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Full Length Research Paper

Numerical study on aluminum panels used in braced steel frames as energy dissipation systems

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In this paper, aluminum panels were used to improve the seismic behavior of the braced steel frames. One of the methods used to improve the seismic behavior of structures is the use of vertical links as energy dissipation systems. Aluminum has a low yielding stress and it yields faster than steel which results in a significant ductility. The investigation method was simulation by ABAQUS software. The steel frames with 1, 4, 8 and 12 stories were modeled by four different bracing systems and two types of rectangular and square aluminum panels. The results of using aluminum panels were compared with Easy Going Steel (EGS) through the structure capacity curves. The results indicate that using the aluminum panel as vertical link in braced steel frames made significant energy dissipation.

Key words: Aluminum panel, energy dissipation, steel braced frame.

INTRODUCTION

One of the most effective as well as the simplest innovative methods to improve the seismic behavior of the structures in high earthquake risk zones is the use of energy dissipation systems. An energy dissipation system acts as a fuse to prohibit the whole structural collapse by local yielding and to maintain the whole structure continuity. The vertical link of Low Yield Stress (LYS), Easy Going Steel (EGS), or the aluminum panels are different kinds of energy dissipation systems that damp the energy of earthquake by yielding the vertical link and the other elements of the structure remain in elastic region. Hence, in recent years, the researchers have paid attention to investigate the function of these types of dissipaters.

Application of braces can increase the lateral stiffness of steel frames (Mosalman and Ramli Sulong, 2010; Mosalman et al., 2011; Daie et al., 2011).

In recent years, materials such as aluminum and low yield stress (LYS) steel have been used to increase the energy dissipation of the vertical link in majority of structures (De Matteis et al., 2007b; Daryan et al., 2008).

The aluminum shear panels with stiffeners have a high capacity of energy dissipation, stable hysteretic loops and prohibit the occurrence of the sudden bucking and this makes the vertical link stable as well as increasing the energy dissipation of the structure.

The vertical link implemented by LYS steel, improves the seismic behavior and increases the energy dissipation of the structure (De Matteis et al., 2007b). Increasing the energy absorption in link beam makes other structural members to remain in the elastic region. Also, these links damp the structure lateral forces to an acceptable extent against a special earthquake; in comparison with the other kinds of lateral-resistant systems used, the structure get a more proper ductility. Therefore, in recent years, the researchers have paid attention to investigate the behavior of these types of links (Zahrai and Bruneau, 1999). Arce et al. (2003) have examined the shear link beams of ASTM-A992 steel in 2003 to investigate the flange slenderness restrictions. According to them, the reason why some samples were destructed was as a result of the web tear that began from the link beam to the end of the web stiffeners (Arce et al., 2003). Mc Danial et al. (2003) had a series of examinations on two samples of the metal link beams in suspension bridges located in Ukne Galf and San-francisco in 2003. The shear capacity of the structures investigated by them was about as much as twice of the ones according to AASHTO code (Mc Daniel et al., 2003).

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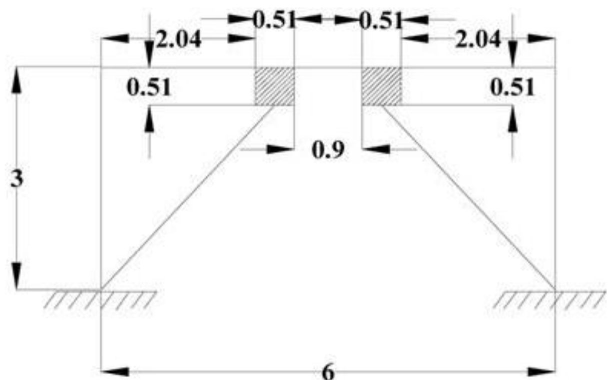


Figure 1. Brace-1 dimensions.

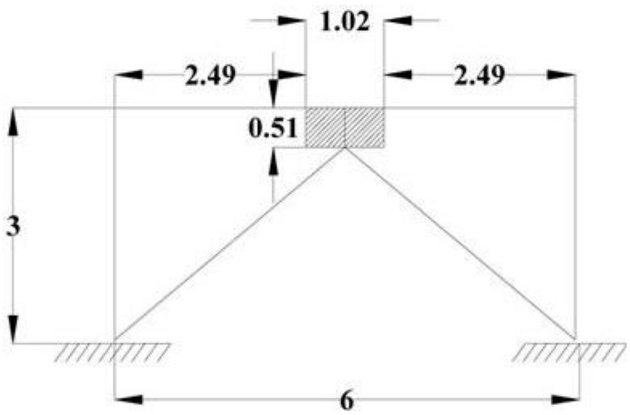


Figure 2. Brace-3 dimensions.

