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Research Article

Evaluation and Comparison of Seismic Performance in Perforated Steel Plate Shear Walls (PSPSW) with Regular Holes Using Modal Analysis

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Abstract:

Steel plate shear wall (SPSW) is one of the structural control devices that started to be used in Japan. Due to the concentration of critical plastic hinges in the boundary elements of the SPSW, engineers created holes in the inner plate so that the hinges can be transferred from the boundary elements to its internal areas, which is common to the PSPSW. Considering the increasing expansion of the PSPSW in the world's steel structures, in the present study, using the finite element modeling of the PSPSW with ABAQUS software, the effect of the number of holes (the inner plate has 16 and 32 circular holes), the cross-sectional area of the holes (the inner plate with holes with radius of 500, 1000 and 1500 mm) and the type of cross-section of the holes (circular, square and triangular), will be evaluated on the performance of the PSPSW. So, PSPSW are subjected to modal analyses in the frequency domain. The results showed that the increase in the number of circular holes in the inner plate has more effects on the von mises stress in lower vibration modes such as the 1st mode on the PSPSW, and its effect decreases with the increase of the vibration mode. Meanwhile, the increase in the number of circular holes and rotational displacement have a direct relationship in all vibration modes. Also, the increase in the cross-sectional area of the hole in the inner plate does not have a direct relationship with the stress and rotational displacement indices in the PSPSW. However, increasing the cross-sectional area of the hole to an appropriate amount, which is equal to 2 times in the current study, reduces the stress. Increasing the cross-sectional area to any extent increases the eigenfrequency in the PSPSW. Also, compared to circular and triangular holes, holes with a square cross-section lead to better performance of the PSPSW and lower stress, rotational displacement and eigenfrequency.

Keywords: *Steel Plate Shear Wall (SPSW), PSPSW, Modal Analysis in the Frequency Domain, Inner Plate, Circular Hole, FE Model.*

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1. Introduction

Steel plate shear walls (SPSW) have been used in the construction industry for several decades starting from the 1970's (Mahdavi, 2020). The use of these systems has increased significantly in the recent years due to research demonstrating SPSW behavior and inclusion in U.S. building codes. They are now being used not only in the high seismic areas, but also for wind and low seismic applications (Deylami and Rowghani-Kashani, 2011). SPSW are commonly used for structures with moderate wall lengths. SPSW are suitable not only for high rise buildings but also for mid-rise construction. As per the recent research in this field (Berman and Bruneau, 2003), it is shown that SPSW may be used for the retrofit of existing structures as well as installation in new buildings. SPSW system consists of steel infill plates bounded by boundary elements such as beams and columns. SPSW are known for their high ductility and energy dissipation capabilities, making them an effective solution for seismic force-resisting systems. It consists of a thin steel web-plate bounded by a surrounding portal frame, which includes horizontal and vertical boundary elements (Balkamou and Papagiannopoulos, 2024). The web-plates are designed to buckle in shear under low lateral loads and develop tension field action, providing ductility and energy dissipation. The design of SPSW is governed by codes such as ASCE 7-10 and AISC 341-10. These codes assume that the web-plates resist the entire design base shear, which can lead to uneconomical designs due to oversized boundary elements. Selecting a dual system where boundary elements carry at least 25% of the base shear can result in more cost-effective designs (AlHamaydeh et al., 2023). SPSW under seismic loading has critical stresses in columns and beam-to-column intersection. Today, structural engineers use regular holes in the inner plate of the SPSW system to reduce the aforementioned stresses (Ibrahim et al., 2024). SPSW with holes is known as PSPSW. These holes are placed for the following reasons:

- Due to the creation of plastic hinges in the internal parts of the SPSW system and preventing the creation of plastic joints in the boundary elements (weakening the SPSW section). If a plastic joint is formed in the boundary element (columns), a strong drop in strength will occur in the structure (Tan et al., 2021; Bal et al. 2017).
- The steel shear wall easily buckles under compressive stress due to its thinness. Due to the thinness of the sheet, its buckling is a dangerous buckling and must be reinforced with a stiffener. This will reduce the buckling of the wall. Also, the creation of holes in the inner plate causes the buckling to change from the general state to the buckling between the holes (Kordbegli et al., 2022; Bal et al. 2017). In Figure 1, the state of stresses in a filler plate at different stages of loading in the SPSW system is shown.

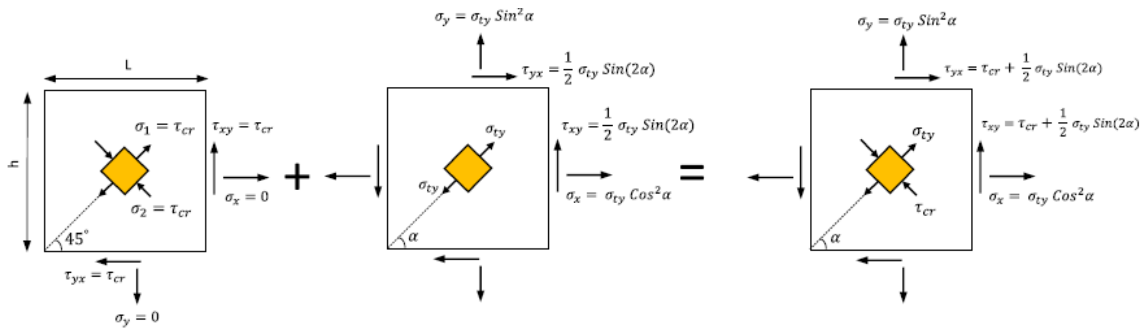

Figure 1- Stresses in a filler plate at different stages of loading in the SPSW system (Farahbakhshtooli and Bhowmick, 2021)

Some investigations including (Balkamou and Papagiannopoulos, 2024; He et al., 2023; Bai et al. 2018) investigated the integrated SPSW system (without holes). Some investigations such as (Bagherinejad and Haghollahi, 2019), (Farahbakhshtooli and Bhowmick, 2021), (Mansouri et al., 2021), (Zarrinkolaei et al., 2021), (Majlesi et al., 2022) and (Hosseinzadeh and Seddighi, 2024) have investigated the effect of circular holes in the inner plate on the performance of the SPSW system. Some studies such as (Sabouri-Ghomi et al., 2008), (Mahdavi, 2020), (Wang et al., 2023) and (Moradi et al., 2020) have investigated the effect of rectangular holes in the inner plate on the behavior of the SPSW system. Some studies including (Wang et al., 2023) and (Verma et al., 2019) have investigated the effect of elliptical holes in the inner plate on the PSPSW system. In Table 1, a summary of the important studies conducted on the PSPSW system is presented.

Table 1- A summary of the investigation about the effects of holes on SPSW systems

Authors (Year)	Name	Object	Investigated Parameters	Type of Research
Afshari and Gholhaki (2018)	Shear strength degradation of SPSW with optional located opening	Study of shear strength of SPSW with openings in different zones	Shape, diameter, location and h/b ratio of SPSW	Numerical
Bagherinejad and Haghollahi (2019)	Topology optimization of PSPSW with thick plate in simple frames	Topology optimization to determine the form, size and location of holes for the special form of PSPSW	Effects of deformation, surface and location of holes in the inner plate	Numerical
Verma et al. (2020)	Effect of openings in stiffened steel plate shear walls using ANSYS	Investigating effect of openings in stiffened SPSW using ANSYS	Internal steel plates with circular and rectangular holes	Numerical
Farahbakhshtooli and Bhowmick (2021)	Nonlinear seismic analysis of PSPSW using a macro-model	Developing a reliable macro-model for regularly spaced circular perforations	Peak column axial forces, peak column bending moments, and maximum inter-storey drift	Numerical
Zarrinkolaei et al. (2021)	Numerical assessment of effect of opening on behavior of perforated steel shear walls	Parametric study to examine the effect of circular and elliptical openings in the SPSW	Arrangement, layout, and number of these openings on the structural behavior, total load-carrying capacity of the system and resulting stress distribution	Numerical
Mansouri et al. (2021)	On the design of PSPSW, an experimental and numerical study	Design of PSPSW	Increasing the surface of the holes in the inner plate	Numerical-Experimental
Hassani and Javanbakht (2021)	Effect of geometrical variations on the failure mechanisms of PSPSW-a parametric study towards a new design	Effect of geometrical variations on the failure mechanisms of PSPSW	Arrangement by various geometrical modifications	Numerical
Majlesi et al. (2022)	On the seismic evaluation of steel frames laterally braced with PSPSW considering semi-rigid connections	Seismic evaluation of steel structures laterally braced with perforated SPSW	Circles with three different diameters	Numerical
Zhao et al. (2023)	Theoretical and experimental investigations of steel plate shear walls with diamond openings	Investigation of SPSW equipped with diamond-shaped openings	Evaluated of strength, stiffness, hysteretic performance, energy dissipation capability and equivalent damping ratio of the SPSW	Numerical - Experimental
Wang et al. (2023)	Lateral behavior of SPSW with cold-formed steel strips reinforcing door opening	Propose reinforcement of SPSW with door openings using prefabricated cold-formed steel strips	One SPSW with a door opening in the centre, and another with the door opening positioned at its edge	Numerical-Experimental
Wang et al. (2023)	Numerical modeling of seismic behavior of ellipse and peanut-shaped auxetic SPSW	Investigating seismic behavior of ellipse and peanut-shaped auxetic SPSW	Investigating seismic behavior of ellipse and peanut-shaped auxetic SPSW	Numerical

