Computers and Concrete, *Vol. 20, No. 5 (2017) 539-544*
DOI: https://doi.org/10.12989/cac.2017.20.5.539

Design and analysis of slotted shear walls equipped with energy dissipating shear connectors

Shaodong Shen[1a], Xin Nie[*1], Peng Pan[1,2b] and Haishen Wang[1c]

[1]*Department of Civil Engineering, Tsinghua University, Beijing 100084, China*
[2]*Key Laboratory of Civil Engineering Safety and Durability of China Education Ministry, Tsinghua University, Beijing 100084, China*

(Received July 25, 2017, Revised August 10, 2017, Accepted August 19, 2017)

Abstract. Shear walls have high stiffness and strength; however, they lack energy dissipation and repairability. In this study, an innovative slotted shear wall featuring vertical slots and steel energy dissipation connectors was developed. The ductility and energy dissipation of the shear wall were improved, while sufficient bearing capacity and structural stiffness were retained. Furthermore, the slotted shear wall does not support vertical forces, and thus it does not have to be arranged continuously along the height of the structure, leading to a much free arrangement of the shear wall. A frame-slotted shear wall structure that combines the conventional frame structure and the innovative shear wall was developed. To investigate the ductility and hysteretic behavior of the slotted shear wall, finite element models of two walls with different steel connectors were built, and pushover and quasi-static analyses were conducted. Numerical analysis results indicated that the deformability and energy dissipation were guaranteed only if the steel connectors yielded before plastic hinges in the wall limbs were formed. Finally, a modified D-value method was proposed to estimate the bearing capacity and stiffness of the slotted shear wall. In this method, the wall limbs are analogous to columns and the connectors are analogous to beams. Results obtained from the modified D-value method were compared with those obtained from the finite element analysis. It was found that the internal force and stiffness estimated with the modified D-value method agreed well with those obtained from the finite element analysis.

Keywords: slotted wall; finite element modeling; pushover; quasi-static analysis; modified D-value method

1. Introduction

Designed to resist the lateral force in high-rise structures, shear walls are rigid and strong, but often lack layout flexibility and the ability to dissipate strain energy. Furthermore, concrete crushing occurs in the corners of the shear wall during severe earthquakes because of the height of the section and high strains in the edge constraint area, which is difficult to repair, or even lead to the damage of the whole structure (Yi *et al.* 2013 and Li *et al.* 2009). To address these drawbacks, Muto (1984) developed a concrete shear wall with slits and demonstrated that it improved the deformability and repairability by arranging a plurality of vertical cracks through the wall, but at the cost of stiffness and bearing capacity. Dai *et al.* (1992) developed a shear wall with slots set along the two diagonal directions to increase ductility while ensuring stiffness; however, the method was limited to short walls. Fortney *et al.* (2007) developed replaceable steel coupling beams for coupled core wall systems, which resulted in energy consumption and functional recovery. Jin *et al.* (2016) developed a buckling-restrained steel plate shear wall with inclined slots and concrete panels that prevented out-of-plane buckling and achieved stable energy dissipation.

Features such as slots, high-performance fiber concrete or steel plates, and dampers have been introduced to improve the deformation capacity and energy dissipation capability of shear walls. However, parametric studies and optimization of the design parameters for such features have not been performed. Moreover, the specific design method providing the slotted shear wall with satisfactory working performance and energy dissipation capacity is rarely reported. In this study, a novel frame-slotted shear wall structure was developed. The slotted shear wall, featuring vertical slots and silt steel energy dissipating connectors, improved ductility and energy dissipation. Additionally, the slotted shear wall exhibited sufficient bearing capacity and structural stiffness; therefore, it serves as a stress component as well as a damper. Because the slotted shear wall only resists lateral force, it is no longer limited by the principle of vertical continuous arrangement and can be freely located rather than arranged continuously from bottom to top. To compare the ductility and hysteretic behavior of slotted shear walls with different steel connectors, two finite element models (FEMs) were developed. The numerical results from pushover and quasi-static analyses indicated that the deformability and energy dissipation were guaranteed only if the steel connectors yielded before plastic hinges in the wall limbs were formed. Finally, a method for calculating the bearing capacity and

