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# Investigating Effect of Steel Plate Shear Wall Opening Change on Amount of Equivalent Viscous Damping

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**ABSTRACT**

One of the new methods to create peripheral resistance of a structural system against loads of wind and earthquake is using Steel Plate Shear Walls. In new designing methods, considering non-linear behavior and amount of energy absorption of desired structural system is an important issue. In this case investigating equivalent viscous damping for this kind of structural system is of great importance. In this research, it has been tried to investigate, based on a comparative method, the effect of change in geometry of Steel Plate Shear Wall in value of equivalent viscous damping. AISC 20 design guide for Steel Plate Shear Wall has been used to work out dimensions. To do a comparative study of equivalent viscous damping, four single Steel Plate Shear Walls without opening and stiffener modeled in ABAQUS software. Then, models went under cycle analysis and using existing method, value of equivalent viscous damping was worked out. Finally, value of damping has been compared for four walls.



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## INTRODUCTION

A system of Steel Plate Shear Wall (SPSW) can be used as a lateral load system against wind and earthquake forces. Usually, each Steel Plate Shear Wall consist of a set of steel panels each of which made of a steel plate and some beams and columns around it that can be regarded as a sheet beam system [1]. Steel plate can both have a stiffener or not. It can, also, either have an opening or some perforations. For sake of simplicity of modeling, in this research shear walls without stiffener of opening have been used.

Until 1980, designing shear walls has been based on prevention from shear buckling. In this regard, for wall panels, thick steel plates, which have stiffeners, have been used. In 1983, Thorburn changed the philosophy of wall design. Based on this method, which was later added to AISC regulation, instead of strong previous walls, walls with thin plates which do not have stiffener are used. In AISC regulations shear walls are designed based on capacity [2].

In 1973, Takahashi et al. [3] conducted some experiments and numerical analyses on shear walls with thin plates having stiffeners. Based on their research, shear wall without stiffener has S-shaped cycle diagram, but when stiffener is added to the wall, cycle diagram gets thick i.e. becomes spindle-shaped. In 1983, Thorburn et al. presented an analysis model for thin steel plate shear wall without stiffener called Stripe Model. Steel plate has been modeled as a series of diagonal stripes across both wall joints in the direction of stretch field. Angel of stretching bands is based on changing the shape of shear panel model which, in this model, is obtained based on minimum work principle [3].

In 1992, Roberts and Saburi Qomi studied behavior of this type of walls under quasi-static cyclic loading, doing experiments on steel shear plate walls without stiffener with different thicknesses and with circular openings or without it [4]. Rezai, in 1999, carried out an experiment on a four-storey model in scale of a quarter using shake tables. Rezai used a different stripe model in which angel of stripes are different from each other [5].

In 2009, Topkaya and Atasoy [6] obtained lateral stiffness of steel shear with two methods. One was based on deep beam theory and the other was a computer method based on comparing truss, and compared it with laboratory results. In 2012, Hosseinzadeh and Tehranizadeh [7] analyzed some finite element models of shear walls without openings and the ones with large openings (as window or door) and stiffener. In 2013, Alavi and

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Nateghi [8], using some experimental models and model of finite elements, investigated a new combination of diagonal stiffeners and central openings.

An appropriate method to describe capacity of structural damping energy dissipation is equivalent viscous [9]. This damping is obtained by equating amount of absorbed energy in one vibrational cycle of a structural system with an equivalent viscous system [10]. As mentioned above, comparative issue of energy dissipation and ratio of equivalent viscous damping in different states of wall crater has not been studied clearly. So, in this research by using some one-story STEEL PLATE SHEAR WALLs modeled with different craters in ABAQUS software, values of equivalent viscous damping has been determined and compared with each other. In steel panel no stiffener has been used, and, this panel does not have any openings.

*Equivalent viscous damping:*

Equivalent viscous damping is used to describe capacity of energy absorption in structures. In other words, it is an appropriate way to estimate amount of dissipated energy and one of key parameters for designing method based on displacement [9]. One common way of defining this damping is equating amount of dissipated energy in a vibrational cycle of a real system with system of equivalent viscous [10].