In the present study, using the finite element method (FEM) and software modeling, it has been tried to investigate the effects of the presence of holes in the inner plate of the PSPSW system. In the worldwide studies about the PSPSW system, usually various parameters such as hole surface, hole shape, hole distance to each other, hole location and other similar factors have been investigated. Therefore, in the current study, it has been tried to examine all these effects completely, so that the results of the study are comprehensive and integrated. Also, in common studies in the world, sequential structural analysis methods such as static and dynamic are used, but in the present study, the buckling analysis method is used to analyze the PSPSW system, is used. The results of this analysis show the buckling of the PSPSW in different vibration modes and determine the strengths and weaknesses of the structural system in possible buckling conditions. The stated items are some of the innovations of the present study and other items can be seen and reviewed in the present study.

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2. PSPSW Finite Element Modeling

In this section, the general steps in software modeling with ABAQUS software are presented and explained, which include the following:

- Step 1: Creating PSPSW system elements

In the present study, PSPSW system has two columns, one beam and one inner plate. The PSPSW has 1-story, with a height of 4000 mm and span length of 6000 mm. Column and beam elements have "HE" and "IPE" sections, respectively. The specifications of the sections used in the modeling can be seen in Figure 2.

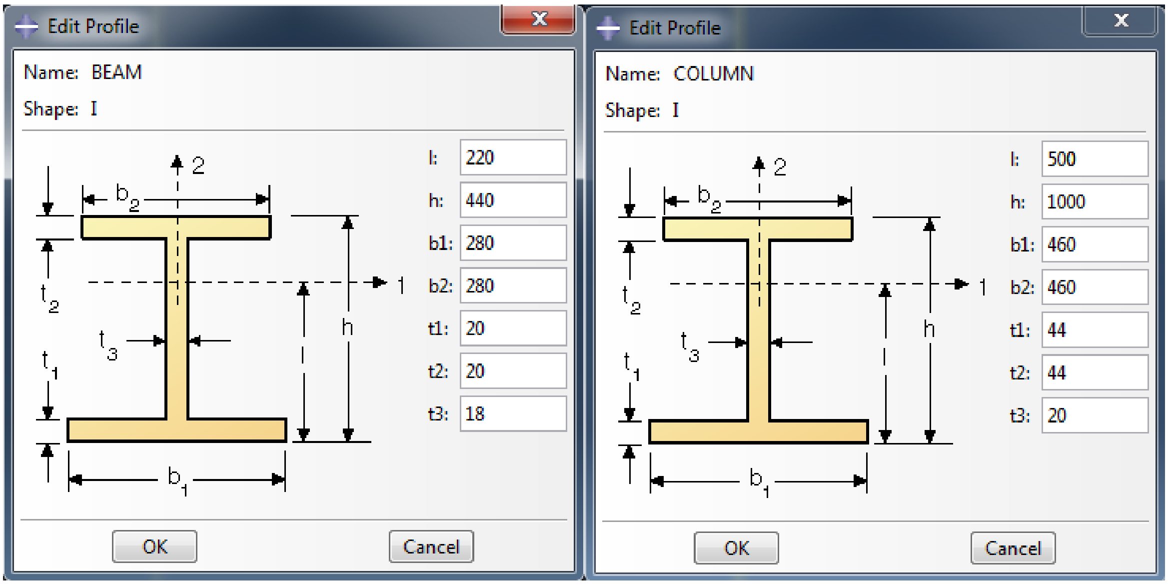


Figure 2- The sections used in the beam and column elements in the software modeling of the present study using ABAQUS software (All units: mm)

- Step 2: Defining the materials, dividing the sections and assigning to the members

St37 steel was used in the software modeling, the specifications of which are presented in Table 2. Also, the sections used in the members were presented in Figure 2. The inner plane is defined as a shell with homogeneous type.

Table 2- St37 steel used in the modeling of PSPSW members

Material	Characteristics	Elastic		Plastic	
Steel	Density (Kg/m^3)	Young's Modulus	Poissons's Ratio	Yield Stress	Plastic Strain
	0.000078	200000	0.3	345	0
				450	0.105

- Step 3: Assembling members

Columns, beams and inner plate are placed in the right place and PSPSW system is created.

- Step 4: Meshing

PSPSW members were meshed with the smallest values equal to 0.01 member length. It should be stated that meshing is one of the most important steps in performing an accurate simulation using the finite element method. The mesh consists of elements that contain nodes and represent the shape of the geometry. An FEA solver cannot work easily with irregular shapes and it is better to use cubic shapes. Meshing is the process of converting irregular shapes into more defined volumes.

- Step 5: Integration of all members and structure specifications

In this section, using the Merge command in the Assembly module, all members and their structural specifications are integrated. The final integrated structure can be seen in Figure 3.

