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Research Article

THE STUDY OF THE OVER STRENGTH FACTOR OF STEEL PLATE SHEAR WALLS BY FINITE ELEMENT METHOD

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ABSTRACT
Despite the valuable research data on the steel plate shear walls, information about the seismic design of these systems are often not available in seismic codes or are too limited. Among the parameters of the seismic performance of these structures is over strength factor. Most previous studies on this factor are as laboratory researches and limited to short frames or the small laboratory scales that resulted in scattered and different values for over strength factor. The obtained different values can occur in steel plate shear wall due to differences in various parameters. According to the obtained results of the non-linear static analysis in this paper, which has been carried out by finite element method, the over strength factor for steel plate shear walls unlike the fixed value proposed by regulations is not constant, and is changed under the influence of different factors and this factor should be considered in their design.

Keywords: *Steel Plate Shear Walls, Finite Element Method, Over Strength Factor, Nonlinear Static Analysis*

INTRODUCTION
For years, researchers have recognized the importance of over strength factor in preventing the deterioration of some structures during earthquake. The strength that the structure shows after formation of the first plastic hinge to mechanism stage (instability) and represents the structures capability in redistribution of internal forces, after entering into the non-linear phase is called over-strength. Over strength of a structure is stored in the structure due to several factors, including the higher real strength of the materials than their nominal strength, the greater size of dimensions of elements and the amount of materials than required amounts in the design, the use of simplified and conservative mathematical models in analyses, the different load combinations, the strength of nonstructural elements (e.g. walls within the frame) and structural elements (including slabs) that are not considered in the estimation of lateral strength, the use of equivalent static method in seismic structure analysis, design regulations, plan layout, redistribution of internal forces within the inelastic limit due to structural uncertainties and geometry of the structural that it has been shown that except for the redistribution of internal forces, the other factors of over strength in the structure are not reliable (Humar and Rahgozar, 1996; Rahgozar and Humar, 1998).
Steel plate shear walls are of the lateral load-bearing systems with two desirable characteristics of high lateral stiffness with great ductility, which are used not only in new buildings, but also in performance improvement and rehabilitation of existing structures. Despite the valuable research data on the steel plate shear walls, the data on seismic design of these systems are not available or are very limited in most seismic codes (including Iran's std. 2800). Most previous studies on response modification factor or over strength are the results of some laboratory studies which are often limited to short frames or with small laboratory scales that the results show the different and scattered values for over strength factor in steel plate shear walls (Sabouri-Ghomi, 2002; Sabouri-Ghom and Gholhali, 2008).
The different values of over strength factor in the steel plate shear walls can be due to differences in parameters such as flexural rigidity of beam and column, wall dimensions, plate thickness, yield strength of steel materials, the columns' axial load resulting from gravity load of the higher floors that the weaknesses of previous studies on important seismic parameters of over strength factor in steel plate shear walls, whether experimentally or analytically, is the ignorance of the impact of changes in these

factors. On the other hand, in the seismic codes such as the US ASCE7-10 and Canadian code NBCC and Iran's std. 2800, over strength factor has been proposed as a constant number (ASCE/SEI 7–10). That this is inconsistent with the values obtained by other researchers. Therefore, in this study the impact of the change of the above factors on over strength factor of steel plate shear walls has been studied with finite element method using Ansys software.
In the seismic design of structures, the elastic strength required for structure is reduced in accordance with its over strength by force reduction factor. This force reduction is taken from its structural capacity curves and idealized form (bilinearized) in accordance with Uang method. According to Figure 1, the structural response modification factor is calculated as follows:

$$R=\frac{V_{eu}}{V_w}=\frac{V_{eu}}{V_y}\frac{V_y}{V_s}\frac{V_s}{V_w}=R_\mu \Omega Y \quad (1)$$

Where, $R_\mu=\frac{V_{eu}}{V_y}$ is the reduction factor due to ductility, $\Omega=\frac{V_y}{V_s}$ is over strength factor, and $Y=\frac{V_s}{V_w}$ is allowable stress factor.
As well as, V_{eu} is the structure maximum base shear in elastic state, V_y is the structural capacity at the yield level of structure, and V_s is the capacity at the level of initial yielding and V_w is capacity at the level of the stresses reaching allowable stress (Uang, 1991).

