Effect of Masonry Infill Walls with Openings on Nonlinear Response of Steel Frames

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Abstract

The infill walls are usually considered as nonstructural elements and, thus, are not taken into account in analytical models. However, numerous researches have shown that they can significantly affect the seismic response of the structures. The aim of the present study is to examine the role of masonry infill on the damage response of steel frame without and with various types of openings systems subjected to nonlinear static analysis and nonlinear time history analysis. For the purposes of the above investigation, a comprehensive assessment is conducted using twelve typical types of steel frame without masonry, with full masonry and with different heights and widths of openings. The results revealed that the influence of the successive earthquake phenomenon on the structural damage is larger for the infill buildings compared to the bare structures. Furthermore, when buildings with masonry infill are analyzed for seismic sequences, it is of great importance to account for the orientation of the seismic motion. The nonlinear static response indicated that the opening area has an influence on the maximal strength, the ductility and the initial rigidity of these frames. But the shape of the opening will not influence the global behavior. Then, the nonlinear time history analysis indicates that the global displacement is greatly decreased and even the behavior of the curve is affected by the earthquake intensity when opening is considered.

Keywords: Frame; Infill; Masonry; Opening; Hysteresis; Earthquake.

1. Introduction

Masonry structures are among the most common types of buildings, being economical and easily made. The possibility of using conventional materials, the easy method of construction and the lower level of construction expertise needed are characteristics of masonry structures. However, they are brittle structures because of the fragile nature of the materials and elements used in their construction. Using infill masonry walls in steel frames are one of the prevalent type of construction in the world (Figure 1).

Lessons from past earthquakes have demonstrated that some masonry structures are vulnerable and it is essential to investigate their complex performance in detail (Figure 2). However, engineered masonry buildings, which conform to standards, have acceptable seismic performance [1-6].
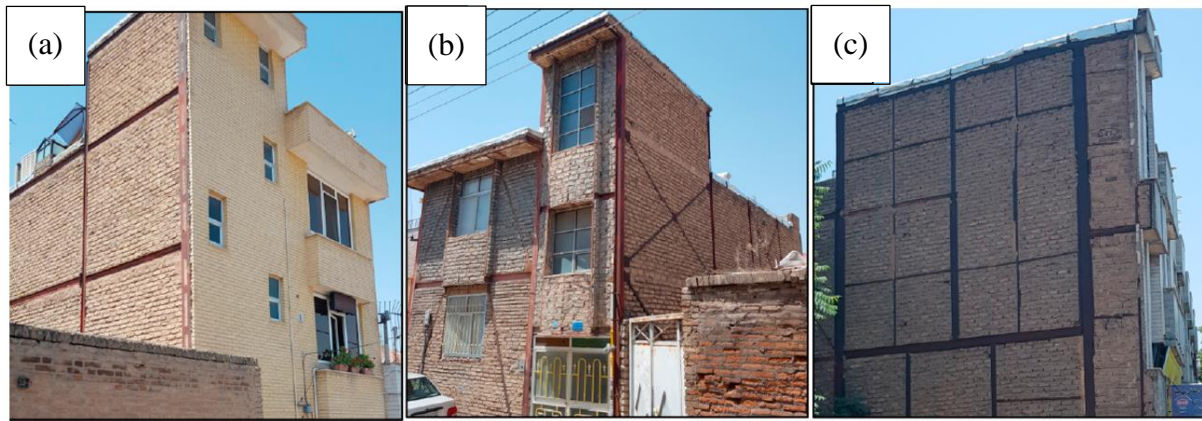

Figure 1. Examples infilled steel frame building: (a) residential, (b) infill masonry wall, and (c) infilled steel frame building

Figure 2. Surveyed damage of the case study building after the 2016–2017 earthquake sequence (significant damage on infills and yielding at beam-column connections)

Strength and stiffness are greatly affected by infills [1, 2]. Polyakov (1960) and Holmes (1961) [3, 4] proposed in first place the concept of diagonal strut for analysis of infilled frames. Stafford (1967) [5] developed a theoretical framework to evaluate the width of the equivalent diagonal strut relying on earlier work of Stafford (1968, 1969) [6, 7]. Mehrabi et al. (1996) conducted a study of the impact of masonry-infill panel on the seismic response of RC frames [8]. Liauw and Kwan (1983) proposed an equation which allows to evaluate the width of diagonal strut for stiffness prediction [9]. Fiorato et al. (1970) [10] performed scaled tests on masonry to determine the impact of parameters such infill openings and number of stories. It was observed that the presence of openings reduces slightly the frame stiffness. However, innovative masonry-infills applications can be hindered by a fact that there are subjected to failure caused especially by horizontal and vertical loads. El-Dakhakhni et al. (2003) [11] classify different failure modes into five modes; corner crushing, sliding shear, diagonal compression, diagonal cracking, and frame failure modes. Many experimental and numerical studies of masonry infills and these problems have been performed.

Kodur et al. (1995) [12] present a review of these studies. Then, they propose a technical analysis for seismic design of infilled frames for practicing engineers. It consists in modelizing the infilled frame as either a frame diagonal strut or as an equivalent frame system. Aliaari et al. (2005) [13] use modelizing approach for single bay, one story, two bay, and three story system under monotonic load condition in order to assess the sequence of seismic infill wall isolator sub frame system (SIWIS) element failure and overall response. Moghadam et al. (2006) [2] present experimental and analytical studies are carried out to evaluate the crack strength of infilled frames. Liu and Manesh

(2013) [14] conduct 14 specimens are tested for behavior and capacity of concrete masonry-infills bounded by steel frames. A study presented by Manesh (2013) [15] where combined lateral and axial loads are considered for the testing of eight concrete masonry-infilled steel frames. It is observed that the failure mode is unique. Frames with openings show extensive cracks without failing abruptly and a decrease of the lateral resistance once the ultimate load is reached. Results of an experimental program, presented by Mohebkhah et al. (2008) and Tasnimi and Mohebkhah (2011) [16, 17] of investigation of the in-plane cyclic deformation of brick masonry infills steel frames with centered window and door openings. To evaluate shear strength, infilled steel frames with openings are tested, a simplified analysis method "macro modeling strategy" is utilized. Conclusion made by Liu and Soon (2012) [18] that the predominant failure mode is characterized by a corner crushing with solid infills while the specimens with openings showed the most significant diagonal cracking. The behavior of infilled frame systems is influenced by many parameters as the panel aspect ratio, the coefficient of friction, and beam rigidity. This parametric study is presented by Dawe et al. (2001) [19, 20]. An analytical method based on finite element analysis is used with a certain number of parameters such as frame, masonry, panel, hinge, joint, and interface elements [21].

Ghobadi et al. (2019) displayed the logical data about masonry structures as far as the structural execution of various masonry walls, normal pre-seismic tremor retrofitting strategies and post-quake fix techniques. In the proposed fix technique, breaks in the harmed masonry infill are skewed by pleated wire networks in the state of Band-Aid and cementitious mortar is utilized to cover the appended wire networks. Moreover, the outcomes demonstrated that the fix strategy not just reestablished the lost strength of the harmed infill yet, in addition, recouped the solidness and ductility of the reference example dependent on the experimental proof [22].

