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Numerical and Experimental Investigation of Steel Frames Equipped with Shear Walls with and without Openings

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Abstract

Steel plate shear walls (SPSWs) are one of the modern seismic engineering systems used as a lateral load-bearing system. In this study, two SPSWs specimens with and without an opening, incorporating stiffeners in their upper beams, were subjected to cyclic loading in an experimental setting. The walls had a scale of one-third and were tested under cyclic displacement control loading. Subsequently, calibrated numerical models were utilized to conduct further studies. The opening in the specimens was considered as the independent variable, and the ductility, maximum base shear, and stiffness of the models were considered as dependent variables. For this purpose, the hysteretic curve of each specimen was extracted, which was then used to derive the equivalent bilinear and backbone curves. Finally, based on these curves, the models' seismic parameters, including the base shear, ductility, and stiffness, were calculated. Furthermore, this study demonstrates that with an increase in the percentage of the opening, the parameters of base shear, ductility, and stiffness experience a change, with the smallest change observed in the ductility of the models. Finally, a set of equations was proposed for structural designers and engineers to calculate the seismic parameters based on the percentage of openings.

Keywords: *Steel plate shear wall (SPSW), Opening, Hysteresis behavior, Experimental test, Ductility.*

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1- Introduction

Steel plate shear walls (SPSWs) are an innovative lateral load-resisting system capable of effectively stabilizing buildings against wind and earthquake forces (abdollahzadeh and Malekzadeh, 2013, Broujerdian et al., 2017, Labibzadeh et al., 2021). One advantage of SPSWs is the provision for openings in the infill plate, which may be required for architectural purposes (Cheraghi et al., 2023a). The high strength and ductility of SPSWs make them highly suitable for buildings located in seismic high-risk zones (Shukla and K, 2024, Mehmood et al., 2020). These lateral load-resisting systems exhibit significant strength. In cases where an opening is created in the SPSW, the impact on performance is influenced by the area and geometry of the opening (Sabouri-Ghomi and Mamazizi, 2015).

SPSWs have attracted significant attention from researchers due to their numerous advantages. Wang et al. (2018) studied a novel composite shear wall integrating a steel plate within reinforced concrete to enhance seismic performance. Testing 16 composite and three reinforced concrete specimens under cyclic loading, they analyzed parameters like aspect ratio and wall thickness. The study proposed design formulas for shearing capacity based on extensive experimental data. Wang *et al.* (2018) investigated the shear resistance behavior of sinusoidally corrugated panels in steel corrugated shear walls through finite element analysis. They examined the effects of initial imperfections and geometric dimensions on shear performance. Based on extensive study, they proposed predictive equations using normalized height-to-thickness ratios, offering insights for designing corrugated panels in these shear walls. Farzampour et al. (2018) investigated the seismic performance of corrugated SPSWs compared to simple steel plates. They studied the effects of corrugation angle, openings, and subpanel length under monotonic and cyclic loads. Results showed that corrugated plates improve damping ratios and energy dissipation, with a 100 mm subpanel length enhancing performance. Gorji Azandariani et al. (2020)investigated the cyclic behavior of low-yield-strength SPSWs through experimental and numerical methods. Their results showed good stiffness, high ductility, and energy dissipation. They found that beam-to-column connection type affected ductility, strength, and energy dissipation, while material properties further influenced performance.

Researchers have also made significant efforts to study the behavior of openings in shear walls. Massumi et al. (2018) studied the impact of openings on steel shear wall performance, considering both technical and seismic design criteria. Using nonlinear cyclic analysis and finite element modeling in ABAQUS, they investigated various opening shapes and locations. Results showed that opening location and shape significantly affect seismic parameters, with openings closer to columns resulting in higher stiffness and strength. At the same time, those near the center led to more pronounced changes in seismic behavior as the opening area increased. Meghdadaian and Ghalehnovi (2019) explored the performance of composite SPSWs, a new system combining steel plates and reinforced concrete walls. They evaluated the impact of openings on seismic performance and proposed methods to mitigate negative effects. An empirical relation for calculating ultimate strength was also introduced to assist in design and analysis. Kordzangeneh et al. (2021) analyzed the cyclic performance of SPSWs with rectangular openings through experiments. Results indicated significant reductions in maximum shear capacity and initial

