ORIGINAL RESEARCH

Study of Scale Effect on Seismic Performance of Steel Plate Shear Wall under Cyclic Loading

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Abstract:

Through recent years, several types of research have been performed about steel plate shear walls numerically, experimentally, and a combination of these two methods. Scaled samples have been implemented to make transportation and movement processes easier. However, the accuracy of models with real scale is of concern. This research was performed experimentally and by software implementation. At first, cyclic loading was applied on a single-story, single-span steel shear wall sample made with a one-third scale in the laboratory. Then, it was modeled in ANSYS and loaded in the same condition. The comparison between these two methods represents an acceptable conformation. After the verification was accomplished, various conditions were modeled and analyzed in the software as one-fifth, one-fourth, one-third, one-second, two-third, and one scale. The results indicate that, on average, a 25% decrement of maximum shear is observed in the scaled models. Still, the result from contours shows a good conformation in the scaled results and indicates their reliability.

Keywords:
Finite Element, Steel Plate Shear Wall, Scaling Effect, Experimental Modeling.

1. Introduction

The steel plate shear wall (SPSW) is used to resist lateral loads such as earthquakes and wind. Generally, SPSW consisted of a thin steel plate with two columns on the sides and two beams at the top and bottom. The columns perform as the flanges, the main plate acts as the web, and the beams are considered to perform as stiffeners. This system is executed in various types, including with or without stiffeners, with or without openings, plain or corrugated plate, and composite design. Some advantages of this system are energy transformation and dissipation, high primitive strength, story displacement restriction, lower volume and weight in comparison to the concrete shear wall, and, as a result, lower seismic weight. It is also proper from architectural aspects as it has a high execution pace .[١]

Vast research is performed on steel shear walls based on diagonal tension field theory that asserts: "In case a force is applied to a steel panel, the steel plate would be wrinkled, and pure tensional stress would be observed till it buckles." Timler and Kulak affirm this theory, and it is also the basis of design codes [2, 3]. According to the research, shear walls and plain or corrugated plates could be categorized as with or without stiffeners, with or without openings. Some other studies in this field are brought here.

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Vian et al. (2013) tested a single-story, single-span SPSW model with a width/height ratio of 2, and steel plates with low strength were used in their research. They obtained that using low-strength steel plates could result in rapid failure and energy absorption, and besides, the existence of holes in the plate leads to a reduction of seismic characteristics of the shear wall system [4]. Sabourighomi et al. (2008) studied two 3-story, single-span steel shear walls and interpreted that low-strength steel plates could increase energy absorption. This article does not include the scale effect [5]. Valizadeh et al. (2012) studied a single-story, single-span steel shear wall with a one-sixth scale and a circular hole in the center. In this research, eight samples were evaluated, and it was interpreted that the hole has decreased the primitive stiffness and strength of the system. This is intensified when the diameter of the hole is increased [6]. Alavi et al. (2013) performed experimental research in which three stiffened, unstiffened, and simultaneously stiffened with opening models were studied. This single-story and single-span model was made and tested in a one-second scale sample. The results show that the opening-included sample is more ductile [7]. Emami et al. (2013) studied the performance of 3 steel shear wall samples, including plain plate, horizontal corrugated trapezoidal plate, and vertical corrugated on a one-second scale. Through this research, it was interpreted that energy absorption, ductility rate, and primitive stiffness are increased in corrugated models in comparison with plain models [8]. Bhowmick et al. (2014) studied the effect of openings and their effect on base shear using relations and implementation of ABAQUS finite element software. This research uses a model with a width-to-height ratio of 2. The reason for this selection of the scale and dimensions is not explained [9]. Sabourighomi et al. (2015) performed experimental research to study a single-span steel shear wall with two rectangular openings in a one-third scale. This research presents that the arrangements of voids do not affect the results, but the openings decrease seismic parameters by themselves [10]. Wang et al. (2015) studied four experimental single-story, single-span samples on a one-third scale, and values of height-to-thickness ratio and span length-to-height ratio were observed [11]. Ge et al. (2017) studied a steel frame, including a steel shear wall, using a shaking table on a one-third scale. Dynamic parameters of acceleration, displacement, and shear force have been evaluated, and it is determined that this system is strong enough to resist against high seismic loads [12]. Shekastehband et al. (2017) studied an SPSW with an opening in a one-third-scale research. This model was a novel method to design a shear wall in which the steel plate is only connected to beams and is not connected to columns [13]. Wang et al. (2017) performed software research to study the SPSW with the same length and width, which is SPSW-SBR buckling resistant. This research shows that conventional relations of SPSW design are also correct for this model [14]. Nassernia et al. (2017) studied a specific type of SPSW experimentally and using software under hysteresis cycles in which the shear wall is in the middle of the span and shear bracings are connected to frame corners. There is a circular hole at the center. The scale used in this research is the same length and width of small, 80 cm dimensions, presenting an acceptable behavior even in high displacements [15]. Cao et al. (2018) experimentally studied two single-span, double-story trapezoidal corrugated steel plate models using software, in which the wall dimensions are 1m and no specific scale is considered for them. This indicates the model could present an appropriate primitive stiffness and shear strength [16]. Lu et al. (2018) studied a steel shear wall with a groove on a one-third scale, indicating that the groove's existence increases energy dissipation capacity and flexibility [17]. Ashrafi et al. (2018) In this research, the effect of the size of the stiffening spring on the coefficient of behavior of the steel shear wall was investigated in ABAQUS software and it was found that the plasticity and the coefficient of behavior increased significantly with the reduction of the coefficient of behavior of the steel shear wall. In this research, the main scale is considered [18]. Pachideh et al. (2019)

