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SEISMIC PERFORMANCE OF MULTI-STOREY CFS-SWP WITH DIFFERENT HEIGHT-TO-WIDTH ASPECT RATIOS

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ABSTRACT

Shear wall panels (SWP) are the main lateral resisting elements of cold formed steel (CFS) structures. Their seismic behaviour is governed essentially by the performance of the connectors e.g.: sheeting-to-sheeting connectors, and sheeting-to-framing connectors. This can be achieved by an acceptable evaluation of the load bearing capacity of the walls that can be obtained from full scale experimental test results which are available for different type of sheathing configurations (Fulop and Dubina, 2004). However, these data are based on laboratory testing on SWPs having a maximum height of a single or double storey and a variable width to obtain different height-to-width aspect ratios (Shamim et al., 2013). In practice, for multi-storey buildings, the storey height-to-width aspect ratio of a SWP can be significantly different from the total height-to-width aspect ratio of the multi-storey shear wall. The latter tends to behaves more in bending than in shear. In this paper, a brief presentation of a recently developed hysteresis model for CFS SWP which integrates the stiffness, strength degradation and pinching is first presented followed by an analytical investigation of multi-storey shear walls using a non-linear time history analysis. The objective of this study is to assess the effect of the overall height-to-width aspect ratio of the SWP on the seismic performance of the CFS structure. For this purpose, several lateral load resisting systems with different aspect ratios (multi-storey systems) are modeled using the macro-element hysteresis model implemented in OpenSees and subjected to both quasi-static and seismic loading. The performance is evaluated in terms of shear strength and lateral displacement time histories, energy dissipation capacity and axial loading at the end studs of the SWP.

INTRODUCTION

In recent decades, the cold-formed steel (CFS) sections are increasingly used in low to medium rise buildings as primary elements, even in seismic prone regions. In which, the shear wall panel (SWP) is the main lateral load resisting system; it is made of CFS C-shaped framing members (studs and tracks) attached to steel or wood sheathing using screw connections. A SWP which is designed appropriately always should be checked to provide enough shear strength and stiffness, the latter dissipates energy by the inelastic behaviour of its framing-to-sheathing connections (Shamim et al., 2013). The provisions based on experimental test results specified in American Iron and Steel Institute (AISI, 2007) and other similar codes are addressed to isolated SWPs rather than to multi-storey SWP with a maximum height-to-width (h/w) aspect ratio equal to 4:1. However, in multi-storey CFS buildings, shear walls could have an h/w aspect ratio well beyond those of SWPs published in codes which leads to the necessity of investigating the multi-storey shear walls performance under seismic loading.

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In pursuance of investigating the seismic performance of CFS SWP, several experimental quasi-static test programs have been carried out by researchers Fulop and Dubina (2004), Branston et al. (2006), Yu (2010), Balh (2010), Shan and Pan (2011), Nithyadharan and Kalyanaraman (2012), Liu et al. (2012), DaBreo et al. (2013), and Shakibanasab et al. (2014), as well as a dynamic test program performed by (Shamim el al., 2013). The test outcomes underscored the impact of SWP physical and mechanical characteristics such as: fastener spacing, sheathing thickness, framing thickness, and height-to-width aspect ratio on its hysteresis behaviour, where SWPs having a high h/w aspect ratio (i.e. 4:1) need more lateral drift in order to develop their maximum shear strength. The provisions specified in AISI S213 (2007) and other similar codes require that the shear strength of SWP with a height-to-width aspect ratio (h/w) of greater than 2:1 should be reduced by the factor 2w/h in order for satisfying the allowable story drift limitation (Shakibanasab et al., 2014). However, neither experimental nor numerical study has addressed the lateral behaviour of multi-storey shear walls.

In this paper, a brief description of a recently developed hysteresis model for CFS SWP that takes into account strength and stiffness degradation, as well as pinching effect, is illustrated. The model parameters are related to the physical and mechanical characteristics of the panel. The accuracy of proposed analytical model is validated using the experimental test results obtained from literature. Thereafter, and in order to investigate the seismic performance of a multi-storey lateral load resisting system with various h/w aspect ratios, several non-linear time-history analyses have been carried out.