Shan et al. (2019) worked on the impact of masonry infill walls on breakdown components of steel frames enduring fire situations. Three six-story by five-cove steel frames were structured in this examination. One of these frames had no infill walls, another had flat infill walls and the last one had vertical infill walls. Load redistribution and imperviousness to fire were researched under the edge narrows fire situation and focal inlet fire situation. At long last, a fundamental structure technique was proposed with a plan to anticipate the breakdown of steel frames with infill walls enduring onslaught situations [23].

Furtado et al. (2018) discussed about the methodical review of experimental investigations with regard to infill masonry walls out-of-plane (OOP) behavior. An all-encompassing database was assembled containing data from each experimental battle and example tried. The outcomes exhibited that past harm brought about by in-plane tests that arrived at a most extreme °oat until 1.25% can lessen about 70% the OOP limit of the board, changing the disappointment method of the board that can bring about delicate collapses [24].

Markulak et al. (2019) concentrated an experimental examination on four different kinds of steel frames and infill and an exposed frame. The structural behavior properties of these arrangements are examined and assessed dependent on received hysteresis loops and their envelopes — ductility, initiate stiffness and extreme load. Frame infilled with new units has high ductility and power, joined with lower stiffness. This guaranteed the conservation of the frame from more grounded impending impacts, with charms of positive parts of the frame-infill cooperation [25].

Amongst others, Araújo and Castro (2017) performed a comparative study of the European and American procedures and highlighted some limitations in the current EC8–3, such as the lack of safety verification criteria for linear analysis method and inconsistencies in seismic demands obtained from different analysis methods. In addition, it has been pointed out that the compliance criteria for assessing steel beams and columns reported in EC8–3 is found to be identical to the relevant acceptance criteria in the old version American code ASCE41–06, which have been improved in its successors [26].

Khalilzadeh et al. (2019) investigated in study of seismic parameters, ultimate tensile damage, and force transfer mechanisms in a reinforced concrete structure under in-plan load. After compared the analysis outcomes with the bar frame, it was indicated that the ultimate load, stiffness, and toughness of the full in-filled frame were increased while the ductility was decreased [27].

In this paper examined the effect of area and configuration of window opening on seismic behaviour of steel frames. A numerical nonlinear static analysis and nonlinear time history analysis using a commercial software ADINA. The main aim of this manuscript is to present a seismic assessment framework approach for undamaged and damaged RC structures. For this, an twelve typical types of masonry infill steel frame will be studied: bare steel frame structure; bare steel frame structure with full masonry and steel frame masonry infilled with different area and configurations of window openings: 0.5 masonry; 1m masonry; 1.5m masonry; 2m masonry; 1m-H masonry; 1.5m-H masonry; 2m-H masonry; 1m-V masonry; 1.5m-V masonry; 2m-V masonry. The details of the prototype models are show in Figure 1. Several non-linear static and non-linear dynamic analyses with tow time history: Imperial Valley-Holtville Post Office and El Centro were carried out to assess the seismic vulnerability of the undamaged structures. The research flow chart is shown in Figure 3.
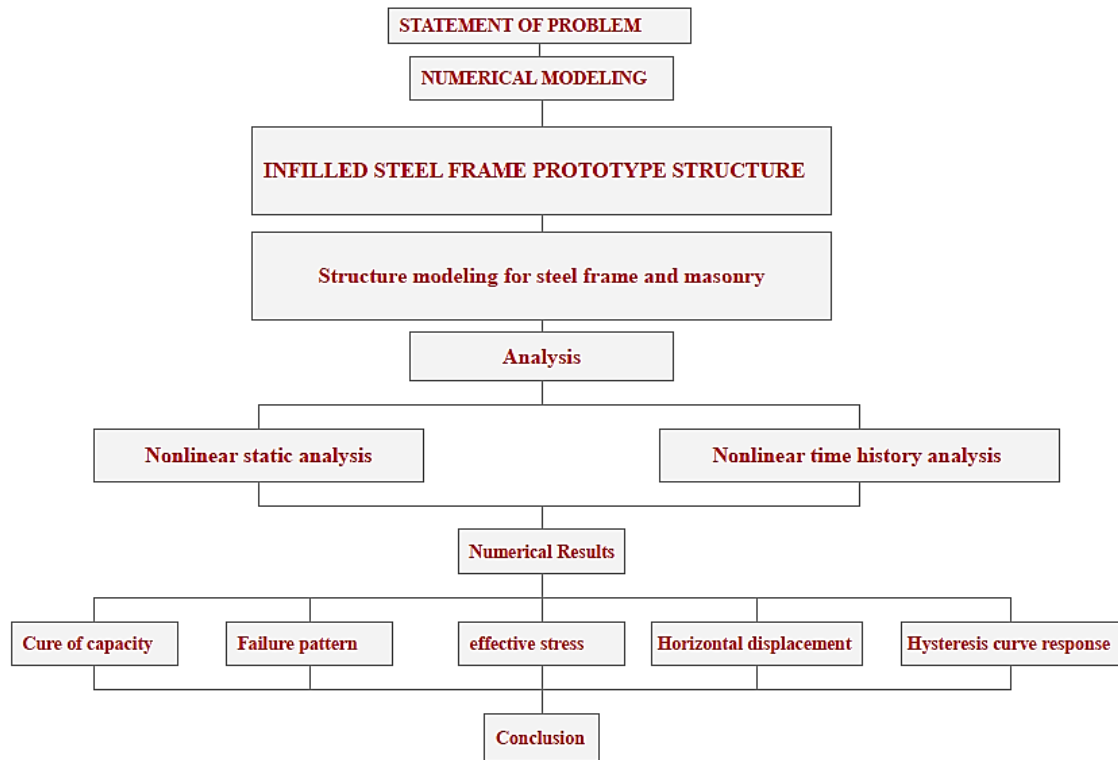
Figure 3. Flow chart of the research study

2. Infilled Steel Frame Prototype Structure

Twelve typical types of masonry infill arrangement are considered in this study:

- Infilled steel frame without masonry;

- Infilled steel frame with full masonry;

- Masonry infilled steel frame with openings: 0.5 masonry; 1 masonry; 1.5 masonry;2 masonry; 1 H masonry; 1.5 H masonry; 2 H masonry; 1 V masonry; 1.5 V masonry; 2 V masonry.

The details of the prototype models are shown in Figure 4.