analyzed the damage index of steel plate shear walls in software-based research and it was determined that implementation of SPSW in tall buildings leads to fewer damage indexes. Also in this research, no scale has been considered [19]. Gholhaki et al. (2019) In this research, the effect of the size of the hardening spring on the coefficient of behavior of the steel shear wall was investigated in the ABAQUS software and it was found that the plasticity and the coefficient of behavior increased significantly with the reduction of the sub-plates. In this research, the main scale is considered [20]. Paslar et al. (2020) The present study investigated the behavior of plates with circular cuts in different boundary conditions of the filler plate and it was found that any increase in the dimensions of the opening led to a decrease in ultimate strength, stiffness, ductility, and energy absorption in proportion to the effective height of the wall. In this research, the scale used is not mentioned [21]. Luo et al. (2023) Investigated the relationship between interaction and seismic efficiency of composite shear walls in this research. Based on the simulation results with different parameters, the sensitivity of the seismic performance and the interaction relationship of the horizontal corrugated steel composite shear wall have been analyzed. The results showed that when the shear ratio was greater than 1.45, the column had sufficient restraint to improve the performance of the corrugated steel plate. This research has no information about the scale [22]. Zhao et al. (2023) In this study, theoretical formulas are derived to predict the elastic strength and stiffness of SPSW-DO. Based on the experimental results of two specimens with different height-to-width ratios subjected to cyclic loading, SPSW-DO has reliable seismic performance. In this research, the scale has been used according to the height change [23]. Wang et al. (2023) This paper investigates the seismic performance of low-yield point steel plate shear wall (LSPSW) by performing cyclic loading tests on three single-span steel plate shear wall (SPSW) specimens, including an unstiffened LSPSW (LYP) case. A typical non-stiffness (NW) strength SPSW was studied. Then, a new LSPSW with steel tube stiffeners (HSS) is proposed to restrain the out-of-plane deformation of the infill panel. Scale is not mentioned in this research either [24]. Razavi et al. (2023) In this study, self-centering steel sheet shear wall has been simulated using finite element (FE) modeling, then the effect of relaxed stress on stiffness and energy dissipation capability of the system in initial prestressing forces and different time intervals has been evaluated. The scale used is not mentioned [25]. Liang et al. (2023) In this study, a square steel tubular frame filled with concentrated concrete with split steel plate shear walls (SC-SSPSW) using a post-tensioned (PT) column foundation is proposed. A 1/3 scale is used in this experiment. This research shows that the hysteretic curves of the specimens show a typical double flag shape, and the residual deformation of all specimens when loaded up to 2.0% floor drift is approximately 0.20% .[۲۶]

Reviewing the studies related to the research topic, it could be concluded that many researchers had studied experimental and numerical modeling of the SPSW and the effect of many parameters had been evaluated. However, there are few types of research about the effect of scale on the shear behavior of shear walls experimentally and numerically. This research studies the effect of scale on seismic performance on steel shear walls under cyclic loading. To do this, shear wall modeling is performed in the laboratory and ANSYS software on various scales .