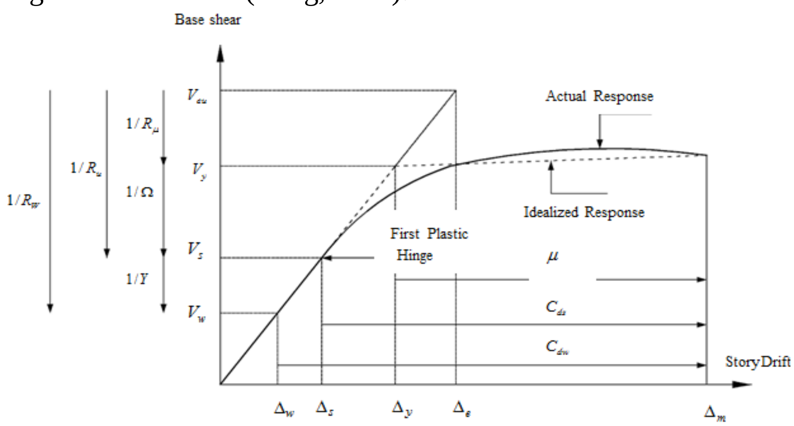

Figure 1: The Actual Response (Pushover Curve) and Idealized Response (Bilinear Diagram) of the Structure

According to tests done on of steel plate shear walls, although in most cases the samples are in the form of multi-storey, but this is the first floor that always totally fails and experiences plastic deformations and the energy absorption is more done by this floor; in other words, ductility or strength of this floor typically controls the ductility or the strength of the total structure, therefore, the modeling done in the study is as one-storey one-bay specimen (Behbahanifard *et al.*, 2003; Sabouri-Ghom and Gholhali, 2008).
In the basic design of steel plate shear walls in accordance with the regulations, including AISC341 code, in the first step it is assumed that the web plate bears the whole shear force of the earthquake in the steel plate shear walls and that the plate shear capacity less than theoretical strength of web plate is based on the steady tensile yield along the diagonal of the plate (the complete yield of web plate). Therefore, the first point of wall yield is the first yield point of steel plate due to unsteady distribution of tension in the elastic range, and the amount of web shear strength has been considered as the first yield point for steel plate shear walls in its capacity curve (ANSI/AISC 341-10; Berman and Bruneau, 2003a).
Based on the method chosen to calculate the parameter of over strength factor, it is necessary to determine a criterion for structural failure; so in this research, the target displacement, which represents a structural failure in the nonlinear static analysis (pushover), is assumed as exceeding of storey drift ratio of 3% (Mwafy and Elnashai, 2002).

The Numerical Modeling

Model Specifications, Materials and Analysis Method

To estimate the way of changes in over strength factor with steel plate shear wall structures with different geometric and structural characteristics, a one-storey one-bay steel shear wall is studied with finite element method. For this purpose, first using an accredited laboratory model the modeling done in the software is validated and then the curve of steel plate shear wall is obtained through nonlinear static analysis (pushover). Floor height in the samples was 3 meters and according to the failure criterion of 3 percent of the storey drift ratio, the stop point in all displacement analyses has been considered as 90mm for each storey. Also, the regulations of ASCE 41-06 code were used to do analysis and determine over strength factor and define the characteristics of materials. All analyses include the geometric non-linear analysis and nonlinear analysis of materials, and Newton-Raphson method is chosen to solve nonlinear equations. Von-Mises yield criterion and kinematic hardening rule were defined for steel materials and the slope of the stress-strain curve after the yield has been considered as one percent of the initial modulus of elasticity. Also, the sections used for horizontal and vertical boundary elements, thickness of steel plate and dimensions of the wall have been selected in accordance with American AISC standards such that they can satisfy the regulations of AISC341-10 code for steel plate shear walls (ANSI/AISC 341-10).

Table 1: Mechanical Properties of the Steel Used for Beam, Column and Plate

Yield Point (MPa)	Elastic Modules (MPa)	Hardening Elastic Modules (MPa)	Poison's Coefficient
235	206000	2060	0.3

Finite Element Modeling

Finite element analysis is one of the methods to study the structural behaviors, which is common due to high speed and accuracy and low cost compared to other methods. In this study, Ansys software has been used to model the steel plate shear walls; to model the boundary elements, the element of Beam 188 which is a three-dimensional element and based on the Timoshenko beam theory, considers the effects of shear deformations and has 6 translational and rotational degrees of freedom and one twisting degree of freedom at every node has been used; Also to model the steel plate, the four-node element of Shell 181 has been applied, which is useful to model the nonlinear shell structures with low to high thickness and has 6 translational and rotational degrees of freedom in every node; both elements have plasticity properties, ductility, large strains, and hardening capabilities. In nonlinear static analysis, the nonlinear behavior of steel materials and large displacements has been considered (ANSYS Academic Research, Release 14, Help System).

