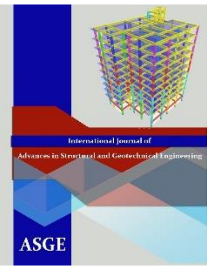

International Journal of Advances in Structural and Geotechnical Engineering

https://asge.journals.ekb.eg/

Print ISSN 2785-9509 *Online ISSN 2812-5142*

Special Issue for ICASGE'19

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ASGE Vol. 04 (04), pp. 1-14, 2020

International Conference on Advances in Structural and Geotechnical Engineering

ICASGE'19
25-28March 2019, Hurghada, Egypt

CYCLIC PERFORMANCE OF VERTICAL SHEAR LINKS MADE OF DIFFERENT METALLIC ALLOYS

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ABSTRACT

Use of vertical shear links (VSLs) imposed in eccentrically braced frames to resist earthquake ground motions has been shown to exhibit excellent seismic performance. The main reason of that is its capability of dissipating seismic energy while keeping the whole structure in the elastic stage, i.e. it acts as a ductile fuse. The objective of this paper is to compare the results of a finite element parametric study of VSLs made of different metallic alloys such as steel, stainless steel, copper and magnesium having different cross sections, and different arrangement of web stiffeners. The parametric study involves modelling of 22 specimens using ANSYS Workbench subjected to cyclic loading. Results of the finite element analysis represented by the hysteresis loop of each specimen are compared to each other in order to determine the most appropriate and sufficient material of fabrication which leads to maximum seismic energy dissipation. Also, the effect of utilizing different cross sections with different width to depth ratios along with different arrangements of web stiffeners have been investigated.

Keywords: vertical shear links, eccentrically braced frames, energy dissipation, hysteresis loop, cyclic loading.

INTRODUCTION

A current area of interest in structural engineering is the search for better ways to enhance the seismic protection of structures. This paper discusses a study of VSLs implemented in eccentrically braced frames for lateral resistance. Eccentrically braced frames are those in which the bracing joins at a work pointdistances form the end points of other framing members forming a portion called VSL which is one of the passive energy dissipation systems that is installed between the node of the two chevron braces and the lower flange of the upper beam. The primary function of the VSL is to provide a weak segment in the frame which grant plastic deformation capacity and dissipate the seismic energy. It is identical to a short beam which is joined to the eccentric braces and dissipates seismic energy by yielding [1]. In fact, VSL perform like a ductile fuse which dissipates the seismic energy,and protects the main structural elements, such as beams, columns and bracing from damage.

Shear links may be fabricated vertically or horizontally as shown in Fig. 1. However, generally speaking, the advantages of vertically placed links compared to horizontally ones, are the simplicity of replacing the shear links after occurrence of the earthquake, and the possibility for its application in seismic rehabilitation of the existing buildings due to its low cost and easy construction [2-4].

(Zahari and Bruneau) and (Bruneau and Sarraf) investigated the use of VSLs for rehabilitation of existing bridges. The results of their laboratory experiment showed an increase in ductility of the system and maintaining its other components in the elastic range. Hysteretic loops obtained from their researches shows a stable behavior for the system under earthquake ground motions [5-6].

Detailed numerical studies have been conducted by Ghobarah and Abou Elfath to rehabilitate reinforced concrete structures using steel eccentric bracing.The results of their investigation proved the obvious effect of such bracing as compared to other systems [7].

The idea of shear links as a general ductile element that can be replaced after damage, has developed further in later work by (Dusicka et al.) [8]. Also, Ohsaki and Nakajima presented a method for optimizing the locations and thicknesses of the stiffeners of the link member [9].

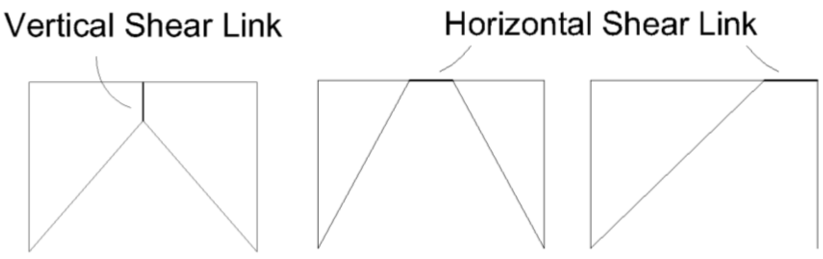
(Kuşyılmaz and Topkaya) conducted a parametric study adopting the computer program Fedeas Lab, and reported that the design overstrength of EBFs was found to increase mainly by the link length to bay width ratio increment [10].

Analytical dynamic analysis of retrofitted reinforced concrete frames has been performed by Al-Dawik and Armouti. It showed that adding new structural elements such as eccentric bracing proves to be effective in enhancing seismic performance and reducing cost compared to column jacketing [11].

(Baradaran et al.) conducted both analytical, and experimental studies to assess the cyclic performance of VSLs. The study showed that before buckling, lack of stiffeners had no significant effect on the behavior of the sample, but after that, structures' strength decreased very quickly. It was also reported that increasing the VSL length from 20 to 30 centimeters had no significant impact [1].

Based on experiments, and numerical modelling, (Vetr et al.) concluded that no lateral bracing e. g. stiffener is needed at the lower end of the VSL. Lateral bracing at the middle is sufficient. It was also found that ultimate strength of VSL reaches more than 202 times of nominal shear yielding [12].

(Caprili et al.) presented the results of a wide experimental test campaign executed on EBF real scale one storey/one bay frames. A simple model has been developed and calibrated using the results of the experimental tests. The model can be employed for the representation of EBF multi-story buildings without requiring a strong computational effort [13].



(a) **(b)**

Fig. 1: Different positions of shear link, (a) VSL, (b) midspan and edge shear link

Properly designed, VSLs can dissipate seismic energy, provide high ductility, and maintain the other structural elements elastic. Length of the link is an important factor in the design of VSL. Weaker performance of long link beams compared with short ones has been proven in numerous experiments [14]. By writing down the equilibrium equation of the VSL assuming that the values of shear force and bending moment in the link reach $1.5V_P$ and $1.2M_P$, respectively, where M_P and V_P are the plastic moment, and plastic shear force, respectively,the VSL length denoted by e would be obtained by Eq. 1, which was first proposed by (Roeder and Popov) and (Ricles and Popov) [2,4].

$$e \leq \frac{2 \times 1.2 M_P}{1.5 V_P} = 1.6 \frac{M_P}{V_P} \tag{1}$$

Several studies investigated different formulas to determine the link length to meet shear behavior, and proposed equations to obtain shorter links in order to make sure that the shear failure occurs before the bending failure [14-17]. However, it is worth mentioning that regulations such as AISC Seismic Provisions, and Eurocode are still adopting Eq. 1,and have limited the length to that value [18-19].