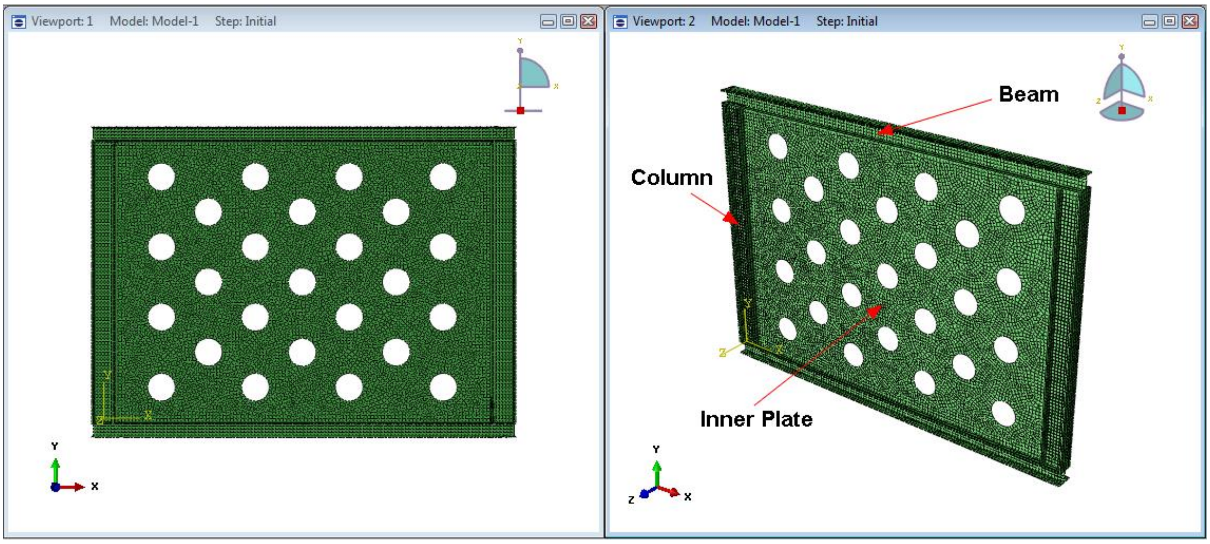


Figure 3- PSPSW system integrated in ABAQUS software

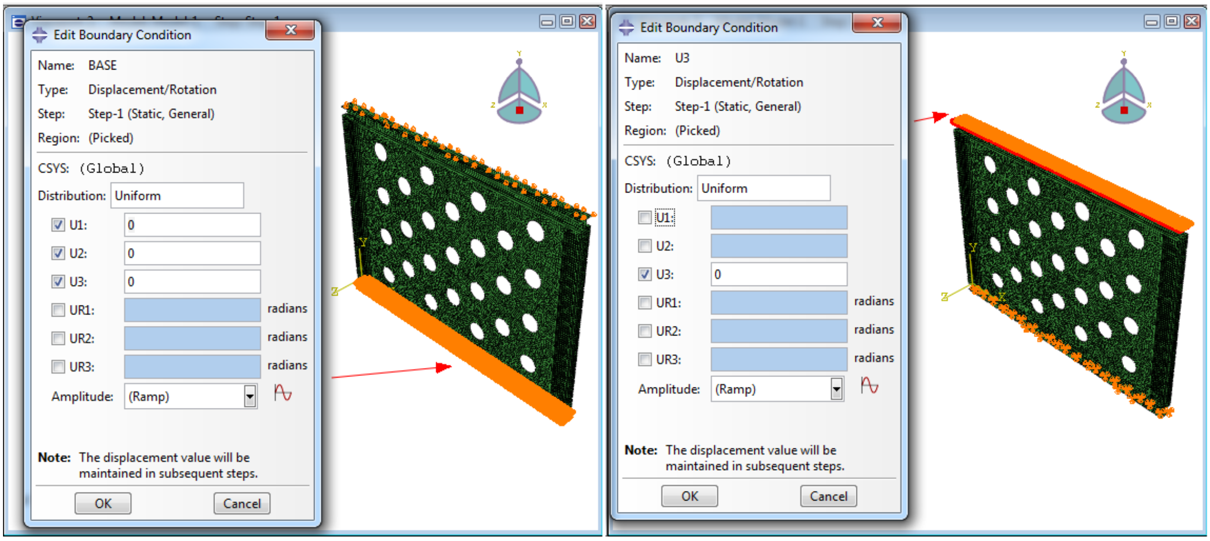
After the integration of the PSPSW system, the whole structure becomes a flat plate, which can be seen in Figure 3.

- Step 6: Creating supports

The SPSW system has a hinged support in the lower part (Base) and pinned support in the upper beam (U3). The specifications of the supports are presented in Figure 4.

- Step 7: Definition of modal analysis in the frequency domain

In the present study, the structural analysis is of modal type in the frequency domain. Therefore, 30 vibration modes of the SPSW system were investigated and the maximum number of iteration in the analysis was considered equal to 30. The specifications of the type of analysis and its definition are presented in Figure 5.



(a) **(b)**

Figure 4- Creating supports in the SPSW system (a) Lower support and (b) Upper support

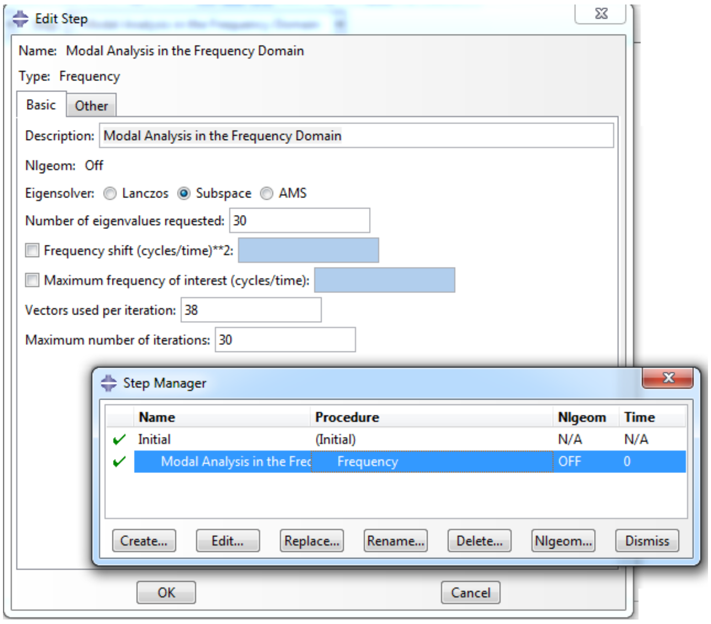


Figure 5- How to create analysis type in ABAQUS software

After performing the stated steps, structure analysis is done. The models examined in the present study are presented in Figure 6. The diameter of all the holes is equal to 200 mm. In Figure 6, small circular holes (in PSPSWN16, PSPSWN32 and PSPSWC models) have a diameter of 200 mm. The distance from the center to the center of the holes in the PSPSWN16 model is 1500 mm. The holes diameter in PSPSWR500, PSPSWR1000 and PSPSWR1500 models is 500, 1000 and 1500 mm, respectively. In the PSPSWS model, the cross section is square and the sides of the square are equal to 200 mm. In the PSPSWT model, the cross section is triangular with three equal sides equal to 320 mm.

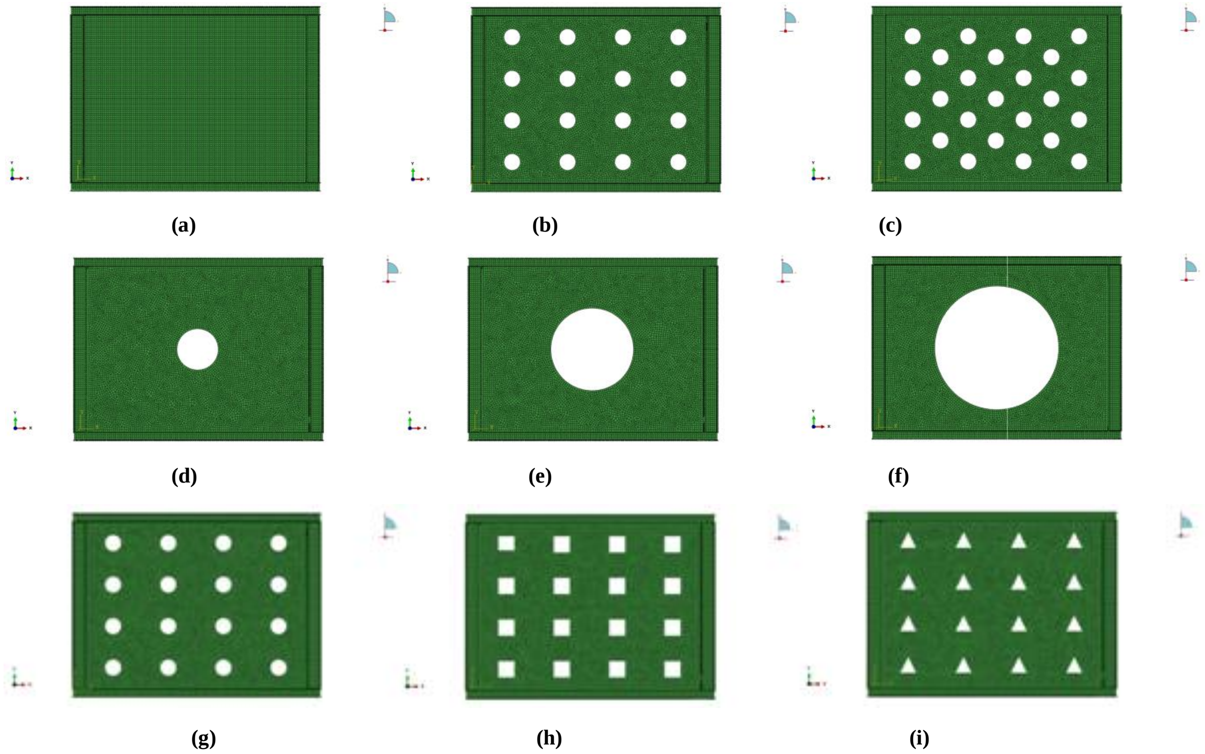


Figure 6- FE models in the present study (a) SPSW, (b) PSPSWN16, (c) PSPSWN32, (d) PSPSWR500, (e) PSPSWR1000, (f) PSPSWR1500, (g) PSPSWC, (h) PSPSWS and (i) SPSWT

In general, the yield strength of the SPSW when it flows, which is the ultimate load limit, is determined by Equation (1):

$$V_w = bt(\tau_{cr} + \frac{1}{2}\sigma_0 \sin 2\theta) \quad (1)$$

The parameters in Equation (1) are as follows:

σ_0: Yield stress of steel plate in uniaxial tensile test,

τ_{cr}: The critical shear stress of the plate is calculated according to Equation (2),

t: Thickness of steel plate,

b: Shear wall width,

θ: The angle of the generated tensile field (Gholhaki et al., 2021).

$$(2)\quad \tau_{cr} = \frac{k\pi^2 E}{12(1-\mu^2)}\left(\frac{t}{b}\right)^2$$

$$(3)\quad \begin{cases} k = 5.35 + 4\left(\frac{b}{d}\right)^2 & if \quad \frac{d}{b} \geq 1 \\ k = 4 + 5.35\left(\frac{b}{d}\right)^2 & if \quad \frac{d}{b} \leq 1 \end{cases}$$

In Equation (2), the parameters are as follows:

μ: Poisson's coefficient of steel plate,

d: Shear wall height,

E: Modulus of elasticity,

k: It is calculated based on Equation (3) (Gholhaki et al., 2021).