2. Experimental methodology

2.1 Manufacturing the models in the laboratory

This single-story, single-span steel shear wall was manufactured according to instruction 20 of the AISC code [2]. In this model, stiffeners are used in the joint place of beams and columns to prevent the flanges from being crushed because of load application. Two stiffeners are used to avoid local buckling of the main beams' flanges. Columns and beams are plate girders, and the thickness of the plates used in their web and also in stiffeners is 20 mm. The plate thickness for beam flanges is 15 mm, and an L60×60×6 angle section is used to connect the steel plate to the frame. The thickness of the steel plate used is 1mm. To connect the frame and the plate to the chassis in the lab, a 30mm plate is used on which four rows of punches are made and connected with high-strength 10.9 screws. To connect the sample to the jack, two 30 mm thick plates are welded to the column flange of the column, and this connection has been performed with high-strength screws capable of resisting 150 tons load. Also, to prevent the column from connected to the plate while the test is being held and to increase accuracy, this sample was designed in TEKLA STRUCTURE software, and the plan was given to the factory that is apparent in Figure 1 and Primitive assembly of the model in the laboratory is shown in Figure 2.

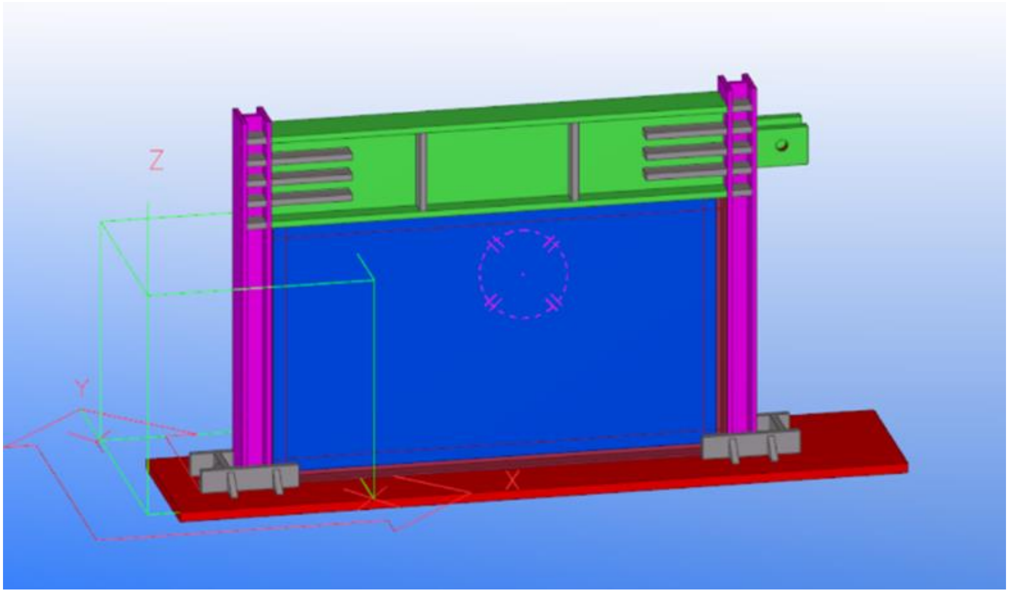

Fig. 1. Initial model in TEKLA STRUCTURE software.

Fig. 2. The steel plate shear wall modeled in the laboratory.

The steel used in this sample has been of ST37, in which Fy=2400 kg/cm2 and Fu=3700 kg/cm2. Also, to apply load on the model, cyclic loading is implemented according to the ASCE7 loading protocol [19]. It is presented in Figure 3 for the elevation of the top beam center from the plate connected to a shear wall.

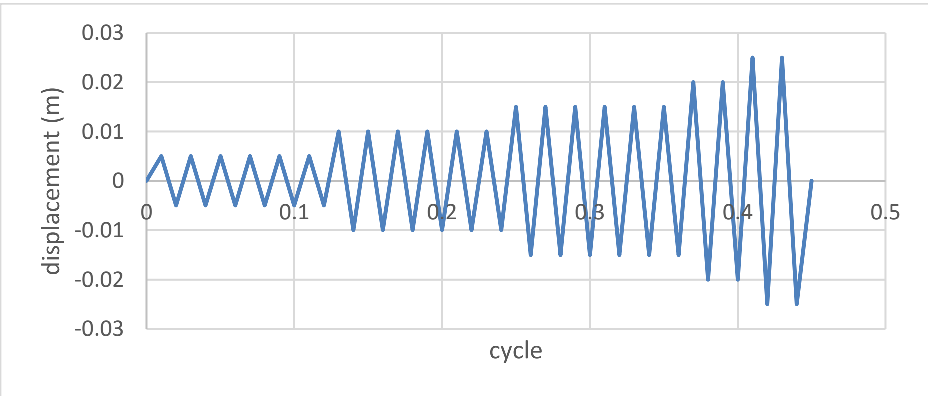

Fig. 3. Cyclic loading according to ASCE7 protocol.