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stiffness with increasing opening sizes. Stiffeners effectively mitigated tearing around openings initially, but strength degradation occurred at higher drift ratios due to buckling effects. Todea et al. (2021) conducted experimental tests on composite steel-concrete coupled walls with and without openings, analyzing the effects of steel fiber reinforcement and composite connections on seismic behavior. Results showed that steel fibers improved ductility, compensating for losses from openings, while composite connections effectively resisted cyclic loads until ultimate failure, enhancing overall wall performance. Bypour et al. (2021) worked on predicting the shear capacity of stiffened SPSWs with openings using a response surface method. The results of this study showed that the response surface method is an accurate tool for predicting the shear capacity of the specimens. Sabouri-Ghomi et al. (2023) conducted experimental and numerical studies on the behavior of stiffened SPSWs featuring rectangular openings. The results of this study showed that the presence of openings has no effect on the shear strength and stiffness of steel plate shear walls. Kechidi and Iuorio (2022) numerically investigated the performance of cold-formed steel framed shear walls with openings under in-plane lateral loads. The results demonstrate that cold-formed steel framed shear walls with openings can effectively resist lateral loads, confirming the reliability of the finite element analysis modeling protocol. Meghdadian et al. (2020) proposed an equivalent reduced thickness model for composite SPSWs containing an opening. The results demonstrate that cold-formed steel framed shear walls with openings can effectively resist lateral loads, confirming the reliability of the finite element analysis modeling protocol. Zhao et al. (2023) carried out theoretical and experimental investigations on SPSWs with diamond-shaped openings. The study proposes a steel plate shear wall with diamond openings to enhance seismic performance by fully utilizing energy dissipation through flexure and shear in butterfly links. Zabihi et al. (2021) focused on analyzing mid-panels of steel shear walls with dual openings. The study concludes that optimizing mid-panel design enhances energy dissipation and post-buckling capacity in steel shear walls with openings.

As observed in previous studies, ambiguities remain concerning the impact of circular opening areas on the seismic parameters of steel frames with shear walls. In instances where openings must be created within shear walls, the findings of this study can demonstrate the effect of these openings on the behavior of such structures. Thus, this study addresses the impact of the opening area on the seismic parameters of steel frames equipped with shear walls without openings. The aim of this study was to investigate the impact of an opening area on the seismic parameters of a steel frame equipped with a shear wall, an area that has been less addressed in previous studies. To this end, two experimental models of a steel frame equipped with a shear wall, one with and one without an opening, were initially examined. These models were subjected to cyclic loading. Subsequently, further numerical studies were conducted to evaluate the effect of the opening percentage on the seismic performance of the model. The geometry of the opening was circular, which was kept constant for all models. The models were analyzed under cyclic analysis, and the outputs included elastic stiffness, ultimate strength, and ductility. Based on these results, equations for calculating elastic stiffness and damper strength, considering the effect of opening dimensions, were proposed.

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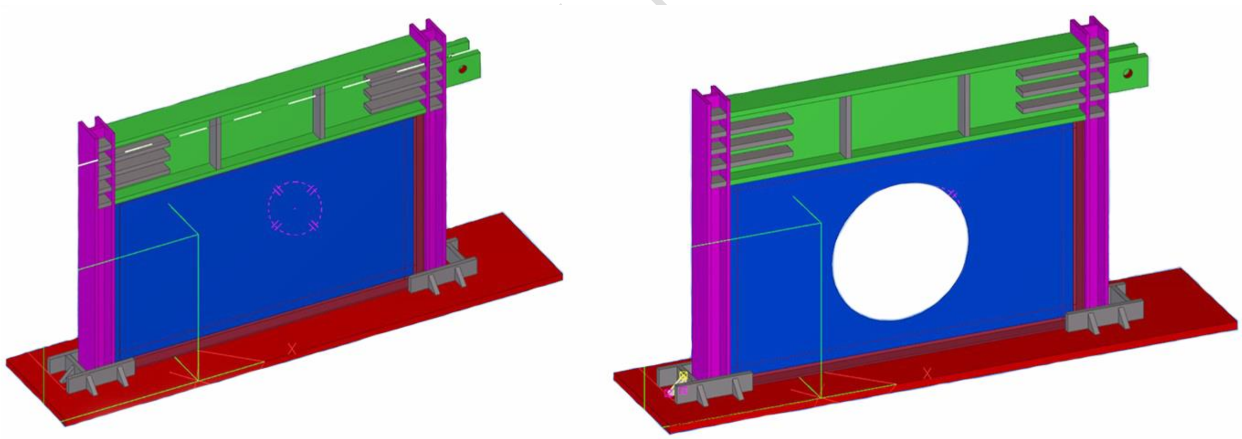
2- Experimental study

