Design Method of Steel Plate Shear Wall with Slits Considering Energy Dissipation

K. Ke & Y.Y. Chen State Key Laboratory of Disaster Reduction for Civil Engineering Tongji University, Shanghai, China



SUMMARY:

The calculation method of energy dissipation of links as well as steel plate shear walls with slits can predict the energy dissipation of the wall precisely, when the wall is subjected to lateral loads. It is obtained that the energy dissipation capacity is determined by aspect ratio of flexural links when the dimension of plate is confirmed, despite that plastic buckling will reduce the energy absorption. It is also observed that the sequencing of non-linear behaviour will significantly influence the energy dissipation capacity of the wall. With the measure of energy dissipation, the design method of such wall can be optimized, in which strength and stiffness can be united in attaining an optimum solution.

Keywords: Steel plate shear walls, Energy dissipation, Design method

1. INTRODUCTION

As an effective horizontal load carrying member, steel plate shear wall with slits (SPSWS), which consists of rows of vertical links, is of great significance in resisting seismic load. Being an excellent energy dissipative device as well, it can be significantly functional in design and retrofit of structures. Moreover, its stable mechanical behaviour as well as flexibility of fabrication and installation also makes such wall an efficient alternative in structures.

Generally, strength and stiffness are put much attention as key measures to evaluate the property of the wall. However, no universal design guidelines are attained due to complex procedure to solve many geometric variables. Additionally, in the perspective of energy dissipation, it will not completely reflect seismic behaviour of the wall just with stiffness and strength, and it would be lacking of a comprehensive measure to assess the seismic behaviour.

In this study, numerical study and theoretical analysis are both conducted to investigate the energy dissipation capacity of SPSWS, which aims at achieving the mechanism of the wall as well as the optimum design method when energy dissipation is considered. Based on the mechanical model of flexural links, the calculation method of energy dissipation capacity is obtained. On this basis, the simplified formulas and the detailed procedure for calculating energy dissipation capacity of the SPSWS are presented. A series of FEM analysis covering different parameters were completed to validate the formula. Furthermore, in order to expand the application of the wall, the design methodology of SPSWS considering energy dissipation is also discussed.

2. PREDICTION OF ENERGY DISSIPATION CAPACITY

2.1. Energy Dissipation Capacity of Flexural Link

The mechanism of the wall is for the steel plate between the slits to behave as a series of flexural links, which will dissipate energy through plastic flexural behaviour under lateral loading. The simplified

mechanical model of flexural link is illustrated in Fig. 2.1, in which the variable h and b represents the length and width of flexural link respectively.



Figure 2.1. Steel plate shear wall with slits and mechanical model of link

Based on assumed model, link will dissipate energy by rotation of plastic hinges forming at ends, which is given by Eqn. 2.1, assuming that plastic hinges are elasto-perfectly plastic and the effect of buckling is neglected.

$$E_d = \sum M_{pi} \theta_{pi} \tag{2.1}$$

Where E_d =plastic energy dissipated; M_{pi} =plastic bending moment of link and θ_{pi} =plastic rotation at a plastic hinge. Then the energy dissipation capacity of flexural link can be expressed as shown in eqn.2.2

$$E_d = \left(\frac{\delta}{h} - \frac{f_y h}{3Eb}\right) \frac{f_y b^2 t}{2} \tag{2.2}$$

Where δ = total lateral displacement of the link; f_y =yielding stress; E=Young's modulus and t= thickness of plate. As shown in Eqn. 2.2, the energy dissipation of link can be calculated when the lateral displacement is obtained.

2.2. Energy Dissipation Capacity of Steel Plate Shear Wall with Slits

Since the link behaves as the basic element in SPSWS, the energy dissipation capacity of the wall can be captured. Generally, SPSWS will firstly form plastic hinges at ends of links under lateral loads. Moreover, the global shear deformation of plates as well as plastic deformation of band zones will also contribute to energy dissipation. It is observed that geometric parameters of slits significantly influence the behaviour of the wall, and test result indicates that the wall exhibit a stable performance when designing the slits and dimension properly. Based on the calculation model of flexural links, the energy dissipation of the wall can be calculated as:

$$E_{d-\text{wall}} = \left(\frac{n\Delta}{h} - \frac{nmf_yh}{3Eb}\right) \frac{f_yb^2t}{2}$$
(2.3)

Where *n*=number of links in a row; *m*=number of rows in wall and Δ = total lateral displacement of the wall. The equation is based on the assumption that slits are distributed uniformly and the wall or link will not buckle. Correspondingly, lateral displacement Δ approximately equals the displacement of link in the wall.