In general, if the damping in the system with one degree of freedom is represented by the damping matrix, the equation of motion is according to Equation (4):

$$(4)\quad [M]\{\ddot{x}\} + [C]\{\dot{x}\} + [K]\{x\} = \{0\}$$

In Equation (4), the parameters are as follows:

M: The mass matrix,

C: The damping matrix,

K: The stiffness matrix,

x: The displacement vector,

$\dot{x}$: The velocity vector,

$\ddot{x}$: The acceleration vector (Mahdavi et al., 2023).

The solution for Equation (4) is in terms of eigenvalues and eigenvectors. Special vectors show vibration modes. The generalized mass matrix is defined in Equation (2):

$$(5)\quad \hat{m} = \varphi^T M \varphi$$

In Equation (5), the parameters are as follows:

$\hat{m}$: The system's generalized mass matrix,

φ : The eigenvector matrix,

φ^T : Transducer of the matrix φ (Mahdavi et al., 2023).

The influence vector examines a rigid body motion in all modes. Define a coefficient vector $\bar{L}$ as:

$$(6)\quad \bar{L} = \varphi^T M \bar{r}$$

In Equation (6), the parameters are as follows:

$\bar{L}$: The coefficient vector,

$\bar{r}$: The influence vector.

The modal participation factor matrix Γ_i for mode i is:

$$\Gamma_i = (\bar{L}_i / \hat{m}_{ii}) \quad (7)$$

In Equation (7), the parameters are as follows:

Γ_i : The modal participation factor matrix.

The effective modal mass (m_{eff}), for mode i is:

$$m_{eff,i} = (\bar{L}_i^2 / \bar{m}_{ii}) \quad (8)$$

In Equation (8), the parameters are as follows:

m_{eff} : The effective modal mass (Mahdavi et al., 2023).

3. Results

In this section, the results of analyzes performed on the FE software models are presented. Considering that the focus of the research is on the performance of the inner plate, therefore, the analyses results are displayed in the element of the inner plate.

3.1. Verification

In the present study, the verification of the modeling has been done using Wang and Xie (2019). The mentioned study is titled "Experimental and numerical investigation of steel beam-to-CFST column frame-thin steel plate shear walls with cross stiffness". In the reference study, 2 laboratory models were made, which can be seen in Figure 7.

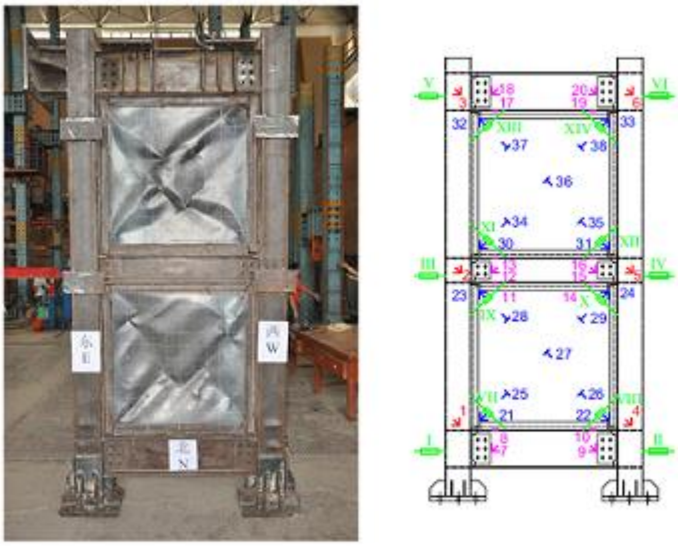


Figure 7- Laboratory model and its schematic in Wang and Xie (2019)

To verification the modeling in the present study, FE model was made from the laboratory sample in Wang and Xie (2019), which can be seen in Figure 8. Cyclic loading was applied to the software model.

After performing the structural analysis and applying the load on the FE model, the stiffness of the SPSW system was investigated. In Figure 9, the comparison of stiffness in the models in the study of Wang and Xie (2019) and the present study is presented. To perform validation, SPSW-BS is modeled.

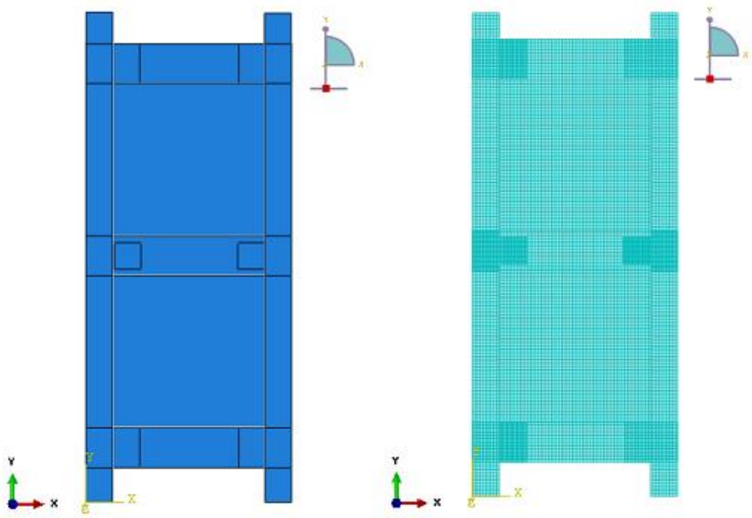
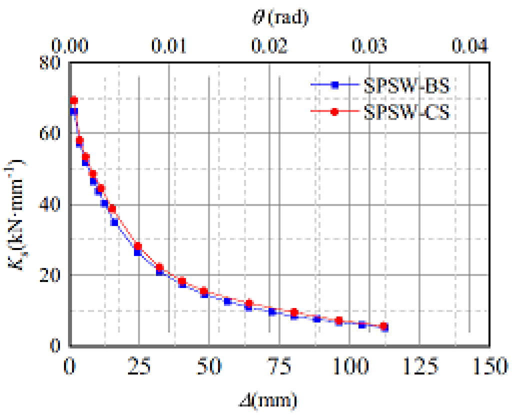
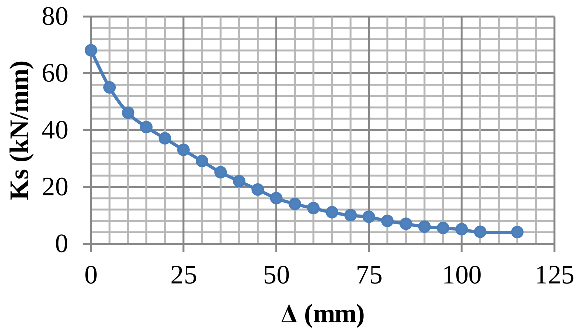


Figure 8- FE model from the laboratory sample of Wang and Xie (2019) for verification using ABAQUS



(a)



(b)

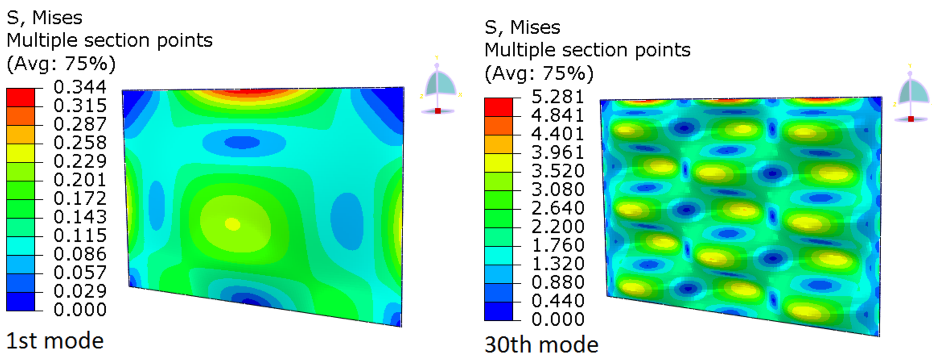
Figure 9- Verification of the software model (a) Current study and (b) Wang and Xie (2019)

The numerical evaluation of the results showed that the rate of change in the reference article and the current research is about 2.1%. Therefore, the modeling is confirmed.