HYSTERESIS MODEL

A hysteresis model for CFS SWP based on the model proposed by Lowes LN and Altoontash A (2003) that takes into account strength and stiffness degradation with pinching effect has been developed (Fig.1). Two analytical methods for wood sheathed and steel sheets sheathed CFS SWP proposed by, respectively, Xu and Martinez (2007), and Yanari and Yu (2013) have been used for the lateral strength assessment and the correspondent displacement as well.

A multi-linear envelop curve of the hysteresis loops based on the Equivalent Energy Elastic Plastic (EEEP) model was adopted (Bourahla et al., 2012).

The model parameters are directly related to the physical and mechanical characteristics of the SWP such as: fastener spacing, sheathing thickness, framing thickness, and height-to-width aspect ratio. The model has been implemented in OpenSees program, as a user-defined uniaxial material named CFSSWP using a dynamic link library (DLL) (Kechidi, 2014).

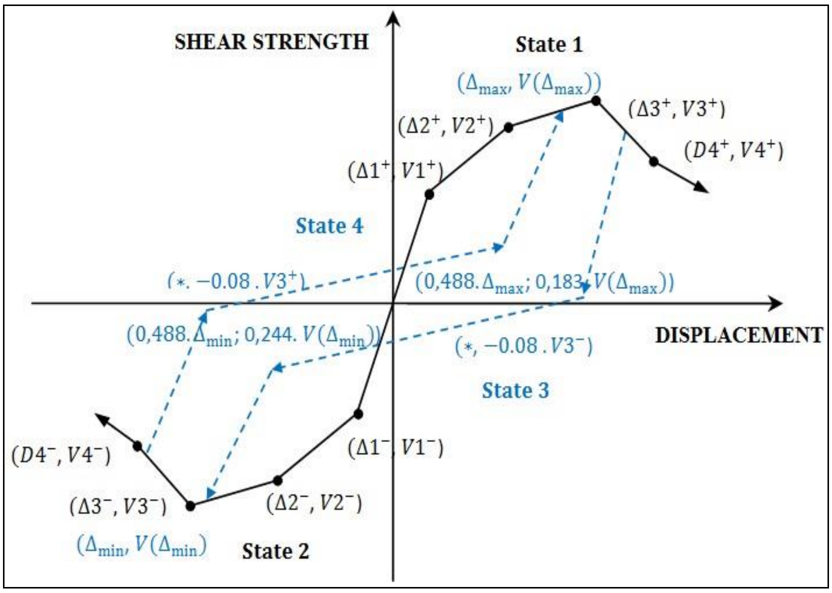


Figure 1. Hysteresis model for CFS SWP implemented in OpenSees

OPENSEES FINITE ELEMENT MODEL OF CFS SWP

In order to account for the overall lateral stiffness and strength of the SWP, an equivalent simple non-linear zeroLength element with CFSSWP model connected to rigid Truss elements which transmit the force to the end elements (chord studs) that resist to uniaxial tension and compression stress (Fig.2). This modeling tip lead to a considerable reduction in terms of element number constituting the CFS SWP. The boundary members form a mechanism and lateral stiffness and strength are derived directly from zeroLength element.

The CFS SWP details, as well as its schematic representation of finite element (FE) model are illustrated in Fig.2.