De Matteis et al. (2003, 2007b) did extensive numerical analyses on the aluminum shear panels, ductile and LYS steel. They investigated the panel geometry parametrically and found out that the most important geometric parameter affecting the vertical link function is the ratio of width to thickness of the panel and presented some relationships for designing such panels too (De Matteis et al., 2004, 2007b). They investigated the cyclic behavior of the aluminum panel numerically and laboratorial calculated the amount of energy dissipation according to the cyclic loading and presented it for several panels. They used the aluminum panels as energy dissipations only for X-bracings; the place of setting the panel is in junction of two bracing members. They stated that simultaneous effect of aluminum and steel increases ductility as well as the energy dissipation of dissipator (De Matteis et al., 2007a). Chao et al. (2006) investigated the web failure of the steel link considering the beginning of the failure, and that the basis of calculation of the link ductility improved the place of the failure beginning according to the laboratorial results in 2006 (Chao et al., 2006). Formisano (2006) did some examinations on the aluminum shear panel of 1000 to 1500 mm and concluded that the examined samples had a very high ductility and the panels had a proper function for energy dissipation. Chan et al. (2009) did single and cyclic loading examinations on shear link beams in 2008 and recommended applying such beams for seismic improvement of the existing frames because of their high energy dissipation (Chan et al., 2009). Saedidaryan et al. (2008) investigated the behavior of Vertical link-Eccentrically Braced Frame (V-EBF) using ductile EGS steel and showed that using EGS improves the seismic behavior and increases the energy damping in braced frame (Saedidaryan et al., 2008). Shayanfar et al. (2008) introduced Double Vertical-Link (DV-Link) for eccentrically-braced frame and investigated its cyclic behavior. The DV-Link showed a proper stability and seismic behavior against buckling (Shayanfar et al., 2008). De Matteis et al. (2008) used the aluminum and steel panels for strengthening of the reinforced concrete building in 2008 and concluded that the aluminum panels have more ductility in comparison with the steel ones (Mazzolani, 2008; De Matteis et al., 2008). Diaferio et al. (2010) researched about the design of the optimum dissipator made of aluminum and steel and investigated four kinds of panels with different stiffeners analytically .The steel stiffeners in thin aluminum plates improve the bucking behavior of the plates and also the shear strain in these kinds of panels is increased (De Matteis et al., 2011).

In past years, a kind of aluminum panel has been used as vertical link only in 4-story structure with convergent bracing system. The aluminum panel has not been used in divergent bracing systems and for short-order, mid-order and long-order structures so far. Also, it has not been used in convergent bracing systems of steel frames of mid-order and long-order structures. In this research, rectangular and square aluminum panel has been set in a proper place by an innovative method. Four bracing systems with Flexural-Rigid-Frame (FRF) have been used in low-rise, mid-rise and high-rise structures to investigate how setting an aluminum panel in frame affects on energy dissipation, improving the seismic behavior and base shear. A series of aluminum panels with different bracing systems are investigated. A numerical method by ABAQUS software has been used to evaluate the behavior of aluminum panels.

MATERIALS AND METHODS

Specifications of the models

In this research, numerical method and computer modeling have been applied. The powerful software of ABAQUS, which is well-known software in the context of Finite Element Method (FEM), has been used. The analysis method used here is nonlinear static analysis. To evaluate the aluminum panels, panels were used in frames. In this case, four different kinds of bracing with panels of square and rectangular are applied in rigid frames. The details of panels and bracing systems are presented in Figures 1 to 4. Table