In the past, the method suggested by Jacobson (1930) was used to estimate equivalent damping. In this method, hysteretic model had to have full loops and system had to undergo harmonic (sinusoidal) excitation. In this case, damping was obtained through one of the following relations [5]:

$$\xi_{eq} = \frac{1}{4\pi}\frac{E_D}{E_{S_0}} = \frac{A_{loop}}{2\pi D_{max} F_{max}} \qquad (1)$$

In the relation above value of $E_D$ is absorbed energy inside full loop which corresponds complete level of a cycle ($A_{loop}$) and $E_{S0}$ is elastic strain energy corresponds force maximum ($F_{max}$) and displacement ($D_{max}$) obtained in a cycle of cyclic graph which have been shown on the following force-displacement figure (figure 1).

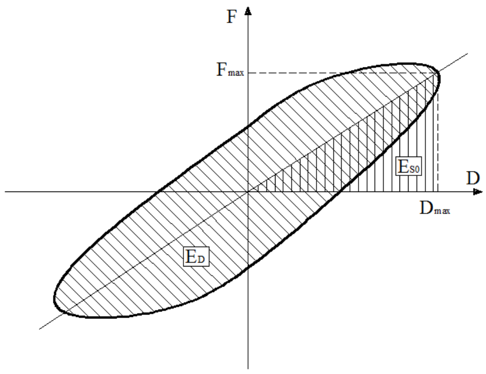


**Fig. 1:** Showing parameters needed to calculate equivalent viscous damping.

*Models studied:*

In this research, four one-storey models, with different length to width ratio, have been used without stiffener and opening. First, using guidelines of steel shear plate walls design AISC 20 [11], a steel plate shear wall was designed using LRFD method. Then, by changing wall crater, other needed models were created. Columns, as vertical boundary element (VBE) and beams as Horizontal boundary element (HBE), in addition to forces of structure weight, are designed to bear base plate's tensile strength. Beam-to-column connection has been considered rigid and dead and live loads applied on columns have been estimated to be 80 KN. To define a support, column footing is supposed to be rigid and upper wing of HBE element has been restrained due to existence of floor slab. Figure (2) shows a general model of selected system. In table (1) characteristics of used bar plates have been shown as VBE and HBE. In order to name walls, names SPSW-1 to SPSW-4 have been used, respectively and in table (2) characteristics of these walls have been presented:

**Table 1:** Characteristics of selected secondary sections for VBE and HBE members

| Member HBE(cm) | Member VBE(cm) | |
|---|---|---|
| 40 | 30 | H(external height) |
| 14 | 25 | B(wing width) |
| 1.0 | 1.8 | tf(wing thickness) |
| 0.5 | 1.0 | tw(base thickness) |

**Table 2:** Characteristics of selected walls.

| Height (m) | (m) | $t_{p\ (mm)}$ | HBE | VBE | |
|---|---|---|---|---|---|
| 3.3 | 3 | 1.5857 | As shown in table (1) | As shown in table (1) | SPSW-1 |
| 3.3 | 4 | 1.5857 | As shown in table (1) | As shown in table (1) | SPSW-2 |
| 3.3 | 5 | 1.5857 | As shown in table (1) | As shown in table (1) | SPSW-3 |
| 3.3 | 6 | 1.5857 | As shown in table (1) | As shown in table (1) | SPSW-4 |

In order for numerical modeling ABAQUS software and 4-node shell elements called S4R have been used. Mesh size was limited, by trial and error and balancing accuracy and velocity, to 100 mm. also, geometrical non-linear effect was noticed in analysis. Characteristics of used materials has been chosen according to Alavi and Nateghi [8]'s research.