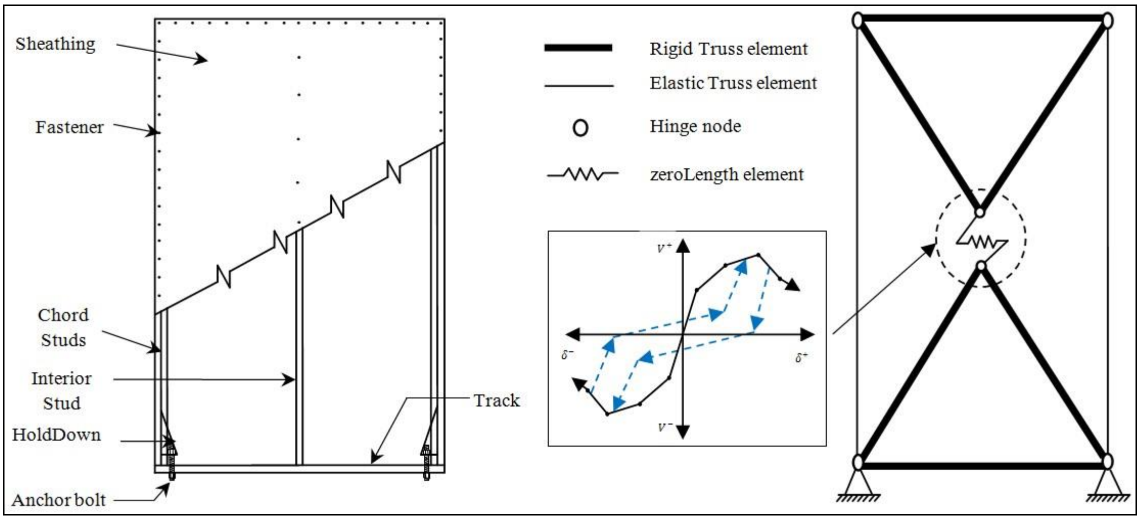


Figure 2. CFS SWP details and equivalent OpenSees FE model

HYSTERESIS MODEL VLIDATION

For further checking of the accuracy of the proposed CFSSWP model, quasi-static non-linear analyses of CFS SWPs have been carried out using OpenSees software.

Specimen n°16 tested by Branston et al. (2006), and specimen n° 3C-a tested by Balh (2010) have been selected from the literature in order to validate the proposed approach.

Each SWP was subjected to the Consortium of Universities for Research in Earthquake Engineering CUREE (2001) loading protocol.

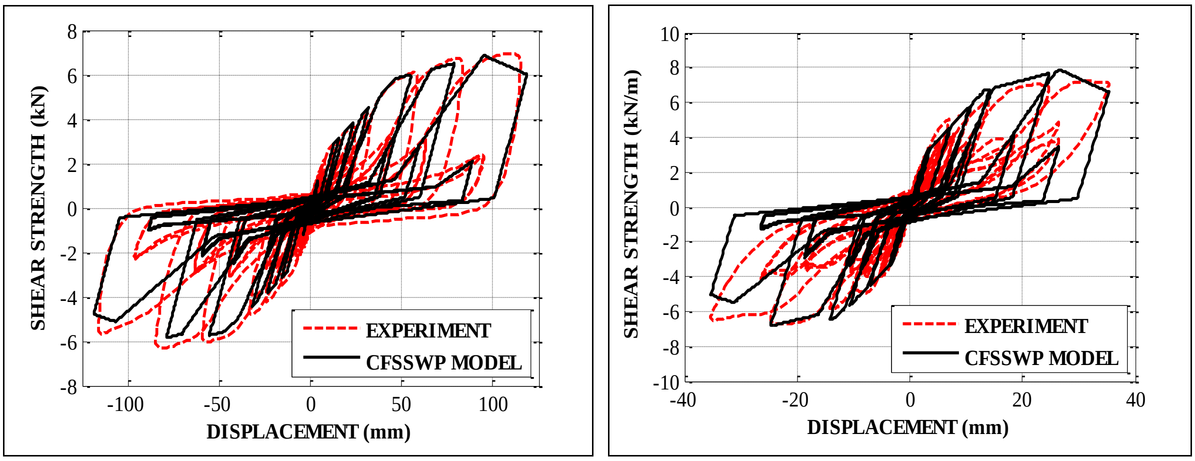


Figure 3. Comparison between CFS SWP experimental and numerical hysteresis loops, specimen n° 16 Branston et al. (2006) and specimen n° 3C-a Balh (2010)

The shear strength-lateral displacement hysteresis loops of wood and steel sheathed CFS SWPs from tests are plotted together with finite element (FE) model results in Fig.3. In general, a good agreement is observed between the experimental and numerical results.

It is noticed from these figures that the CFSSWP model simulates the fundamental response characteristics of the CFS SWP such as: strength and stiffness degradation, as well as the pinching effect reasonably well. The positive loops' performance of the cyclic response is better than negative ones in terms of strength capacity; this is due to the fact that firstly the SWP is loaded in positive direction, the ability of the SWP to resist shear load in the negative side becomes weak because of the deteriorations experienced during positive incursions. This behaviour is well captured using CFSSWP model.

SEISMIC PERFORMANCE OF MULTI-STOREY CFS SHEAR WALL

In order to study the lateral behaviour of multi-storey CFS shear wall, a seismic performance's comparison between a two storeys two-element with 1:2 aspect ratio and a two storeys one-element with 1:4 aspect ratio shear walls (Fig.4) was carried out.