*Corresponding author, Ph.D.
E-mail: xinnie@mail.tsinghua.edu.cn
[a]Ph.D. Student
E-mail: ssd15@mails.tsinghua.edu.cn
[b]Professor
E-mail: panpeng@tsinghua.edu.cn
[c]M.Sc. Student

http://www.techno-press.org/?journal=cac&subpage=8
ISSN: 1598-8198 (Print), 1598-818X (Online)

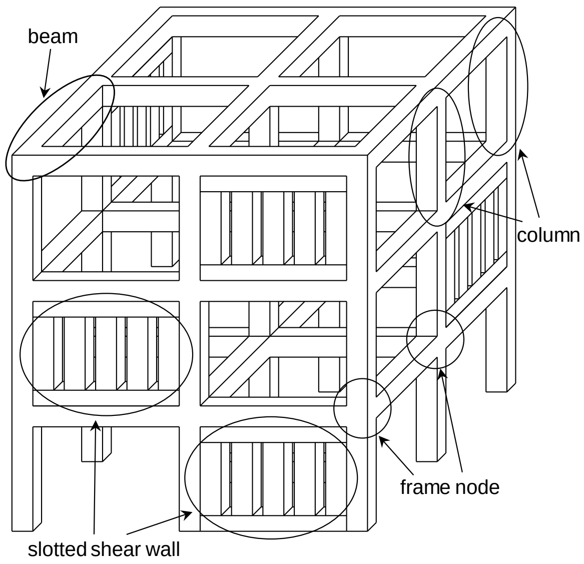


Fig. 1 A representative frame-slotted shear wall structure

stiffness of the slotted shear wall was developed. Analogizing the wall limbs to columns and the connectors to beams, a modified D-value method based on the traditional D-value method was developed. The internal force and stiffness of the slotted shear wall calculated from the modified D-value method were compared with the results from the finite element analysis (FEA), and it was found that the modified D-value method provided good accuracy.

2. Configuration of the slotted shear wall

The application of the slotted shear wall is made possible by the frame-slotted shear wall structure, which consists of slotted shear walls, beams, columns, and frame nodes, as shown in Fig. 1. The frame nodes, which are post-tensioned self-centering connections (Ricles *et al.* 2001 and Song *et al.* 2014), combine beams and columns into a frame that bears most of the vertical load in the structure. The shear walls primarily carry the lateral load. Because the shear walls no longer need to bear vertical load, their placement is not limited by the principle of vertical continuous arrangement and they can be freely located in the structure. Therefore, a more flexible structural design can be used to meet the architectural demands. Moreover, the structure has the advantages of high energy dissipation, flexible layout, fast construction, and repairability. In this work, the structural performance of slotted shear walls installed between upper and lower beams were studied using a specific slotted shear wall configuration.

Fig. 2 shows the configuration of the slotted wall used in this work. The 6000 mm×3000 mm×340 mm shear wall was divided into seven identical wall limbs by 300-mm-wide rectangular slots. The concrete, longitudinal reinforcement, and stirrup materials used were C40, HRB400, and HPB300, respectively. The energy dissipating connectors, made of H-shaped mild steel, were installed in the slots to coordinate the deformation of each wall limb.