Rotation angle is another important factor in the design of VSLs. For link beams shorter than the value of (1), rotation angle of the VSL is limited to 0.08 [18-19].

Web stiffeners of the VSL enhances the ability to dissipate seismic energy in the VSL by delaying the web shear buckling and it slows down the deterioration of the load bearing capability of the VSL [19]. According to standards, these stiffeners shall have a thickness not less than the larger of ($0.75t_w$ or 10 mm), where $t_w$is the VSL web thickness.For VSLs shorter than Eq. 1, the spacing of the stiffeners shall not exceed ($30t_w$-d/5) [18-19].

The basic configuration of EBFs equipped with VSLs is the usage of one VSL. On the contrary, (Shayanfar et al.) studied using double VSLs, it was concluded that no elastic instability (buckling) occurred. Hysteresis behavior of double VSLs was also stable and bulky which is the sign of their proper seismic behavior [21].Sabouri-Ghomi and Saadati presented a new configuration of VSLs imposed in EBFs consisting of two VSLs connected together using horizontal link. Based on experimental tests and numerical modelling, it was elicited that the elastic and hardening regions of the hysteresis loops can be predicted by finite element modelling [22].

VSLs are in common made of steel, but,Shinab and Takahashifocused their attention to the use of steel of low yielding tensile strength in VSLs. They made use of sections with low strength steel web and high strength steel flanges. The results showed more energy dissipation capacity [23].Aluminum VSLs were developed by Rai and Wallace for earthquake-resistant structures.It exhibited excellent stiffness and energy dissipation capacity over a wide range of strains [24]. Sahoo and Rai concentrated their researches on strengthen reinforced concrete frames with Aluminum VSLs. It was observed that strengthened frames exhibited enhanced stiffness and energy dissipation potential compared to bare frames [25]. (Rai et al.) conducted shake table study of two frames of which one is equipped with Aluminum VSL. These tests helped validate the design methodology for Aluminum VSLs [26].

To improve the seismic behavior of EBFs, (Daryan et al) presented VSLs made of easy-going steel. The results demonstrated that opposing to VSLs made of construction steel no shear buckling occurs in VSLs made of easy-going steel, and the energy dissipation and ductility are improved considerably. Consequently, frames with VSLs made of easy-going steel showed better performance, energy dissipation, and better seismic behavior [27].

FINITE ELEMENT MODELLING

Modelling and Analysis of VSLs are performed using ANSYS Workbench 19.1 Academic. Solid elements were used for the mesh of VSLs. Different metallic alloys such as Steel, Stainless Steel, Copper and Magnesium have been adopted. Properties of the proposed alloys are shown in Table 1. These properties are already included in ANSYS Workbench material library, so there is no significant need to get any property from external sources or materials databases.

Plastic hardening was defined using bilinear kinematic hardening rule in order to properly capture the response of VSLs subjected to cyclic loading.

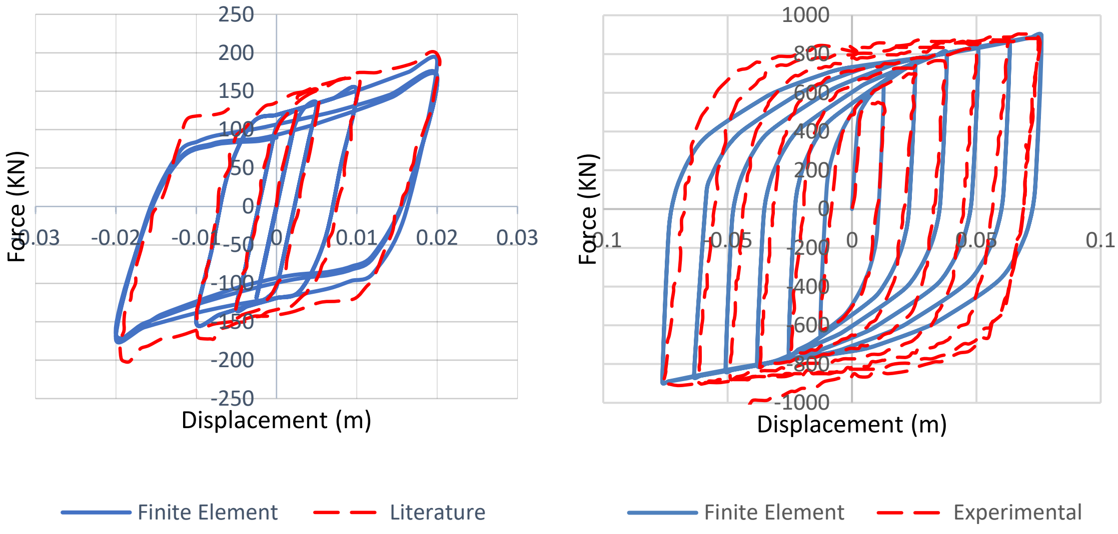
As will be shown later, there is no urgent need to model the whole EBF. Modelling of the VSL only is sufficient to obtain the hysteretic loops of the VSL. Boundary conditions applied to the VSL were fixed support at one end, and cyclic loading protocol was enforced to the other side in a certain direction, while restraining the remaining degrees of freedom.

Table 1: List of materials properties

Material	Alloy	Yield Strength (MPa)	Young's Modulus (MPa)	Tangent Modulus (MPa)
Steel	EN 1.0434 +U	250	200,000	1450
Stainless Steel	AISI 304L	210	193,000	1800
Copper	C19100	280	110,000	1150
Magnesium	ZK61A	193	45,000	920

VERIFICATION STUDY

Studies conducted on VSLs by Baradaran et al. (2015) and Hjelmstad (1983) [1,28] are considered for verification of calibrated material properties and finite element modelling approach. Specimens 3 and 4 from the prementioned studies, respectively, are analyzed as a proof of confidence in this paper. Although the plastic hardening of the first specimen was defined using bilinear kinematic hardening rule, the second specimen post yield behavior was defined as multilinear kinematic hardening rule in order to obtain a hysteresis loop consistent with the one obtained from experimental test.The hysteresis curves for the chosen samples obtained after the analysis is plotted and compared with the results of literature. Evident in Fig. 2, the results almost agree with each other from the point of energy dissipation capacities and ultimate strengths. It is also obvious that modelling of the VSL only is sufficient to capture its hysteretic behavior and there is no need to model the whole frame.