Fig. 4. Top floor acceleration Time History, a) X direction, b) scatter plot in X direction, c) Y direction, d) scatter plot in Y direction

2.2 Lab instruments' properties

A jack with a nominal power of 150 tons is used for this test, in which power is restricted to 70 tons to consider precaution and prevent possible damage to the sample. Also, a load cell is installed at the top of the jack, and the model is fixed to the chassis with 36, 10.9, high-strength screws of 28 mm thickness. Also, the sample is connected to a jack using high strength, 36mm thick, custom-made screw with a load-bearing capacity of 150 tons. To determine the displacement at the top of the beam, two LPs are used on the jack side and at the end of the beam and are calibrated before being used. Also, two strain gauges with a 120 Ohm resistance and a gauge factor of 2.08 are used, shown in Figure 4. Also, an encoder is installed at the center point of the beam to determine displacements. According to Figure 5, 4 metal trusses are used to restrict the free plane movement of the sample.

Fig. 4. Initial connection of sample to the bottom chassis and jack.

Fig. 5. Arrangement of measurement instruments on the samples and lateral bracing.

1.3 Properties of steel materials used

The specifications of the steel used in the steel shear wall for the software model are based on Table 1.

Table 1. Properties of steel materials.

Row	Modulus of elasticity (N/m^2)	Young's modulus	Density (kg/m^3)	Yield stress (N/m^2)	Ultimate tension (N/m^2)
1	2.1e11	0.3	7850	2830	3951

1.4 Verification

Due to the limitations of the scale effect study, ANSYS finite element is used. At first, the model was analyzed like other experimental samples. To simplify editing the model, APDL software is used to write codes and macros. To model the steel plate, boundary elements, and stiffeners, the shell element of shell181 is implemented [20]. 0.1m size of the mesh is used to make grids. The plates and columns' end part is fully clamped to simulate the experimental model. Manufacture defects are applied to the plate as loads, and cyclic load is completely applied to the top beam. The sample is confined along the Z-axis to prevent eccentricity and synchronization with trusses used in the laboratory. The Non-linear analysis is performed according to the protocol using an experimental model. Figure 6 shows the finite element model on a one-third scale.

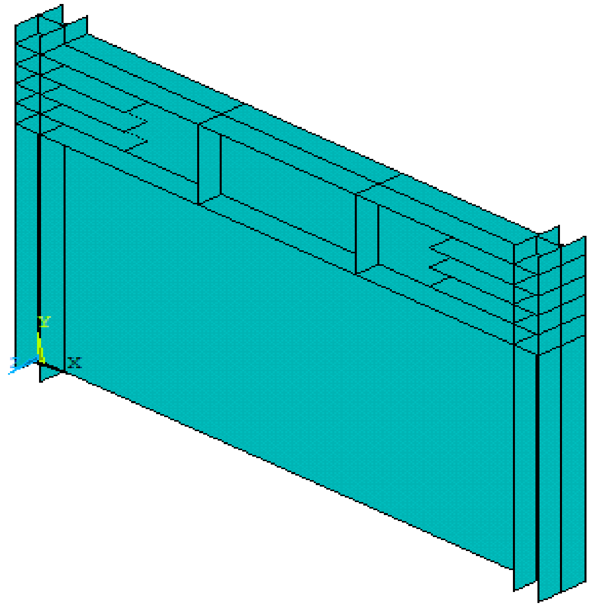

Fig. 6. Finite element model in ANSYS software.

After all the tests were completed, the hysteresis cycle diagram -apparent in Figure 7- is compared with the experimental model using the output data of experimental measurement instruments from the data logger for LP01 that was attached at the top of the beam and to the jack in the application point of loads, considering the load values presented by the Load cell.

