Study on Nonlinear Static Analysis of R/C Frames Retrofitted With Steel Plate Shear Wall

A.R. Shokrzadeh & M. Miri
Department of Civil Engineering, University of Sistan and Baluchestan, Iran

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SUMMARY:
This paper concentrates on analytical studies of steel plate shear walls (SPSWs) added to concrete frames. First, several tested concrete frames are considered. The specimens are analyzed with Seismostruct, the results are compared with the values of experiments, and so analytical models are verified by several experimental results. After that, the practical application of nonlinear Seismostruct material models in the analysis of RC structures is considered. A series of analysis for a frame with different material models is performed. The results are compared and suitable material types are chosen. Then we continue our investigations with a parametric study on the behavior of concrete frames retrofitted by SPSW. In addition, the ability of the two finite element programs (Seismostruct, SAP2000) to perform nonlinear static analysis is compared. In the conclusion, some considerations about the simulation of RC frames with SPSW are suggested and some design recommendations for the structural system are proposed.

Keywords: Steel plate shear wall, fiber-based finite element analysis, nonlinear static analysis, parametric study

1. INTRODUCTION

While steel plate shear wall system can be easily integrated into existing steel frames, its suitability in concrete frames is still in the development stage. This paper concentrates on analytical studies of SPSWs added to concrete frames. First some tested concrete frames are considered. These frames were examined under incremental lateral and/or hysteresis loads by other researchers. The specimens are analyzed with Seismostruct ver. 4.0.3; the results obtained are compared with the values of experiments. So using the fiber-based finite element analysis, some analytical models are proposed and they're verified by several experimental results. Thus, the suitability of Seismostruct software in the analysis of reinforced concrete structures (especially in concrete frames with steel elements) is investigated. After that, the practical application of nonlinear Seismostruct material models in the analysis of reinforced concrete structures is considered. A series of analysis for a frame with different material models is performed. The results are compared and applications of them are distinguished. Then we continue our investigations with a parametric study on the behavior of concrete frames retrofitted by SPSW. We study the influence of changing in parameters such as concrete and steel plate characteristics, width to height ratio of the frame and etc on behavior of such structures. In addition, with two finite element programs (Seismostruct, SAP 2000) numerical simulation of two tested frames is created, and the responses obtained are compared.

2. THE EXPERIMENTS THAT HAVE BEEN USED FOR VALIDATION OF SIMULATIONS

2.1. Stroband and Kolpa (1983) Experiment

Specimen A8 of Stroband and Kolpa (reinforced concrete portal frame) was considered. The material properties that were used in the analysis are as table. The radial displacement of central point of the beam was incremented between 0.2-10 mm. The experimental value of the ultimate load was 26.4 KN. This experiment was used for choosing steel and concrete material models from SeismoStruct material library (see section 3.3).

Table 2.1. The Material Properties Used in the Simulation Of Stroband And Kolpa (1983) Experiment

Concrete	$E_c = 24$ KN/mm^2	$f'_c = 28.3$ N/mm^2	$\nu_c = 0.2$	$f_t = 2.1$ N/mm^2	$\varepsilon_{crush} = 0.004$	$\varepsilon_u = 0.001$
Steel	$E_c = 210$ KN/mm^2	$f_y = 450$ N/mm^2	$\nu_s = 0.3$			

2.2. Ghaffarzadeh *et al.* (2006) Experiment

Unit frames were modeled using a mid-span panel measuring 4.0 m by 3.0 m from the third floor of a four storey frame with the dimensions of 12.0 m by 12.0 m. A 2/5 scaled model, measuring 1.76 m by 1.36 m, was found satisfactory. Tests setup and the lateral load–drift hysteresis for the frame are shown in Fig. 1.

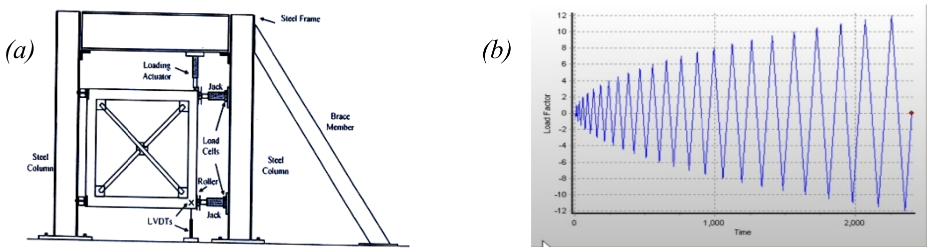

Figure 1. (a) Setup for cyclic testing of the model frames; (b) Detail of applied load (Ghaffarzadeh *et al.* 2006)

2.3. Lubell (1997) Experiments

Lubell conducted experiments on two one-story steel plate shear wall specimens (SPSW1 and SPSW2), depicted in Fig. 2.a and Fig. 2.b.