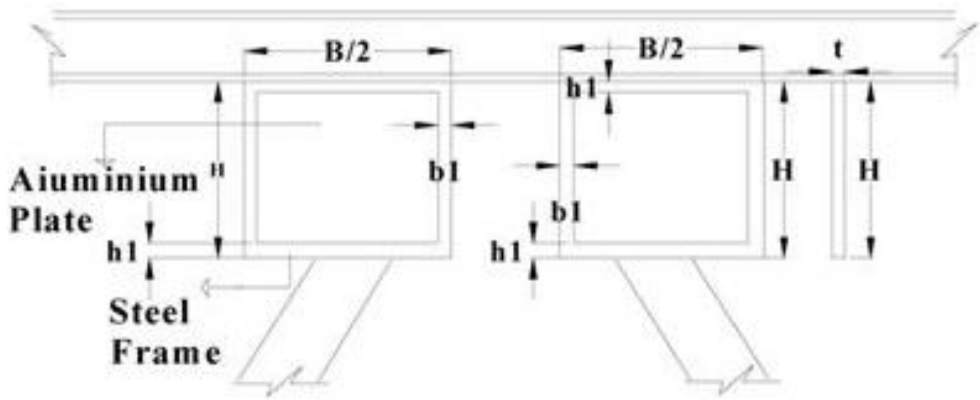


Figure 3. Square panel dimension (Panel -A).

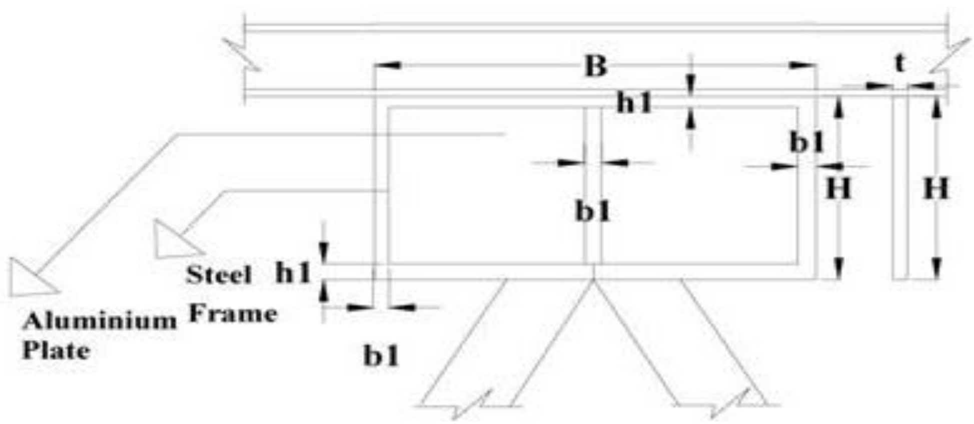


Figure 4. Rectangular panel dimension (Panel -B).

Table 1. Frame sections for 1-story frame.

Frame sections for 1-story frame	
Element type	**Section**
Beam	IPE 220
Column	IPB240
Brace	2 UNP 140

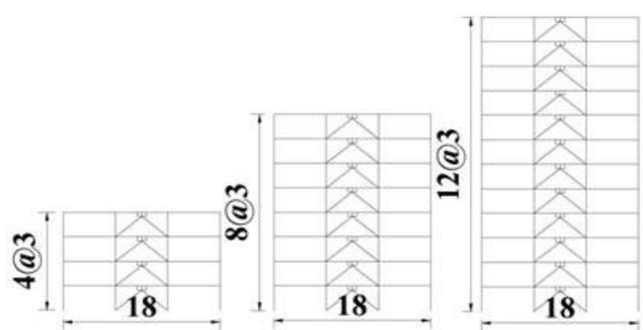


Figure 5. Models with different floor stories.

Table 2. Square and rectangular panels dimensions.

Aluminum panel dimensions	
Square Aluminum Panel A (mm)	510-510
Rectangular Aluminum Panel B (mm)	1020-510
h_1	10
b_1	10
H	510
B	1020
t	10

1 indicates the frame sections for 1-story frame, and Table 2 shows the specifications of the aluminum panels.

To evaluate the behavior of the aluminum panel more precisely, it is used in low-rise, mid-rise and high-rise structures so that the specifications of the structural models is as follows: In structural models, four, 1, 4, 8 and 12-stories frames with 6 m spans and story height of 3 m and restrictions of Y/L<1.5, 1.5<Y/L<3, Y/L>3 are used where *Y* is the height of the whole frame and *L* is the width of the frame span. Figure 5 shows one type of bracing

Table 3. Structural system specifications.