In the model of the steel plate shear walls in the software, when load is applied on the wall plate, the software is not able to detect the buckled form of the steel plate, and if the initial imperfection of the steel plate is ignored, the software estimates the initial rigidity and the yield force of steel plate shear wall more than the actual value, and therefore the plate does not buckle, so to create an imperfection in the plate, we apply a small perpendicular load on it that this load has notany effect on the results of the analysis and only causes a buckling mode-shape in the plate.

This basic imperfection is caused by a load about $0.0001\sqrt{3000x4200}$, and is much less than the amount of $0.01\sqrt{bh}$ (b is the length and h is the height of wall); therefore it does not have any effect on the stiffness and ultimate capacity of the system (ANSI/AISC 341-10).

The Validation of the Model with Experimental Results

At first to validate the modeling in Ansys software, an accredited laboratory specimen is analyzed using this software; the accredited laboratory model is an experimental 4-storey model tested by Driver *et al.*, (1998a, 1998b) at the University of Alberta Canada, which the laboratory sample profile, the fabricated model, deformation and Von-Mises stresses can be seen in Figures 2 to 3. In this experiment, the plate yield stress is 341 MPa and the yield stress of frame elements is 308 MPa.

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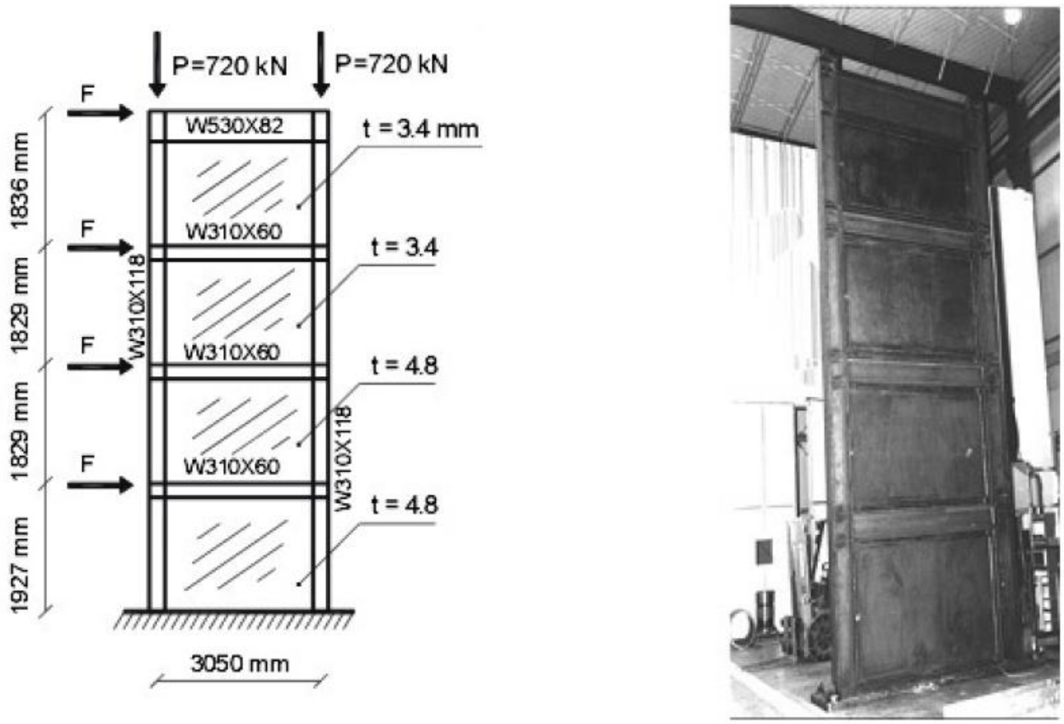


a) Schematic of specimen b) Photograph of specimen

Figure 2: The Specifications of the Specimens Tested by Driver *et al.*, (1998a) at the University of Alberta