(a) (b)

Fig. 2: Verification study hysteresis loops, (a) Baradaran, (b) Hjelmstad

DESCRIBTION OF STUDIED SAMPLES

In order to perform numerical analysis on VSLs, first, a MATLAB code was written based on AISC and Eurocode requirements [18-19] in order to determine the VSL length, number of stiffeners, and the spacing between them. Since, AISC is only concerned with steel structures, and Eurocode is concerned with structures made of concrete, steel, composite concrete and steel, timber, masonry or aluminum, it is clear that there exist no specific formulas to design VSLs fabricated from otherwise metals. This paved the way for designing only steel VSLs, and on the other hand, distinctive metallic VSLs are assumed to have the same dimensions as steel ones.

Table 2: Summary of design parameters of the specimens

Specimen No.	Material	Section	VSL Length		Stiffeners	
			e (mm)	$e/(M_P/V_P)$	Number	Spacing (mm)
1	Steel	IPE160	300	1.42	0	-------
2					2	100
3		IPE180	300	1.26	0	-------
4					2	100
5		HEB160	300	0.66	0	-------
6					2	100
7		HEB180	300	0.58	0	-------
8					1	150
9			500	0.97	2	166.66
10			700	1.36	3	175
11	Stainless Steel	IPE160	300	1.42	2	100
12		IPE180	300	1.26	2	100
13		HEB160	300	0.66	2	100
14		HEB180	300	0.58	1	150
15	Copper	IPE160	300	1.42	2	100
16		IPE180	300	1.26	2	100
17		HEB160	300	0.66	2	100
18		HEB180	300	0.58	1	150
19	Magnesium	IPE160	300	1.42	2	100
20		IPE180	300	1.26	2	100
21		HEB160	300	0.66	2	100
22		HEB180	300	0.58	1	150

There exist several deformation-controlled loading protocols which are often recommended by regulations and standards. In this study, a displacement control method is used to apply the cyclic loading protocol shown in Fig. 3, which was proposed by (Shayanfar et al.) [21].

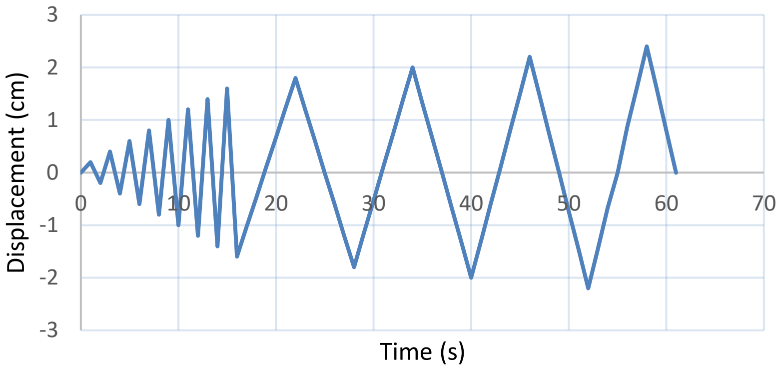


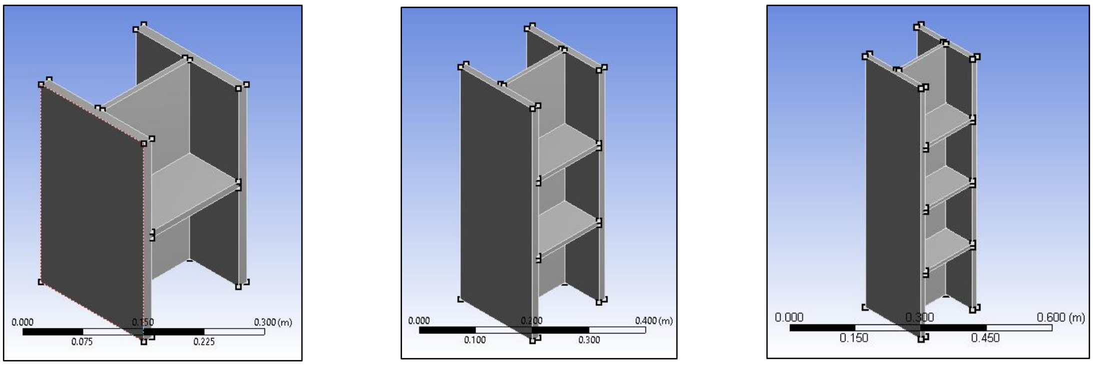
Fig. 3: Cyclic loading protocol applied to the VSLs

RESULTS AND DISCUSSION

In order to assess the effect of VSL length on energy dissipation, the finite element models of specimens 8,9, and 10 (Fig. 4) have been analyzed. Fig. 5 shows the hysteresis curves of these specimens compared to each other. Despite the fact that the VSLs lengths are within the range allowed by Eq. 1, it is obvious that increasing the VSL length from 300 to 500 and 700 mm has a negative effect on the hysteresis loop, thus, decreasing the amount of dissipated energy. Therefore, all other specimens' lengths have been limited to 300 mm in order to obtain the optimum hysteretic energy dissipation.

Concerning the impact of stiffeners on the load capacity of VSL, Fig. 6 shows the hysteresis curves of first eight specimens. It can be noticed that the existence of stiffeners slightly increases the load capacity of the VSL, especially after the buckling begins to propagate, which is consistent with findings of the previous studies.

Based on the data forming the hysteresis curves, the loops have been plotted and integrated using OriginPro 2019 in order to get the amount of hysteretic energy of each cycle of loading. Fig. 7 shows a comparison of the amount of hysteretic energy dissipated in each cycle for the first eight specimens. According to the hysteretic energy results, specimen 8 was the one which dissipated more energy.