First, the steel plate shear wall was designed using existing codes, particularly Guideline No. 20 of the AISC standard (AISC, 2007). The experimental models consisted of two specimens constructed at a one-third scale. The experimental specimens included two steel frames equipped with shear walls, one with an opening and the other without. The height of the specimen, from the connection plate to the highest point of the column, was 1.165 meters, and the length of the beam was 1.160 meters. The dimensions of the steel plate were 0.765 meters by 1.135 meters. To connect the specimen to the frame and prevent column buckling during testing, a 2.25 m by 0.3 m plate was used. Additionally, this plate had 36 holes that were utilized for securing the columns with bolts. In the specimen with an opening, a circular opening with a diameter of 544 millimeters was used. The opening had an area equal to 25% of the steel plate's surface area. Fig. 1 illustrates the schematic representation of the experimental models used in this study. The dimensions of these two experimental frames are also presented in Fig. 2. For the material characterization of the steel used in the study, tensile tests were performed on three samples. The average yield strength was found to be 347 MPa for beams and columns, with an ultimate tensile strength of 500 MPa. The associated error and standard deviation were estimated to be ±10 MPa and ±5 MPa, respectively. For the shear walls, the yield strength was 247 MPa, and the ultimate tensile strength was 400 MPa, with an error of ±8 MPa and a standard deviation of ±4 MPa. Furthermore, the ultimate strain for the second model was determined to be 0.34. This statistical information enhances the reliability of the material properties utilized in the structural assessments.



(a) (b)

Fig. 1: Final design of the steel plate shear wall (a) without opening and (b) with opening

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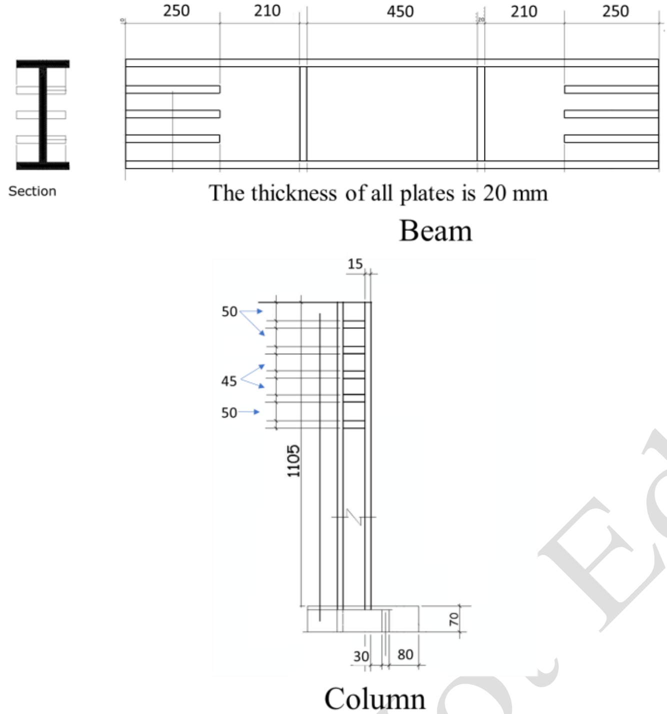

Fig. 2 Details of the beam and column (Units: mm)

In this model, a steel plate with a thickness of 1 millimeter was used, and angles with 6 cm side dimensions were utilized to connect the plate to the steel frame. Additionally, the upper beam and columns were tailor-made plate-girders. For the upper beam, the web of the columns, reinforcing plates in the connection of the beam and the columns, and the connection of the column to the connecting plate, 20-millimeter-thick plates were used. Furthermore, plates with a thickness of 15 millimeters were used for the flanges of the columns. The connecting plate had a thickness of 30 millimeters, and two 30-millimeter-thick plates were welded to the columns of the specimen using full penetration welds to facilitate connection to the actuator. To prevent the separation of the columns from the connecting plate, in addition to a support plate, two stiffeners were also used on each side. The hysteresis loading applied to the samples was based on the loading protocol specified in the ASCE (2016). This loading protocol is depicted in Fig. 3. In this figure, the vertical axis indicates the displacement applied to the frame in the lateral direction.

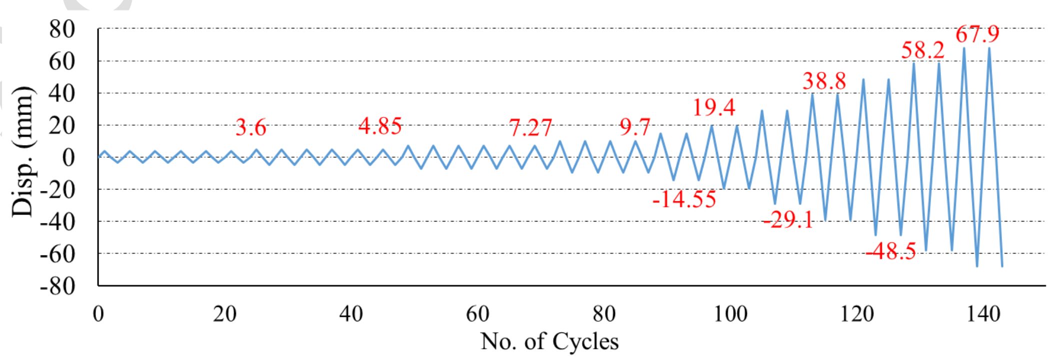

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Fig. 3 The ASCE 7 loading protocol (ASCE, 2016).