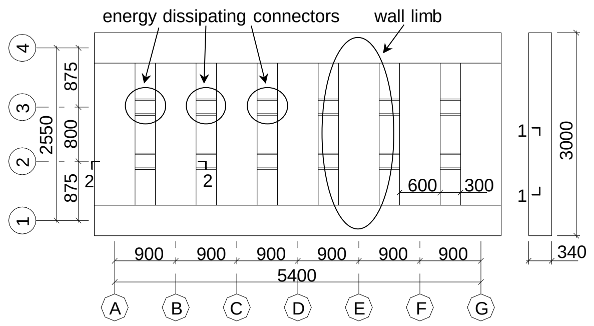
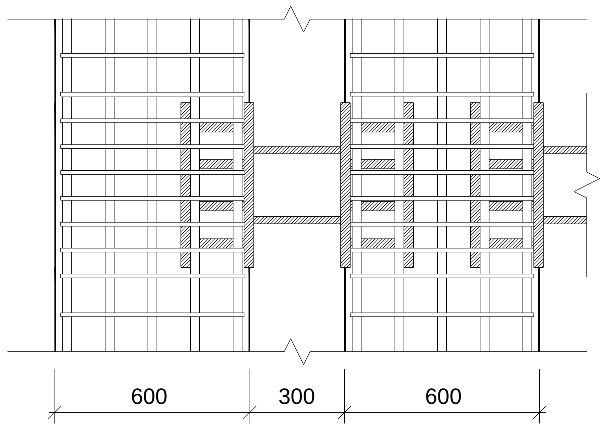
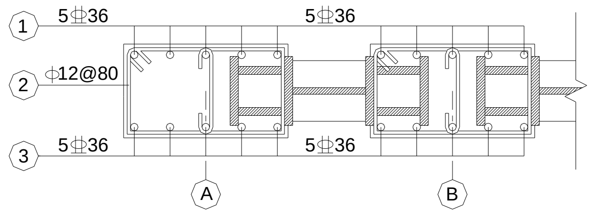


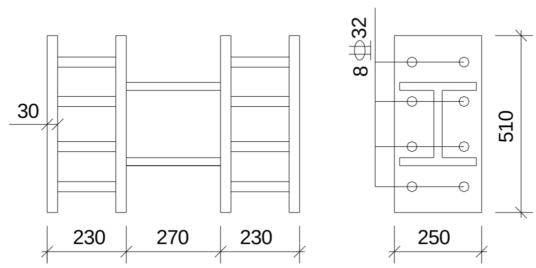
Fig. 2 Dimensions of the slotted shear wall



(a) Cross-section 1-1



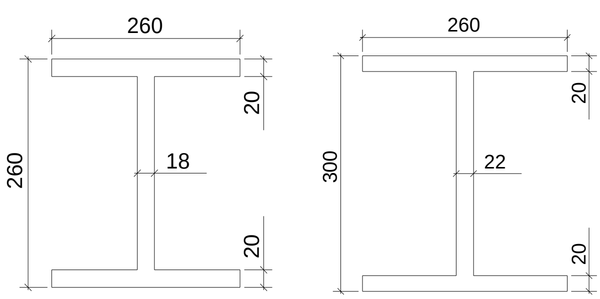
(b) Cross-section 2-2



(c) Embedded parts

Fig. 3 Cross-sections and embedded parts

The connectors were designed to transfer load and dissipate energy, which corresponds to bearing bending moments in service conditions and dissipating energy in large earthquakes. Fig. 3 shows the arrangements of the reinforcements of the wall limbs and the embedded connectors. Note that the connectors should be designed to yield before the wall limbs reach a plastic state, so that the connectors can dissipate energy and protect the wall limbs and surrounding RC frames. Such a yield mechanism is deemed to be a preferred yield mechanism, and endow the structure better ductility and energy dissipation capacity.