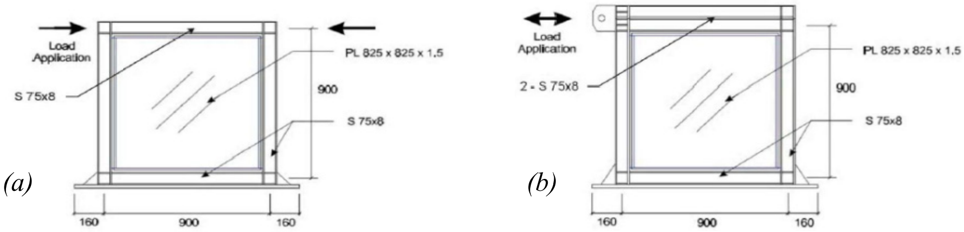

Figure 2. One-story test specimens (Lubell 1997): (a) SPSW1; and (b) SPSW2

2.4. Maheri *et al.* (1997) Experiment

They conducted an experiment on a concrete square frame with steel bracing .The frame was tested using the setup presented in Fig. 5.b. An actuator was used to apply an incremental diagonal load. The dimensions of the beams and columns were chosen to be 100 mm by 100 mm. ($f'_c = 29.42$ MPa)

3. MATERIAL PROPERTIES AND MATERIAL MODELS

The material properties such as f'_c, E_s and f_y were obtained from articles and/or direct communication with experiment researchers.

3.1. Concrete

The concrete has a uniaxial compressive strength f'_c, for each experiment the property may differ (as specified for each experiment). Under uniaxial compression, the concrete strain $\varepsilon_o$corresponding to the peak stress f_c' is usually around the range of 0.002–0.003. A representative value suggested by ACI Committee 318 (ACI, 1999) and used in the analysis is $\varepsilon_o = 0.003$ (except for Stroband and Kolpa (1983) experiment). The Poisson's ratio ν_c of concrete under uniaxial compressive stress ranges from about 0.15-0.22, with a representative value of 0.19 or 0.20 (ASCE, 1982). In this study, the Poisson's ratio of concrete is assumed to be $\nu_c = 0.2$. The uniaxial tensile strength f_t' of concrete is difficult to measure. For this study the value is taken as(ASCE, 1982)

$$f_t' = 0.33\sqrt{f_c'}\ \text{MPa} \tag{3.1}$$

The initial modulus of elasticity of concrete $E_c$is highly correlated to its compressive strength and can be calculated with reasonable accuracy from the empirical equation (ACI, 1999)

$$E_c = 4700\sqrt{f_c'}\ \text{MPa} \tag{3.2}$$

3.2. Steel

The elastic modulus, E_s, and yield stress, f_y, were taken from the experiments and these values were used in the FEM model. A Poisson's ratio of 0.3 was used for the steel.

3.3. Selection and Verification of Material Models

Eleven material types are available in Seismostruct ver. 4.0.3. For the steel reinforcements three material models were considered (stl_bl, stl_mp & stl_mn). Similarly, three different material models were specified for concrete (con_tl, con_cc & con_vc). For selection and validation of material models, Specimen A8 of Stroband and Kolpa versus the six material models were considered. For this frame the three material models of steel had same results, see Fig. 3.a. About concrete material models, "con_cc" and "con_vc" had same results, but "con_tl" differ as represented in Fig. 3.b. Consider displacement 1.7mm from the figure, it can be seen that the obtained load from "con_tl" is 20.9 % lower than corresponding "con_cc" and "con_vc" loads. The reason is, Sismostruct assumes no resistance to tension for "con_tl".

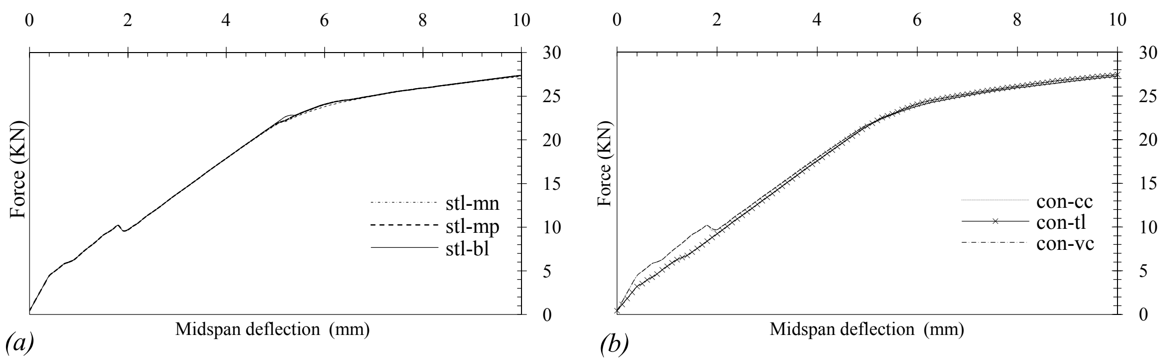

Figure 3. Comparison of SeismoStruct material models. (a) Steel; (b) Concrete.