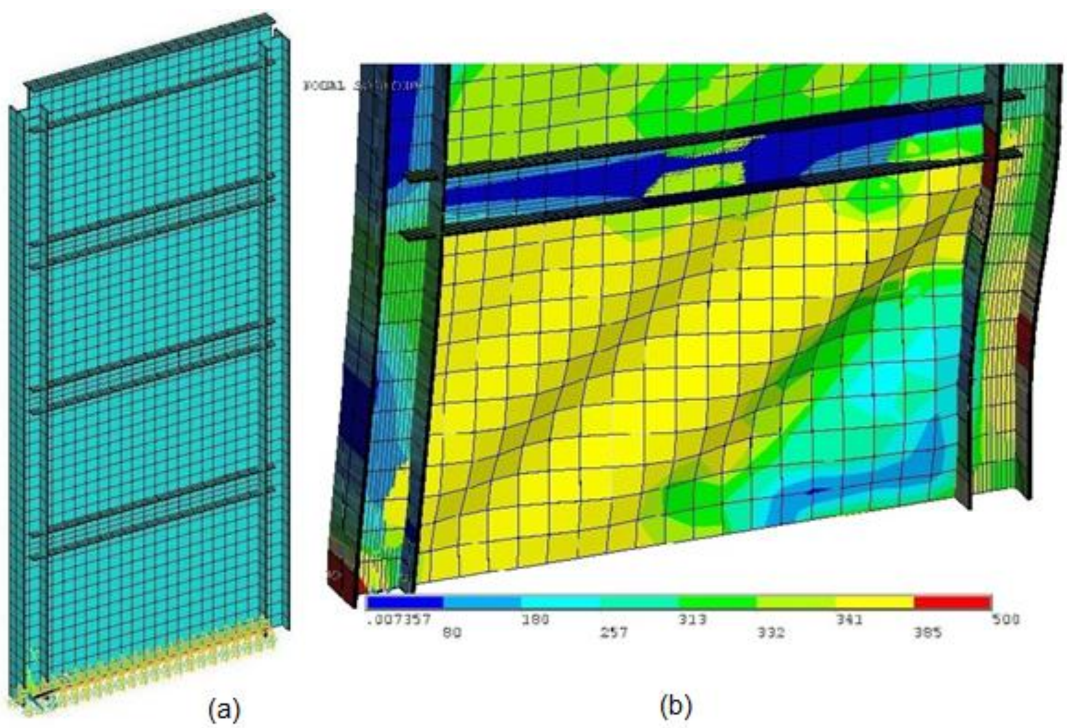


Figure 3: Driver's Numerical Model Fabricated in Ansys Software (a) and its Deformation with Van-Mises Stress for the First Storey (b)

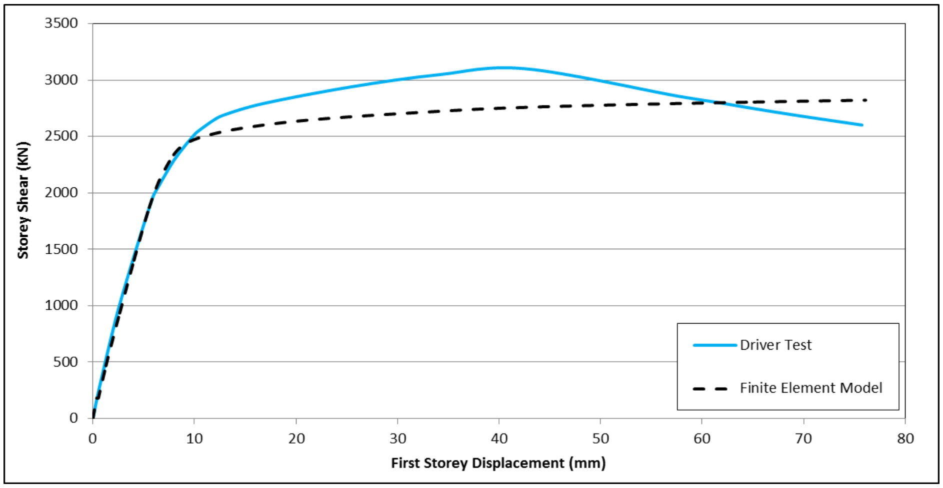


Figure 4: Comparison of the Results of Driver *et al.*, (1998a, 1998b) Laboratory Model and Finite Element Model of the First Storey

By comparing load-displacement curve obtained from the test and specimen modeled in Ansys software, it is observed that the results of finite element modeling have a good fitness with the experimental data, and the modeling done in software has an appropriate and acceptable accuracy, because the software model shows the buckling and post buckling behavior (response) of steel plate shear walls, the formation of diagonal tension field and the place of maximum stresses as well. Also in the final stages of analysis, the surface of the steel plate has fully yielded and the plastic hinges have been formed in columns, which mean good performance and high energy absorption in the system of steel plate shear walls.