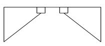
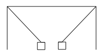
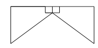
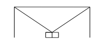
Structural system							
Eccentric Braced Frame with Panel (EBFP)				**Concentric Braced Frame with Panel (CBFP)**			
Brace-1		**Brace-2**		**Brace-3**		**Brace-4**	
Structural name 	**Number of stories (N)**	**Structural name** 	**Number of stories (N)**	**Structural name** 	**Number of stories (N)**	**Structural name** 	**Number of stories (N)**
EBFP-1-1	1	EBFP-2-1	1	CBFP-3-1	1	CBFP-3-1	1
EBFP-1-4	4	EBFP-2-4	4	CBFP-3-4	4	CBFP-3-4	4
EBFP-1-8	8	EBFP-2-8	8	CBFP-3-8	8	CBFP-3-8	8
EBFP-1-12	12	EBFP-2-12	12	CBFP-3-12	12	CBFP-3-12	12

Table 4. Frame sections for more than 1-story.

Story	Element type	Section
4-First story	Beam	IPE 220
	column	IPB 240
	Brace	2UNP 140
	Aluminum Panel	510-510
4-Second story	Beam	IPE 260
	column	IPB 300
	Brace	2UNP 180
	Aluminum Panel (mm)	510-510
4-Third story	Beam	IPE 300
	column	IPB 400
	Brace	2UNP 240
	Aluminum Panel (mm)	510-510

system used for frames with different stories.

For frame, dual structural system (both rigid frame and bracing systems) is used. Four different kinds of bracings with two types of aluminum panels are considered. The bracing systems includes: (a) Eccentric inverted V-bracing; (b) Eccentric V-bracing; (c) Concentric inverted V-bracing, and (d) Concentric V-bracing. The specification of the frames and details of the section are presented in Tables 3 and 4.

The reason of using a dual system (both rigid frame and bracing systems) is that the majority of vertical loads are resisted by frames and the majority of lateral loads are resisted by bracings and aluminum panels. Also, it is such a prevalent system which most of the structural engineers use in withstanding lateral loads. By using this kind of system, large deformation in mid-rise and high-rise buildings can be controlled. For this reason, dual system is used in structural models. Kiggins and Uang (2006) studied the dual systems and concluded that using un-bucklable bracings in dual system decreases the story drift and controls deformations.

Material properties

In this research, two different materials are used. They include: aluminum and ST360 steel. The mechanical properties and stress-strain graph for these two materials are shown in Table 5 and Figure 6.

Regulations governing the design of the shear aluminum panel

If aluminum panels with metal stiffeners are set in proper places in the structure (Figure 7), they will have a high energy dissipation and stable hysteretic loops (Figure 8) and this prohibit the occurrence of sudden failure and make a proper ductility (De Matteis et al., 2007b, 2011).

Two important parameters in the design of the shear aluminum panel are the ratio of width thickness ($\frac{b}{t}$) where *b* is the width and *t* is the thickness of aluminum plates and normalized stiffness parameter (γ_{st}) defined by Equation 1:

$$\gamma_{st} = E.\frac{(\frac{I_{st}}{n_{st}})}{bD} = \frac{12.(1-\nu^2).(\frac{I_{st}}{n_{st}})}{b.t^3} \quad (1)$$

where I_{st} is the moment of inertia of stiffeners, and n_{st} is the number of the internal stiffeners in width. According to European

Table 5. Material properties for steel and aluminum.

Material	Yield stress [$\frac{N}{mm^2}$]	Ultimate stress [$\frac{N}{mm^2}$]	Modulus of elasticity [$\frac{N}{mm^2}$]	Elongation to failure [%]
STEEL 360	240	360	206000	26
Aluminum alloy (EN-AW 5154A)	75.2	203.6	70000	18

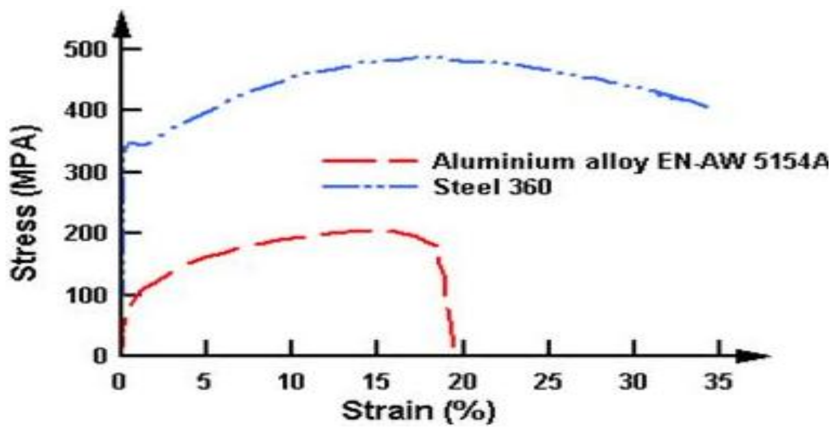


Figure 6. Stress-strain graph for steel and aluminum.