(a) Connector 1 (b) Connector 2

Fig. 4 Section dimensions of the mild steel connectors

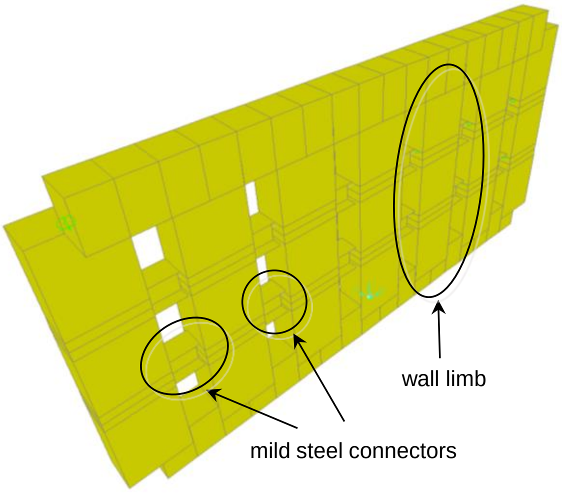


Fig. 5 Finite element model of the slotted shear wall

3. FEM of the slotted shear wall

3.1 FEM

As shown in Fig. 4, the slotted shear wall was modeled with an FEA program called SAP2000 (Beijing Civil King Software Technology Company Limited 2012) so that the behavior of the slotted shear wall could be investigated. The elastic modulus, mass density, and Poisson's ratio of the concrete were 32.5 GPa, 2400 kg/m^3, and 0.2, respectively. The Takeda slip model (Ye *et al.* 2002) was used to model hysteresis in the concrete. The elastic modulus, mass density, and Poisson's ratio of the reinforcements were 200 GPa, 7849 kg/m^3, and 0.2, respectively. In addition, the corresponding strength were the standard value of concrete compressive strength and steel yield point. The kinematic model was used to model hysteresis in the reinforcements (Pham *et al.* 2017). The wall limbs were modeled with column elements, and plastic hinges were inserted near the ends, specifically, the two plastic hinges are set at the location that is 0.05 and 0.95 of the length away from one end. The upper and lower edges of the model were fixed, except to allow for lateral displacements, so as to simulate the fixed connection to the upper and lower beams, while the left and the right boundaries of slotted shear walls were free, which is consistent with the physical constraints of slotted shear walls.

Two H-shaped mild steel beams with different sections

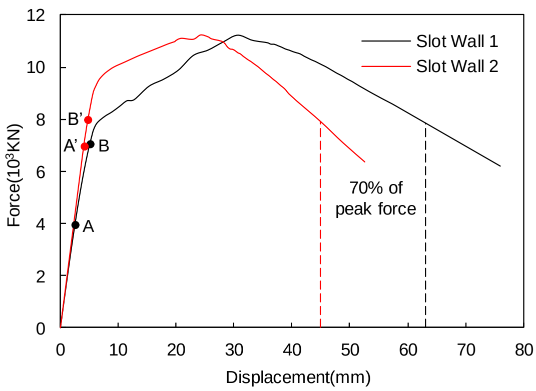


Fig. 6 Pushover curve of the slotted shear wall with two different connectors

were used as the energy dissipating connectors. As shown in Fig. 5, connector 1 was slightly smaller than connector 2, in both the dimension of the web and the width of the flange; therefore connector 2 has higher stiffness, bending bearing capacity, and shearing strength. Pushover and quasi-static loadings were simulated and the ductility and hysteretic behavior of the slotted shear wall with connector 1 (slotted shear wall 1) and with connector 2 (slotted shear wall 2) were compared.

3.2 Pushover loading

Pushover loads were applied to the top nodes of the slotted shear wall to simulate realistic pushover conditions. Force control was used in the FEM until plastic hinges were formed, after which displacement control was used with a lateral load until completion (Ei-Tawil *et al.* 2002). This solution method was designed to produce a stable post-peak load-displacement curve.

Fig. 6 shows the pushover curve of slotted shear walls 1 and 2. For comparison, points A and A' correspond to the yield point of the connectors, and points B and B' correspond to the points at which plastic hinges in the wall limbs were first formed. The force value at points B and B' is taken as the shearing capacity of the connector. It can be seen from Fig. 6 that connector 2 provided the slotted shear wall with 15.3% higher shear strength than connector 1. However, their ultimate bearing capacities were approximately the same, with only a 2% difference. Most importantly, slotted shear wall 1 had an ultimate displacement value of 76 mm, which was 37% higher than slotted shear wall 2.

The area enclosed by the pushover curve are the energy dissipate by the slotted shear walls. To compare the energy dissipation between the two slotted shear walls, only the energy dissipated before the strength degrades to 70% of the peaking value are considered. As shown in Fig. 6, the slotted shear wall 1 dissipated the energy of 586 kN·m and 416 kN.m, showing that the energy dissipation of the slotted shear 1 is 170 kN·m higher than that of wall 2.