(a) **(b)** **(c)**

Fig. 4: Finite element model, (a) specimen 8, (b) specimen 9, (c) specimen 10

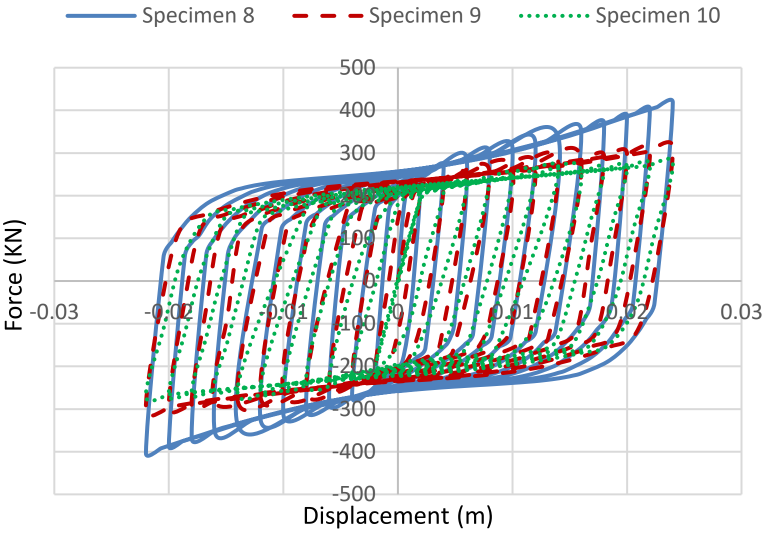
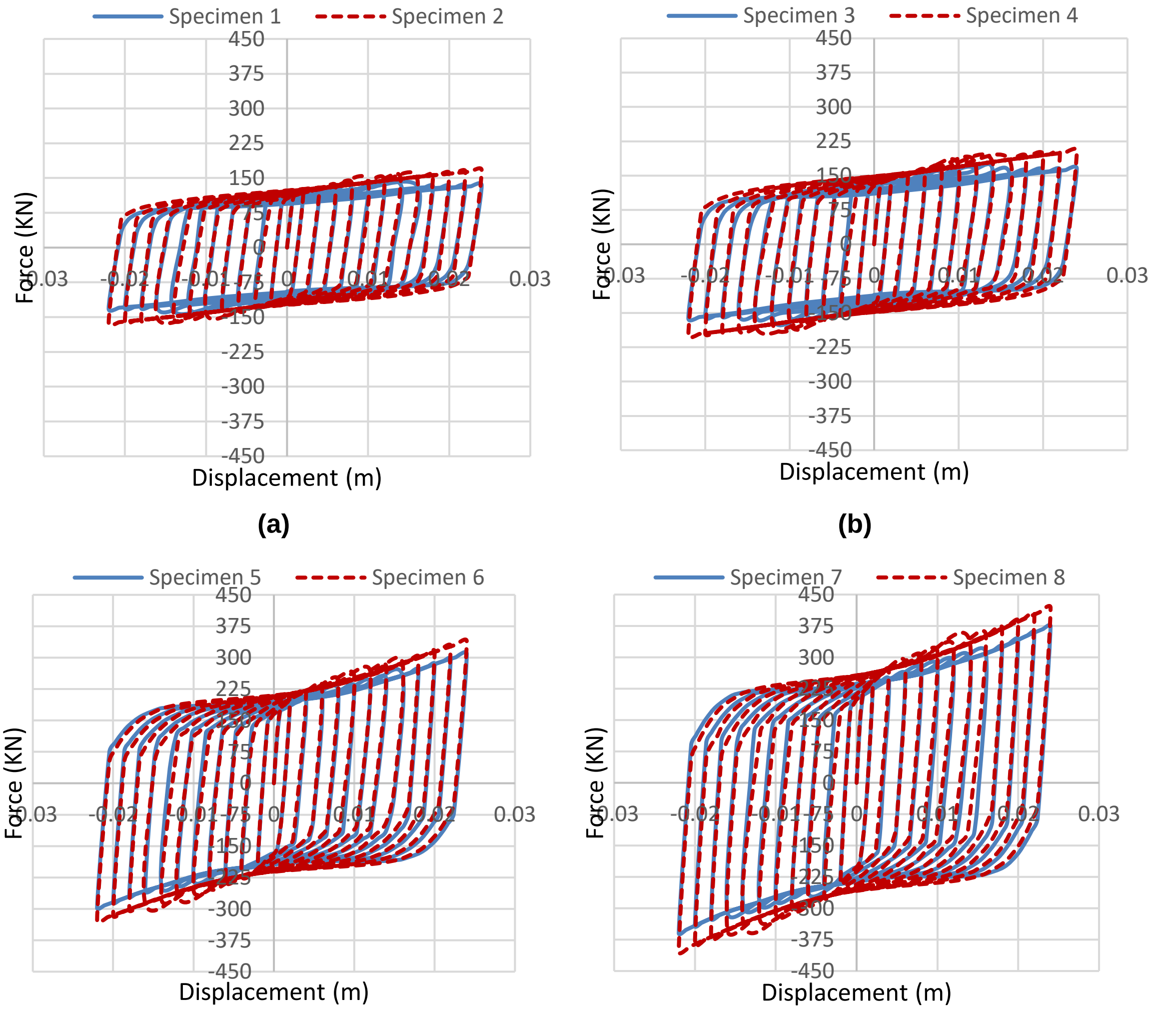


Fig. 5: Force-displacement hysteresis curve of specimens 8, 9, and 10



(a) **(b)**

(c) **(d)**

Fig. 6: Hysteresis curves of the first eight specimens, (a) specimens 1 and 2, (b) specimens 3 and 4, (c) specimens 5 and 6, (d) specimens 7 and 8

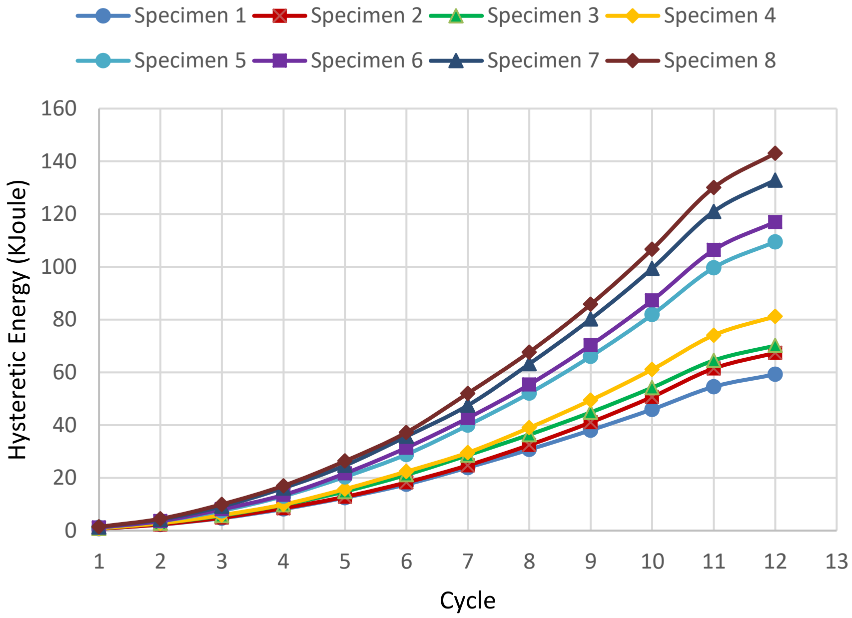


Fig. 7: Hysteretic energy dissipated through each cycle for first eight specimens

In the upcoming figures, hysteresis diagrams of the remaining specimens made of other metallic alloys are drawn. As it is depicted in the curves, all of the specimens have shown stable behavior.