The elements used to create the finite FE models were representative of the properties and behaviour of the relevant structural components of specimen n° 3C-a tested by Balh (Balh, 2010). Elastic truss elements with linear behaviour were used to represent chord studs. The roof and floor were considered rigid diaphragms with no out of plane flexibility and were modeled with rigid truss elements. The seismic mass on each SWP's top was computed in such a way that the fundamental period would be comparable to the one obtained from previous shake table tests for a similar specimens (Shamim, 2012). The latter was equally distributed at the SWPs' upper corners. The E-W component of the acceleration ground motion recorded at the Dar El-Beida station during Boumerdes (Algeria) earthquake of 2003 (30 km from the epicenter) has been used as a reference earthquake input with a PGA equal to 0.55 g.

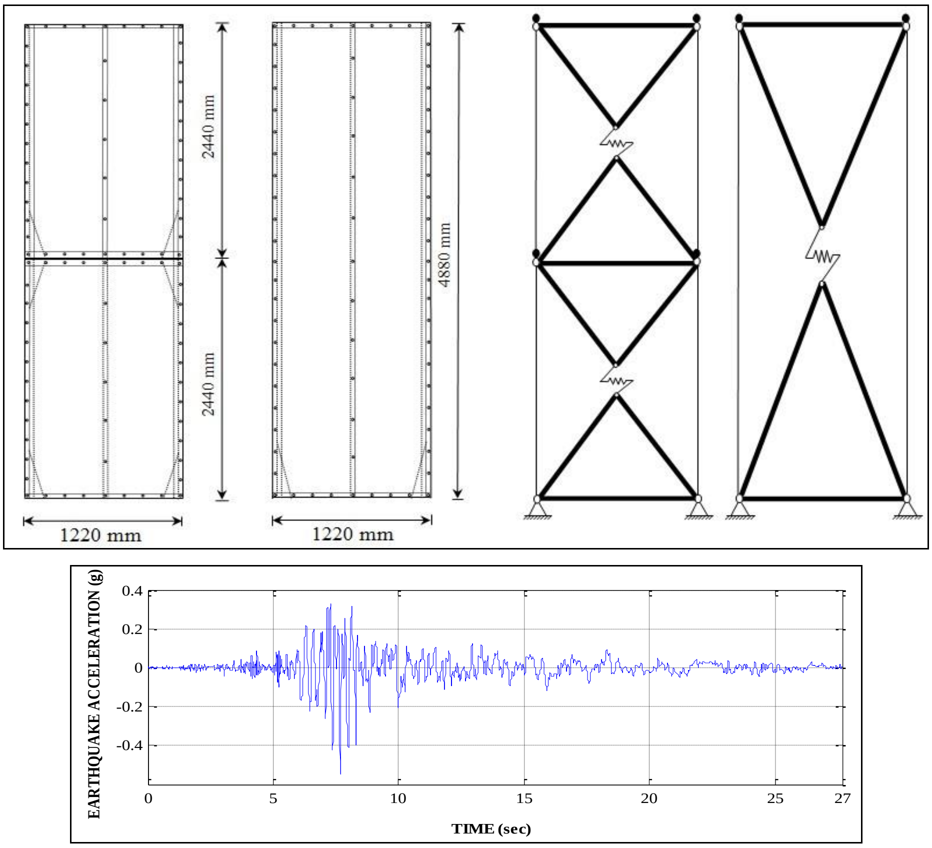


Figure 4. Description of shear walls, details of FE models and seismic loading record