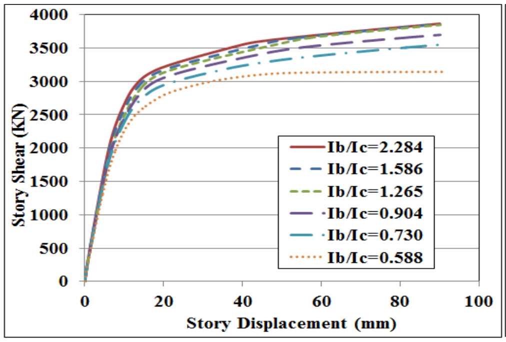
The Study of the Effect of Changes in Various Factors on Over Strength Factor

The Study of the Effect of the Beam Flexural Rigidity on Over Strength Factor

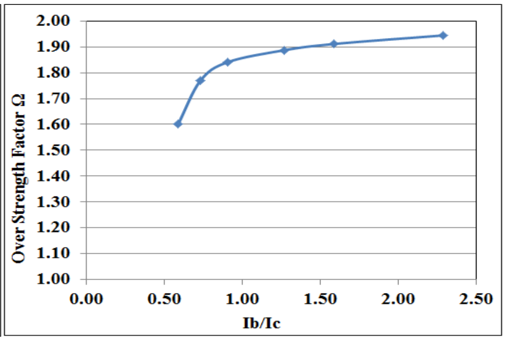
In the specimens tested, the sections of columns are W14x159, steel plate thickness is 4mm, frame dimensions are of 4.2 meters length and 3 meters width and beam sections have been selected as shown in Table 2.

Table 2: Specifications of Beams

Section Name	**W14x99**	**W14x120**	**W14x145**	**W14x193**	**W14x233**	**W14x311**
(Beam to Column Moment of Inertia Ratio) I_b/I_c	0.588	0.730	0.904	1.265	1.586	2.284



(a)



(b)

Figure 5: The curves of Force-Displacement of Specimens (a) and Changes in Over Strength Factor (b)

The results show that increasing the moment of inertia of beam increases the over strength factor in the steel plate shear walls and as the curves in Figure 5 show, this increase is higher in beams with lower moment of inertia.

The reason for this is that increasing the moment of inertia of the beam causes a better and wider distribution of stresses in the plate surface and reduction of the maximum stresses in it, which could be seen in the specimens analyzed.

Also increasing the flexural rigidity of the beam increases energy absorption, rigidity and ultimate strength, particularly in walls with lower bending rigidity.

Estimation of the Effect of the Flexural Rigidity of Columns in the Over Strength Factor

In the specimens tested, the beam sections are W14x283, steel plate thickness is 4mm, frame dimensions are of 4.2 meters length and 3 meters width and column sections have been selected as shown in Table 3.

Table 3: Specifications of Columns

Section Name	**W14x132**	**W14x145**	**W14x159**	**W14x211**	**W14x283**	**W14x398**
(Column to Beam Moment of Inertia Ratio) I_c/I_b	0.398	0.445	0.493	0.688	1.000	1.563