For the tests, an actuator with a capacity of 1000 kN was used, and a load cell was installed on top of the actuator. The specimens were connected to the substructure using 36 grade 10.9 bolts. The diameter of the bolts was 28 millimeters, and the specimen was connected to the actuator using a high-strength bolt with a diameter of 36 millimeters. Fig. 4 illustrates the connection details for both specimens, with and without an opening. To measure displacements at the top and end of the beam, two calibrated Linear Potentiometer Transducers (LPTs) were used, located at the actuator side. Also, two strain gauges with a resistance of 120 ohms and a gauge factor of 2.08 were used. Additionally, an LPT was placed in the middle of the column to measure displacement. Furthermore, as shown in Fig. 4, four metal braces were used to prevent out-of-plane movement in the specimens.

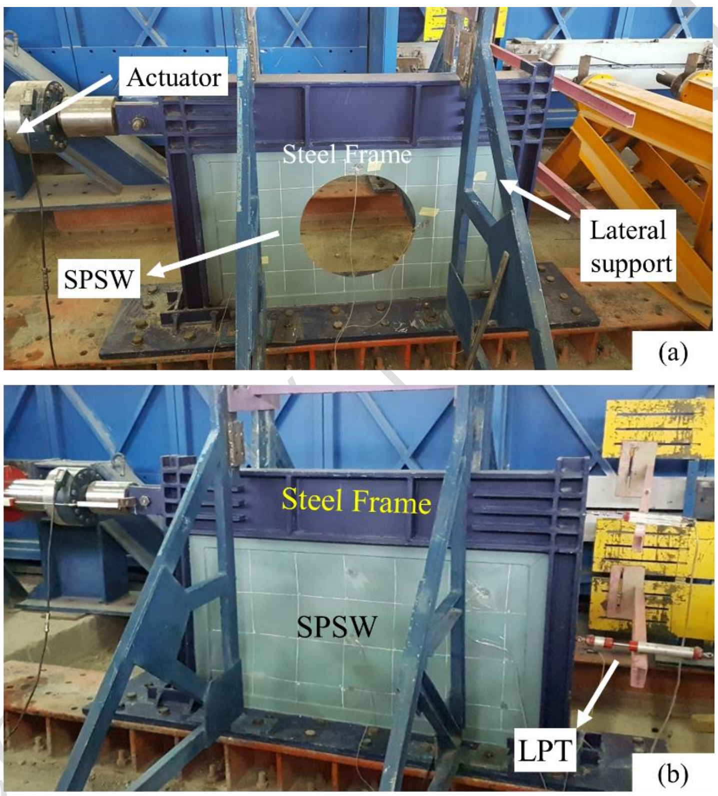

Fig. 4 Steel plate shear wall in the lab (a) with an opening and (b) without opening.

3- Test results

Following the application of loading to the experimental specimens, the results were analyzed in this section. For each loading cycle, the deformations and potential failures of the models were examined. In the model without openings, diagonal tensile fields developed in the shear wall, leading to failure at the end of the loading process. In the model with openings, tensile fields formed at the corners of the shear wall, while no tensile field was observed in the middle due to the presence of the opening. The deformations of the models are shown in Fig. 5. In Fig. 6, the hysteresis curves for both models, with and without openings, are presented. As observed, both

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models exhibit robust and uniform hysteresis loops. Additionally, the results for both models are symmetric.

(a) (b)

Fig. 5 Final loading cycle for the (a) sample with an opening and (b) without an opening.

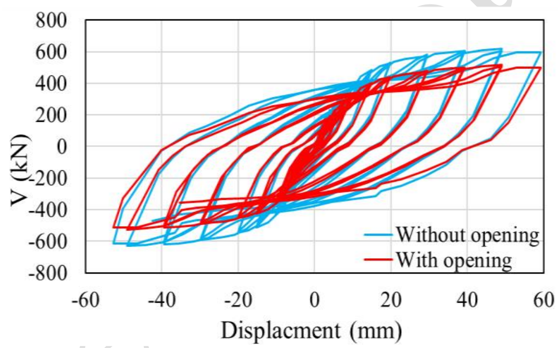

Fig. 6 Comparing the hysteretic curves of the two specimens with and without an opening.

The backbone curves of these two specimens have been plotted and compared. As shown in Fig. 7, the specimen with an opening has a lower load-bearing capacity and experiences a maximum drop of 24% compared to the specimen without an opening.

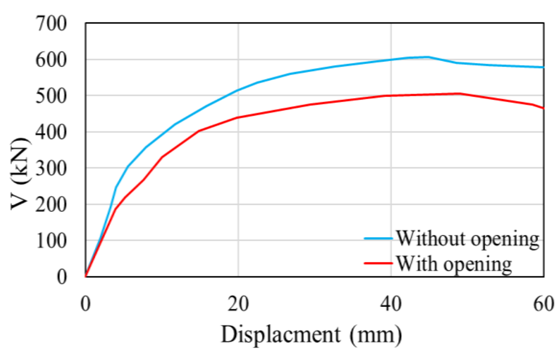

Fig. 7 Comparison between the backbone curves of the samples with and without an opening.