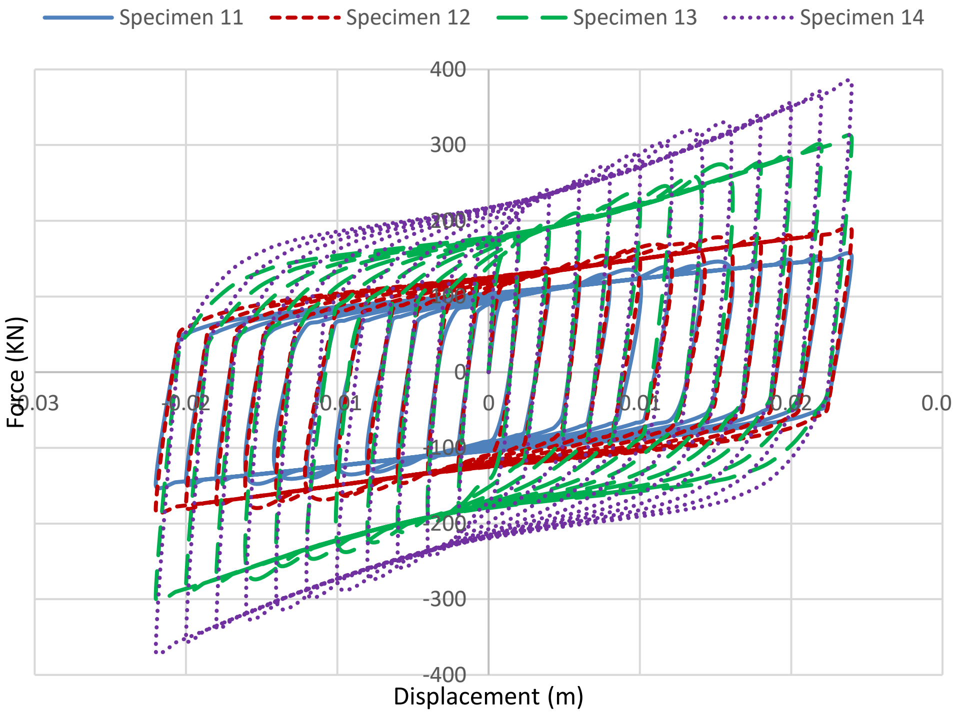


Fig. 8: Hysteretic curves of stainless-steel specimens

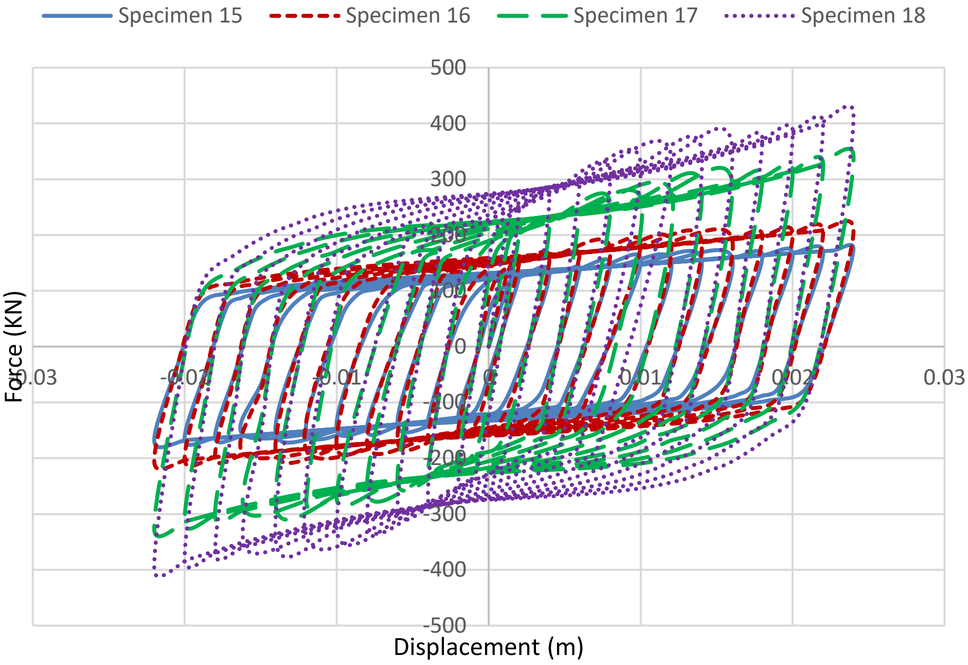


Fig. 9: Hysteretic curves of copper specimens

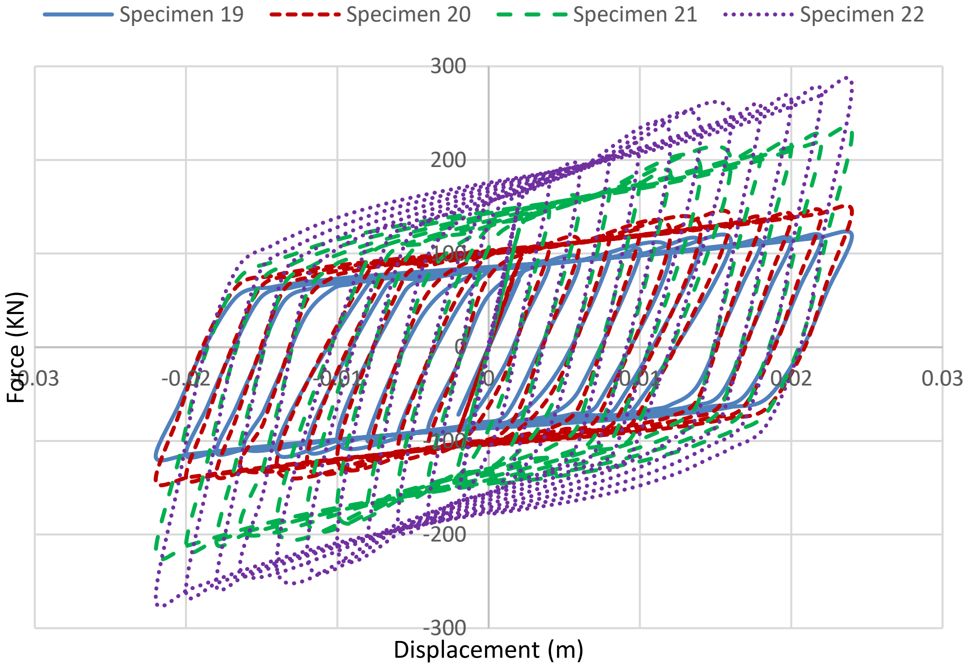
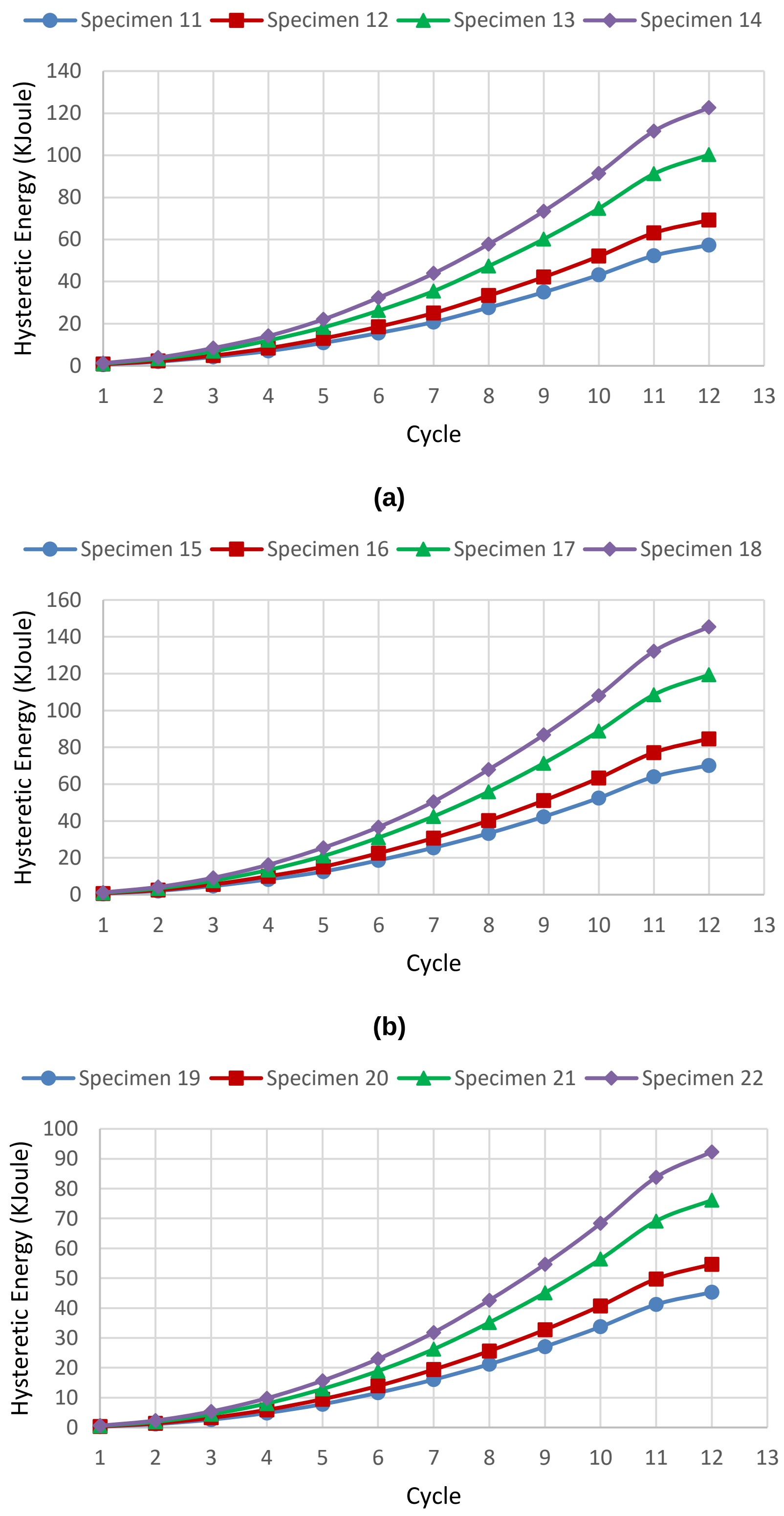


Fig. 10: Hysteretic curves of magnesium specimens

Comparison of the amount of hysteretic energy dissipated is indicated in Fig. 11. It is obvious that the fourth specimen of each group exhibit better cyclic performance rather than the other specimens fabricated from the same material. This is due to the fact that the fourth specimens are HEB sections which differ from IPE sections in the thickness of the flanges and webs, and the breadth of the section, in spite of having the same depth.