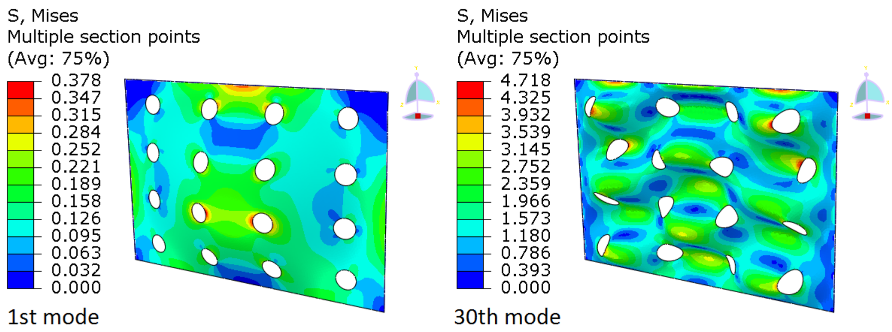
3.2. Effects of Increasing the Number of Holes

In this section, 3 structural systems including SPSW, PSPSWN16 and PSPSWN32 will be evaluated to determine the effects of creating holes and increasing them on the performance of the structural system.

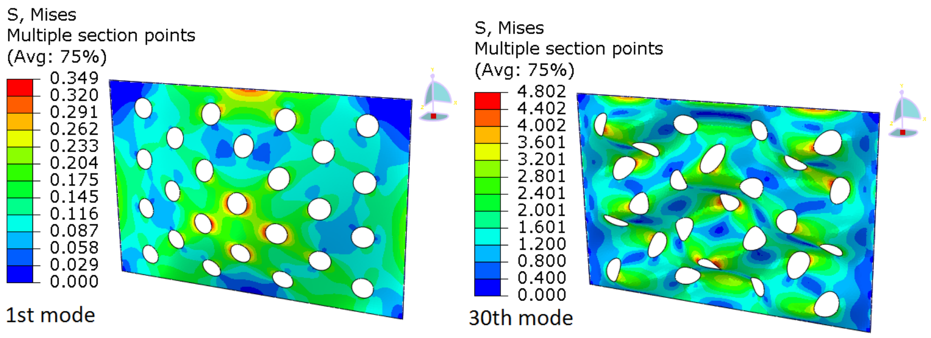
3.2.1. Von Mises Stress



(a)



(b)

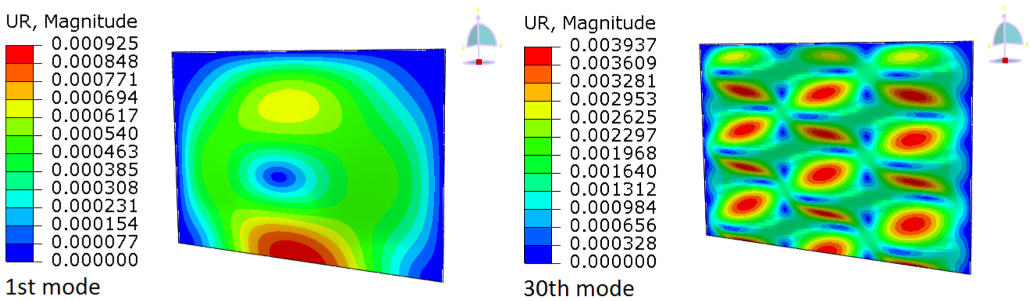


(c)

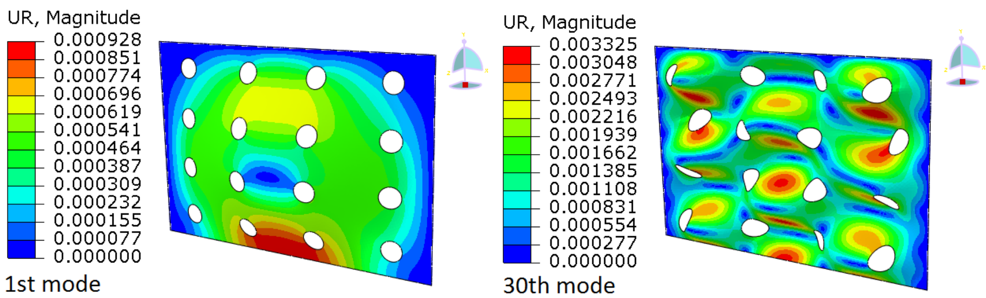
Figure 10- Von Mises stress in FE models (a) SPSW, (b) PSPSWN16 and (c) PSPSWN32 using modal analysis in the frequency domain

Figure 10 showed that the creation of holes in the inner plane increases the von mises stress in the first vibration mode. However, the maximum stress level decreases around the inner plane and creates circular holes around it. This result is completely reversed in mode C. Therefore, creating holes in the inner plane has reduced the von mises stress. This trend was also present in other vibration modes of the PSPSW system

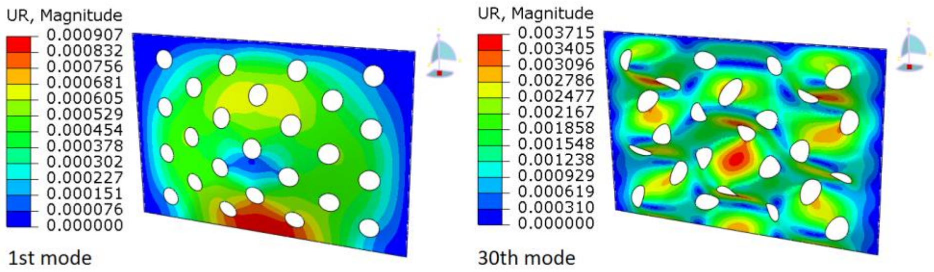
3.2.2. Rotational Displacement



(a)



(b)



(c)

Figure 11- Rotational displacement in FE models (a) SPSW, (b) PSPSWN16 and (c) PSPSWN32 using modal analysis in the frequency domain

Figure 11 showed that in the first vibration mode, increasing the number of holes in the inner plate did not cause specific changes in the rotational displacement. In fact, the PSPSWN16 model has more rotational displacement compared to the PSPSWN32 model. Therefore, conclusions cannot be made in this vibration mode. But in the 30th vibration mode, increasing the number of holes in the inner plate has reduced the rotational displacement. Also, the increase in the number of holes has reduced the maximum rotational displacement level, which exerts less compressive forces on the inner plate. However, there is no clear trend between the increase in the number of holes and the rotational displacement index.

3.2.3. Eigenfrequency

Figure 12 show that increasing the number of holes in the inner plate of the steel plate shear wall has effects on its frequency content. The results showed that the increase in the number of holes has reduced the specific frequency content. The total specific frequency in SPSW, PSPSWN16 and PSPSWN32 systems is 2.08702879, 2.04929381 and 2.00429781 MHz, respectively.