3.3 Quasi-static loading

Quasi-static loading simulations were performed to

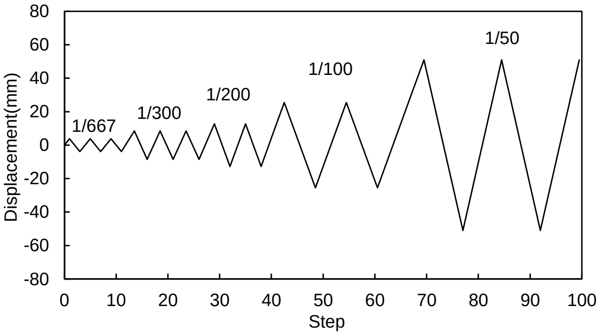


Fig. 7 Loading scheme for the quasi-static simulations

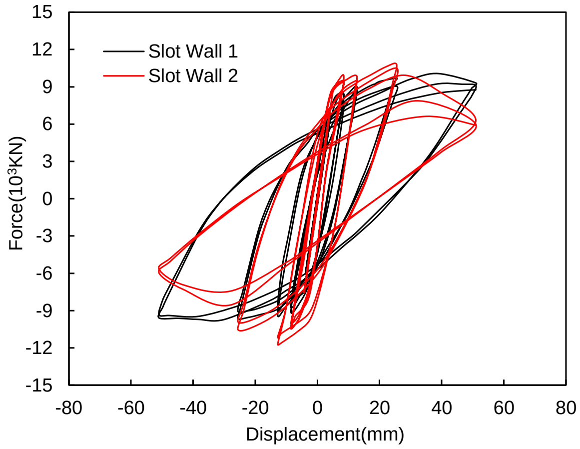


Fig. 8 Hysteretic curves for the slotted shear wall with two different connectors

investigate the behavior of the slotted shear wall (Deng *et al.* 2015). The loading scheme, which was displacement controlled, is shown in Fig. 7. The loading scheme was divided into five stages in which the drift angle was set to 1/667, 1/300, 1/200, 1/100, and 1/50 and was repeated for 3, 3, 2, 2, and 2 cycles, respectively. The target displacements were chosen to replicate increasing levels of seismic intensity. The drift angles were calculated as the lateral displacement divided by the distance between the centerlines of the upper and lower beams.

The hysteresis curves that were obtained for slotted shear walls 1 and 2 are shown in Fig. 8, from which it can be seen that when the drift angle was 1/667, both slotted shear walls maintained their stiffness and strength. However, when the drift angle was increased further, the stiffness decreased slightly with increasing number of loading cycles. This indicated that the maximum drift corresponding to the elastic limit of the wall limbs was 1/667; if the displacement exceeded this value, softening behavior resulted because of damage to the concrete and deterioration of the reinforcements. Comparing the lateral behavior, slotted shear wall 2 exhibited a 12% higher shearing capacity than slotted shear wall 1 when the drift angle was below 1/100. This relationship was reversed when the drift angle reached 1/50, when the shearing capacity of slotted shear wall 1 was 20% higher than slotted shear wall 2, and the hysteresis curves were plumber.

It can be concluded from the pushover and quasi-static loading results that although the energy dissipating connectors with higher stiffness and strength provided the slotted shear wall with higher strength and stiffness, they reduced the ductility and post-yielding strength. In summary, the deformability and dissipation can be guaranteed only if the steel connectors yielded before the wall limbs reached a plastic state.