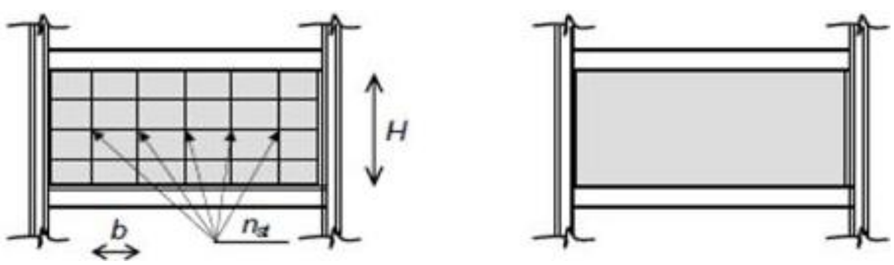


Figure 7. Aluminum panels bounded by columns and beams, with and without stiffeners (n_{st} = number of stiffeners, *t* = thickness of panels).

Code-9 (EC9), the parameters studied in these panels are the ratio of $\frac{b}{t}$ and the moment of inertia of stiffeners (De Matteis et al., 2007b).

Finite element (F.E.) modeling

The term finite element method was created by direct comparative altitude of engineers. This term means direct using of applicable standard methods in discrete systems and it seems that Cloug (1960) was the first person who used this term. This is important both from conceptual and calculating aspects. The first altitude make more understanding of the problem possible and the second one provides the possibility of using a unique approach for solving the various problems and innovating the standard calculating methods (Zienkiewicz and Taylor, 1994; Clough, 1960). Finite element method is a powerful tool for solving an extensive range of engineering problems numerically. It is applicable for an extensive range of stress and strain analysis for bridge, automobile and structures. In this method, continuous environment is discretized by simple and smaller geometric elements called finite elements. According to how the elements are next to each other, their equations are assembled and equilibrium equations of the whole system will be obtained by taking into accounts the external forces and support conditions in joints. This equation relates the nodal loads to the nodal displacements and their constants are elastic and geometrically specified. By solving these equations, the nodal displacements and after that the internal stresses will be calculated (Chandrupatla and Belegunda, 1990).

This research is exclusively numerical (modeling) and ABAQUS software is used for modeling purpose. ABAQUS software with unique capabilities is known as very accurate experimental and applied software in university and industry. The accuracy of this software when solving numerically makes it to be used for analyzing the various engineering problems. Therefore, in this research, the behaviors of the materials are simulated on the basis of nonlinear model. According to linear model, in this model, the kinetic stiffness is considered and their behavior characteristics are given in Table

Figure 8. Energy dissipation of aluminum panels with and without stiffeners.

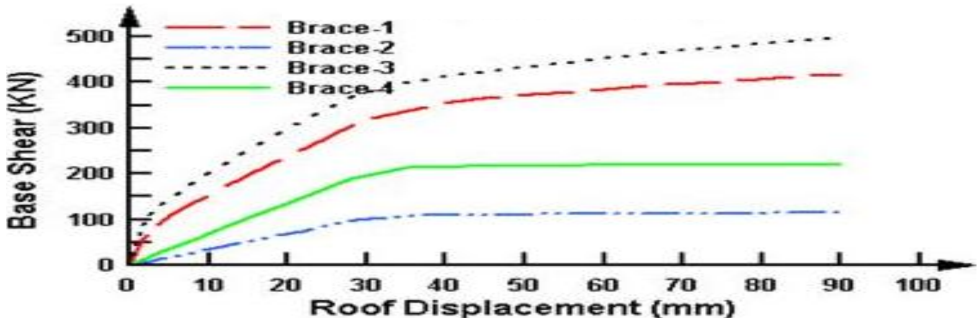


Figure 9. Capacity curve of 1-story frame braced with different bracing types.