After extracting the backbone curves, the seismic parameters, including base shear, ductility, and stiffness, were obtained using the equivalent bilinear curve. The results for both samples are presented in Table 1. As can be seen, the greatest impact of openings is on strength, while the least impact is observed on ductility.

Table 1: The percentage reduction in results due to the addition of openings in the model.

	Base shear (kN)	Stiffness (kN/mm)	Ductility
Without openings	606	83.53	8.84
With openings	500	56.82	7.68
Reduction percentage	17.5%	22%	13%

4- Numerical modeling

Due to the limitations of constructing and testing experimental models and providing practical relationships and diagrams, the ABAQUS finite element software (version 6.14) has been utilized for numerical modeling. To verify the accuracy of the numerical results, the model was first validated using experimental data, which is explained in the following sections.

4-1 Verification

To simulate all components of the model, four-node shell elements were employed due to their small thickness. Each node of these elements has six degrees of freedom (Aghani et al., 2024, Cheraghi et al., 2024). Since no failure was reported in the connections of the experimental model, the connections in the numerical model were modeled using "Tie" constraints. To achieve more accurate results, large deformations and the nonlinear behavior of materials were also considered in the analysis. The material properties of the steel plate shear wall, beam, and column in the plastic phase were obtained from laboratory experiments and are presented in Fig. 8(a). To perform the analysis, imperfections were first introduced into the models using buckling analysis, and then the models were analyzed using implicit dynamic analysis, which is suitable for uniform loading scenarios. The numerical model analysis, in accordance with the experimental tests, was performed using displacement control. To apply the boundary conditions similar to those in the experimental specimen, the bottom of the columns and the shear wall plate were fully fixed. Additionally, to simulate the anchors in the lab, the upper beam was restricted along the z-axis. Additionally, the lateral force was cyclically applied to coupling point A to reduce the concentration of localized forces (Cheraghi et al., 2023b). Fig. 8(b) illustrates the boundary conditions of the meshed numerical model.

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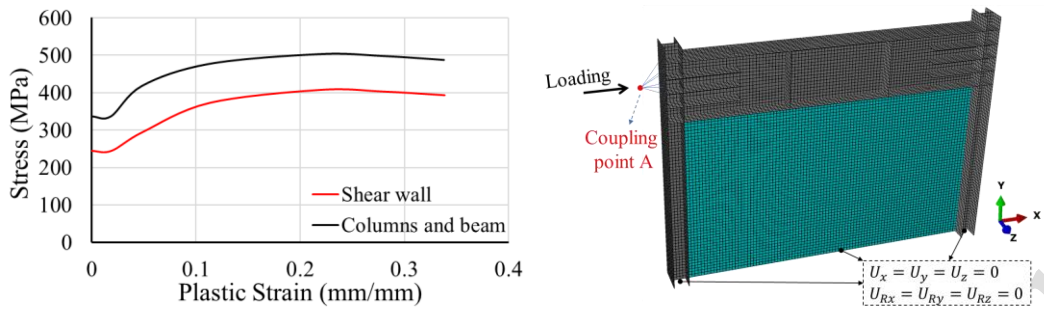
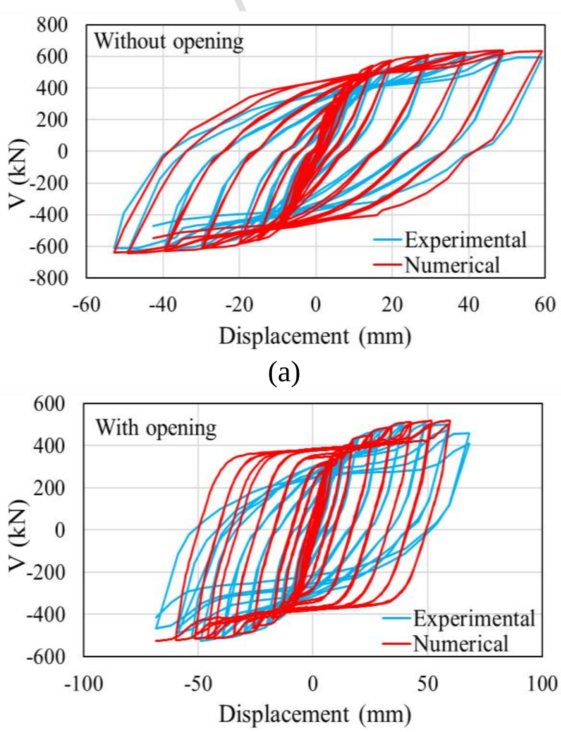


(a) (b)

Fig. 8 (a) Material property (b) Boundary conditions of the numerical model.