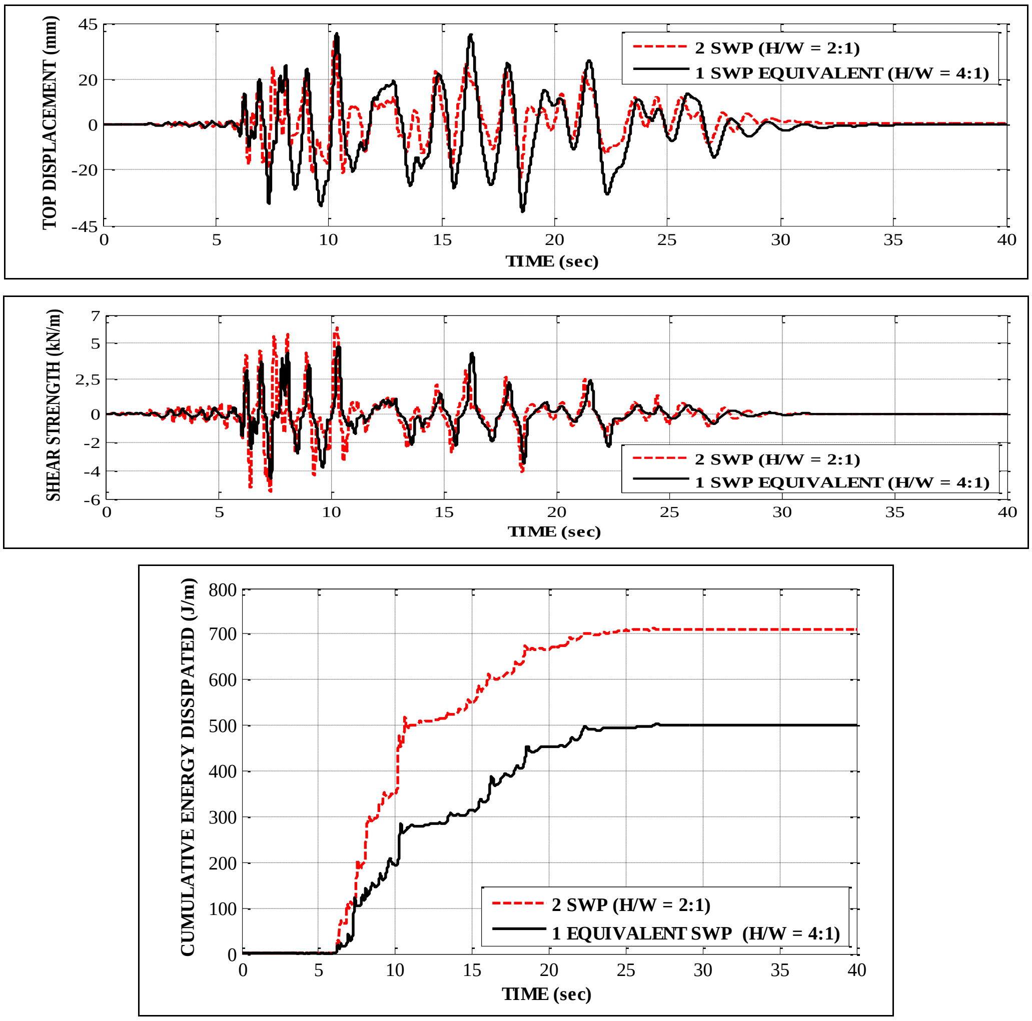


Figure 5. Performance comparison between two storeys two-element and two storeys one-element shear walls, top displacement, base shear strength and cumulative energy dissipated time histories

In Fig.5, it is seen that a two storeys two-element shear wall is laterally stiffer than two storeys one-element shear wall and dissipates more energy.

A two storeys one-element shear wall, if does not have screw fasteners in its mid-height (h=2.44 m), could only transfer the shear force at its top and bottom (h=4.88 m and 0.0 m) and therefore necessarily functions as a 4:1 aspect ratio SWP regardless of the SWP dimensions (Fig.6). The normalized performances are identical as given in Fig.7.

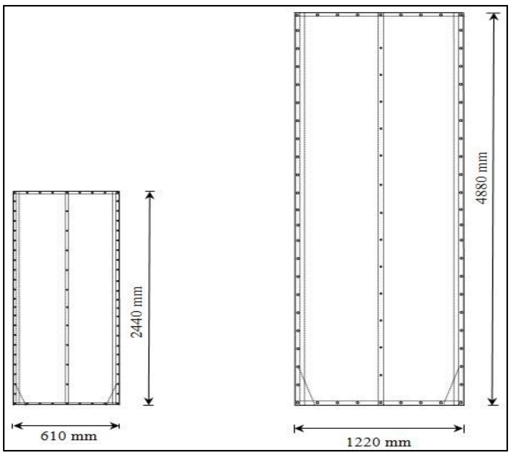


Figure 6. SWP having an aspect ratio 4:1 (2440/610) and (4880/1220)