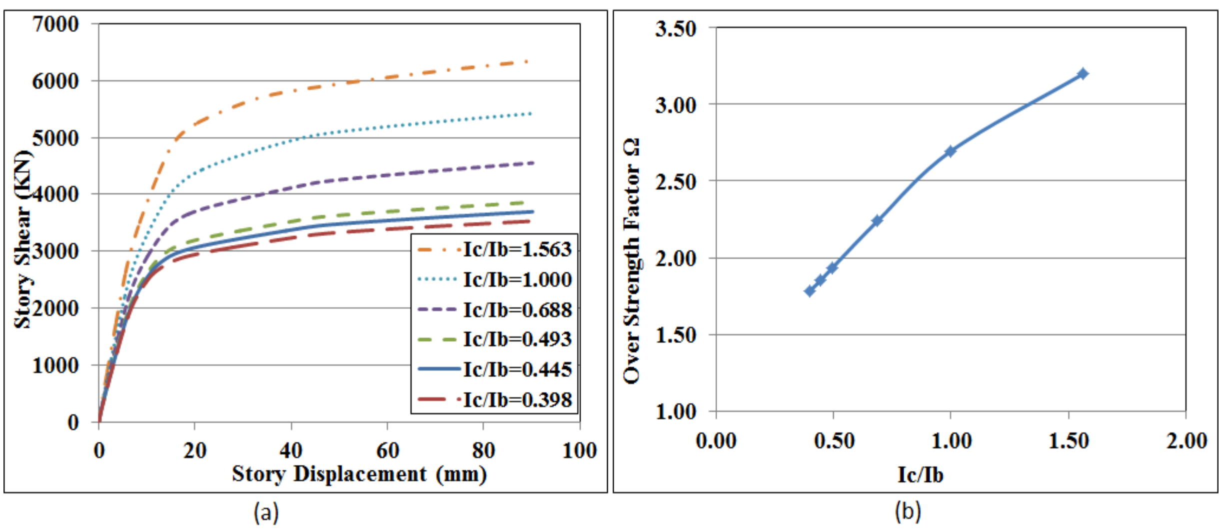


Figure 6: The Curves of Force-Displacement of Specimens (a) and Changes in Over Strength Factor (b)

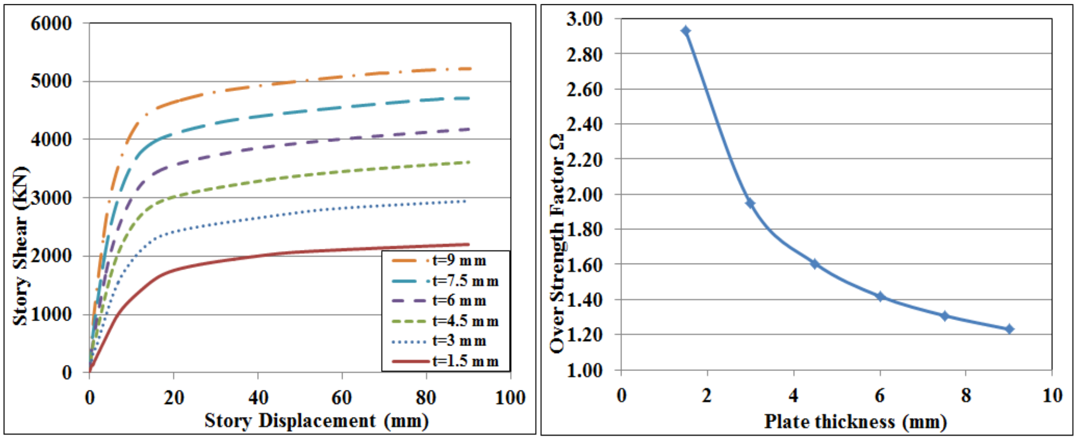
The results show that in the steel plate shear walls the increase of the columns' moment of inertia increases their over strength factor and this increase is almost linear.

The reason is that if we have a beam with high flexural rigidity, the increase of the flexural rigidity of the column causes better and steady distribution of stresses in the plate surface and reduces its maximum stresses and finally, in accordance with Figure 6, increases energy absorption, rigidity and ultimate strength of the steel plate shear walls.

In other words, if we have a column with the appropriate moment of inertia, the steel plate yields before the flow of columns, which its results are the proper performance, high energy absorption, and increase in hardness and strength in steel plate shear walls.

The Study of the Effect of the Thickness of the Steel Plate on Over Strength Factor

In the specimens tested, the sections of beams and columns are selected as W14x132, in a frame with dimensions of 4.2 meters length and 3 meters width. Different thicknesses have been chosen for steel plates as shown in Figure 7.



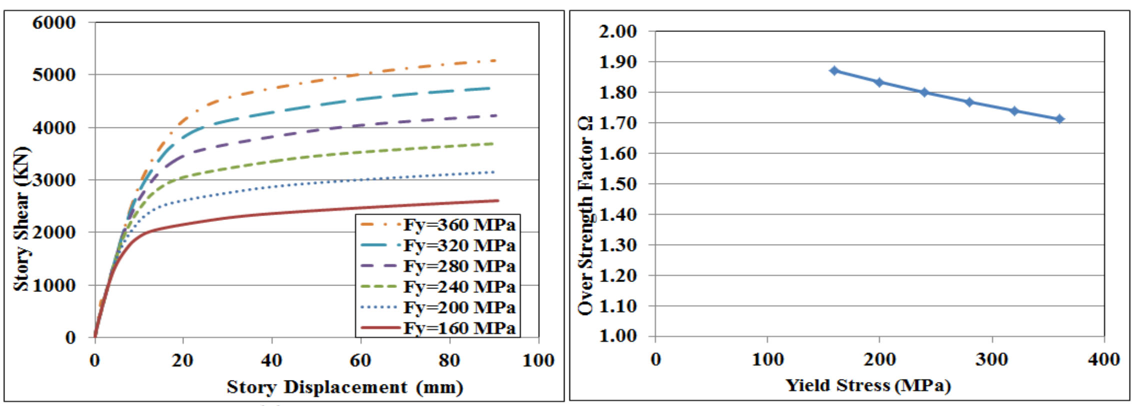
(a) (b)