Fig. 4 shows the force versus deflection curves of the beam at the midspan. It can be observed that the correlation is quite good between the numerical result and the experimental data. So these types of material models were chosen.

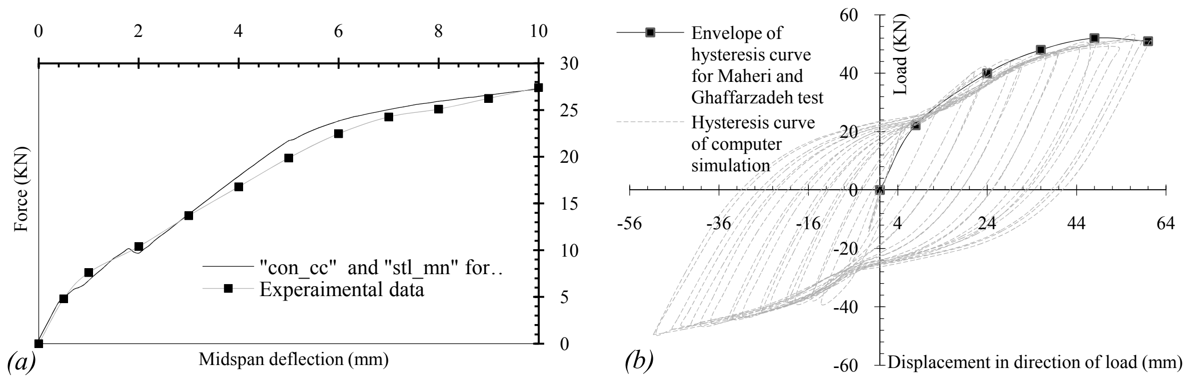

Figure 4. (a) Comparison of numerical and Stroband and Kolpa (1983) results; (b) Hysteresis curve of computer simulation and Ghaffarzadeh *et al*. (2006) test results.

4. VALIDATION OF MODEL

To validate the accuracy of the model, the FE analysis results are compared with the test results of Stroband and Kolpa (1983), Ghaffarzadeh *et al*. (2006), Lubell (1997) and Maheri *et al*. (1997). The comparison results are shown in Fig. 4.a, Fig. 4.b, Fig. 6 and Fig. 5 respectively. It can be seen that the numerical results have good agreement with the test results.

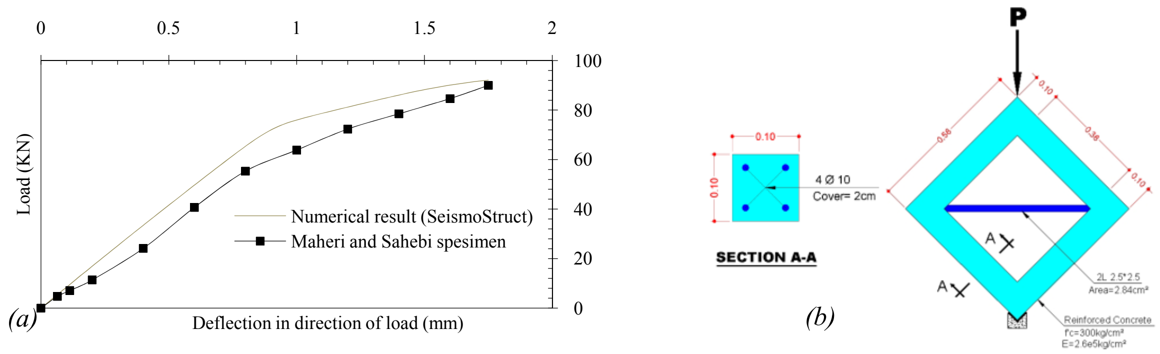

Figure 5. (a) Pushover curves for seismostruct model and Maheri *et al*. (1997) specimen; (b) Test set up and concrete frame geometry (Maheri *et al*. (1997))

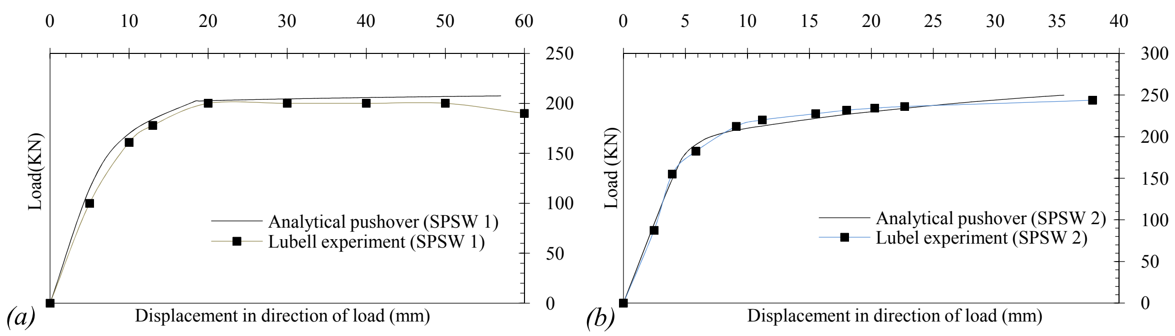

Figure 6. Pushover curves for strip model (see section 5.1) and Lubell (1997) test. (a) SPSW1; (b) SPSW2

5. PARAMETRIC STUDY OF CONCRETE FRAMES RETROFITTED BY SPSW

To better understand the structural behavior of the frames, it is important to investigate the frames with systematic parametric studies. Only one variable was changed at one group so as to assess its effect clearly.

