the elastic range is passed. By decreasing the plastic range, the behavior of the frame is no more ductile and so the energy dissipation of the frame with masonry wall is significantly smaller when compared to those of a steel frame without masonry wall. In the case of crack pattern and failure mode of brick panels, it can be said that for small, medium and out of plane braced large span frames, the crack pattern is in the form of the horizontal propagation of cracks. For large span frames without out of plane bracing, the main cause of the fracture of the wall is out of plane deformations. In conclusion, it can be said that the effect of masonry infilled walls should be considered in design of eccentrically braced frames.

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