4. Design method for the slotted shear wall

4.1 Modified D-value method

When designing frame structures, the lateral stiffness of a column is not only determined by its line stiffness and height, but is also related to the stiffness of the beams to which it is connected. In addition, the position of the inflection point in the column is determined by the stiffness ratio of the beams to the columns, the stiffness ratio of the upper beams to the lower beams, and the height ratio of the upper story to the lower story. Muto(1984) proposed the D-value method to design frame structures, which takes into account all the above factors and significantly improves the accuracy of the calculation. The slotted shear wall with energy dissipating connectors can be represented by a frame structure in a similar fashion. Columns and beams in this frame structure are represented by the wall limbs and the connectors. A modified D-value method was developed for designing slotted shear walls, in which the lateral stiffness of the structural components was redefined.

During the design phase, a wall limb is divided into several parts by connectors, just like columns on each floor. The newly defined stiffness of the wall limb is denoted as D_{wl}, which is proportional to its shearing force. D_{wl} is calculated with Eq. (1).

$$D_{wl} = \alpha \cdot \frac{12 i_{wl}}{h_{wl}{}^{2}} \tag{1}$$

Where i_{wl} is the linear stiffness of the wall limb, h_{wl} is the height of the wall limb, and α is an adjustment coefficient for the stiffness of the wall limb, which can be calculated from Eqs. (2)-(3). Note that Eq. (2) is applicable to the bottom wall limbs, while Eq. (3) is applicable to all other wall limbs.

$$K_{wl} = \frac{i_{c1} + i_{c2}}{i_{wl}} \quad , \quad \alpha = \frac{0.5 + K_{wl}}{2 + K_{wl}} \tag{2}$$

where i_{cl} represents the linear stiffness of the upper two connectors of the wall limb, i_{c1} represents the linear stiffness of the left connector at the top, and i_{c2} represents the linear stiffness of the right connector at the top. If there are no connectors on a side, the default value of i_c is 0.

$$K_{wl} = \frac{i_{c1} + i_{c2} + i_{c3} + i_{c4}}{i_{wl}} \quad , \quad \alpha = \frac{K_{wl}}{2 + K_{wl}} \tag{3}$$

where i_{c1} and i_{c2} are the linear stiffness of the upper two connectors of the wall limb, and i_{c3} and i_{c4} are the linear stiffness of the lower two connectors of the wall limb.

The traditional D-value method is mainly to calculate

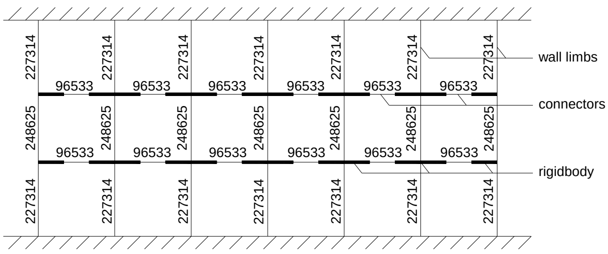


Fig. 9 Linear stiffness of elements in the model

the stiffness and internal force for multi-story building structures, which are fixed at the bottom and free at the top, whereas the modified D-value method proposed in this paper is to estimate the stiffness and internal forces of the slotted shear wall, which are fixed at both the top and the bottom. Therefore, as an analogy to the traditional D-value method, the story number are taken to be the half of that considered in the traditional D-value method. Taking slotted shear wall 1 as an example, the proposed modified D-value method was used to calculate its stiffness and shearing capacity. The accuracy of the modified D-value method was verified by the results from the FEA.

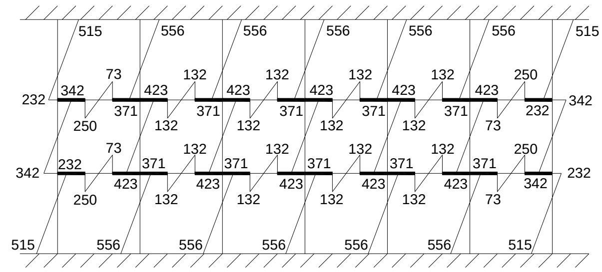
4.2 Calculation

The wall limbs and connectors were simplified to line units (Pan *et al.* 2015) during the internal force calculation. As the width of the wall limbs could not be ignored, rigid bodies were used to make up for the deviation, as Fig. 9 shows. When lateral force was applied to the top of the wall, the internal force distribution in the slotted shear wall was determined from the linear stiffness i of each component. Applying the modified D-value method with the properties of the section, the bending moment under 7000 kN lateral force was calculated and is shown in Fig. 10(a). To verify the accuracy of the modified D-value method, the internal force distribution from the FEA is shown in Fig. 10(b).