5.1. The Strip Model Representation of SPSW

A typical SPSW consists of horizontal and vertical boundary elements, and thin infill plates that buckle in shear and form a diagonal tension field to resist lateral loads. Timler and Kulak (1983) derived the following equation for the inclination angle of the tension field, α, in a SPSW infill plate:

$$\tan\alpha = \sqrt[4]{\frac{1+\frac{L.t}{2.A_c}}{1+h.t.\left(\frac{1}{A_b}+\frac{h^3}{360.L.I_c}\right)}} \tag{5.1}$$

where t is the thickness of the infill plate, h is the story height, L is the bay width, I_c is the moment of inertia of the vertical boundary element, A_c is the cross-sectional area of the vertical boundary element, and A_b is the cross-sectional area of the horizontal boundary element. Using the inclination angle given by Eq. 5.1, an analytical model, known as a strip model, in which the infill plates are represented by a series of pin-ended, tension only strips, was developed by Thorburn et al. (1983), and subsequently refined by Timler and Kulak (1983). We used the strip model for our investigations.

5.2. Effect of Reinforcements and Steel Plate Yield Stress

The comparison results are shown in Fig. 7.a, Fig. 7.b and Fig. 7.c. Fifteen computer models were conducted, and it can be seen that there is not any difference in the initial stiffness. This is because that the stiffness of the materials was not changed. Fig. 7.c, Shows the comparison of change in capacity versus yield stress changing. As shown the influence of the plate yield stress is greater than influence of the reinforcement yield stress (between 0 and 350 MPa).

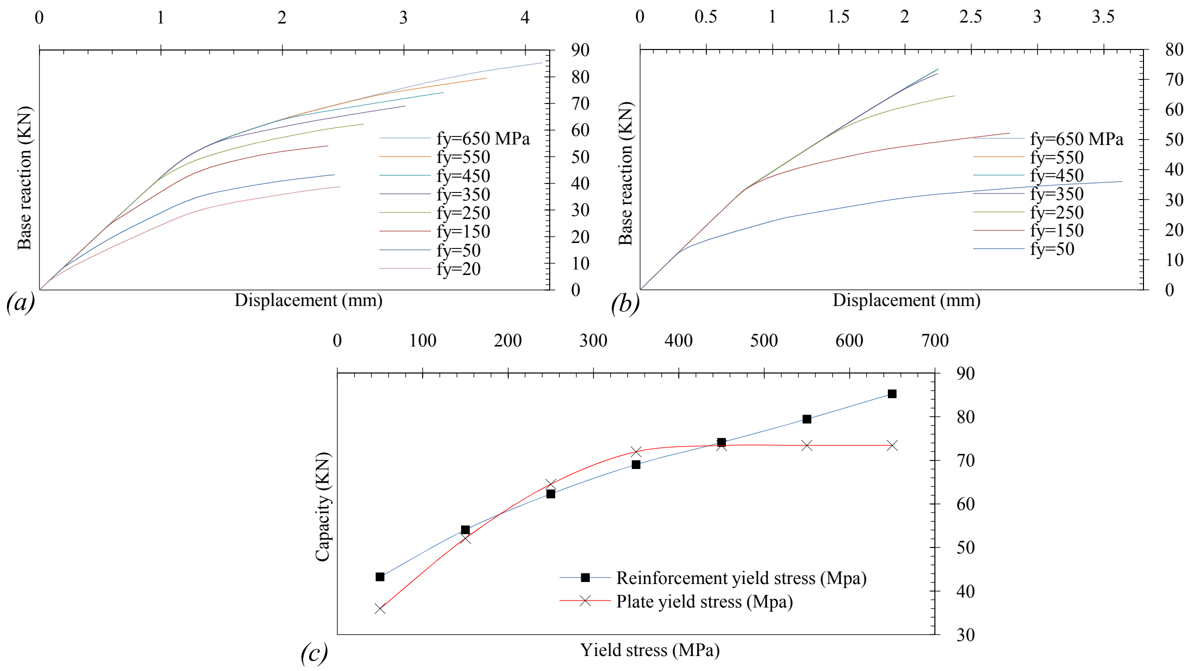

Figure 7. Comparison of change in capacity versus yield stress changing.