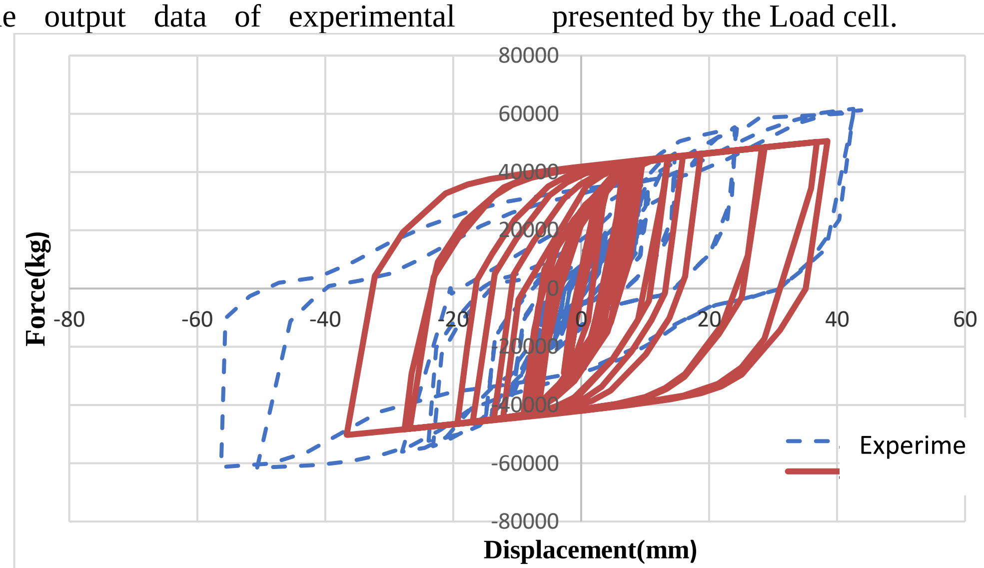

Fig. 7. Comparison between hysteresis behavior of experimental and numerical models in ANSYS software.

Figure 7 of the display shows that with an error of 7%, the laboratory sample matches the software sample. The reason for this difference can be considered in the imperfection and pinching effect.

3- The results of studying the scale effect on steel plate shear wall behavior

To study the effect of scale except for the one-third condition which was used for verification, five other conditions of one-fifth, one-fourth, one-second, two-third, and one scale are modeled, and to simplify modeling, the models are written in the APDL coding environment of ANSYS software as a macro which is capable of editing the dimensions and properties of shear wall. The hysteresis cycle of the experimental model and shell element is used for each model. Hysteresis cycle diagrams, displacement contours in the load application axis, and Von Moises stress contours have been used to study the results. Figure 8 presents the cumulative graph of all six scale conditions. As it is clear in the figure, the five samples that have a scale have similar results. Still, with the original sample, they have at least an 18% difference in the maximum base cut. This issue represents the discussion that when using the experimental and numerical results that the scale is taken into account, you should be more careful and use the confidence factor for these cases. Table 2 also shows the maximum value of the base cut and the reduction percentage for different situations.

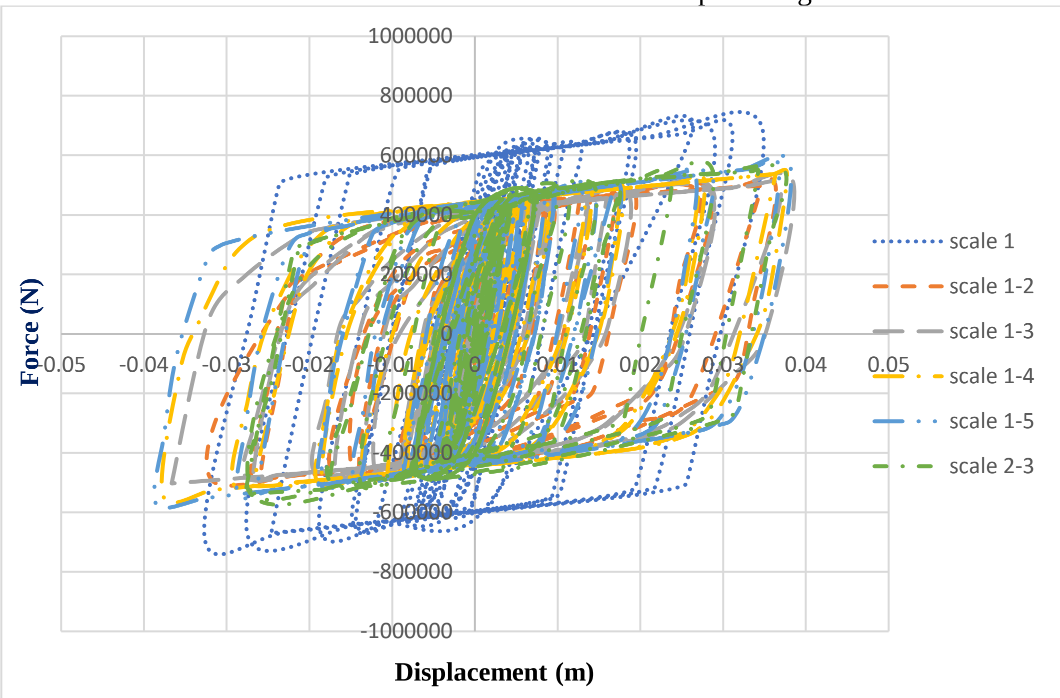

Fig. 8. Comparison of the hysteresis cycle results of software samples.