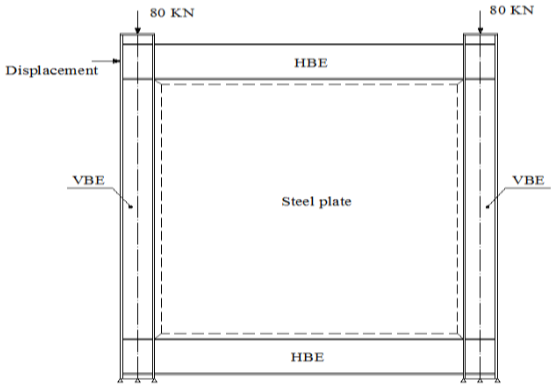


**Fig. 2:** General model of the wall used in this research.

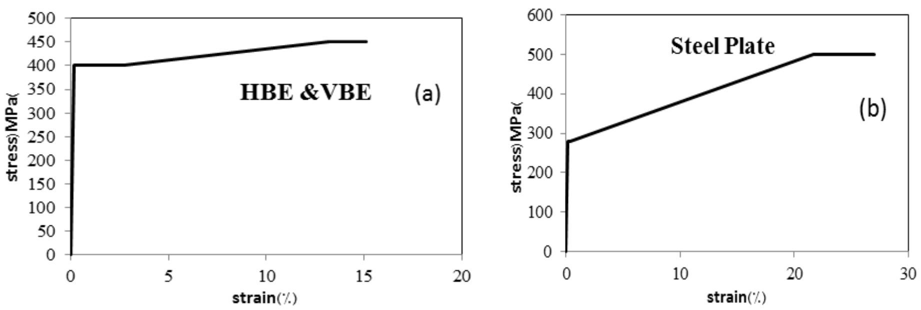


**Fig. 3:** Graph of characteristics of used materials. A) stress-strain diagram of profile HEB 160. B) stress-strain diagram of steel plate.

In figure (4), push-over diagram of five models used in this research has been drawn in one diagram. According to this figure, value of yield displacement for all four walls is about 20 mm and walls' drift equals 0.61 percent, and values of yield displacement force is, respectively, 870, 1020, 1100 and 1150 KN. According to figure (4), by reducing the opening, primary stiffness of system and values of extreme amount of force (plastic force) will decrease.

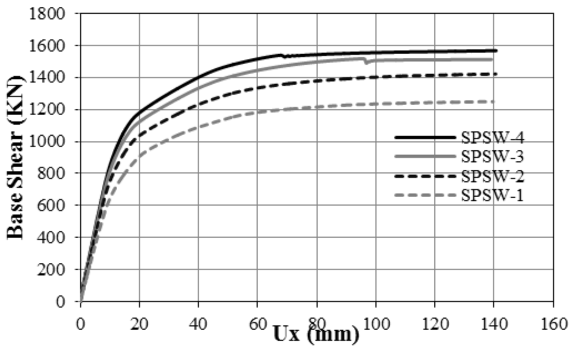


**Fig. 4:** Diagram of push-over analysis for four selected walls.

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*Cyclic loading:*

One of the purposes of push-over analysis is determining displacement and elastic force limit. This information is used to determine cyclic loading protocol based on ATC-24 [13]. According to this protocol, loading history includes gradual increase of displacement applied to structural system and a certain number of cyclic loading in each step of loading. In linear range, displacement of the first step of loading equals 1/3, and in second step of loading it equals 2/3 of estimated elastic displacement. Number of cycles in first two steps of loading has been 3. In later steps, number of cycles decreases to, first, 3 and, then, 2. Value of total displacement increase, in all of loading steps after yielding is $\delta_y$ . In figure (5), explained loading protocol has been shown. Vertical axis of this figure shows amount of displacement applied to intended structural system, and horizontal axis shows the number of cycles. Value of elastic displacement ($\delta_y$) is 20 which is almost equal for all four walls.

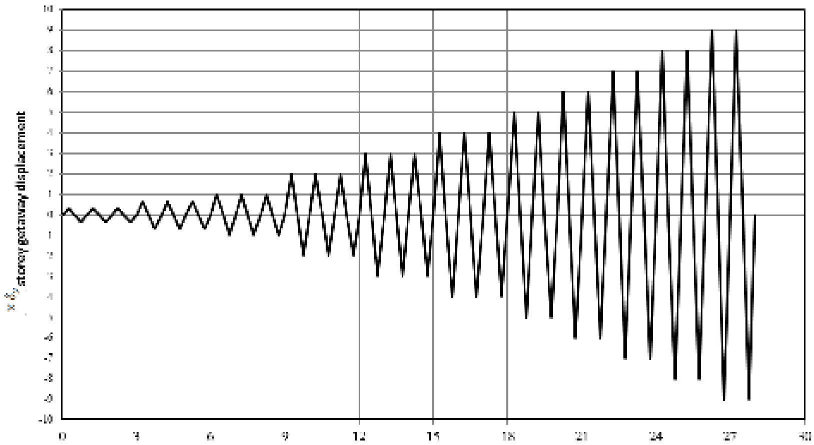
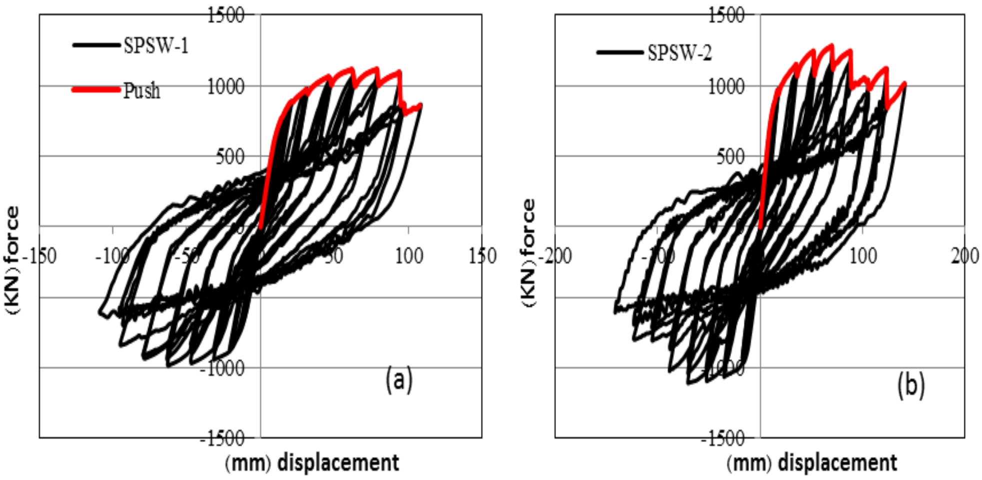