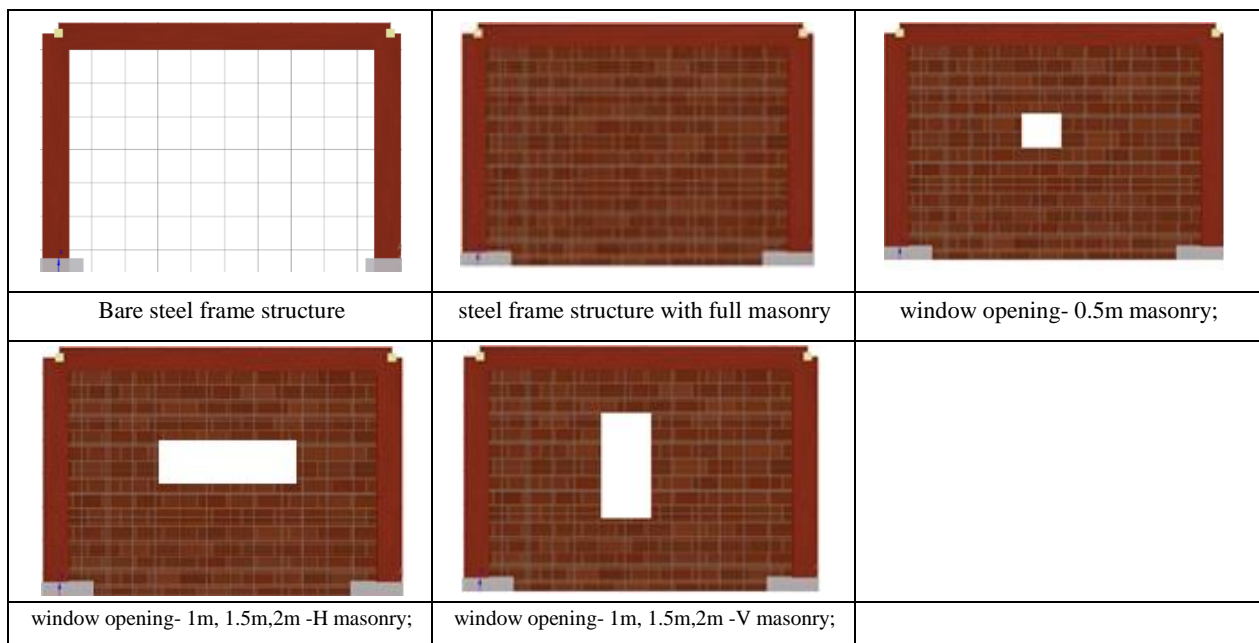|		
Bare steel frame structure	steel frame structure with full masonry	window opening- 0.5m masonry;
window opening- 1m, 1.5m,2m -H masonry;	window opening- 1m, 1.5m,2m -V masonry;	

Figure 4. Masonry infill prototypes (without masonry; full masonry; with openings: 0.5 masonry; 1 masonry; 1.5 masonry; 2 masonry; 1 H masonry; 1.5 H masonry; 2 H masonry; 1 V masonry; 1.5 V masonry; 2 V masonry)

3. Numerical Modeling

3.1. Material Modeling for Masonry and Steel

Bricks were modeled with material property defined in ADINA [28-30] as the "concrete" material type, which has a simple nonlinear stress-strain formulation (Figure 5) with tensile failure at relatively small principal tensile stress and compression crushing failure at relatively higher compression. Softening common for brittle materials like brick was not modeled due to convergence difficulties. In unloading the initial Young's modulus was used.

Usually a bilinear stress- strain behavior is considered for steel which is well known (Figure 5). Hence modulus of elasticity has a value of 200 GPa and the tangent stiffness E2 is based on steel grade and ductility, section of bare frame and the yield stress and can be found in different references.
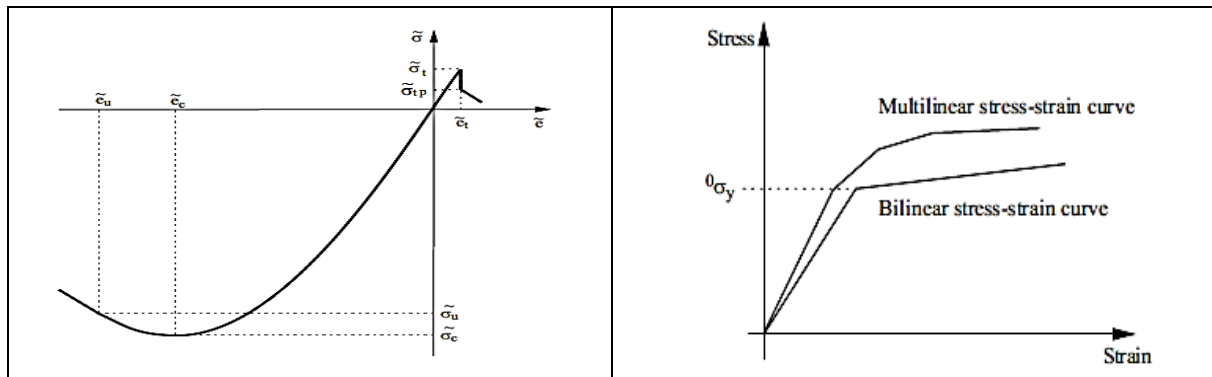

Figure 5. Stress – strain curves for brick and steel material [51]

A bi-linear stress-strain relationship is often assumed for the steel material. This is well-established in the literature as being compatible with the behavior of structural steel (Figure 5). The modulus of elasticity, Es, is assumed to be equal to 200 GPa. The secondary stiffness, sometimes referred to as "tangent stiffness", which is here denoted by E2, varies based on the steel grade and ductility, section of bare frame and the yield stress and can be found in different references.

3.2. Structure Modeling for Bare Steel Frame and Masonry

For modeling steel bare, in ADINA used Beam Element, 2-node Hermitian beam elements are available for their capacity to mediatize transverse, longitudinal, and torsional displacements by the use of Bernoulli-Euler beam theory while , if requested, the shear deformation can be taken into account. Figure 3 shows geometry and displacements. The treated beam elements are: linear: displacements; rotations, and infinitesimally small strains; large elastic displacement beam element: large displacements and rotations while strains are small; nonlinear elasto-plastic beam element: materiel nonlinearities are considered; and moment-curvature beam element: both bending moment-curvature and torsional moment-angle of twist are defined [31, 32]. Figure 6. 2-node Hermitian beam elements according to ADINA.
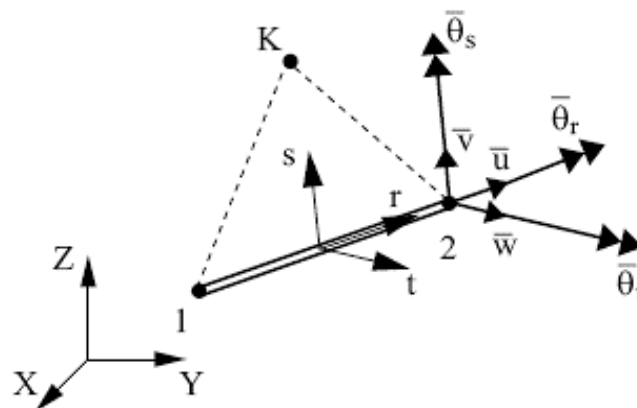