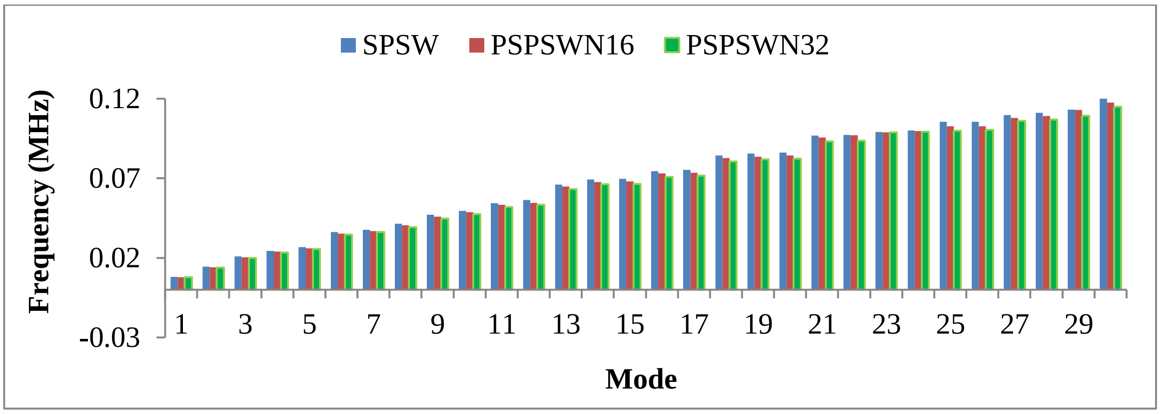
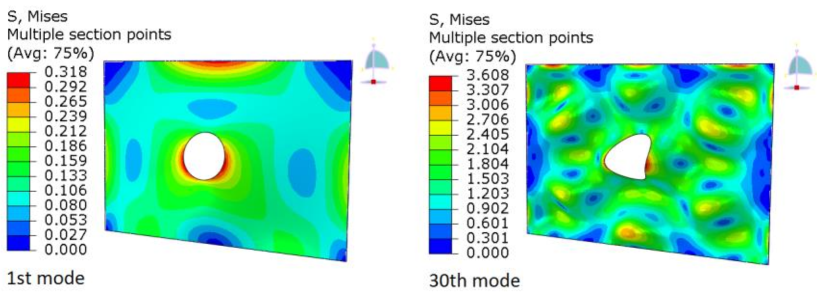


Figure 12- Eigenfrequency in FE models (a) SPSW, (b) PSPSW1 and (c) PSPSW2 using modal analysis in the frequency domain

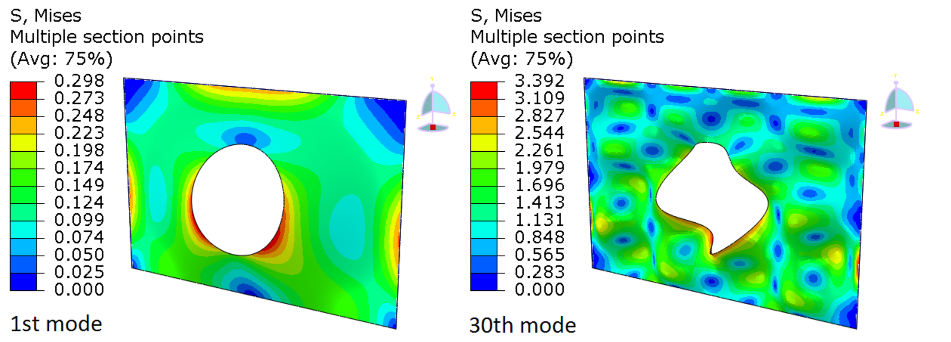
3.3. Effects of Increasing the Hole Area

In this section, the area of the hole in the inner plane will increase exponentially and its effect on the performance of the structure will be determined. For this purpose, 3 structural systems including PSPSWR500, PSPSWR1000 and PSPSWR1500 will be investigated.

3.3.1. Von Mises Stress



(a)



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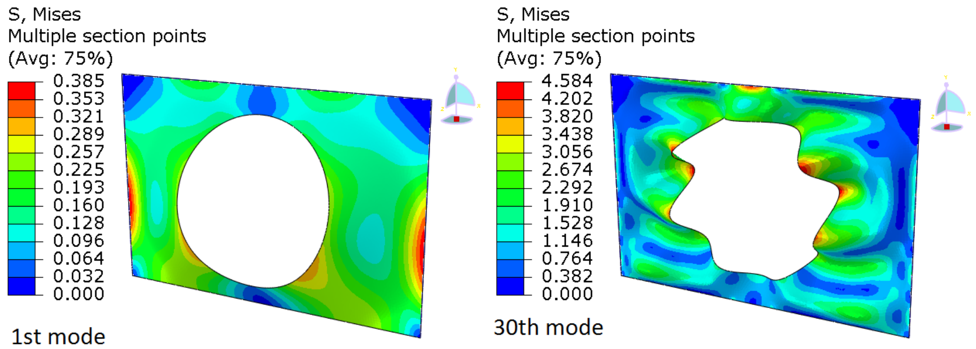
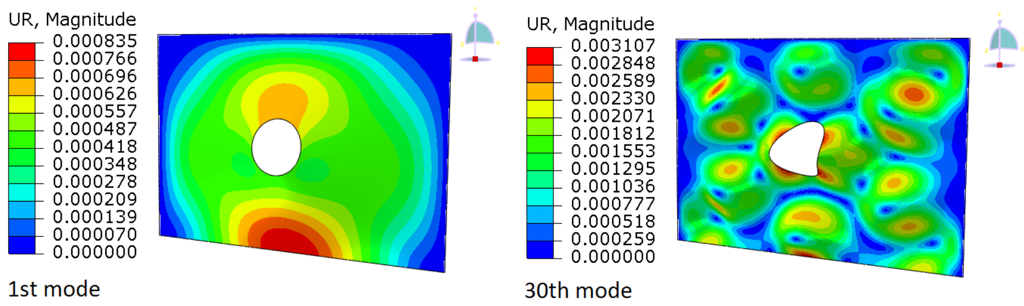


(c)

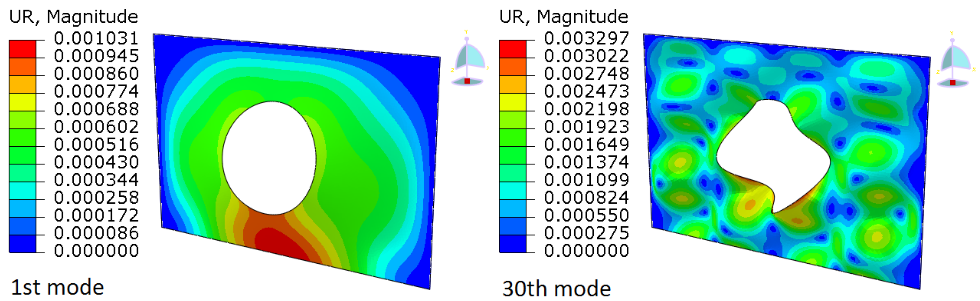
Figure 13- Von Mises stress in FE models (a) PSPSWR500, (b) PSPSWR1000 and (c) PSPSWR1500 using modal analysis in the frequency domain

Figure 13 showed that increasing the cross-sectional area of the hole in the inner plate causes the von mises stress to change a lot. In 1st mode and 30th mode, the lowest and highest stress was created in PSPSWR1000 and PSPSWR1500 models, respectively. By examining the results in other vibration modes, it was found that the effect of holes on stress changes increases in high modes. In fact, as the vibration modes increase, the creation of holes causes a numerical reduction of the maximum stress and the transfer of the maximum stress from the boundary elements (beams and columns) to the inner plate.

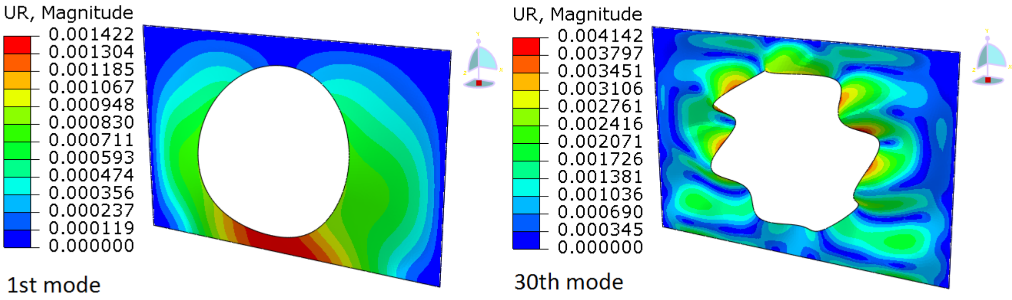
3.3.2. Rotational Displacement



(a)



(b)



(c)

Figure 14- Rotational Displacement in FE models (a) PSPSWR500, (b) PSPSWR1000 and (c) PSPSWR1500 using modal analysis in the frequency domain

Figure 14 showed that increasing the surface of the hole in the inner plate increased the rotational displacement. In the 1st vibration mode, by doubling and tripling the surface of the cavity, an increase of 23.47% and 70.3% has been created in the rotational displacement index, respectively. In the 30th vibration mode, by doubling and tripling the cavity surface, 6.12% and 33.31% increase in the rotational displacement index has been created, respectively. The results in software analyses showed that the process of changes in rotational displacement in other vibration modes was also the same.