**Fig. 5**: loading history based on ATC-24

*Results of cyclic loading:*

After cyclic analysis, wall's base shear diagram can be drawn, like push-over diagram. In figure (6) cyclic diagram of these four walls has been shown. In these figures push amounts of each diagram have been obtained and in figure (7) they have been compared. In figure (7), process of diagram in the first part (for displacement less than 50 mm) is the same as push-over diagram. In displacements more than 50 mm a little confusion is observed in the diagram.



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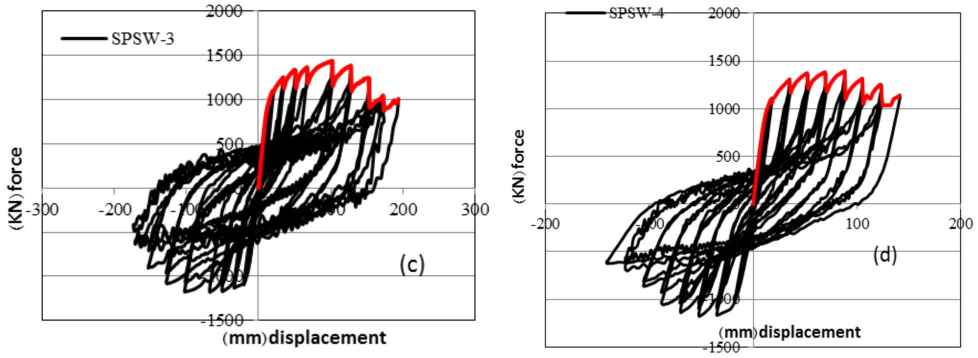


**Fig. 6:** Cyclic diagram for four shear walls. a- SPSW-1, b- SPSW-2, c- SPSW3, d- SPSW-4.

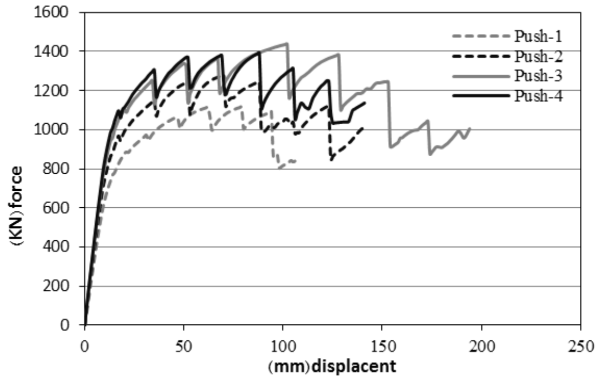


**Fig. 7:** comparison of cyclic analysis results of push diagram for four walls.

For further study, in figure (8), Von-Mises stress contour, and deformation occurred in STEEL PLATE SHEAR WALL system SPSW-1, when displacement of upper wing of upper beam is 8 cm (2.7 percent drift), is shown.