Figure 6. ADINA 2-node Hermitian beam elements [51]

Fore modeling masonry, used thin Plate element scan be modeled with the 3-node, six degrees of freedom per node is used, Figure 7 shows the flat triangular element. Both bending (discrete Kirchhoff) and membrane stresses are accounted for while the shear deformation is neglected [33, 34]. Figure 6 represents the ADINA Plate/ Shell element.
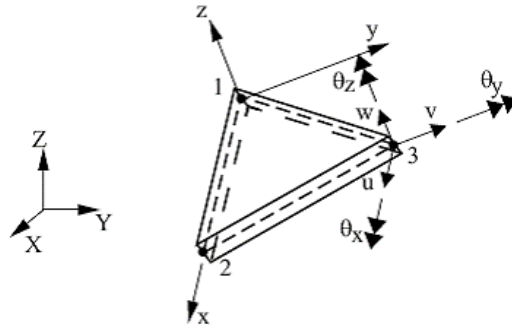
Figure 7. ADINA Plate/Shell Element [51]

4. Numerical Results

4.1. Pushover Results of the Frame with Opening

To obtain the impact of openings on overall strength and ductility behavior of a steel frame, a tactical nonlinear analysis is conducted. Figures 8-a and 8-b, and C show the effect of the openings with an increase in their horizontal and vertical dimension and also in the two direction. It is noticed that the opening area has an influence on the maximal strength and on the ductility of these frames, and also on the initial rigidity in the three cases (horizontal, vertical, and in the directions). As the area increases the strength decreases and the ductility increases showing almost the same values in the two cases (Figures 8-a and 8-b). the decrease of the ultimate strength for a frame without infilling, 0,5H, 1H, 1.5H, 2H, 1 H+V, 1.5H+V et 2 H+V with regard to a frame with infilling is of the order of 63, 1 3, 17, 17 , 34, 27, 41 and 51% respectively. According to Figure 8-d. the form of the opening will not influence the global behavior in this analysis case. According to the literature, there are many ways of crashing in frames with infilling because of the capacity curve drop (crashing mode …)
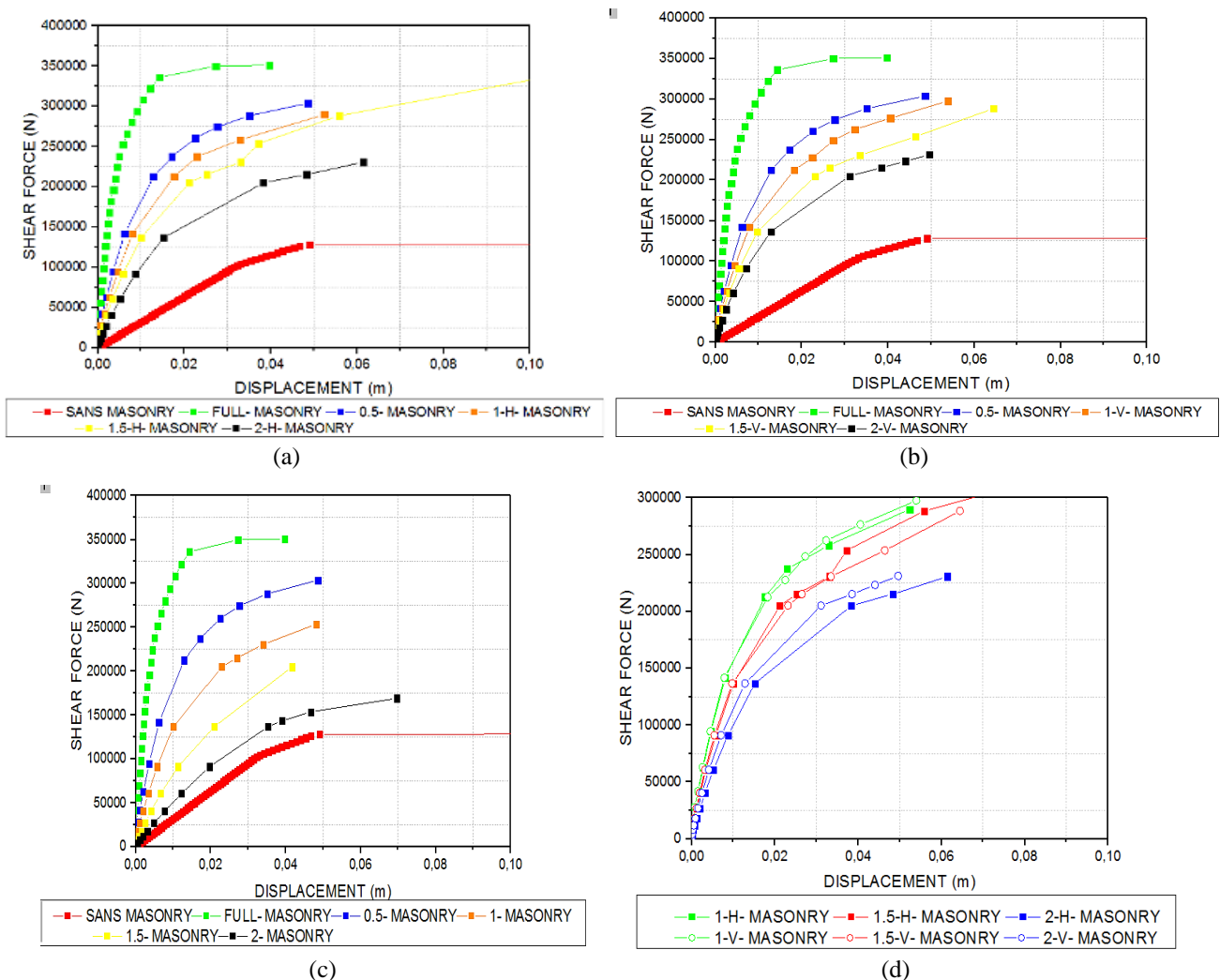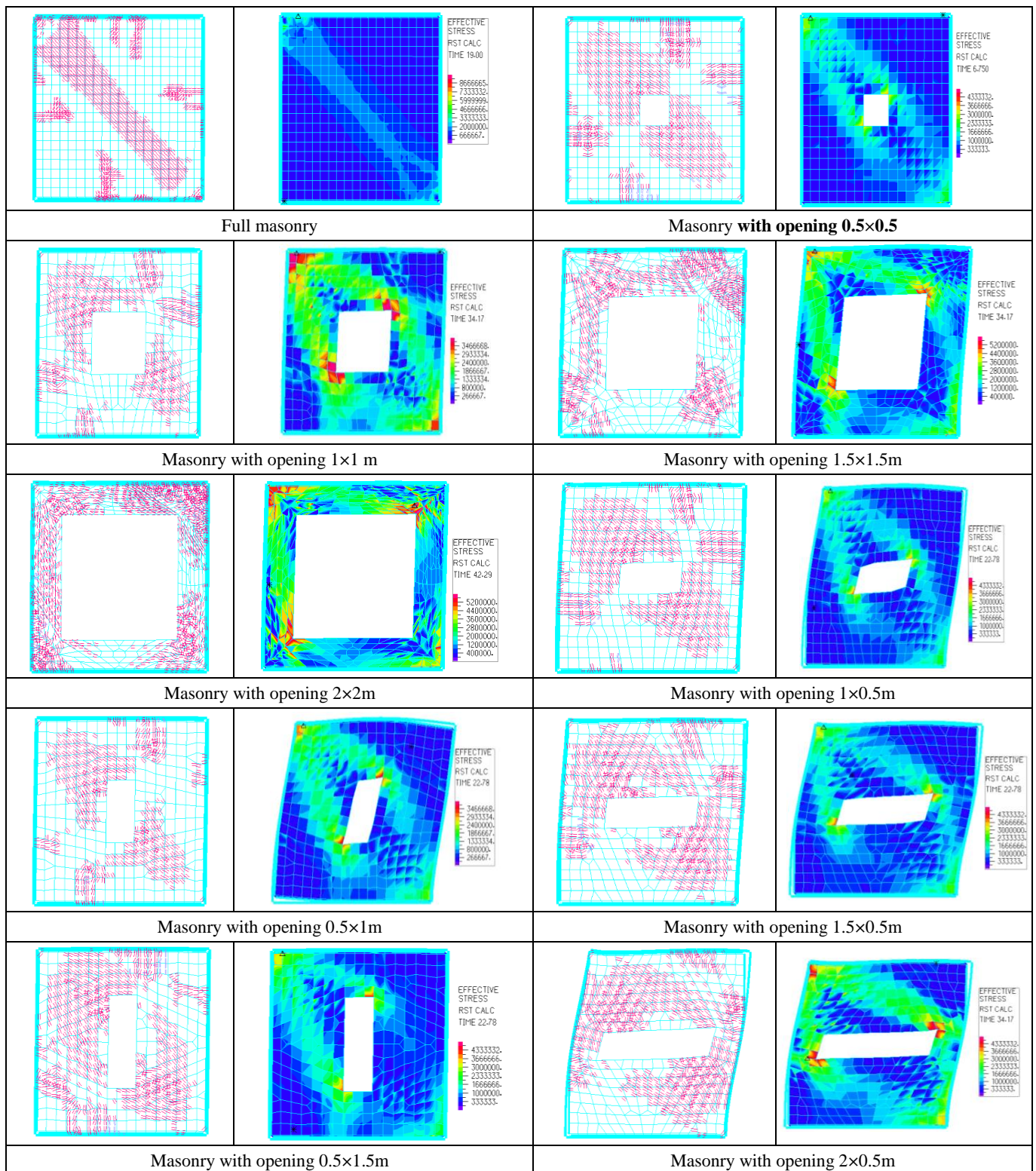