3.3.3. Eigenfrequency

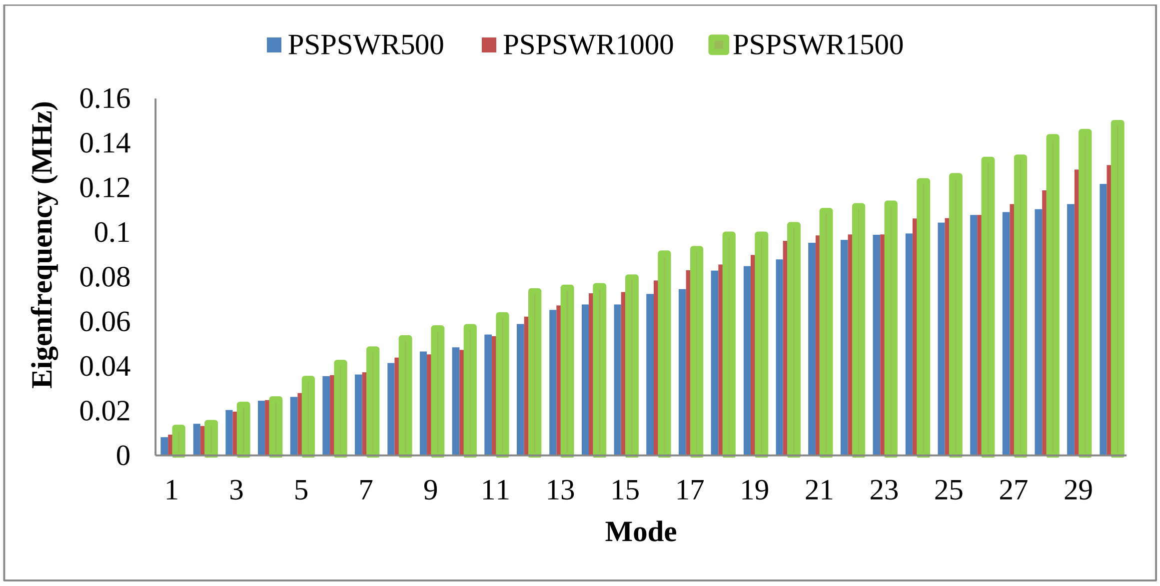


Figure 15- Eigenfrequency in FE models (a) PSPSWR500, (b) PSPSWR1000 and (c) PSPSWR1500 using modal analysis in the frequency domain

Figure 15 showed that increasing the cross-sectional area of the hole in the inner plane caused an increase in the specific frequency. This result is present in all the investigated vibration modes. Numerical analysis showed that the sum of specific frequency in 30 investigated vibration modes in PSPSWR500, PSPSWR1000 and PSPSWR1500 models are equal to 2.07477734, 2.17421424 and 2.5024743 MHz respectively. Therefore, doubling and tripling the cross-sectional area of the cavity in the inner plate has caused a 4.79% and 20.61% increase in the specific frequency, respectively.

3.4. Effects of Cross Section Chanage

In this section, 3 types of cross-sections in holes including circular, square and triangular will be examined. Therefore, 3 structures including PSPSWC, PSPSWS and PSPSWT will be investigated.

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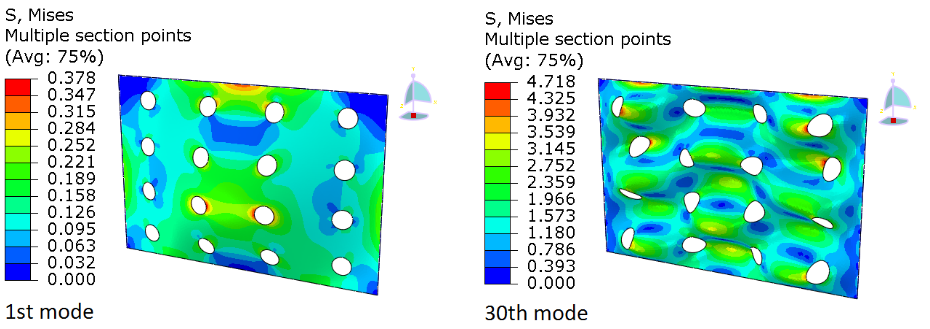
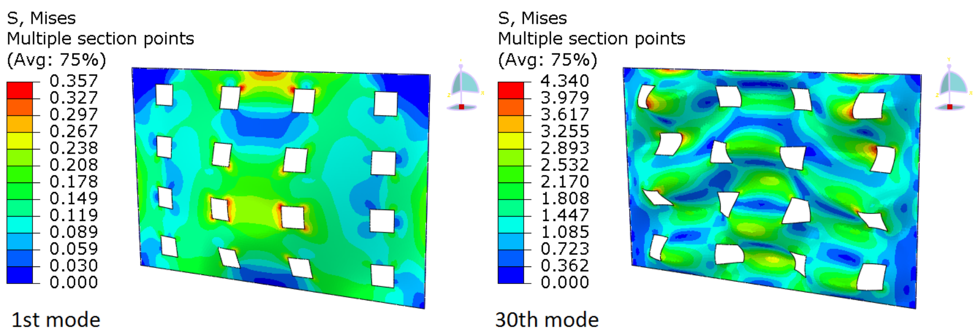
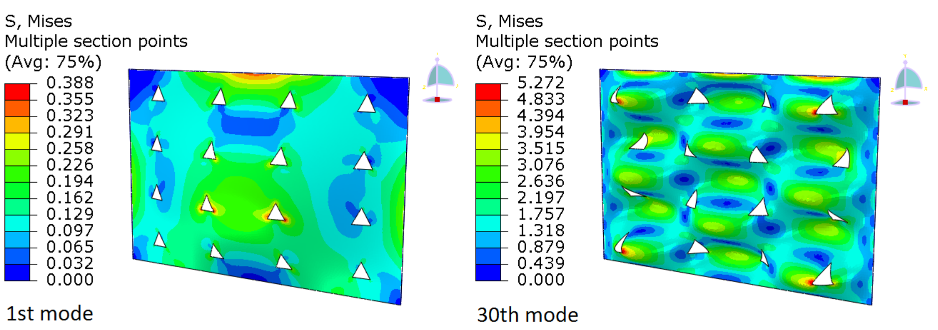
3.4.1. Von Mises Stress



(a)



(b)

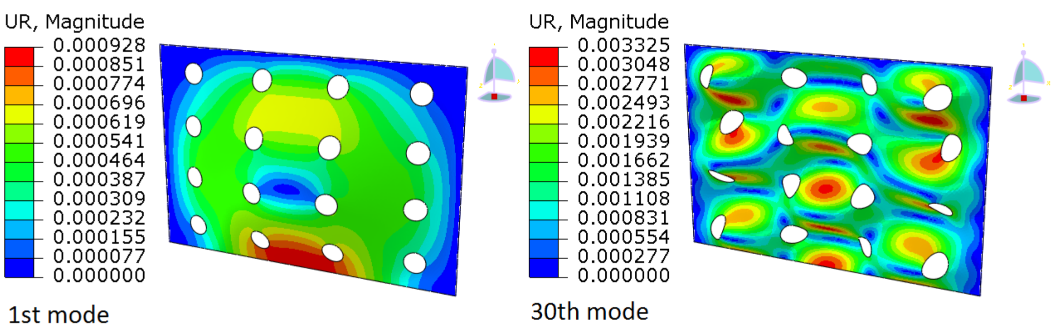


(c)

Figure 16- Von Mises stress in FE models (a) PSPSWC, (b) PSPSWS and (c) PSPSWT using modal analysis in the frequency domain