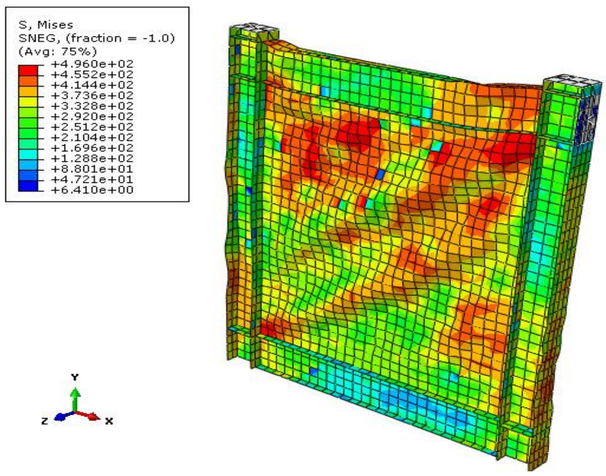


**Fig. 8:** Von-Mises stress contour with diagram of deformation of steel plate shear wall SPSW-1.

*Calculation of equivalent viscous damping:*

According to figure (6), loading cycles of walls is almost symmetrical. In this case, according to equation (1), values of equivalent viscous damping in each loading cycle are calculated. Figure (9) shows diagram of equivalent viscous damping in terms of formation coefficient obtained in each cycle for all four systems of shear walls. Values of equivalent viscous damping have been added to primary value of 0.05 (assumptive damping in elastic state). As a rough, by increasing number of loading cycles, value of damping will increase. To draw diagrams of figure (9), after the shear wall finishes a complete loading cycle, according to equation (1), values of $E_D$ and $E_{S_0}$ parameters were calculated. Then, value of equivalent viscous damping was calculated for this cycle. According to the fact that elastic displacement of system obtained by push-over, by dividing maximum existing displacement in this loading cycle to elastic displacement, value of deformability was calculated; then, diagram of equivalent viscous damping was drawn in terms of deformability.

In order to evaluate results better, two methods of fitting results of equivalent viscous damping, in terms of deformability coefficient for each wall system, was used and shown in figure (9). In first method equation $\xi = a\ln(\mu) + b$ (logarithmic fitting method), and in the second method, equation $\xi = c\mu^d$ (square method) were used. Values of coefficients a, b, c, d, and, also, correlation coefficients for these two methods have been presented in table (3).

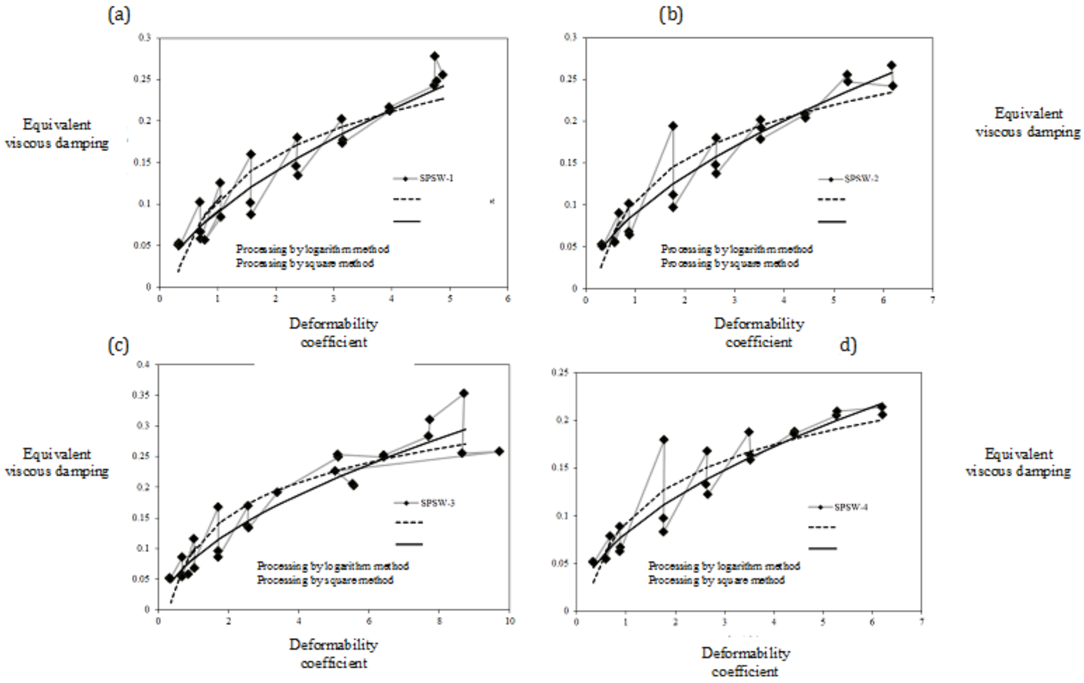


**Fig. 9:** Values of equivalent viscous damping of walls and their fitness by two methods: a-SPSW-1, b- SPSW-2, c- SPSW3, d- SPSW-4