One of the crucial issues in numerical analysis is the conformity between numerical and experimental results. Fig. 9 compares the hysteresis results of the numerical model and the experimental specimen. In terms of the maximum base shear in each cycle, both specimens are in good agreement. The presence of some differences in the two specimens is due to construction errors and non-consideration of certain details in the numerical model. The plastic strain contour results of the numerical model without an opening were compared with the experimental specimen in Fig. 10. These results correspond to the end of the loading process. As observed, the maximum strains in the numerical model are concentrated in the shear wall, which is consistent with the experimental specimen. As observed, Fig. 9(b) shows discrepancies in some areas, but the backbone section of the graph exhibits acceptable agreement. Since the results of this study are derived from the backbone section of the graph, the discrepancies in the results are not significant.



(a)

(b)

Fig. 9 Comparison of numerical and experimental results: (a) without openings, (b) with openings.

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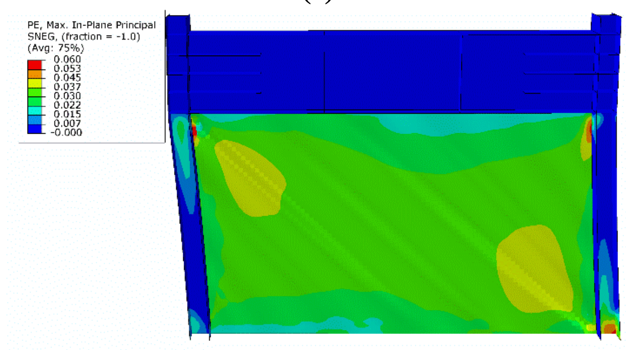
(a)



(b)

Fig. 10 (a) Final deformation of the model in the last loading cycle (b) Plastic strain contour results of the numerical model

4-2 Evaluation of the numerical results

Considering the suitable agreement between the experimental and numerical results, a variable named "opening percentage" has been defined. Based on the cross-sectional area of the wall and the height limitation of the opening (ranging from 5% to 25%), six specimens have been considered for analysis. The details are provided in Table 2.

Table 2: Specifications of the studied numerical models

No.	percentage of the opening (%)	Opening diameter (mm)
1	0	0
2	5	272
3	10	386
4	15	472
5	20	544
6	25	610

The plastic strain contours of the models are presented in Fig. 11. As observed, in the model without openings, a tensile field developed in the shear wall. However, the addition of openings eliminated this field. Increasing the size of the openings significantly raised the maximum strain in the model, while the area affected by strain remained nearly constant despite the increase in the opening size.

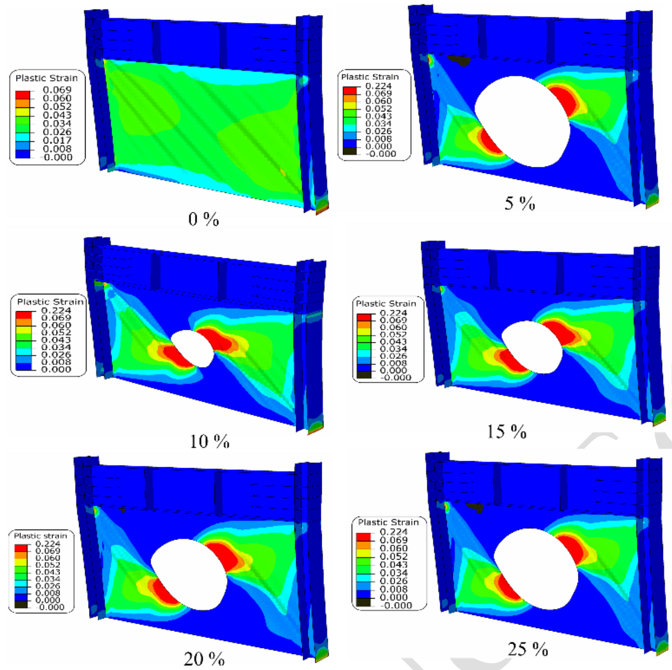


Fig. 11 Plastic strain contour results of models at different opening percentages

The hysteresis results of all models are illustrated in Fig. 12. For a more precise comparison of the models, key parameters were extracted from these diagrams, which are explained in the following sections. As shown in Fig. 13, with an increase in the opening dimensions, the shear force capacity decreases. To extract the bilinear diagram and determine the seismic parameters of the steel shear wall, the backbone diagram is obtained from the cyclic diagram and is shown in Fig. 13. This figure indicates that the specimen without an opening has a higher shear capacity and withstands the highest base shear at the final displacement.