Sensitivity of capacity to variation of the steel plate yield stress is good reason for studies were done on low yield stress plates (LYP). These plates may have 96 MPa yield strength Chen *et al* (2001). In some cases the design plate thickness is very thin. Such hot rolled thin plates don't exist in steel markets, and one solution for this problem is low yield strength plate usage. In Fig. 8.a, two pushover curves compare in a graph, one of them is the pushover curve of retrofitted frame with hot rolled steel plate with f_y = 200 MPa and the other one is the pushover curve of the frame retrofitted by LYP, thicknesses are same in two curves of the graph. Fig. 8.b is same as Fig. 8.a but in the Fig. 8.b the thickness of low yield strength plate multiplies by 2.

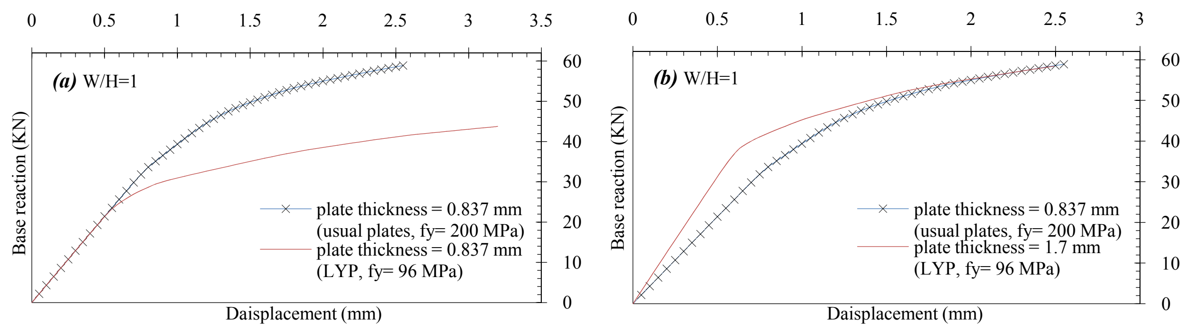

Figure 8. Analytical results (a) Pushover results for the frames retrofitted by LYP and normal steel plate with same thicknesses; (b) Pushover results for the frames retrofitted by LYP and normal steel plate (LYP thickness is twice of the normal plate thickness)

5.3. Effect of Different Magnitude of Elastic Modulus of the Reinforcements and Steel Plate

Fig. 9.b, Shows that the effect of the plate elastic modulus is greater than the effect of the reinforcement module of elasticity on initial stiffness.

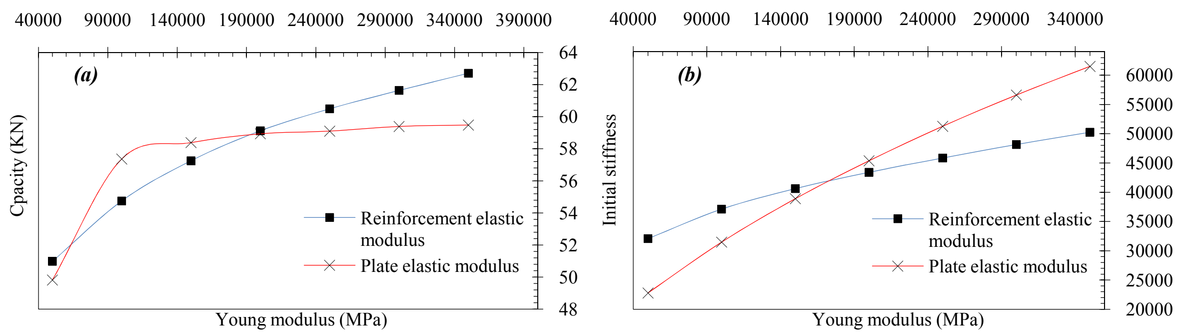

Figure 9. (a) Effect of plate and reinforcement module of elasticity on capacity; (b) Effect of plate and reinforcement module of elasticity on initial stiffness

5.4. Comparative Study on Concrete Frames with and without SPSW and Influence of Some Parameters

5.4.1. Effect of compressive strength of concrete

Two frames were considered, one with SPSW and the other without it. The analysis results are shown in Fig. 10.a, Fig. 10.b and Fig. 10.c. In Fig. 10.c, influence of compressive strength on two models is compared. In the Fig. 10.c can be observed that the compressive strength of the concrete is more effective on retrofitted frame (higher slope in "with SPSW" curve). The reason is, in retrofitted case greater moments develop in the cross sections of the column (because of tension field action of the plate), thus for this frame f_c has more effectiveness.