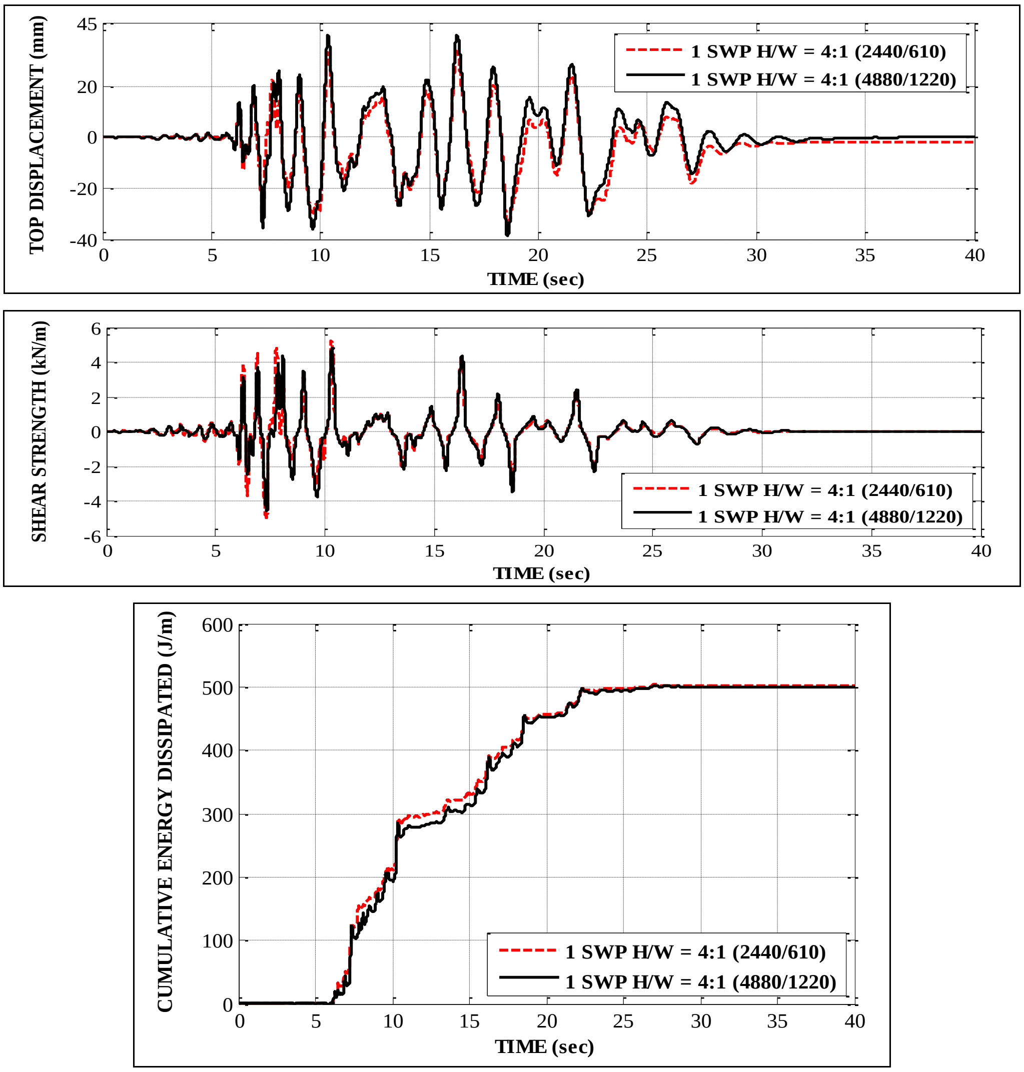


Figure 7. SWP having an aspect ratio 4:1 (2440/610) and (4880/1220), top displacement, base shear strength and cumulative energy dissipated time histories

Now, assuming the screw fasteners have the same pattern in both cases as shown Fig.8, yet in one case i.e. separated panels the chord studs are not continuous and in another case the chord studs are continuous, so the CFS frame itself would have a different performance in one case compared to the other. As long as both types have the same screw fastener configuration, the difference in CFS framing is not significant in the overall performance unless the CFS frame undergoes plastic deformations or shows high degree of elongation which increases the participation of CFS framing action in the amount of the lateral displacement of the shear wall. However, it should be always remembered that the separated SWPs since they are connected with the anchor bolts, they are also influenced by the anchor bolts' elongation (anchor bolt elongation increases the lateral displacement due to the wall rigid rotation). Fig.8 contains a schematic drawing which explains the uplift displacement in a double-storey shear wall specimen.