In Table 2, decrement percentages are presented considering the scales. Various scales and behavior results are presented, including base shear and its decrement percentage for different scales.

Table 2. Decrement percentage considering the scales.

Row	scale	Maximum base shear (N)	Percentage reduction (%)
1	No- scale (scale 1)	693001	0
2	scale 1/3	506533	27

3	scale 2/3	552347	20
4	scale 1/2	499150	28
5	scale 1/4	540089	22
6	scale 1/5	570426	18

Figures 10 to 15 present displacement contour and stress for each scale. As it is obvious in all contours of stress (right side figures), the steel plate failed, and maximum stress is related to the connection point of the beam to column and support connection observed in experimental samples. Concerning the displacement contour images (left side figures), maximum displacement has occurred in a steel plate that seems logical and obvious in experimental test results.

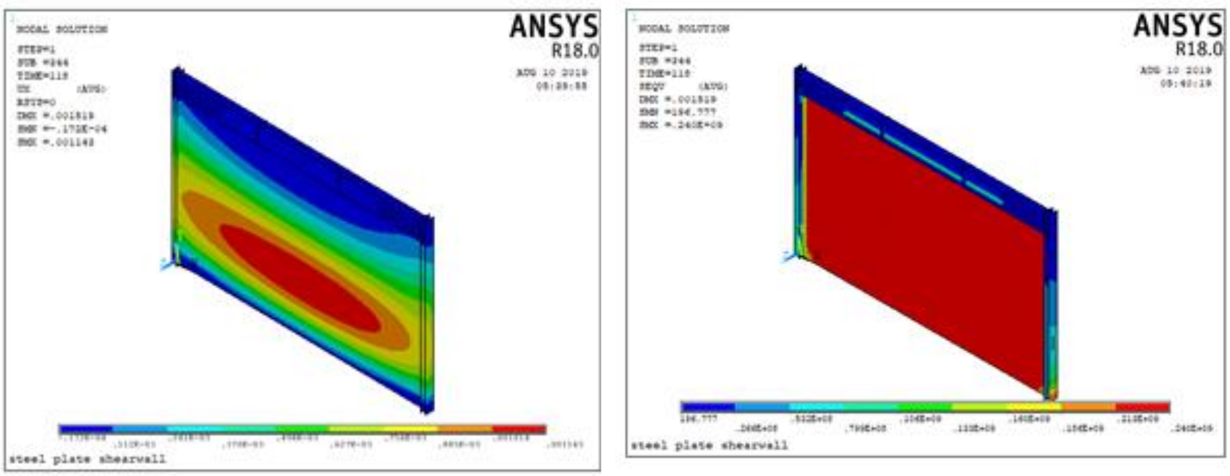

Fig. 9. Stress contour and displacement of unscaled condition.

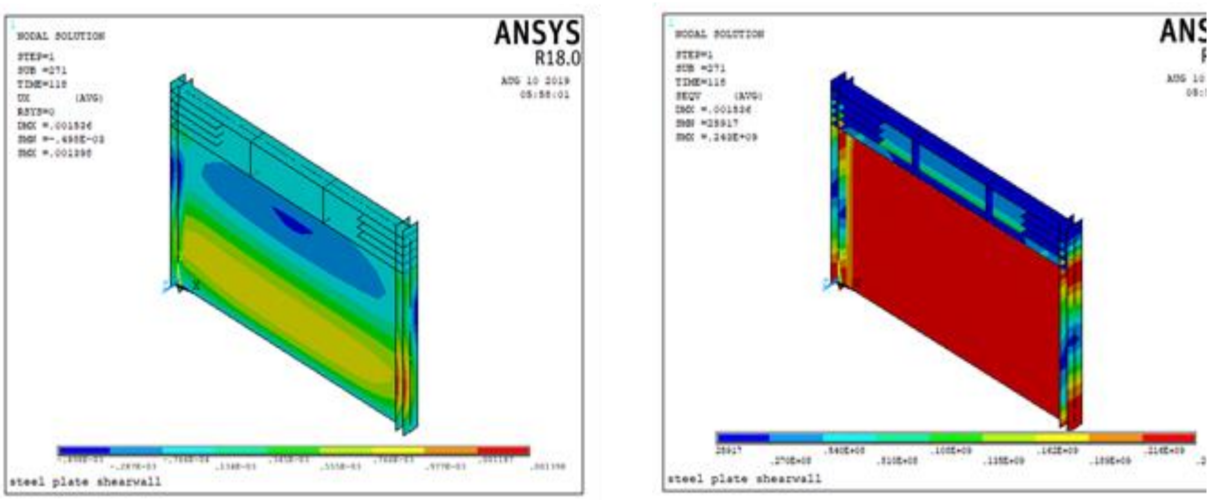

Fig. 10. Stress contour and displacement of one-second scale.