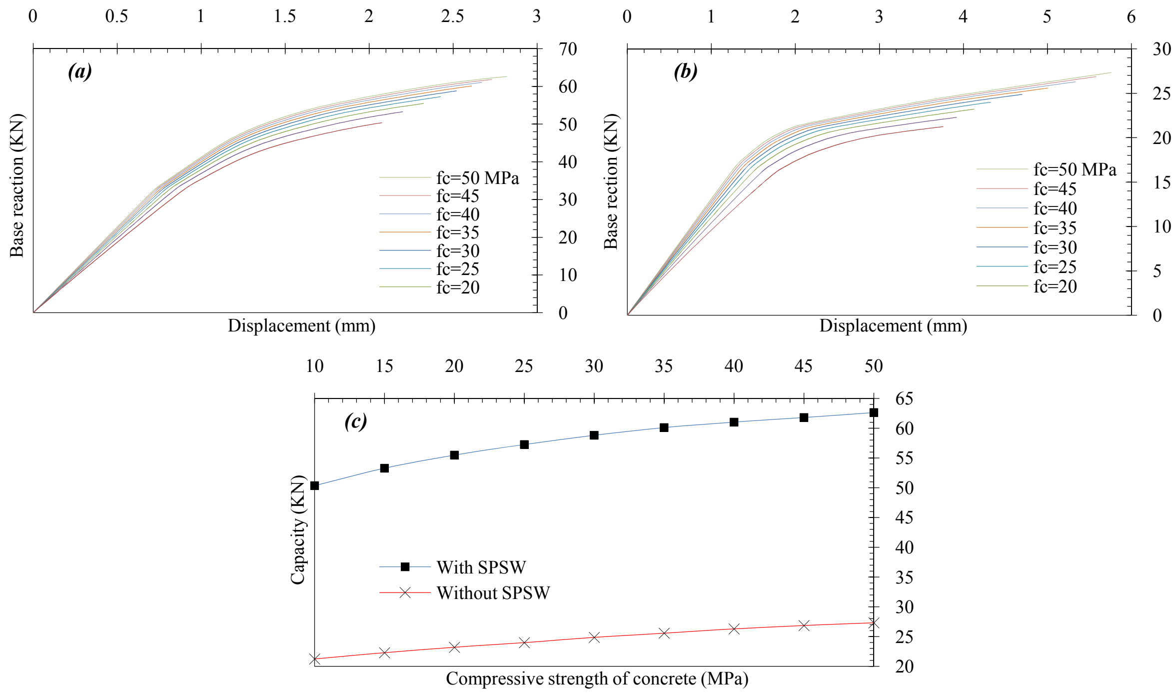

Figure 10. Analytical results (a) Pushover curves of different compressive strength (retrofitted concrete frame); (b) Pushover curves of different compressive strength (not retrofitted concrete frame); (c) Influence of compressive strength changes on capacity for two cases.

5.4.2. Effect of plate thickness, reinforcement ratio and width to height ratio (L/H) of the frame on behavior of the retrofitted and not retrofitted frames

The SPSW model selected for the parametric study presented in this section consist of a single panel bounded by two rigid beams at the top and bottom. Neglecting the bending deformation for floor beams in multi-story unstiffened SPSW is reasonable assumption, because equal and opposite tension fields applied to the interior beams tend to contract the double curvatures expected in a beam in a drifting frame (Driver *et al.,* 1997 and Rezai, 1999). So shear wall system behaves more as cantilever wall than a frame. Assuming cantilever behavior, the rotational flexibility of the lower floor beam of an isolated panel in a multi-story building can be neglected with the top floor beam allowed to rotate as a rigid body relative to the lower floor beam. This allows each panel of the multi-story shear wall to be analysed separately ("panel by panel analysis") if the effect of overturning moments from the top stories is considered in the analysis. The analysis of a single story model gives an accurate result for the first story, assuming the shear wall is connected to a rigid foundation. By accounting for the rotation of the upper floor beams, this model can be extended to capture the behavior top panels as well (Behbahanifard *et al.,* 2003).

5.4.2.1. Frames geometry and finite element model

In the numerical analyses, reinforced concrete frames with four types of width to height ratio, are considered. To study the influence of reinforcement ratio, two types of reinforcement ratios, are considered. Four Ø6 steel bars ($\rho = 0.0028$) are used for columns with low reinforcement ratio and four Ø10 steel bars ($\rho = 0.0079$) are used for columns with high reinforcement ratio. Both high and low reinforcement ratios satisfy the requirement of ACI code (ACI, 1999) for column reinforcement ratio. These frames are subjected to a lateral concentrated load p. The material properties for steel, concrete and steel plate discussed in Section 3 are used in the numerical analyses. In order to provide a base to make a comparison or show how the SPSW changes the frame, ultimate analyses of ordinary reinforced concrete frames without any SPSW are carried out for each case. So for 80 frames analyses were performed, see Fig. 11. The figure shows the lateral base reaction versus the displacement of reinforced concrete frames strengthened by SPSW. It is evident that with the increase of plate thickness stiffness and capacity increase but ductility decrease.