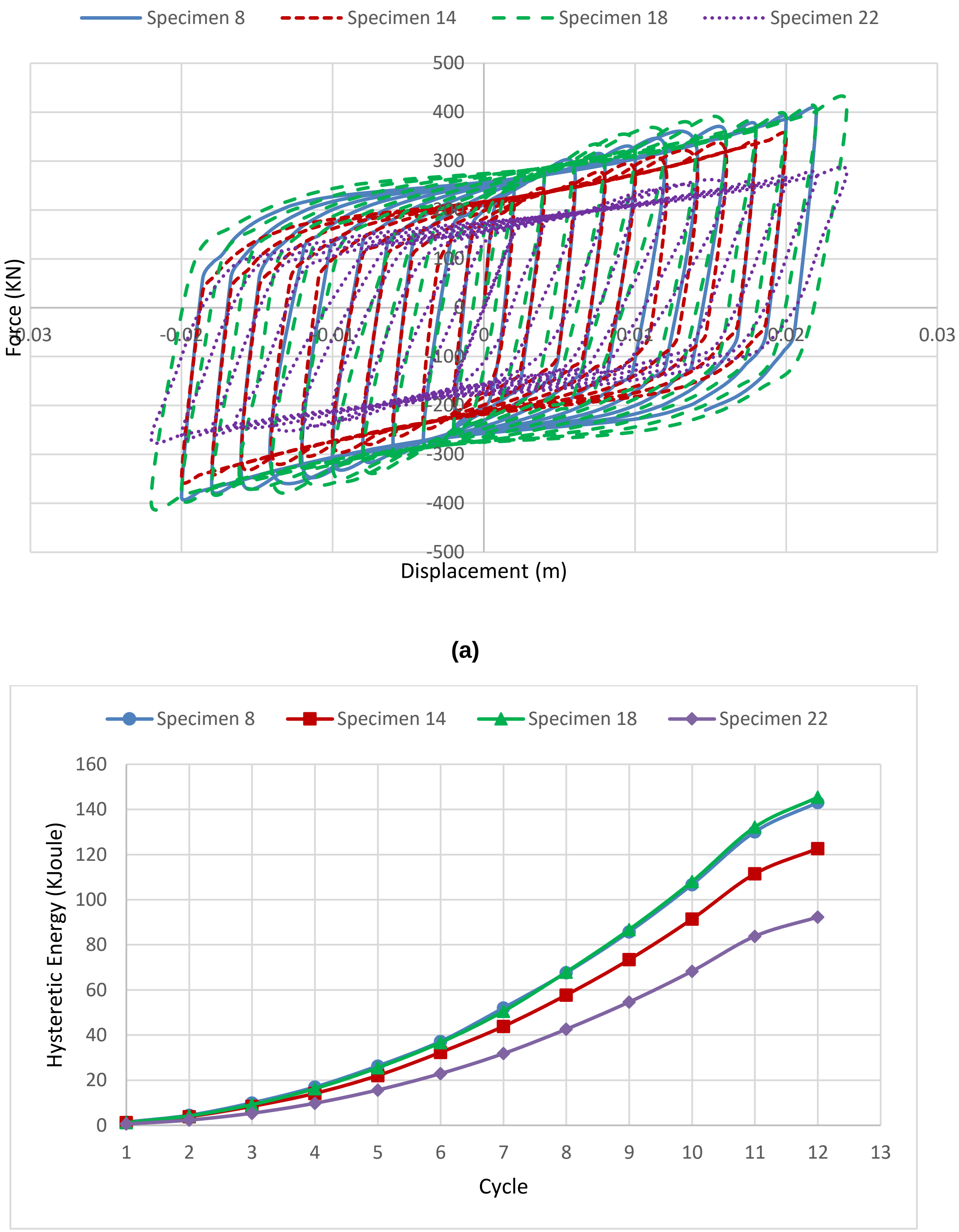
(a)

(b)

(c)

Fig. 11: Hysteretic energy dissipated through each cycle, (a) stainless-steel specimens, (b) copper specimens, (c) magnesium specimens

Hysteresis curves of the best specimen of each material group are combined together in Fig. 12(a) for the ease of comparison. From the general shape of the loop, it can be spotted that copper VSL exhibit the best cyclic performance of all specimens. It is then followed by steel, stainless-steel, and magnesium, respectively. In order to well judge the hysteresis curves, the amount of hysteretic energy dissipated by each specimen is shown in Fig. 12(b). There is no significant difference between the energy dissipation of copper and steel to the extent that the curves representing the amount of energy dissipated by each of them are nearly identical. On the other hand, magnesium specimen performs poorly compared to the other ones.



(a)

(b)

Fig. 12: Energy dissipation of the best specimen of each material group (a) hysteresis energy curves, (b) amount of energy dissipated through each cycle

Lastly, the bar chart shown in Fig. 13 well describes the variation of cumulative energy dissipated of the whole 22 specimens studied in this paper. It is worth mentioning that all specimens survived the applied cyclic loading protocol successfully without any failure observed according to equivalent Von-mises stress plot shown in Fig. 14 for one of the specimens, particularly specimen 1.

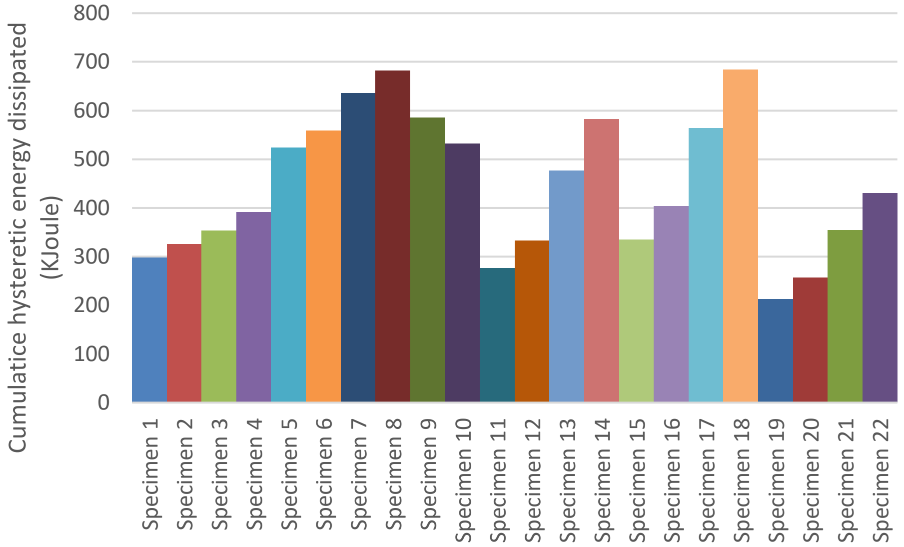


Fig. 13: Cumulative hysteretic energy dissipated of each specimen

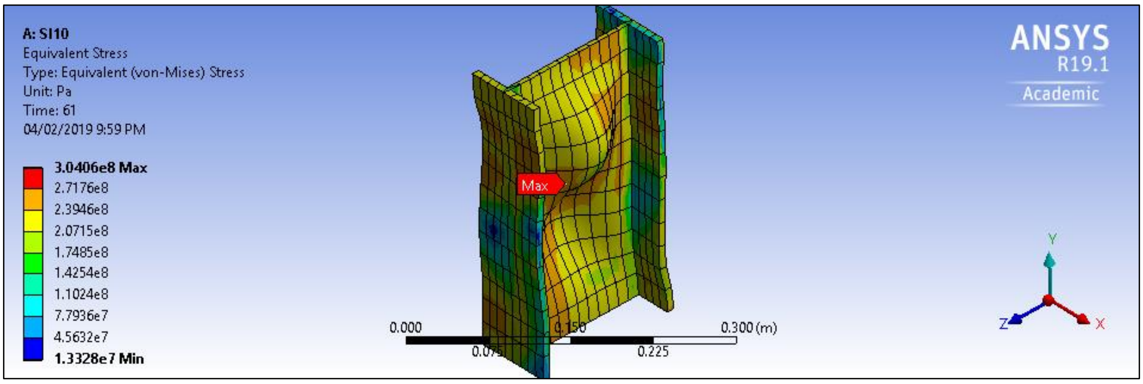


Fig. 14: Equivalent Von-mises stress for specimen 1

CONCLUSIONS

The aim of this study was to compare different design parameters of VSLs especially the material of construction. The following results can be concluded:

- VSLs can be modelled using finite element analysis software, such as ANSYS Workbench without the need to model the whole EBF.
- Although most regulations and standards propose the formula described in Eq. 1 to determine the VSL length, there exist an urgent need to modify that equation, as it is found that shortening the VSL length than that value would lead to more energy dissipation.
- Application of stiffeners on the specimens increase stiffness and strength degradation, particularly post buckling.
- HEB sections are preferred over IPE ones as they dissipate more energy. The main reason of this is their larger dimensions, like breadth, web and flange thickness.