(a)

(b)

(c)

(d)

Figure 8. Curve of capacity with openings different

The Figure 9, shows the failure pattern and the effective stress. The cracks are formed in a diagonal way in the panel following the compression diagonal and when the displacement increased in the infill continues to crack. Cracks initiate at approximately 45° at the top corners in compression once the imposed displacement increases, this shows the full development of a diagonal compression strut mechanism and the efficiency of the infill in enhancing the frame lateral resistance. After this step, successive horizontal and vertical cracks appear in the infill panel. When the opening is realized in the panel, the crack, at the beginning, appears at the corner of the opening and then continue until reaching the two corners of the frame. The field and the shape of the crash are function of the taking form and the position of the compression and tension diagonals. When the dimensions or the shape of the opening are increased, the compression diagonals deviate which leads to a longer tension diagonal. Hence the infill panel, in the presence of window, reacts like a five-member truss. This will require one tension element to balance the bent compression struts in order to be governed by tensile state of cracked masonry.
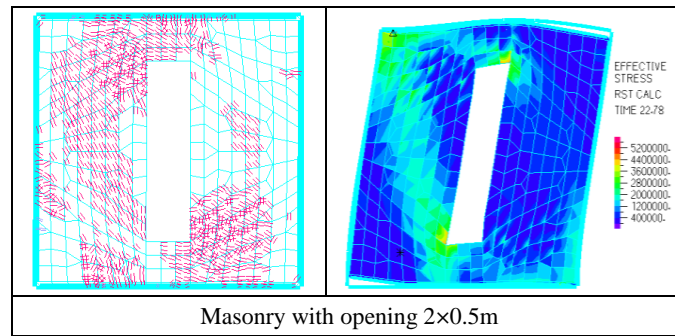
Full masonry	Masonry **with opening 0.5×0.5**
Masonry with opening 1×1 m	Masonry with opening 1.5×1.5m
Masonry with opening 2×2m	Masonry with opening 1×0.5m
Masonry with opening 0.5×1m	Masonry with opening 1.5×0.5m
Masonry with opening 0.5×1.5m	Masonry with opening 2×0.5m

Masonry with opening 2×0.5m

Figure 9. Failure pattern and the effective stress

5. Nonlinear Time History Analyses Results

Because of the response spectrum analysis restriction to apply nonlinear response of a complex structure, nonlinear time-history analysis should be the issue regarding the degradation of different elements of the structure, load pattern characteristics resulting from ground motion intensity, and also the parameters induced in the nonlinear dynamic analysis. Besides the nonlinear time history analysis allows to evaluate the effect of supplementary energy-dissipation devices introduced in structural systems [34-37].

The high computational and analytical volume required within a large output information represent the main disadvantage when using the time history analysis. When proceeding to the analysis of capacity of the different components of the structure, a time function is needed to express the nonlinear behavior for elements as well as for materials [38-43].

Generally, the direct numerical integration of the dynamic equilibrium is the main approach to solve the dynamic response of structural systems at a discrete point with provided time [44-50]. The accelerograms used in this investigation are the horizontal components of the Imperial Valley-Holtville Post Office and Imperial Valley- EL Centro (Figure 10). The peak ground acceleration of the horizontal component of Imperial Valley-Holtville Post Office is 0.2 g and for of Imperial Valley El Centro is 0.49 g (Figure 11).
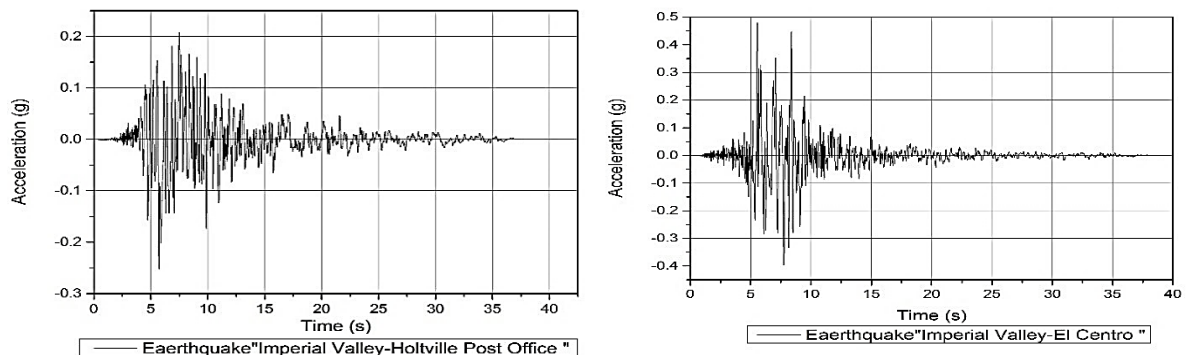