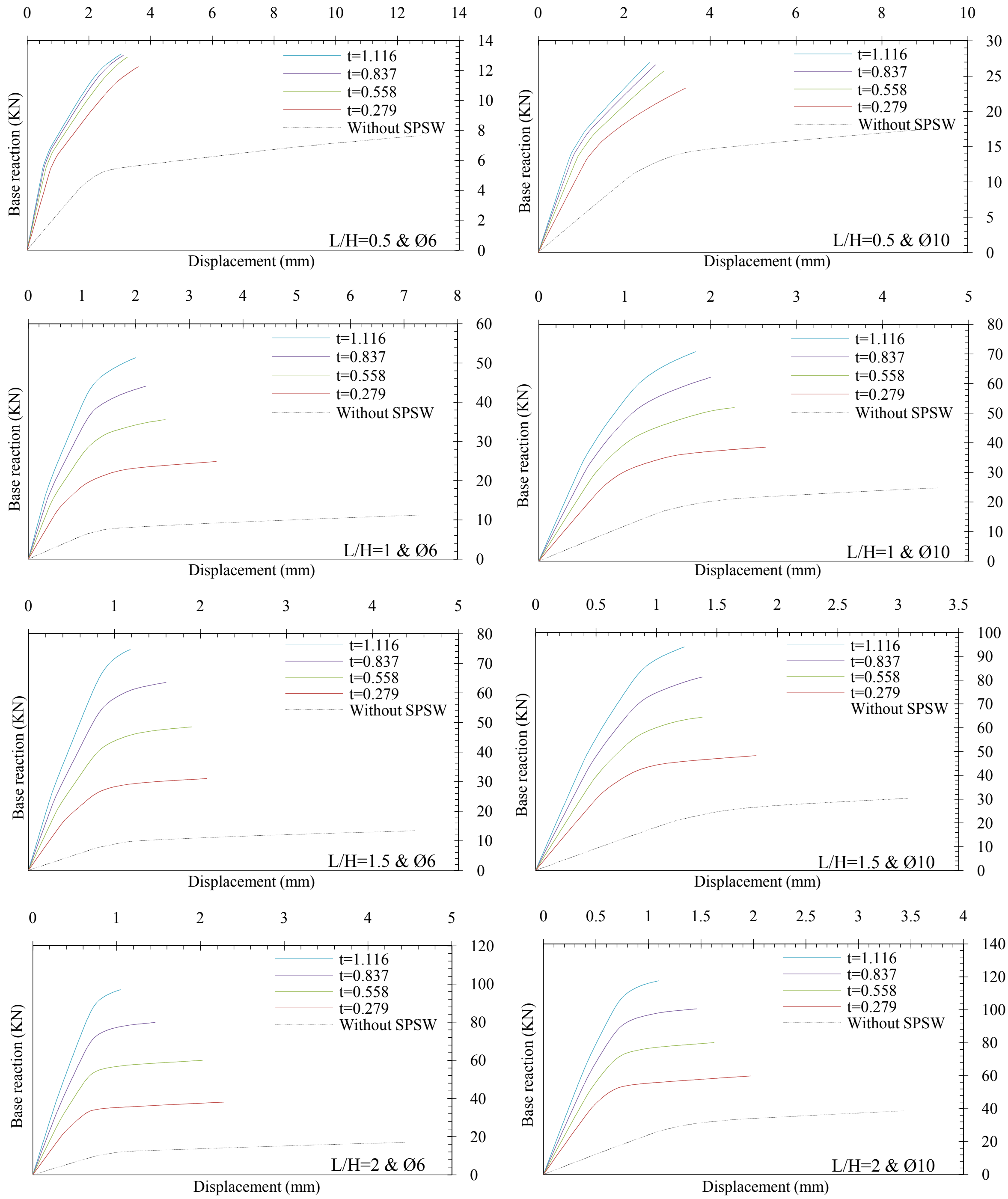

Figure 11. Effect of the parameters on behavior of the Retrofitted and not Retrofitted Frames

Fig. 12 shows the increasing of the ultimate load p_u versus the plate thickness. For greater width to height ratios, p_u seems to increase linearly with plate thickness. From the figure it can be seen that as ρ increase (for same W/H ratios), this increase in p_u decrease. On the other hand for higher width to height ratios p_u increase with greater slope. This may indicate that the behavior of the frames with low W/H ratio is not influenced by the plate thickness. In addition the behavior of the frames with high reinforcement ratios and strengthened with SPSW is less sensitive to W/H ratio in comparison with the lower reinforcement ratios one.