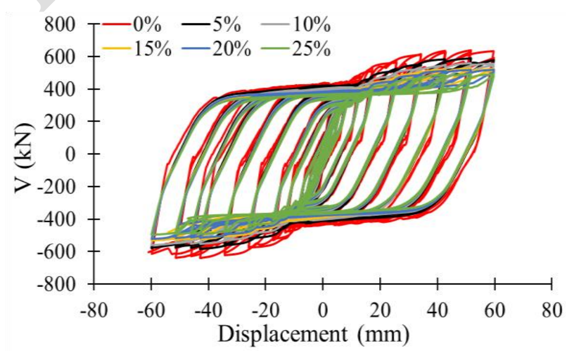


Fig. 12 Hysteretic curves for different opening configurations.

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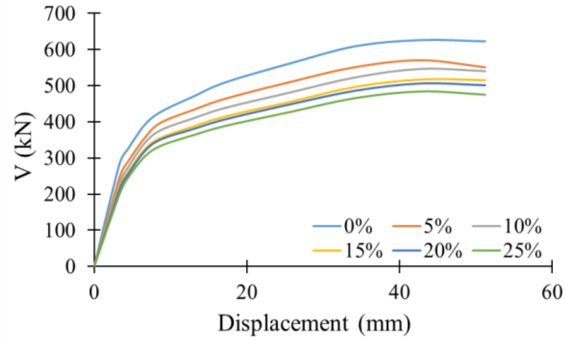

Fig. 13 Backbone curve for different openings.

To extract the parameters of elastic stiffness, strength, and ductility, bilinear diagrams were derived. An example of the shear wall without openings is illustrated in Fig. 14. Parameters of the shear wall without openings: strength is 623.56 kN, elastic stiffness is 83.23 kN/mm, and ductility is 8.78.

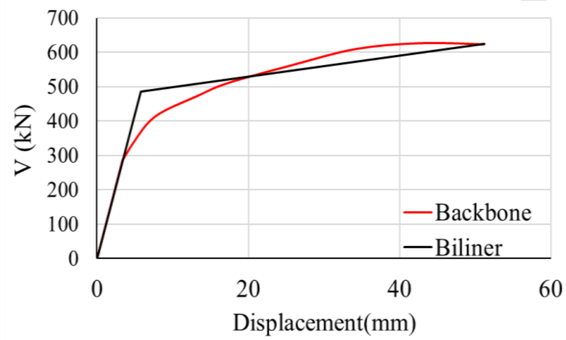

Fig. 14 Backbone and bilinear diagrams of the shear wall without an opening.

For all models, bilinear diagrams were similarly plotted, and these three parameters were extracted, which are further analyzed in the following sections.

Fig. 15 illustrates the maximum strength of the models relative to the opening percentage. The right vertical axis of this diagram represents the normalized results compared to the model without openings. It is observed that increasing the opening area reduces the model's strength nonlinearly. For instance, a model with 25% openings exhibits a 20% reduction in strength. To estimate the effect of opening area on strength, Eq. (1) was proposed. The results of this equation, shown in Fig. 15, demonstrate good agreement with the numerical results. In this equation, V, $V_{w/o}$, and A represent the strength of the model, the strength of the model without openings, and the percentage of the opening area, respectively. One of the advantages of these equations is the continuity of their results (as opposed to numerical results)(Cheraghi and TahamouliRoudsari, 2024).

$$V = V_{w/o}(1 - 0.87A) \quad (1)$$

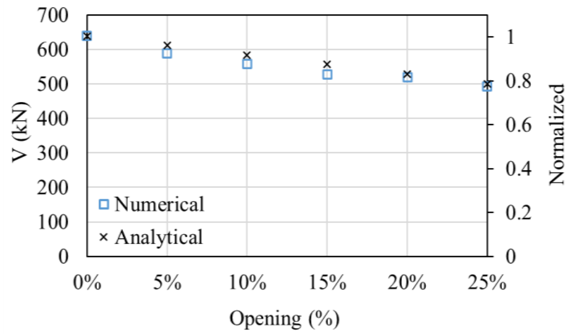

Fig. 15 Base shear relative to opening percentage.

The ductility results of the models are presented in Fig. 16. It is observed that increasing the opening area up to 20% has minimal impact on this parameter. However, the model with a 25% opening area results in a 50% reduction in ductility.

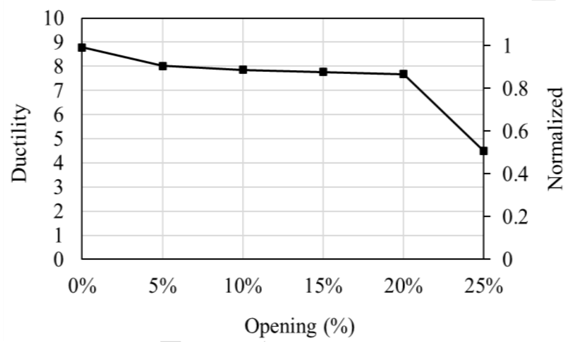

Fig. 16 Ductility relative to opening percentage.