Figure 10. Earthquake records A) Imperial Valley-Holtville Post Office (EARTH Q2) –B) Imperial Valley- El Centro (EARTH Q3)
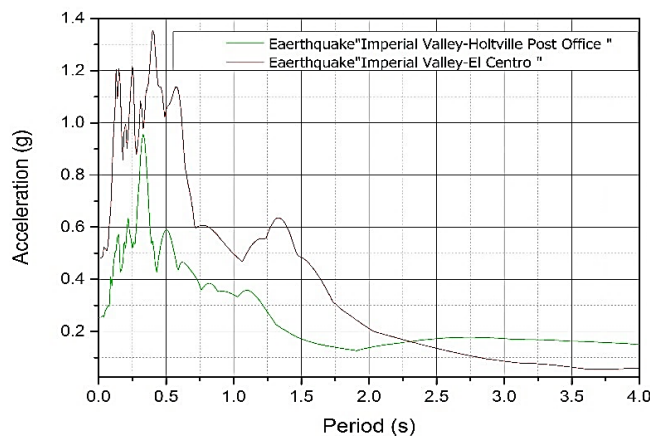

Figure 11. Specter of response

6. Maximum Inter-Storey Drift

Horizontal displacement of the top of the bare frames and bare frame with full masonry or with opening is shown in Figure 12. According to this figure, in the case of a frame filled with masonry, the global displacement is greatly decreased and even the behavior of the curve in affected by the earthquake intensity. When a 0.5×0.5 m opening is realized the displacement increases about 20% regarding to a filled masonry wall (Figure13). The shape of the openings influences on the behavior of the frame under earthquake action, for example the vertical openings lead to greater displacement values than horizontal openings. As a vertical opening is placed, in the first step of loading, the masonry between the opening and the column crashes and the horizontal rigidity decreases (Figure 14).
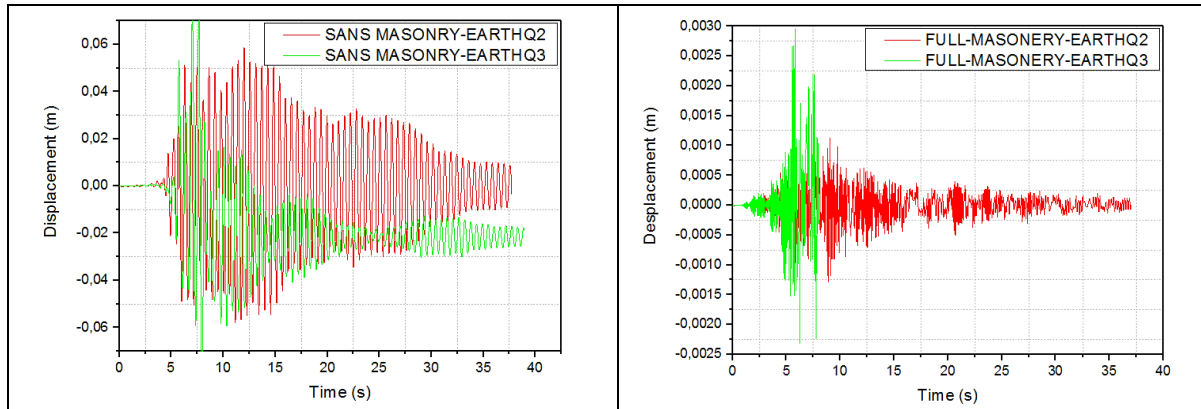
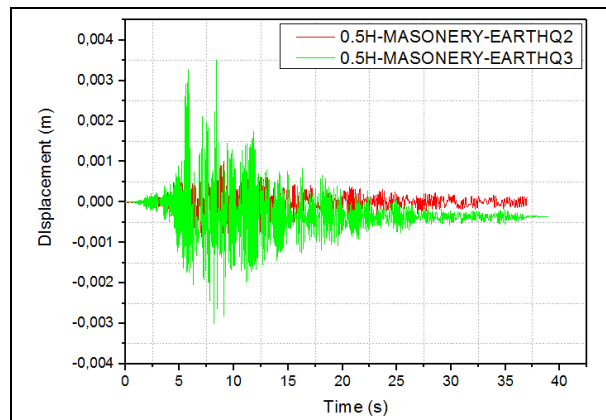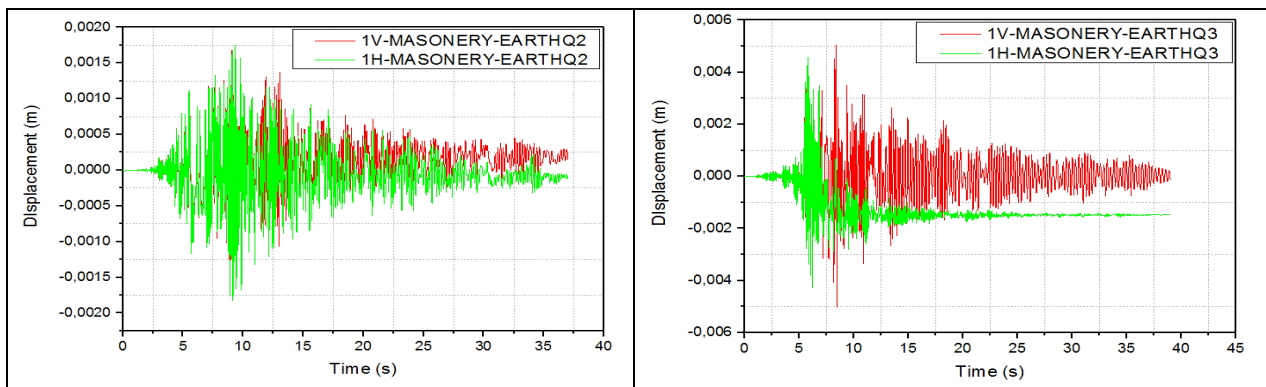**Figure 12. Horizontal displacement top node in frame structure**