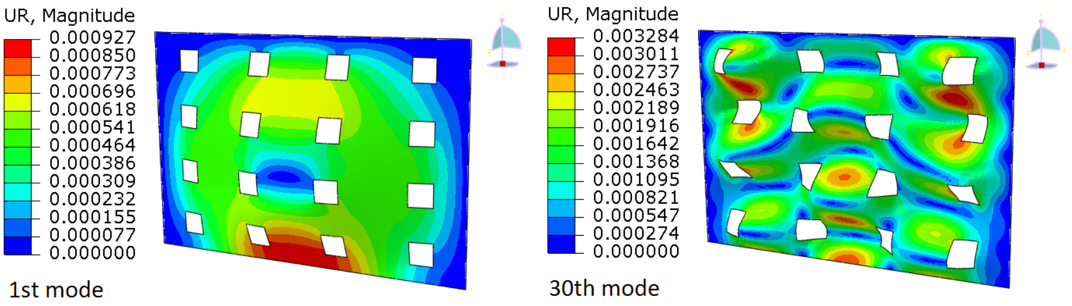
Figure 16 showed that the internal cavity with a square cross section caused the lowest von mises stress in the shear wall of the steel plate. The presence of a hole with a square section, compared to circular and triangular sections, has caused a 5.92% and 8.69% reduction in the stress index, respectively. The distribution of stress in all three types of cross section is almost uniform and the amount of stress has changed with the change of the cross section of the holes.

3.4.2. Rotational Displacement

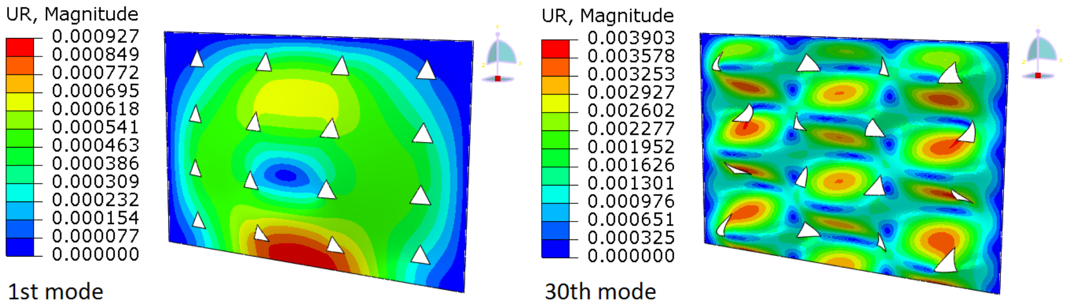


https://doi.org/10.22034/cpj.2024.467584.1306

(a)



(b)



(c)

Figure 17- Rotational displacement in FE models (a) PSPSWC, (b) PSPSWS and (c) PSPSWT using modal analysis in the frequency domain

Figure 17 showed that the internal cavity with a square cross-section caused the least rotational movement in the structure. The existence of holes with a square cross-section compared to circular and triangular cross-sections has decreased by 0.98% and 12.67%, respectively. Also, holes with a square cross-section have reduced the rotational displacement distribution level compared to other holes in the steel plate.

3.4.3. Eigenfrequency

Figure 16 show that the internal cavity with a square cross section caused the lowest specific frequency with a total of 2.02847841 MHz in modes 1 to 30. The total frequency in the structure with circular and triangular holes in 1st to 30th mode is equal to 2.04929381 and 2.04334311 MHz, respectively. Therefore, the presence of square holes has caused a 1.02% and 0.73% decrease in the total specific frequency, respectively, compared to circular and triangular holes.

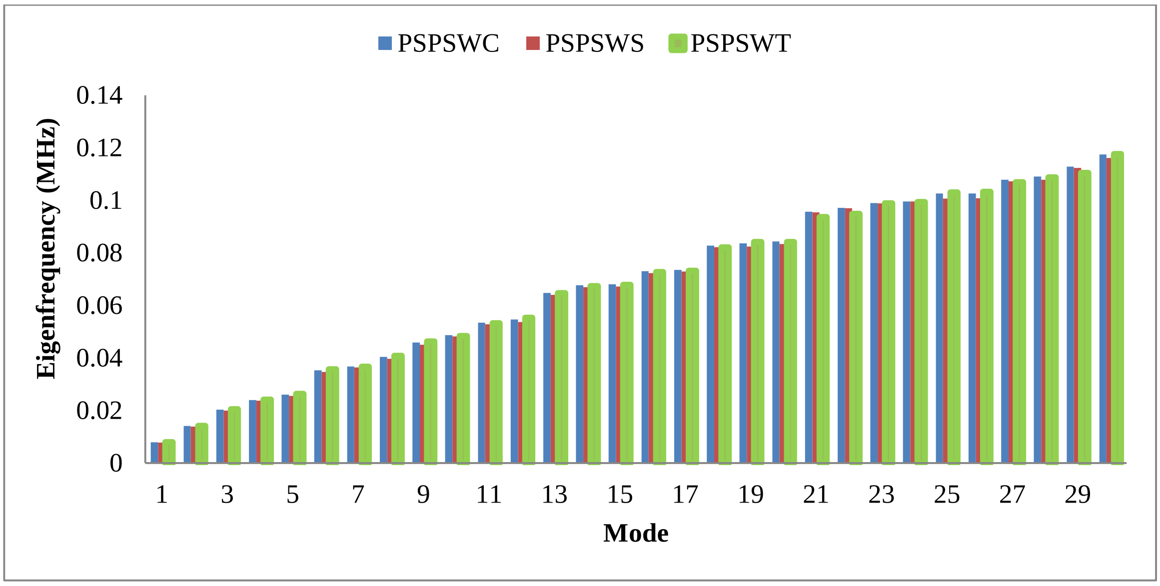


Figure 18- Eigenfrequency in FE models (a) SPSWC, (b) PSPSWS and (c) PSPSWT using modal analysis in the frequency domain

4. Conclusion

In the present study, it was tried to evaluate the effect of regular holes in the inner plate on the PSPSW system. For this purpose, holes with circular, square and triangular sections were placed in the finite element models of the structure and the software models were subjected to modal analysis in the frequency domain. The most important results of this research are as follows:

- The creation and increase of the number of circular holes in the internal plate in the PSPSW system, in low vibration modes such as 1st mode, is much more than in higher modes such as 30th mode, on the process of von mises stress changes.
- Creating and increasing the number of circular holes in the internal plate in the PSPSW system does not cause constant changes in low vibration modes such as 1st mode. However, in higher vibration modes such as mode 30, the creation of holes in the inner plane will definitely reduce the von mises stress, which has no specific relationship with the number of holes.
- Creating and increasing the number of circular holes in the internal plate in the PSPSW system, in low vibration modes such as 1st mode, increases the rotational displacement. However, in higher vibration modes such as 30th mode, the creation of holes will definitely reduce the rotational displacement. In general, there is no clear relationship between the number of holes and the rotational displacement changes in the above modes.
- Creating and increasing the number of circular holes in the internal plate in the PSPSW system will reduce the specific frequency in all vibration modes. Therefore, there is an inverse relationship between the number of holes and the special frequency in the PSPSW system.
- Increasing the cross-sectional area of the circular holes in the internal plate in the PSPSW system by 2 times reduces the von mises stress and increasing it by 3 times increases the stress. This trend holds in all vibration modes. Therefore, increasing the cross-sectional area to an appropriate amount, which will be done in future researches, will reduce the stress and reduce the probability of failure in the structural system. However, an excessive increase in the surface of the hole causes an excessive decrease in the hardness of the element and an increase in its failure.
- Increasing the surface of the circular holes in the internal plate in the PSPSW system increases the rotational displacement in all vibration modes and there is a direct relationship between the surface of the holes and the rotational displacement in the PSPSW system.
- Increasing the surface of the circular holes in the internal plate in the PSPSW system increases the specific frequency in all vibration modes and there is a direct relationship between the surface of the holes and the specific frequency in the PSPSW system.
- Holes with a square cross-section cause the greatest reduction in von mises stress, rotational displacement and specific frequency indices in the PSPSW system, compared to circular and triangular holes.

Conflict of Interest

No conflicts of interest are disclosed by the authors.

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