3. Beams and columns have been modeled by three dimensional, two nodal beam elements of B31, so this model can take into account great displacement as well. Four nodal element of shell has been used to simulate the aluminum plates. Link element of Tie in ABAQUS software has been used for linking stiffeners to aluminum plates. This element correspond the degree of freedom of stiffener nodes to the nearest node of the plates. Nigeom option also should be active considering the nonlinear geometric effects.

Analysis method

In the research, pushover method has been used to analyze the models. In recent years, push over analysis has been used as an applicable tool in codes and instructions of structural seismicity evaluation. In this method, the specifications of materials and inelastic materials are introduced directly into structural model. Then, this structural modal is pushed increasingly under the effect of a lateral load pattern until reaching an objective displacement and the values of internal deformation and loads are determined. This process continues until the structural collapses. In fact, pushover analysis is the process of step by step yielding of structural critical points, and in recent decade, researchers and engineers have paid attention to it as a powerful tool for investigating the real behavior of the structure under earthquake. One of the objectives of this analysis is to obtain the capacity curve of the structure. The capacity curve of the structure (Base Shear versus Roof Displacement curve) is a suitable tool for investigating overall behavior of the structure.

RESULTS AND DISCUSSION

The results of model analysis have been presented through the capacity curves. These results indicate that using the vertical link with aluminum panel makes a proper ductility therefore, two panels have been used. The panel of B-type is rectangular with an internal stiffener in width. In this panel, mechanism of pure shear governs. This panel has a high capacity of energy absorption and prohibits the occurrence of sudden buckling and before buckling, significant plastic shear deformation occurs. The panel of A-type has no internal stiffener in width. In this panel, buckling occurs in elastic region and tensile field action happens that results in out of plane displacements because of shear buckling in panel. Figures 9 to 12 are the capacity curves of 1, 4, 8, and 12 stories structures, respectively. They indicate that panel B shows a better behavior of energy absorption in plastic environment; comparing with panel A, panel B has the best function in shear behavior and makes the maximum lateral load absorption and damping. It can be said that one of the factors affecting the capacity curve of the structure are the panel geometry and its related frame having a stiffener in width.

The capacity curves in Figures 9 to 12 indicate that Brace-3 or Convergent inverted V-bracing is the best bracing system in this study because this system has a better behavior of energy absorption than other bracing systems and it shows the high capacity of energy damping in this system. As subarea of the diagram of capacity curve of this bracing system is more than the other bracing systems, it can tolerate more deformation before collapsing. As a result, this kind of bracing system controls displacements due to lateral loads with a more suitable stiffness than other bracing systems.

Figure 9 curve of capacity designated that convergent inverted V-bracing system with panel –B has more base

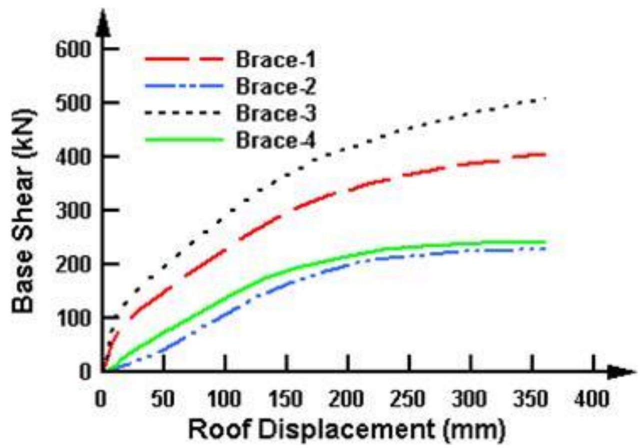


Figure 10. Capacity curve of 4-story frame braced with different bracing types.

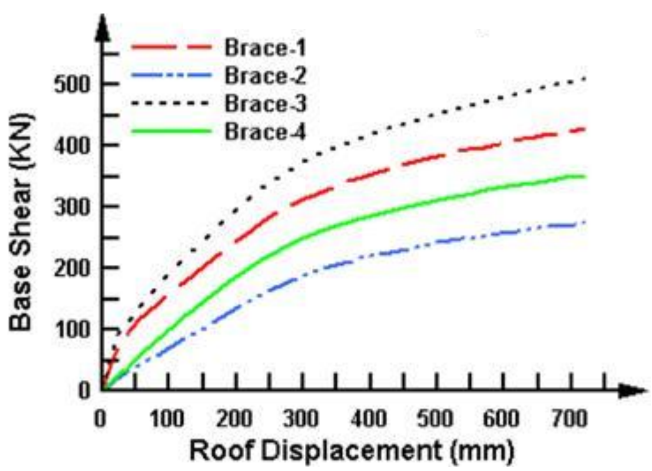


Figure 11. Capacity curve of 8-story frame braced with different bracing types.