3. VERIFICATION OF CALCULATION METHOD

In order to validate the accuracy of proposed equations, nonlinear analysis software ABAQUS 6.9 is used in this paper to validate the theoretical derivation and to investigate the behaviour of links as well as SPSWS. The FEM model is based on the constitutive relationship of steel material with $E=2.06 \times$ 10^{5} MPa and yield stress f_y=235MPa. The stress-strain relation is supposed elasto-perfectly plastic.

3.1. Verification of Prediction Method of Link

As is shown in Table 3.1, a series of link models of different geometric parameters are analysed. To simulate its performance under monotonic lateral load, S4R element is adopted to conduct the analysis.

Table 3.1. Parameters of Links						
Models	<i>b</i> /mm	<i>h</i> /mm	<i>t</i> /mm			
Link-1	135	500	8			
Link-2	135	1000	8			
Link-3	135	2000	8			

Table 2.1 Demonstrang of Links

By comparing the plastic energy dissipation calculated through simplified equations and analysis result, it can be obtained that the proposed prediction method may excellently reflect the energy dissipation of links, which is shown in Fig. 3.1



Figure 3.1. Energy dissipation-displacement curves of links

As is presented in Fig. 3.2, when the link is subjected to shear force, plastic deformation is always concentrated at ends which complies with the theoretical model well. During the process, it is also observed that flexural links will develop plastic behaviour firstly under lateral force, and analysis results indicate that the proposed prediction method will still have considerable accuracy when links undergo relatively large drift ratio of 10%.



Figure 3.2. Analysis results of flexural links

3.2. Verification of Prediction method of SPSWS

Similarly, a series of SPSWS are modeled to simulate the behaviour of wall system. Parameters of analysis are dimension variables of flexural links determining the form of slits, including aspect ratio of link (h/b) and width to thickness ratio (b/t). The properties and comparison of predicted energy dissipation and analysis results of models are listed in Table 3.2.

Table 5.2. I alameters of 51 5 w 5 and Comparison of Frederice Energy Dissipation and Analysis Results								
Models	<i>W</i> /mm	<i>H</i> /mm	<i>b</i> /mm	<i>h</i> /mm	<i>t</i> /mm	т	п	E_{pred}/E_{FEM}
								(<i>∆</i> / <i>H</i> =5%)
SPSWS-1	2140	1950	128	500	8	3	14	1.02
SPSWS-2	2140	1950	128	500	10	3	14	0.92
SPSWS-3	2140	1950	128	500	12	3	14	0.90
SPSWS-4	2140	1950	128	825	8	2	14	0.88
SPSWS-5	2140	1950	128	825	10	2	14	0.88
SPSWS-6	2140	1950	128	825	12	2	14	0.87

Table 3.2. Parameters of SPSWS and Comparison of Predicted Energy Dissipation and Analysis Results

It is observed that calculation method of energy dissipation of SPSWS by Eqn.2.3 can predict the energy dissipation capacity of the wall quite well. Previous Research indicates that both aspect ratio of link (h/b) and width to thickness ratio (b/t) will influence the failure mode of links, and out plane deformation will occur when b/t or b/h is relatively large. In SPSWS-1, the predicted energy dissipation is a little larger than analysis results, which is induced by buckling of links due to relatively large width to thickness ratio and small aspect ratio. And the predicted energy dissipation is relatively conservative since the plasticity of stiffeners as well as band zones is not considered. As is presented in Fig. 3.3, the analysis results indicate that the plasticity concentrates at ends of links in the wall, complying with the assumptions.



Figure 3.3. Analysis results of SPSWS

It is also observed that the sequence of development of non-linear behaviour including plasticity and buckling will significantly affected the energy dissipation capacity of SPSWS, which means it is necessary to ensure that plasticity has been developed sufficiently before buckling occurs.

4. DESIGN METHOD OF STEEL PLATE SHEAR WALL WITH SLITS

As a rule in general, strength and stiffness are regarded as key measures to evaluate the property of the wall. However, the design process is complicated due to uncertainty of a series of geometric variables. By acquiring the energy dissipation, the strength and stiffness can be united in design process to attain a optimum solution.