- Increasing the depth of the section which is parallel to the applied cyclic loading boosts up the amount of energy dissipated.
- Copper and steel VSLs behavior are nearly identical with slightly advantage of copper over steel.
- Although stainless steel VSLs performance is weaker than copper and steel, it is still acceptable, and it may be used in low seismic regions after further research.
- Magnesium VSLs are very weak and not recommended to be used under any circumstances.

REFERENCES

1. Baradaran, M. R., Hamzezarghani, F., Ghiri, M. R., & Mirsanjari, Z. (2015). The Effect of Vertical Shear-Link in Improving the Seismic Performance of Structures with Eccentrically Bracing Systems. *World Academy of Science, Engineering and Technology, International Journal of Civil, Environmental, Structural, Construction and ArchitecturalEngineering*, *9*(8), 1078-1082.
2. Roeder, C. W., & Popov, E. P. (1977). Inelastic behavior of eccentrically braced steel frames under cyclic loadings. *NASA STI/Recon Technical Report N*, *78*.
3. Kelly, J.M., and Naeim, F. (1999), “Design of seismic isolated structures”, John Wiley & Sons, Inc., New York.
4. Ricles, J. M., & Popov, E. P. (1987). *Dynamic analysis of seismically resistant eccentrically braced frames*. University of California, Earthquake Engineering Research Center.
5. Zahrai, S. M., & Bruneau, M. (1999). Ductile end-diaphragms for seismic retrofit of slab-on-girder steel bridges. *Journal of structural engineering*, *125*(1), 71-80.
6. Bruneau, M., & Sarraf, M. (2000). Innovative Application of Ductile Systems in Seismic Retrofit of Deck-truss Bridges. In *12th World Conference on Earthquake Engineering*.
7. Ghobarah, A., & Elfath, H. A. (2001). Rehabilitation of a reinforced concrete frame using eccentric steel bracing. *Engineering structures*, *23*(7), 745-755.
8. Dusicka, P., Itani, A. M., & Buckle, I. G. (2009). Cyclic behavior of shear links of various grades of plate steel. *Journal of structural engineering*, *136*(4), 370-378
9. Ohsaki, M., & Nakajima, T. (2012). Optimization of link member of eccentrically braced frames for maximum energy dissipation. *Journal of Constructional Steel Research*, *75*, 38-44.
10. Kuşyılmaz, A., &Topkaya, C. (2013). Design overstrength of steel eccentrically braced frames. *International Journal of Steel Structures*, *13*(3), 529-545.
11. Al-Dwaik, M. M., & Armouti, N. S. (2013). Analytical case study of seismic performance of retrofit strategies for reinforced concrete frames: steel bracing with shear links versus column jacketing. *Jordan Journal of Civil Engineering*, *7*(1), 26-43.
12. Vetr, M. G., Ghamari, A., & Bouwkamp, J. (2017). Investigating the nonlinear behavior of Eccentrically Braced Frame with vertical shear links (V-EBF). *Journal of Building Engineering*, *10*, 47-59.
13. Caprili, S., Morelli, F., Mussini, N., & Salvatore, W. (2018). Experimental tests on real-scale EBF structures with horizontal and vertical links. *Data in brief*, *21*, 1246-1257.
14. Engelhardt, M. D., & Popov, E. P. (1992). Experimental performance of long links in eccentrically braced frames. *Journal of Structural Engineering*, *118*(11), 3067-3088.
15. Kasai, K., & Popov, E. P. (1986). General behavior of WF steel shear link beams. *Journal of Structural Engineering*, *112*(2), 362-382.
16. Vetr, M. G. (1998). *Seismic behavior, analysis and design of eccentrically braced frames with vertical shear links* (Doctoral dissertation, Ph. D. Thesis. University Tech. Darmstadt W. Germany. http://www. tudarmstadt. de).
17. Shayanfar, M. A., Barkhordari, M. A., & Rezaeian, A. R. (2012). Experimental study of cyclic behavior of composite vertical shear link in eccentrically braced frames. *Steel and Composite Structures*, *12*(1), 13-29.
18. AISC (2016), “Seismic provision for structural steel building”, American Institute of Steel Structure.
19. EUROCODE 8

20. Mazzolani, F., Georgescu, D., & Astaneh-Asl, A. (1995). 26 Remarks on behaviour of concentrically and eccentrically braced steel frames. *Behaviour of Steel Structures in Seismic Areas*, 310.
21. Shayanfar, M. R., Rezaeian, A. R., & Taherkhani, S. (2008). Assessment of the seismic behavior of eccentrically braced frame with double vertical link (DV-EBF). *The*, *14*, 12-17.
22. Sabouri-Ghomi, S., & Saadati, B. (2016). Numerical modeling of links behavior in eccentric bracings with dual vertical links. *Journal of Numerical Methods in Civil Engineering*, *1*(1), 14-20.
23. Shinabe, Y., & Takahashi, Y. (1995). The present state of eccentric brace design in Japan. In *Proceedings of the 4th Pacific Structural Steel Conference, Singapore* (pp. 813-820).
24. Rai, D. C., & Wallace, B. J. (1998). Aluminium shear-links for enhanced seismic resistance. *Earthquake engineering & structural dynamics*, *27*(4), 315-342.
25. Sahoo, D. R., & Rai, D. C. (2010). Seismic strengthening of non-ductile reinforced concrete frames using aluminum shear links as energy-dissipation devices. *Engineering Structures*, *32*(11), 3548-3557.
26. Rai, D. C., Annam, P. K., & Pradhan, T. (2013). Seismic testing of steel braced frames with aluminum shear yielding dampers. *Engineering Structures*, *46*, 737-747.
27. Daryan, A. S., Bahrampoor, H., Ziaei, M., Golafshar, A., & Assareh, M. A. (2008). Seismic behavior of vertical shear links made of easy-going steel. *American Journal of Engineering and Applied Sciences*, *1*(4).
28. Hjelmstad, K. D., & Popov, E. P. (1983). Cyclic behavior and design of link beams. *Journal of Structural Engineering*, *109*(10), 2387-2403.