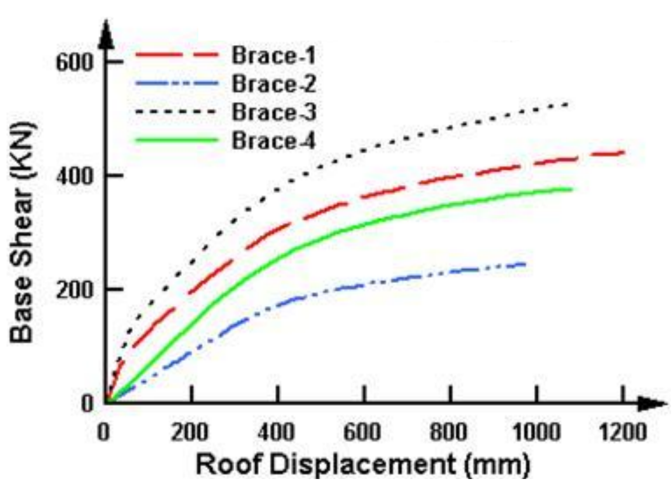


Figure 12. Capacity curve of 12-story frame braced with different bracing types.

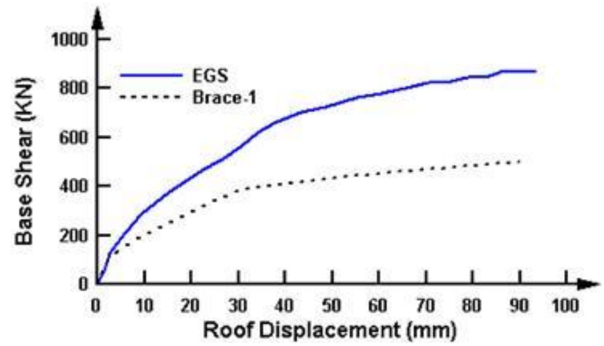


Figure 13. Capacity curve of EGS and aluminum panel for brace-3 (1-story frame).

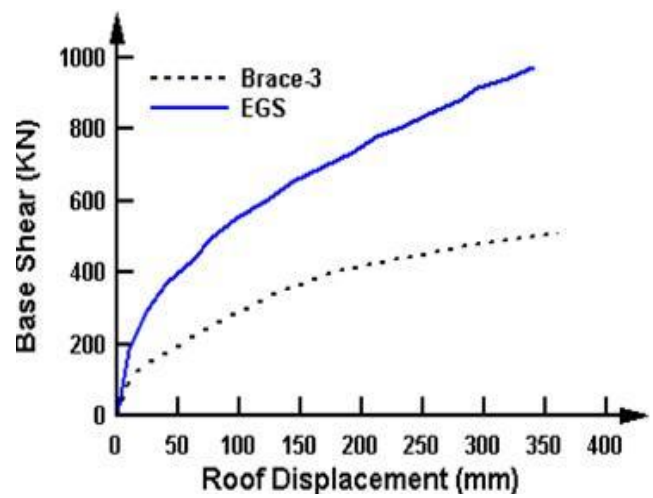


Figure 14. Capacity curve of EGS and aluminum panel for brace-3 (4-stories frame).

shear than other bracing systems and divergent V-bracing system with panel -A has less base shear than other bracing system and as the number of stories in Figures 13 to 16 increases, this procedure is valid in 4, 8 and 12-story structures, respectively. This investigation indicated that because aluminum has a lower yield stress and yields faster, system collapsing or local buckling begins with yielding of aluminum panel. Contrarily, it does not mean that the system's instability prohibits the whole system from collapse. Using aluminum is preferred to EGS. Also, it was designated that using aluminum panel decreases the base shear in all studied samples and controls displacement due to lateral loads. In Figures 13 to 16, the capacity curve of aluminum is half of that of EGS. Therefore, using aluminum decreases the base shear. If the capacity curve of the structure is expressed appropriately, then it can make a more economical design. So, using this system is recommended for short-order and mid-order structures because of relatively high energy absorption and ductility that makes more