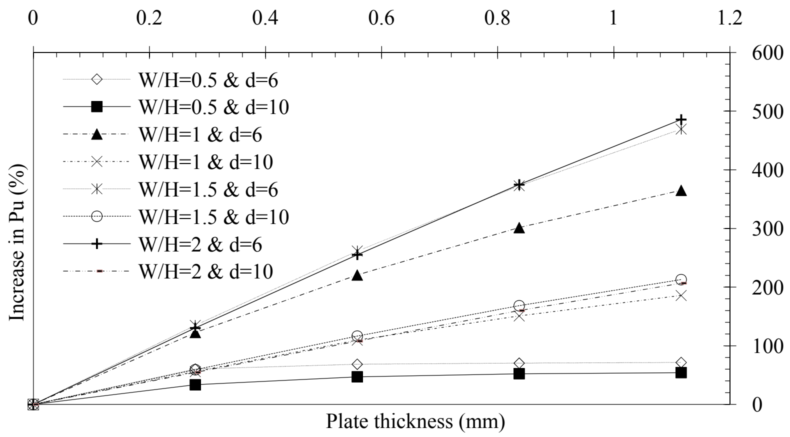

Figure 12. Increase of p_u versus plate thickness for RC frames strengthened by SPSW.

6. COMPARISON OF CURVES OBTAINED IN SEISMOSTRUCT VS SAP 2000

In this section we present the force-displacement curves obtained with SAP2000 (SAP2000, 2009) and BIAX, developed at University of Porto, (used for the moment-curvature behavior curves), and SeismoStruct, and then compare them with the values measured in the test. We present the results for Specimen A8 of Stroband and Kolpa (sections 2.1 & 3.3) and Ghaffarzadeh *et al*. (2006) experiment (sections 2.2 & 4). The force-displacement results are shown in Fig. 13.a and Fig. 13.b. The curve obtained in Seismostruct has the same shape that the experimental curve. The pushover curve in SAP2000 is also similar to the experimental curve. Results show that differences in the capacity curve are not significant regardless the modeling option for plastic hinges or fiber elements. Note that in Fig. 13.b, the curve obtained from test is envelope curve of the hysteresis test but numerical results are obtained from pushover analysis, so there are some differences between analytical and test results. In concrete structures pushover curve stand upper than hysteresis curve, the cause of it is in each cycle of cyclic tests, several cracks generate and stiffness of the frame are reduced.

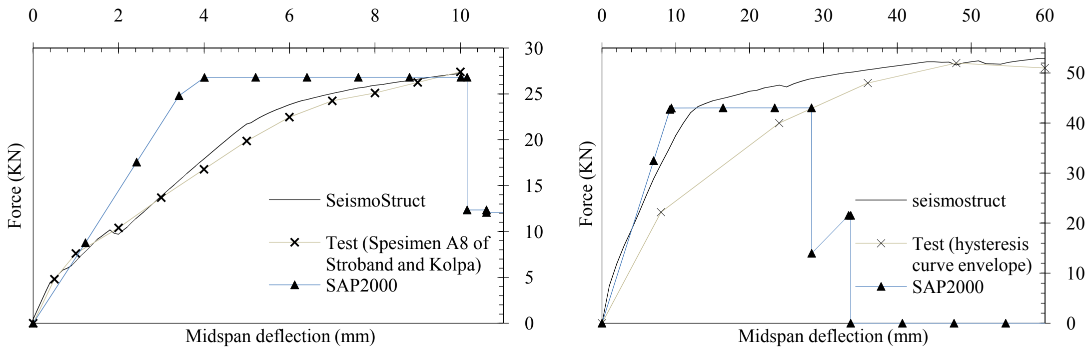

Figure 13. (a) Capacity curves for Specimen A8; (b) Capacity curves for Ghaffarzadeh *et al*. (2006) test.

7. CONCLUSIONS

In this paper, nonlinear finite element analyses of RC frames retrofitted by SPSW were performed. It can be concluded that the proposed FE modeling can accurately represent many of the main features of the behavior of concrete frames retrofitted by SPSWs. To better understand the behavior of SPSW, a series of analyses either using simple strip model were developed to analyze Lubell tests on two one-story SPSWs. The adequacy of the strip model using tension-only strips was found accurate to predict the nonlinear behavior of SPSW, as demonstrated by the experimental results. The pushover curves were shown to be equally well predicted by a monotonic pushover analysis using a FE model, when comparing to the experimental results. Different variables have been studied on their influence on the structural behavior of the frames. Below the findings are summarized:

1. The behavior of the frames with high reinforcement ratio and strengthened with SPSW is less sensitive to L/H ratio of the frame in comparison with the lower reinforcement ratios.
2. For frames with low reinforcement ratio and strengthened with SPSW, the frame L/H ratio do affect their behaviors significantly.
3. This system is very sensitive to yield stress of the steel plate so; many studies can perform in this field in future. Studying on low yield strength plates (LYP) is an important case of this field.
4. By using of LYPs in frames we can use thicker plates, so some problems in construction and welding procedure can be solved.
5. Analytical and experimental studies show maximum tension occurs in corners, so the connection of the plate to frame's corners must be performed carefully.
6. For retrofitting purposes, placement of steel plates in frames with greater width to height ratio leads to more increment in initial stiffness and capacity. On the other hand in greater ratios columns experience lower moments.

At the end, the pushover analyses were performed using two programs. The pushover analysis in Seismostruct has a lower computational effort, because it is not necessary to make sectional analyses.

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