In order to compare results related to four walls, diagram of logarithm fitness and diagram of square fitness have been compared with each other. In figure (10) results of logarithm fitness and in figure (11) results of square fitness have been drawn in order for comparison. According to figure (10), SPSW-4 wall has the minimum value of equivalent viscous damping in deformability more than 1. Also, since difference between three diagrams SPSW-1, SPSW2, and SPSW3 is little, a good result can be obtained using this method. Correlation coefficient in square fitness method, compared with logarithm method, is more. So, comparative study of equivalent viscous damping is done based on figure (11). According to this figure, from damping more than 1, the difference between diagrams is obvious. In this case for a constant value of deformability, structure SPSW-1 has had the maximum value of damping and value of damping for other walls decreases, respectively, in this order: SPSW-2, SPSW-3, and SPSW-4. It shows that wall SPSW-1 has the best energy absorption and wall SPSW-4 has the least energy absorption. Since designing walls has been done based on structure SPSW-1, increasing width of crater without changing design of plate thickness and boundary elements in terms of non-linear behavior and process of energy absorption is an undesirable matter.

**Table 3:** Fitness coefficients with logarithm and square methods and correlation coefficient of these two methods.

| | a | b | )logarithm method($R^2$ | c | d | )square method($R^2$ |
|---|---|---|---|---|---|---|
| SPSW-1 | 0.0762 | 0.1066 | 0.858 | 0.0923 | 0.6104 | 0.9062 |
| SPSW-2 | 0.0712 | 0.1048 | 0.8833 | 0.0898 | 0.5799 | 0.924 |
| SPSW-3 | 0.0785 | 0.1001 | 0.8709 | 0.0857 | 0.5703 | 0.9214 |
| SPSW-4 | 0.0583 | 0.0953 | 0.875 | 0.0837 | 0.5275 | 0.912 |

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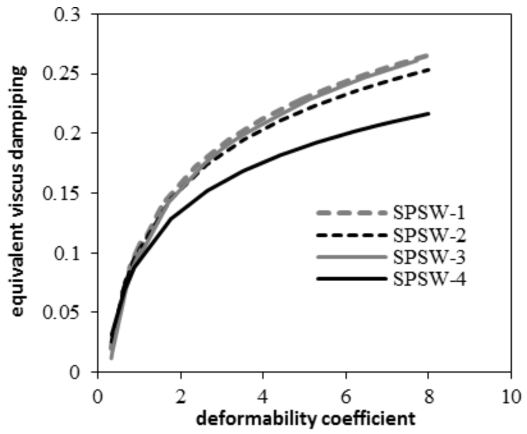


**Fig. 10:** Comparing diagram of equivalent viscous damping for four systems of steel plate shear walls based on logarithm fitness

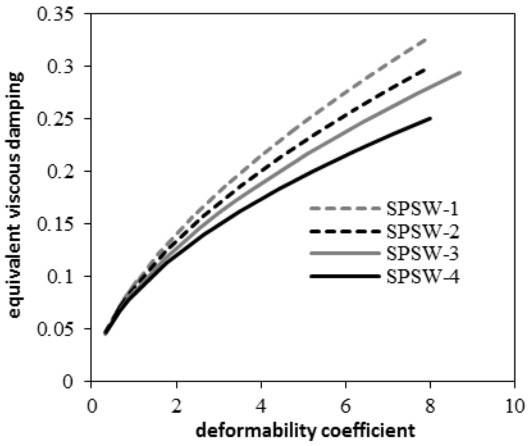


**Fig. 11:** Comparing diagram of equivalent viscous damping for four systems of steel plate shear walls based on square fitness

*Conclusion:*

In this research we attempted to study, based on non-linear analyses, behavior of steel plate shear wall systems. To study this behavior, parameter of equivalent viscous damping which shows amount of energy absorption capacity by a structure was noticed. In this research, first, a model of steel shear wall was designed based on guidelines of designing steel plate shear walls AISC 20 and SAP2000 software. Then, by increasing width of crater, geometry of other models was developed. Eventually, four models created by ABAQUS software went under cyclic analysis, based on loading protocol ATC-24. Equivalent viscous damping was determined according to deformability coefficient of these four structures. For better comparison, results of equivalent viscous damping were fitted using logarithm and square methods and since fitness using square method had higher correlation coefficient, results of damping were compared with this method and it was found that increasing wall crater without changing design of boundary elements cause damping to decrease in constant deformability coefficient. In this case by increasing width of steel plate shear wall crater, without changing design of model, energy absorption will decrease.

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