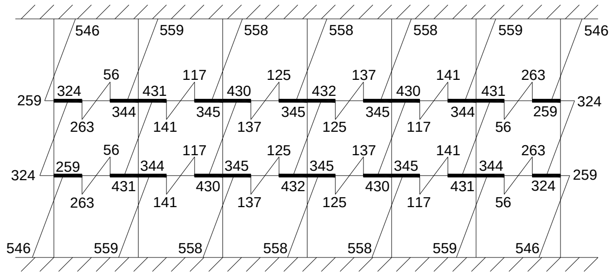
The results obtained from the modified D-value method show good agreement with the results from the FEA. The average relative error is less than 3.62%, which is acceptable for structural designs. However, some slight differences were found in the bending moment of the boundary wall limbs and their attached connectors. This is particularly because the modified D-value method ignores the in-plane bending of the entire structures, which generates the elongation and shortening of the boundary wall limbs. In addition, from the torsion angle (the maximum value is 1/9076) obtained from the FEM results, it can be concluded that the larger the distance between the connectors and the stiffness center, the larger the torque that will be introduced. Although this error is inevitable, it is within the allowable range, and thus the modified D-value method still has sufficient accuracy.

To calculate the lateral stiffness, the displacement under the specified load was determined with a diagram multiplication method, shown in Eq. (4).

$$\Delta_{sw} = \sum \int \frac{\overline{M}_i M_{ik}}{EI} ds + \sum \int \frac{\overline{V}_i V_{ik}}{GA} ds \qquad (4)$$



(a) Calculated by "Modified D Valued Method"



(b) Calculated by finite element software

Fig. 10 Moment diagram of the linear model

where M_{ik} and V_{ik} are the bending moment and shear force under the action of the specified load, respectively, and $\overline{M}_i$ and $\overline{V}_i$ are the bending moment and shear force under the action of the unit-load in the direction of the target displacement, respectively. To obtain the lateral stiffness, the displacement of the top node subjected to a lateral force of 1000 kN (equivalent to the shearing capacity of the slotted shear wall) was calculated with the diagram multiplication method and FEA. The calculated displacement was 0.1792 mm from the diagram multiplication method and 0.1975 mm from the FEA, and the corresponding stiffness was 5580357 kN/m from the diagram multiplication method and 5063291 kN/m from the FEA. The difference between the stiffness obtained from the diagram multiplication method and those obtained from the FEA was no more than 9.3%. In conclusion, although some minor errors existed because of simplifications, the modified D-value method can be used to accurately calculate the internal force and stiffness of slotted shear wall structures.

5. Conclusions

In this study, a novel slotted wall for a frame-slotted shear wall structure was proposed. Two slotted shear wall specimens with different connectors were designed. The first, termed slotted shear wall 1, had connectors with relatively low stiffness and strength, whereas the second, termed slotted shear wall 2, had connectors with relatively high stiffness and strength. FEMs of both walls were built, and pushover and quasi-static loading were applied to study the ductility and hysteretic behavior of the two structures. Finally, the modified D-value method was proposed for calculating the bearing capacity and stiffness of slotted shear walls, and its accuracy was verified by comparison with the FEM results. Major conclusions obtained from this study are as follows:

(1) The slotted shear walls maintained their stiffness and strength when wall limbs were in the elastic stage; however, when the plastic hinges were formed, the stiffness and bearing capacity decreased gradually with increasing number of loading cycles.

(2) The shearing capacity of slotted shear wall 2 was 15.3% higher than that of slotted shear wall 1. However, as wall limbs reached the plastic state, the shearing strength of slotted shear wall 1 gradually became higher than that of slotted shear wall 2. At 1/50 drift angle the strength of slotted shear wall 1 was 20% higher than that of slotted shear wall 2.