4.1. Optimum Design of Links Based on Energy Dissipation

When reduction of plate area due to slits is neglected, based on the condition that slits is uniformly distributed and ratio of total link length in the vertical direction to the wall height is relatively large, Eqn. 2.3 can be expressed as Eqn. 4.1 presented as follows,

$$E_{d-wall} = \left(\frac{\Delta f_y t W}{2}\right) \left(\frac{b}{h}\right) - \left(\frac{f_y^2 t}{6E}\right) A \tag{4.1}$$

Where A=Area of steel plate ($H \times W$). It shows that when external dimension is confirmed, the energy dissipation is in linear relationship with the lateral displacement under certain aspect ratio of links, which is demonstrated in Fig. 3.1. Similarly, dissipated energy is in linear relationship with b/h and thickness of plate under a certain displacement. Accordingly, based on the strength and stiffness, the design method can be optimized when considering energy dissipation of the wall. As an effective way, it will improve the energy dissipation capacity with a smaller aspect ratio. It also should be noted that wall with comparably smaller aspect ratio will buckle easier, which will conversely reduce the energy dissipation.

4.2. Verification of optimum Design

When the external dimension of wall is determined, the energy dissipation of wall can be optimized by adjusting the geometric variables of link under lateral force. Three models are built with different geometric variables.

Models	<i>W</i> /mm	<i>H</i> /mm	<i>b</i> /mm	<i>h</i> /mm	<i>t</i> /mm	т	п	b/h
SPSWS-7	2140	1950	113	500	14	3	14	0.23
SPSWS-8	2140	1950	188	800	14	2	10	0.24
SPSWS-9	2140	1950	128	800	14	2	14	0.16

Table 4.1. Models of SPSWS with different link parameters

In the model of SPSWS-7 and SPSWS-8, although the geometric parameters of links are different, aspect ratio of links are pretty close, which leading to almost the same energy dissipation as presented in Fig. 3.4. It is also obtained that energy dissipation of SPSWS-9 under same displacement will be comparatively less due to larger aspect ratio of links. As a result, the analysis demonstrates that the energy dissipation capacity is significantly affected by links, which indicates that design can be optimized by adjusting this parameter. However, it should be noted that in order to avoid the buckling of links or plates, it is necessary to add limitations of geometric parameters. And further investigations are needed to promise the developing sequence of nonlinear behaviour in wall to avoid reduction of energy dissipation due to occurrence of out plane deformation of wall or links.

4.3. Design Method of SPSWS considering Energy Dissipation

Accordingly, based on prediction method of energy dissipation capacity of SPSWS, the design method

of wall can be improved combining the strength and stiffness. On the one hand, the noteworthy feature of such wall in which strength and stiffness can be designed separately will make the design more flexible and rational. On the other hand, the measure of energy dissipation capacity can be adopted in designing process to attain an optimum solution. The Procedure is presented in Fig. 4.2.



Figure 4.1. Analysis results of SPSWS with different geometric variables



Figure 4.2. Flow chart of design procedure for SPSWS considering energy dissipation

During the design procedure, stiffness, strength and energy dissipation are all considered in attaining an optimum design, while in conventional design method they are isolated in meeting the structural requirement, which may not achieve the largest energy dissipation. By introducing the measure of energy dissipation capacity, the design is of great significance especially in the perspective of energy in seismic engineering. As the procedure illustrates, the energy dissipation is also considered by adjusting the aspect ratio properly.

5. CONCLUSION

Based on the theoretical model of flexural link, the calculation method of energy dissipation in SPSWS is proposed and validated by FEM analysis. It is observed that the proposed equations can predict the energy dissipation quite well when the slits form complies with the assumption. By varying the geometric variables of links, it is also observed that the aspect ratio as well as thickness to width ratio does influence the plastic energy absorption significantly. Furthermore, the sequencing of non-linear behaviour also imposes an effect on energy dissipation capacity of the wall.

Accordingly, design process concerning energy dissipation is proposed. On the one hand, SPSWS can reserve its noteworthy features of separate design of stiffness and strength. On the other hand, the energy dissipation of the wall can combine these two measures to attain an optimum design.

However, the calculation method is constrained in the assumption that out plane deformation is not considered, and the dissipated energy of wall is derived based on the assumption that slits are uniformly distributed along the height direction of wall. Additionally, the cyclic behaviour is also neglected during the research and further investigation is still needed.

ACKNOWLEDGEMENT

This research is supported by National Science Foundation of China (Grant No.51038008)

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