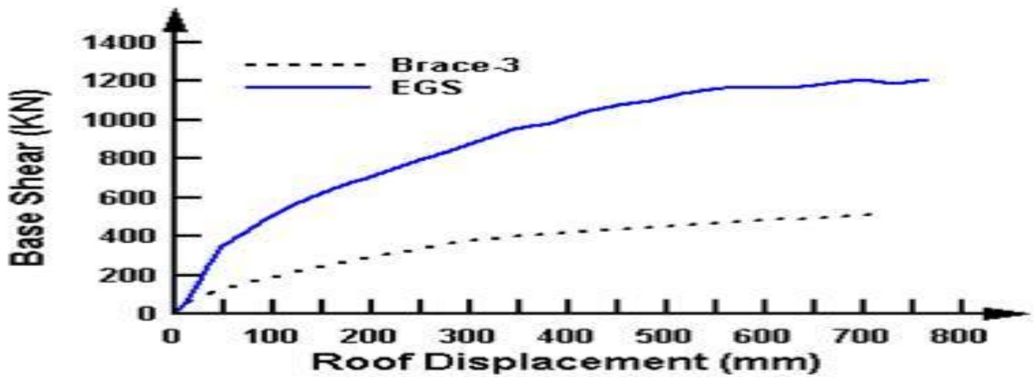


Figure 15. Capacity curve of EGS and aluminum panel for brace-3 (8-stories frame).

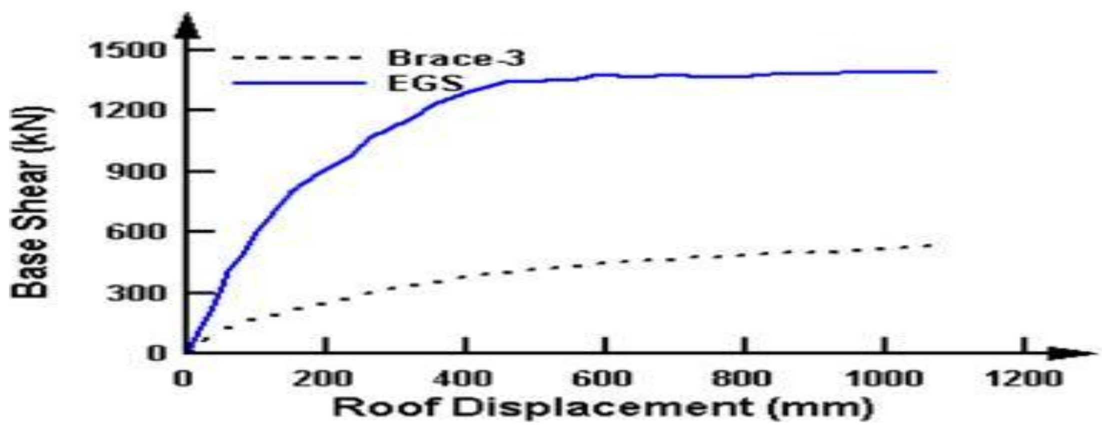


Figure 16. Capacity curve of EGS and aluminum panel for brace-3 (12-stories frame).

deformation before collapsing. This system can be used for strengthening the short-order and mid-order steel structures but it is not suitable for long-order structures, because the capacity curve of structures having aluminum panel was very different from structures having EGS and it was not a suitable system for absorbing the energy of lateral loads and it did not have a good capacity of energy damping for high-order structures.

Conclusions

The results showed that using aluminum panel as an energy dissipation system in steel braced frames had shown significant energy dissipation and ductility for the whole structural system. Using aluminum panel in all models decreased base shear of the structure significantly. The rectangular panel B had a better behavior in earthquake energy dissipation compared with the square panel A. One of the important parameters affecting the results was the panel geometry. Also, applying eccentric inverted V-bracing or brace-3 showed a better performance against lateral displacement than other investigated bracing systems. Using Brace-3 with rectangular panel is recommended for strengthening steel structures for low-rise and mid-rise structures. Also, it was indicated that using aluminum panel as a dissipator for high-rise structures was not suitable.

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