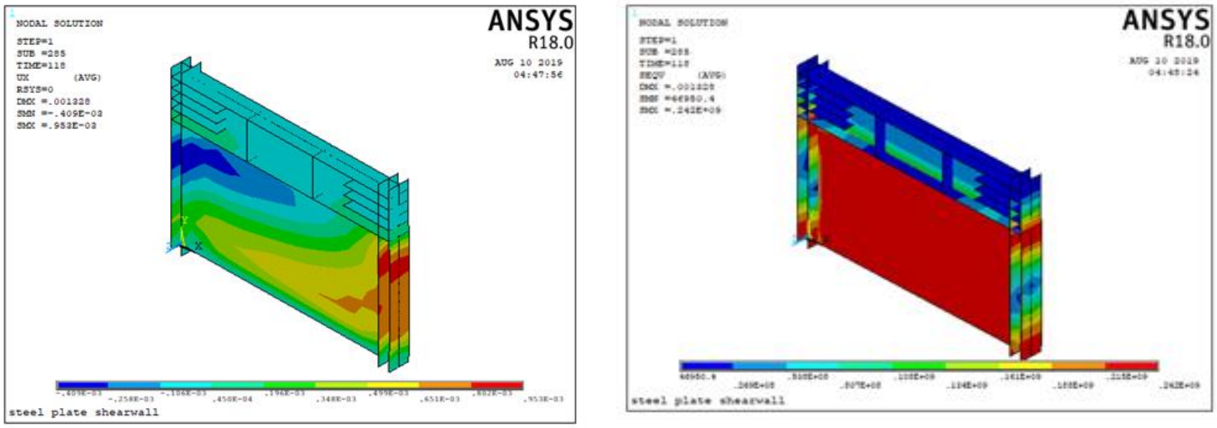

Fig. 11. Stress contour and displacement of one-third scale.

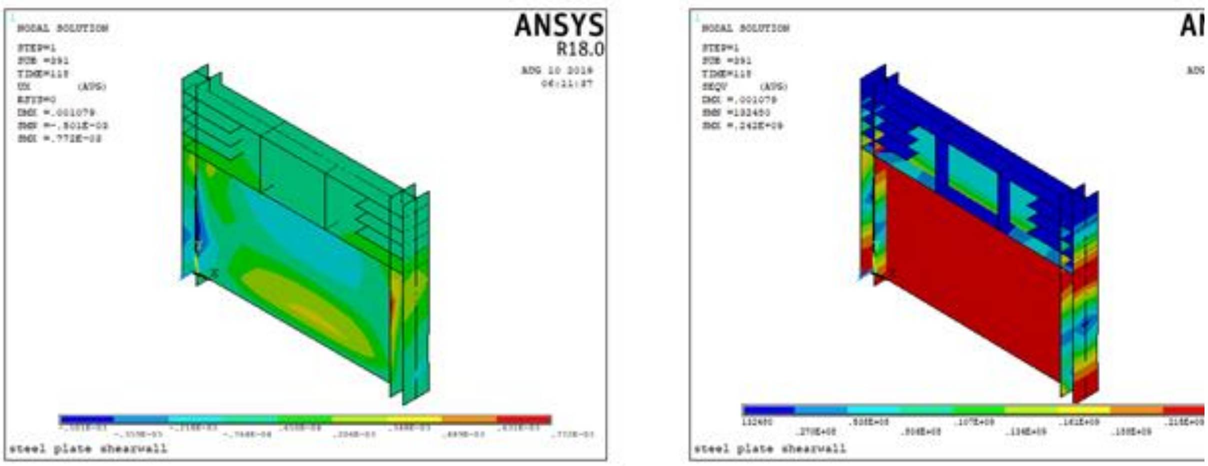

Fig. 12. Stress contour and displacement of one-fourth scale.