Figure 7: The Curves of Force-Displacement of Specimens (a) and Changes in Over Strength Factor (b)

As can be seen in Figure 7, by increasing the thickness of the steel plate, the over strength factor is reduced and this reduction is much in lower thicknesses; as well as by increasing the thickness of the steel plate, the energy absorption, rigidity in elastic region and final strength increase. However, in the walls with thinner plate, the plate enters the nonlinear area earlier and absorbs energy.

The Study of Effect of Steel Yield Stress on Over Strength Factor

The studied frame has dimensions of 4.2 meters length and 3 meters width, the column section is W14x159, the beam section is W14x132, and steel plate thickness is selected as 4 mm; the yield stresses of different specimens are shown in Figure 8.



(a) (b)

Figure 8: The Curves of Force-Displacement of Specimens (a) and Changes in Over Strength Factor (b)

According to Figure 8, with increasing the yield strength of steel used in the plate, the over strength factor reduces, and that for LYP (low yield point) steel, this factor is higher than ordinary steel. According to load-displacement curves, with the increase of yield strength of steel materials, the energy absorption, yield strength and ultimate strength and rigidity of inelastic region will increase, but the advantage of using LYP steel is that the structure enters into nonlinear area earlier (in lower force and displacement) and begins to absorb energy.

The Investigation of the Geometry of Frame Effect on Over Strength Factor

In order to evaluate the impact of frame geometry on over strength factor, the factor has been obtained for different ratios of the length to height. Also, for beams the section of w14x426, for columns the section w14x159 and steel plate thickness of 4mm have been selected. The proportions of length to height in the specimens have been considered such that they are not inconsistent with the allowable level of AISC341 code (from 0.8 to 2.5).

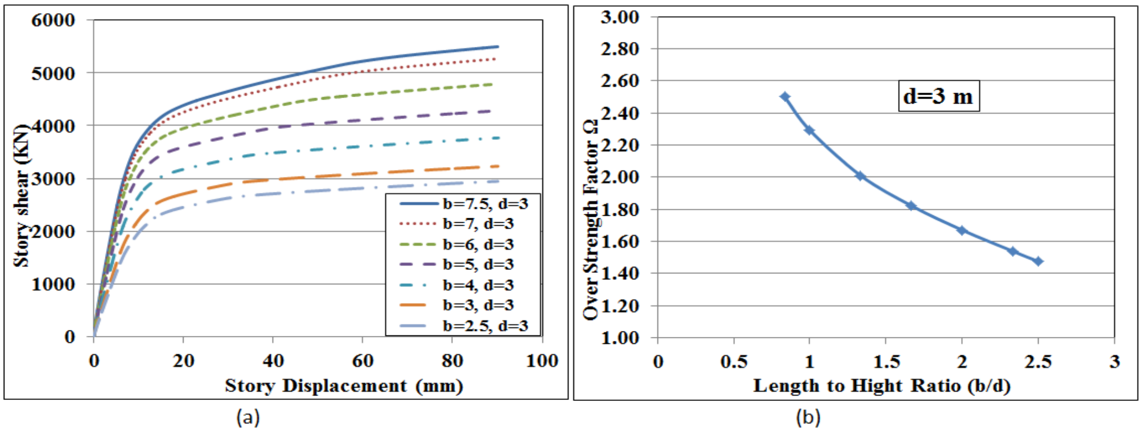


Figure 9: The Curves of Force-Displacement of Specimens (a) and Changes in Over Strength Factor (b)

According to the results in Figure 9, by increasing the proportion of length to height in the steel plate shear walls, the over strength factor decreases. Also, by increasing this ratio, the elastic hardness and plastic hardness, the ultimate yield strength and energy absorption of wall increase. Finally, we can say that the walls with less proportion of length to height (square-shaped) enter into the non-linear region sooner (in lower displacement and force) and absorb energy.