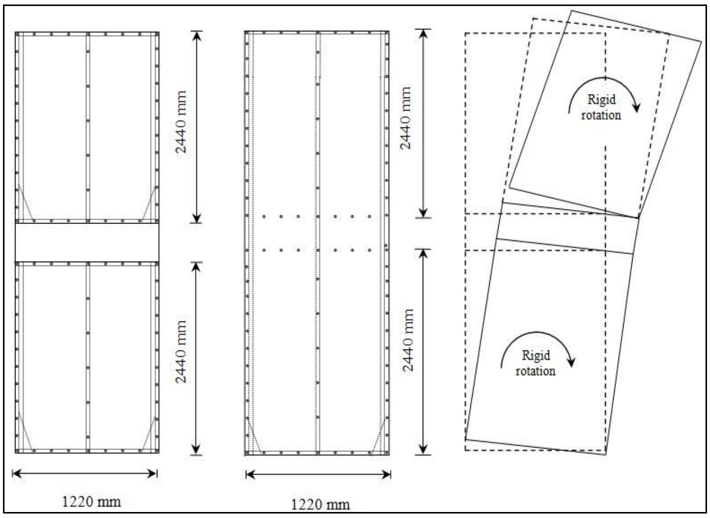


Figure 8. Two storeys two-element and two storeys one-element shear walls having a same sheathing-to-framing connections arrangement and uplift and lateral displacement for each SWP of a double-storey shear wall specimen

PARAMETRIC STUDY

In an attempt to investigate the influence of the number of stories (shear wall's height) on the SWP response, a parametric study using non-linear time history analysis was performed. Three lateral load resisting systems with 1, 3 and 6 stories have been selected (Fig.9). In order to construct FE models in OpenSees with different types of HoldDown system, anchor bolt stiffness was modeled separately as a FE with linear (uplift) springs (Shamim et al., 2013) and removed from the analytic equation which assesses the whole lateral drift used in CFSSWP model program which allows for the contribution of uplift to be taken into account in total lateral displacement of the shear walls. All shear walls are assumed to have a seismic mass of 150 kN placed on the top of each SWP, and a HoldDown system placed at the two bottom corners of each SWP having an anchor bolt stiffness of 30.4 kN/mm (Fig.9). In order to compare the structural behaviour under a severe earthquake with a high mechanical non-linearity and without any sudden failure, the seismic peak acceleration (PGA) of the above-described earthquake wave was adjusted to 0.275 g.