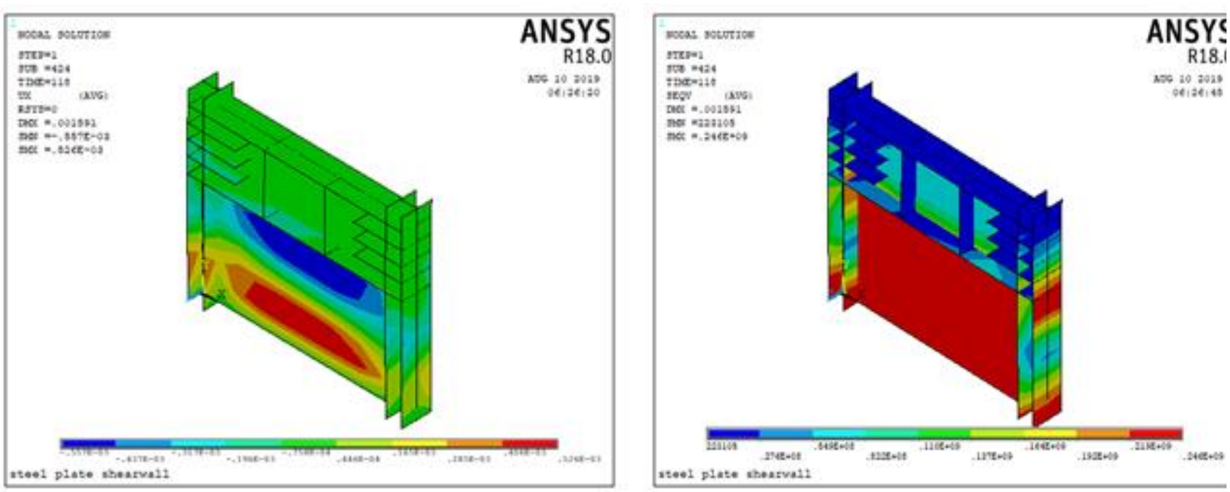

Fig. 13. Stress contour and displacement of one-fifth scale.

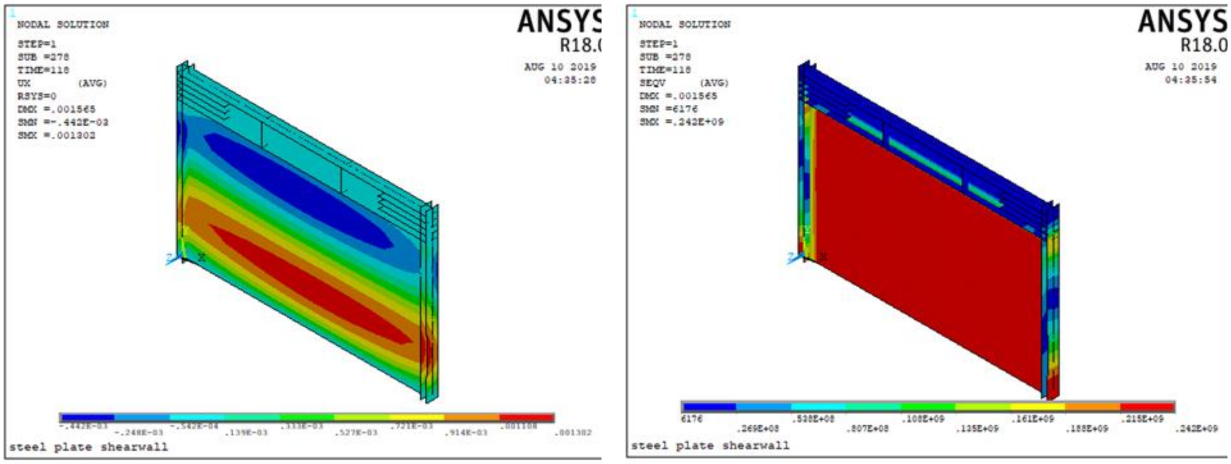

Fig. 14. Stress contour and displacement of two-third scale.

4- Discussion and conclusion

Through this research, the scale effect was studied on the seismic behavior of steel plate shear walls under cyclic load. One of the ambiguities in scaling is related to experimental research, which is studied through verification through various experimental samples and simulation of several conventional scales. After the experimental tests, ANSYS software extracted and verified hysteresis diagrams. The result summary is as follows:

The results show that all the scales studied, except the unscaled condition, are near one level, and there is a shear force decrement of 25% in relation to the main condition. In regard to this, while modeling for experimental tests, load capacity could be considered less, up to 25%, and vice versa; the scaled results could be considered more regarding presented coefficients.

-By comparison of results obtained from contours, there is good conformity considering the stress and displacement conditions, and the results of scaled analysis and those of experimental tests are reliable.

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