(3) The connectors in slotted shear wall 1 yielded far earlier than in slotted shear wall 2. As a result, slotted shear wall 1 had higher deformability than slotted shear wall 2. The ultimate displacement of slotted shear wall 1 was 76 mm, which was 35% greater than that of slotted shear wall 2. Furthermore, brittle failure of slotted shear wall 2 was observed during the simulation.

(4) Deformability and energy dissipation are guaranteed only when the yielding of the steel connectors happens before plastic hinges are formed in the wall limbs. Therefore, to take full advantage of the slotted shear wall, this condition should be met in the wall design.

(5) The modified D-value method can accurately calculate the internal force and stiffness of slotted shear walls, which can be used to aid in their design.

Acknowledgments

This work was supported by the National Key Research and Development Program of China (Project No. 2016YFC0701901), the Natural Science Foundation of China (Grant No. 51422809 and 51578314), and the Beijing Science and Technology Program (Grant No. Z161100001216015).

References

Beijing Civil King Software Technology Company Limited (2012), *SAP2000 Chinese Version Using Guide*, 2nd Edition, China Communication Press, Beijing, China.

Dai, H., Ding, D.J. and Liu, Q. (1992), "Comparative experimental studies of models of shear walls with and without lateral short keyways on shaking table", *Eng. Mech.*, **9**(2), 76-85.

Deng, K.L., Pan, P., Nie, X., Xu, X.G., Feng, P. and Ye, L.P. (2015), "Study of GFRP steel buckling restraint braces", *J. Compos. Constr.*, **19**(6), 04015009:1-8.

Ei-Tawil, S., Kuenzli, C.M. and Hassan, M. (2002), "Pushover of hybrid coupled walls. I: Design and modeling", *J. Struct. Eng.*, **128**(10), 1272-1281.

Fortney, P.J., Shahrooz, B.M. and Rassati, G.A. (2007), "Large-scale testing of a replaceable 'fuse' steel coupling beam", *J. Struct. Eng.*, **133**(12), 1801-1807.

Jin, S.S., Ou, J.P. and Liew, J.Y.R. (2016), "Stability of buckling-restrained steel plate shear walls with inclined-slots: Theoretical analysis and design recommendations", *J. Constr. Steel Res.*, **117**, 13-23.

Li, H.N., Yi, T.H., Gu, M. and Huo, L.S. (2009), "Evaluation of earthquake-induced structural damages by wavelet transform", *Progr. Nat. Sci.*, **19**(4), 461-470.

Muto, K. (1984), *Structural Dynamic Design*, China Architecture & Building Press, Beijing, China.

Pan, P., Wu, S.J. and Nie, X. (2015), "A distributed parameter model of a frame pin-supported wall structure", *Earthq. Eng. Struct. Dyn.*, **44**(10), 1643-1659.

Pham, T.M. and Hao, H. (2017), "Effect of the plastic hinge and boundary conditions on the impact behavior of reinforced concrete beams", *J. Imp. Eng.*, **102**, 74-85.

Ricles, J.M., Sause, R., Garlock, M.M. and Zhao, C. (2001), "Posttensioned seismic-resistant connections for steel frames", *J. Struct. Eng.*, **127**(2), 113-121.

Song, L.L., Guo, T. and Chen, C. (2014), "Experimental and numerical study of a self-centering prestressed concrete moment resisting frame connection with bolted web friction devices", *Earthq. Eng. Struct. Dyn.*, **43**(4), 529-545.

Ye, L.P. and Zeng, Y. (2002), "Elasto-plastic dynamic analysis of dual functional shear wall with built-in slits", *Eng. Mech.*, **19**(3), 74-77.

Yi, T.H., Li, H.N. and Sun, H.M. (2013), "Multi-stage structural damage diagnosis method based on 'energy-damage' theory", *Smart Struct. Syst.*, **12**(3-4), 345-361.

HK