Fig. 17 represents the stiffness of the shear wall as a function of the increase in opening dimensions. As evident in the figure, a noticeable change occurs in the initial stage when the shear walls transition from the state without an opening to the state with an opening. Additionally, as the dimensions of the opening increase, the stiffness decreases to a lesser degree compared to the base shear and ductility, with the decreasing path of the graph being approximately linear. A 25% increase in the opening area of the shear wall results in a 30% reduction in stiffness. To estimate this parameter, Eq. (2) was proposed based on curve fitting. The results of this equation and the numerical results are shown in Fig. 17. In this equation, Ke, $Ke_{w/o}$, and A represent the stiffness of the model, the stiffness of the model without openings, and the percentage of the opening area, respectively.

$$K_e = Ke_{w/o}(0.92 - 1.08A) \tag{2}$$

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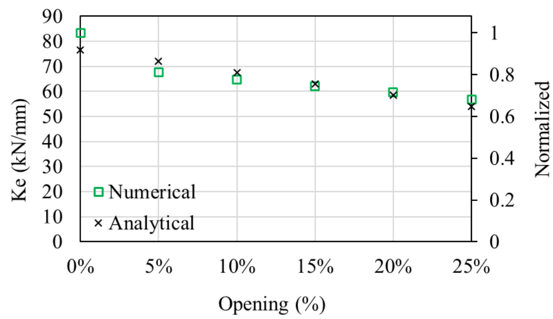

Fig. 17 Stiffness relative to opening percentage.

Fig. 18 presents one of the fundamental seismic diagrams. This diagram shows the results of ductility and normalized strength versus normalized stiffness. Based on this figure, by knowing the stiffness ratio of the model with openings to the model without, the percentage reduction in ductility and strength of the model can be estimated.

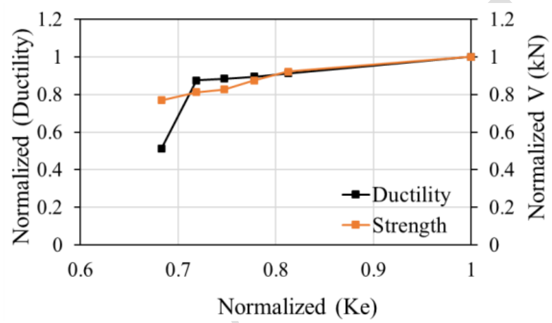

Fig. 18 The results of normalized ductility and strength versus normalized stiffness

To evaluate which parameter of the frame is most affected by the percentage of opening area, Fig. 19 was presented. This figure illustrates the normalized results for ductility, stiffness, and strength across various opening percentages. It is observed that, at 5% opening, the reduction in ductility and strength is equal, while stiffness experiences the greatest reduction. For models with 10% to 20% openings, stiffness shows the largest decrease, whereas ductility exhibits the smallest reduction. In the model with a 25% opening area, ductility undergoes the most significant reduction.

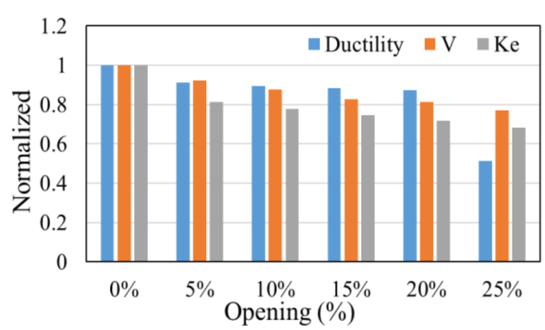

Fig. 19 The impact of the opening area on normalized results.

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5- Conclusions

In this study, experimental and numerical investigations were conducted to evaluate the effect of circular opening percentages in steel shear walls. Initially, two experimental steel frame specimens equipped with shear walls, one with and one without openings, were examined. Subsequently, numerical analyses were carried out to assess the impact of opening areas on the stiffness, strength, and ductility parameters of the walls. Furthermore, equations were proposed to estimate the stiffness and strength of the models, enabling the prediction of the influence of various opening percentages on these parameters. A summary of the findings from this research is presented in the following sections:

- The experimental hysteresis results continued without any degradation up to a displacement of 60mm for both the models with and without openings.
- The dimensions of the openings can have a direct relationship with the reduction in base shear. When less base shear is required, creating openings can reduce costs. Based on the results of this study, the reduction in base shear of the frame can be calculated given the opening percentage.
- In the design of steel shear walls with openings, using the provided relationships and knowing the required percentage of openings, the seismic parameters (base shear and stiffness) can be calculated.
- By comparing the effects of openings on stiffness, strength, and ductility, it was observed that stiffness is the most affected parameter for opening percentages of 5% to 20%, while ductility shows the least reduction. However, at 25% opening, ductility experiences the greatest decrease, indicating its sensitivity to larger openings.

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