The Investigation of the Effect of the Column Axial Load on Over Strength Factor

To investigate the effect of column axial load due to gravity load of top stories of the column on the over strength factor, a frame with the height of 3m and the span of 3m was considered, and this factor has been obtained for walls with different axial loads. For the beam a section of w14x426, for columns the section of w14x159 and steel plate thickness of 4 mm were chosen in accordance with AISC341 code.

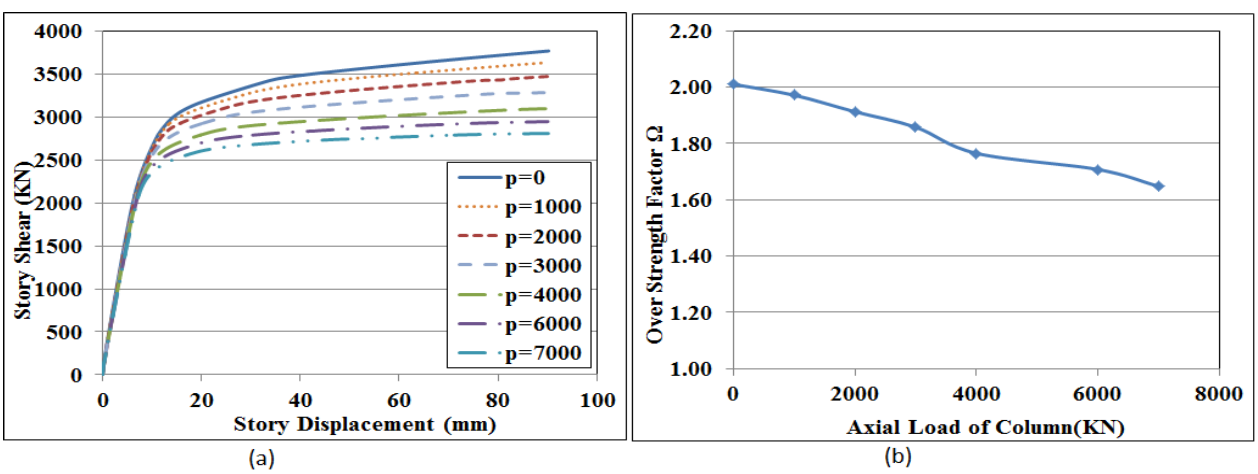


Figure 10: The Curves of Force-Displacement of Specimens (a) and Changes in Over Strength Factor (b)

The results in Figure 10 show that by increasing the column axial load, the over strength factor of the wall decreases and this decrease is almost linear. Also, the increase of the gravity load of columns reduces energy absorption, displacement and ultimate strength of the structure.

Conclusion

In this study, the factors affecting on over strength factor which is one of the most important seismic parameters of steel plate shear walls and directly affects the response modification factor, were studied. These factors also affect on energy absorption, rigidity and strength that the way of influence was identified. The results indicate that the increase in the flexural rigidity of beams and columns increases the over strength factor and the increase of the proportion of the span length to the height of the wall frame is a reducing factor for the over strength factor. On the other hand, the increase in steel plate thickness and yield strength of materials used also reduces the over strength factor. According to the obtained results the increase of the axial load of column is one of the reducing parameters in over strength factor. In addition, it also reduces the energy absorption and the strength of steel plate shear walls.

ASCE07-10 standard suggests the over strength factor for structures armed with steel plate shear walls equal to 2 (ASCE/SEI 7–10), but according to our results, this factor is not constant and under the influence of various factors, its value is variable. Therefore, structures with steel plate shear walls that their over strength factors are less than that of code and have been designed with the proposed value of the code, during earthquake may encounter the structural failures and collapses. The reason for this is that considering the over strength factor proposed by the code causes the small design forces are obtained, so the structure designed with these forces does not responsible for necessary strength during the occurrence of earthquake. Also, the structures with steel plate shear walls that their over strength factors are higher than that of the code and have been designed with the proposed value of the code are not appropriate economically, because considering the over strength factor proposed by the code causes the great design forces are obtained that designing the structure for these forces is not economical. In addition, this standard has considered the first yield point for steel plate shear walls as the first yield point of the steel plate and has ignored the share of frame surrounding the plate in wall strength that by considering it, an over strength factor higher than the actual value is obtained which this factor is far from the reality.

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