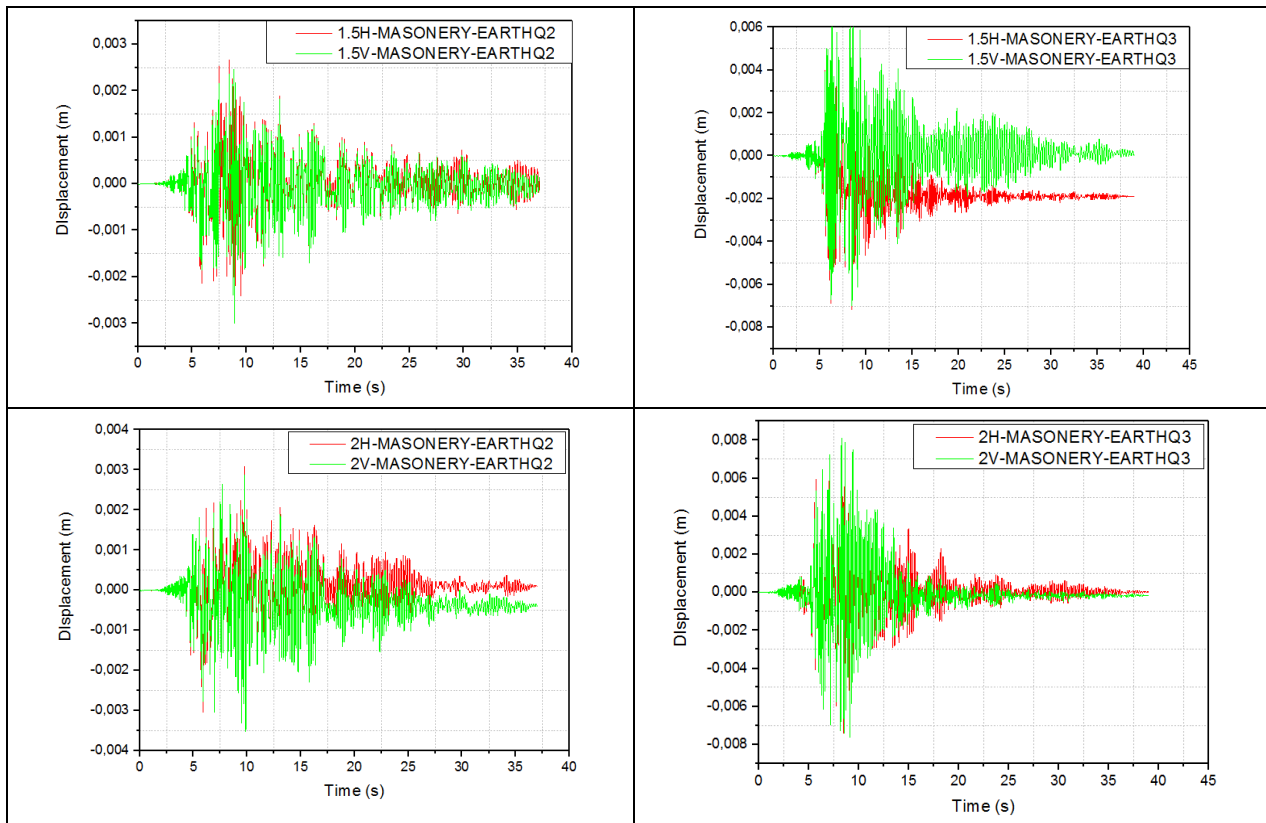**Figure 13. Horizontal displacement node at top story in 0.5-masonry**

Figure 14. Horizontal displacement node at top story structure

7. Hysteresis Response of Models

Figure 15 shows a comparison of the capacity hysterical curves of frames with and without masonry filling under two seismic excitations with different levels. According to these figures a decrease in the value of shear demand about 60% for earthquake 1 and about 40% for the second one, and a loss in ductility of the frame filled with masonry. The frame with masonry filling are more rigid than those without filling. The first earthquake analysis for frames with openings shows no influence whatsoever on the values of shear and ductility (Figures 17-a, 18-a, and 19-a). Whereas the second earthquake analysis shows an increase of shear in the case where the opening is vertical with a percentage of 10%, even of the displacement there is a shift in the hysterical curve of about 42 to 128% regarding to a frame fully filled with masonry (Figures 17-b, 18-b, and 19-b).
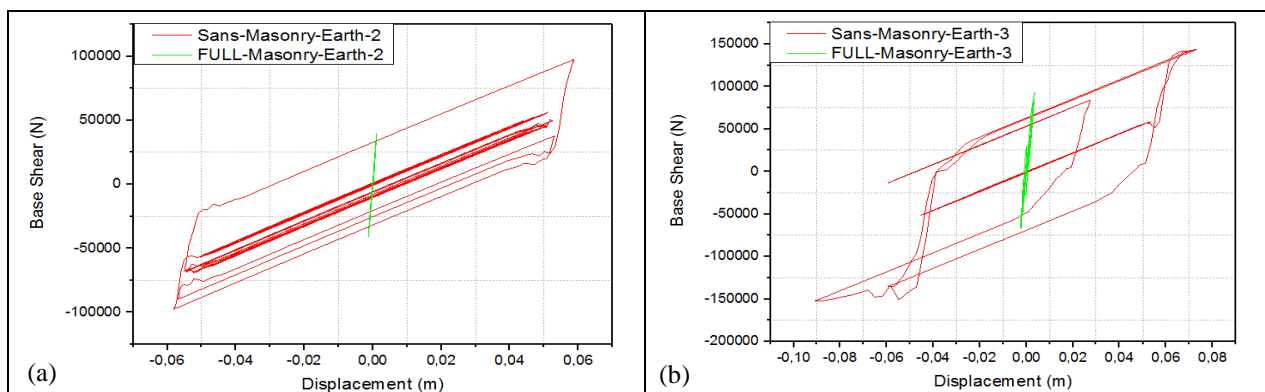

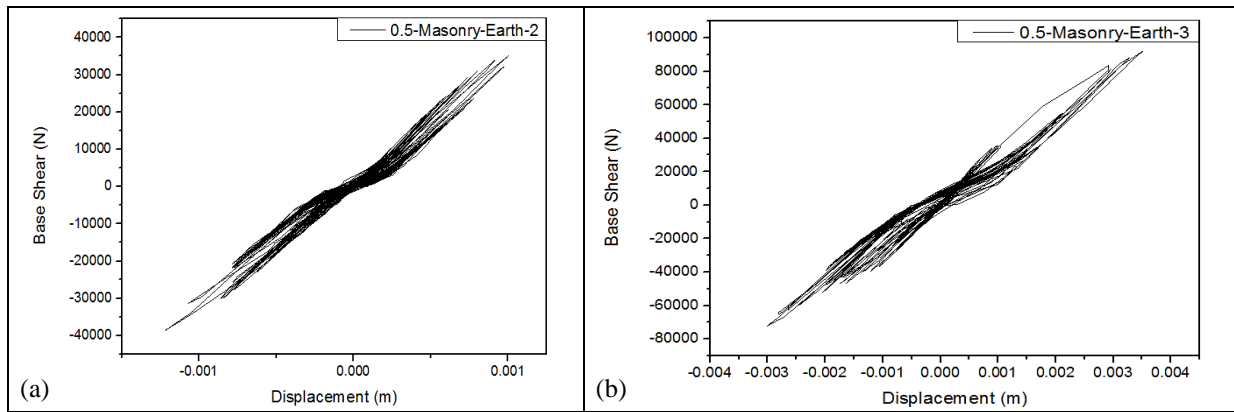**Figure 15. Hysteresis curve response for masonry with and without openings**

Figure 16. Hysteresis curve response for masonry with a 0.5 m opening
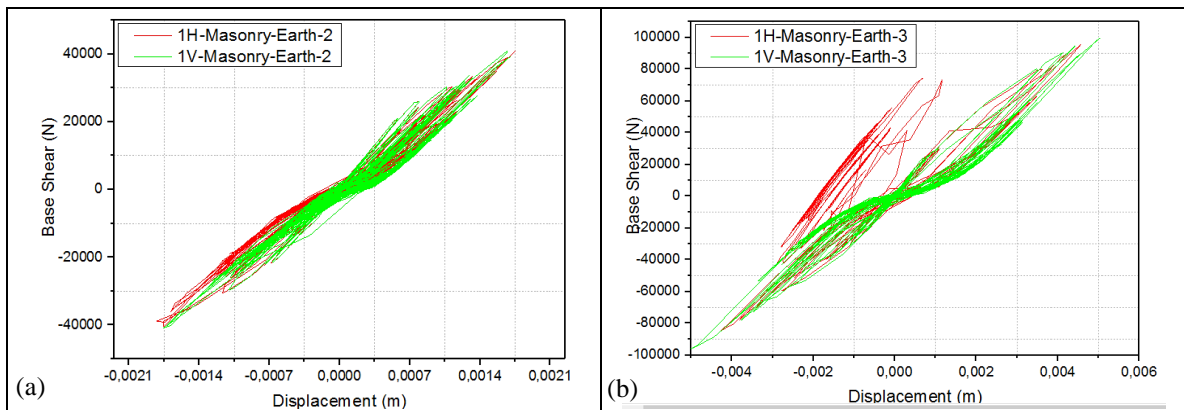

Figure 17. Hysteresis curve response of masonry with opening equal 1m
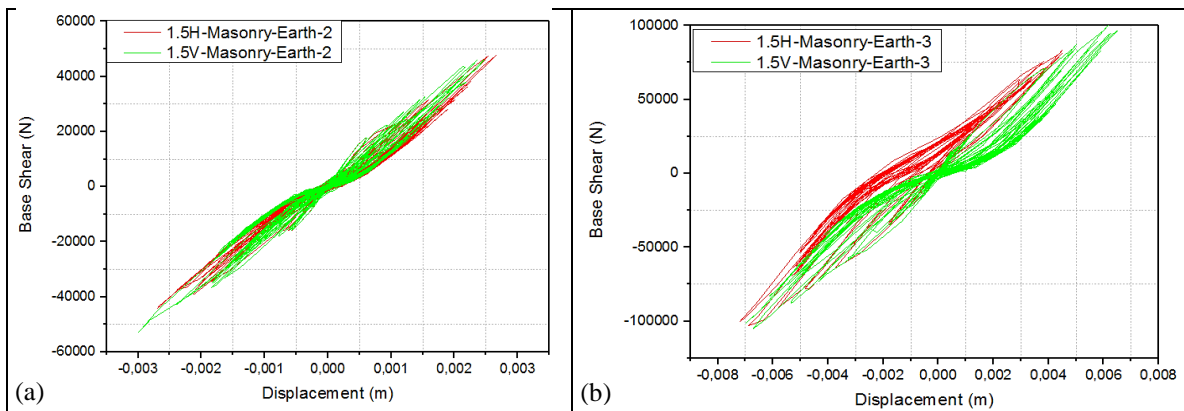

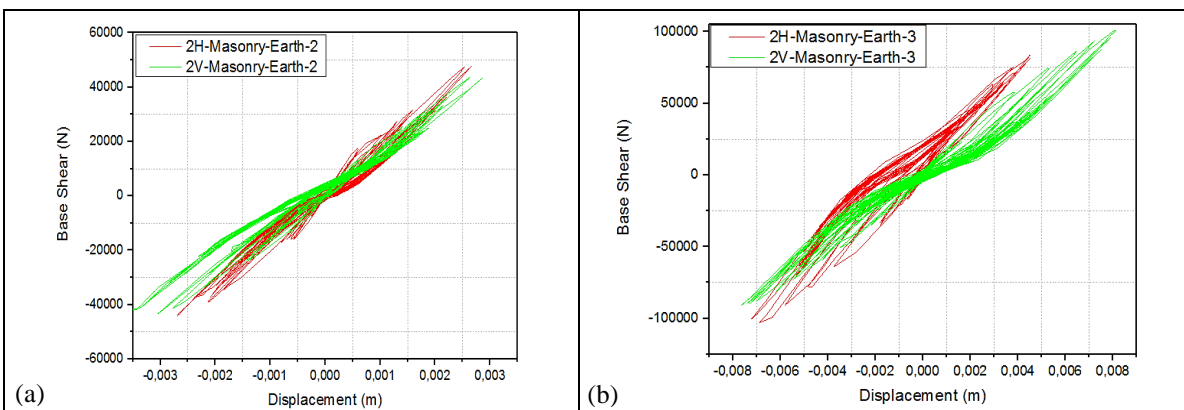**Figure 18. Hysteresis curve response of masonry with opening equal 1.5m**

Figure 19. Hysteresis curve response of masonry with opening equal 2m

8. Conclusion

Seismic design codes of many countries neglect the contribution of masonry infills steel frame and the effect of opening in behavior and design under lateral load of steel frame as bare frame. Several conclusions can be drawn from the numerical investigations:

The first step showed that masonry infill frames were significantly stiffer, stronger and dissipate more energy, but the ductility is low than the corresponding bare frames. The dimensions of the opening influence on the initial rigidity, decrease in the maximal strength, and increase in the ductility of such frames. But the nonlinear analysis does not capture the influence of the opening position on the global behavior.

The cracks initiate at approximately 45°at the top compression corners once the imposed displacement is increased. This shows the full development of a diagonal compression strut mechanism and the efficiency of the infill in enhancing the frame lateral resistance. After this step, successive horizontal and vertical cracks appear in the infill panel. Hence, the infill panel, in the presence of a window, reacts like a five-member truss. This will require one tension element to balance the bent compression struts in order to be governed by tensile state of cracked masonry.

According to these results in the case of a masonry infilling frame analysis with nonlinear time history method under tow earthquake, the global displacement is decreased greatly and even the curve shape is influenced by the earthquake intensity. When an opening 0.5×0.5 m is realized, the displacement increases about 20% regarding to a completely masonry infill steel frame.

The shape of the openings influence the behavior of the frame under earthquake loading. Hence the vertical openings lead to a large displacement than the horizontal ones. This is due to the fact that when a vertical opening is realized, at the first loading stage, the masonry between the opening and the columns begins to crack along the decrease of the horizontal rigidity.

9. Declarations

9.1. Data Availability Statement

The data presented in this study are available in article.

9.2. Funding

9.3. Conflicts of Interest

The authors declare no conflict of interest.

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