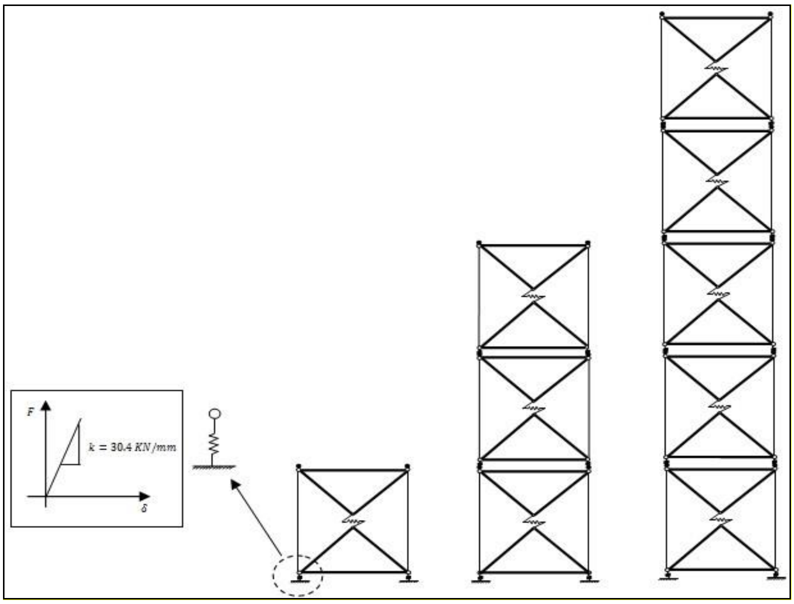
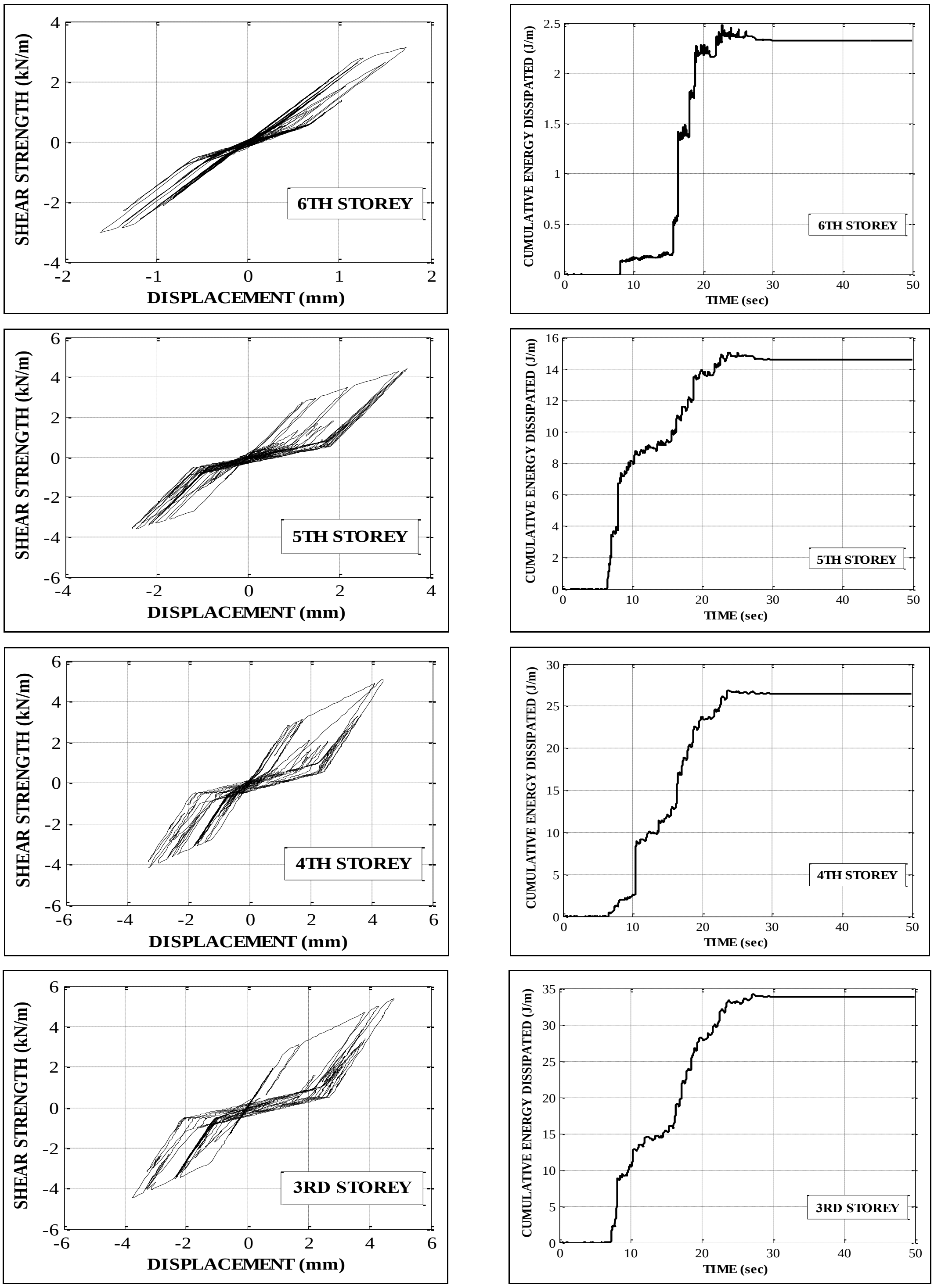


Figure 9. OpenSees FE models of one, three and six storeys shear walls

Fig.10 presents the relationship between resistance and displacement for each SWP in the six-storey shear wall when subjected to the above-described record. The uppermost storey remained almost in the elastic region as presented in Fig.10 where the curve of the corresponding cumulative energy dissipation is characterized by several fluctuations.



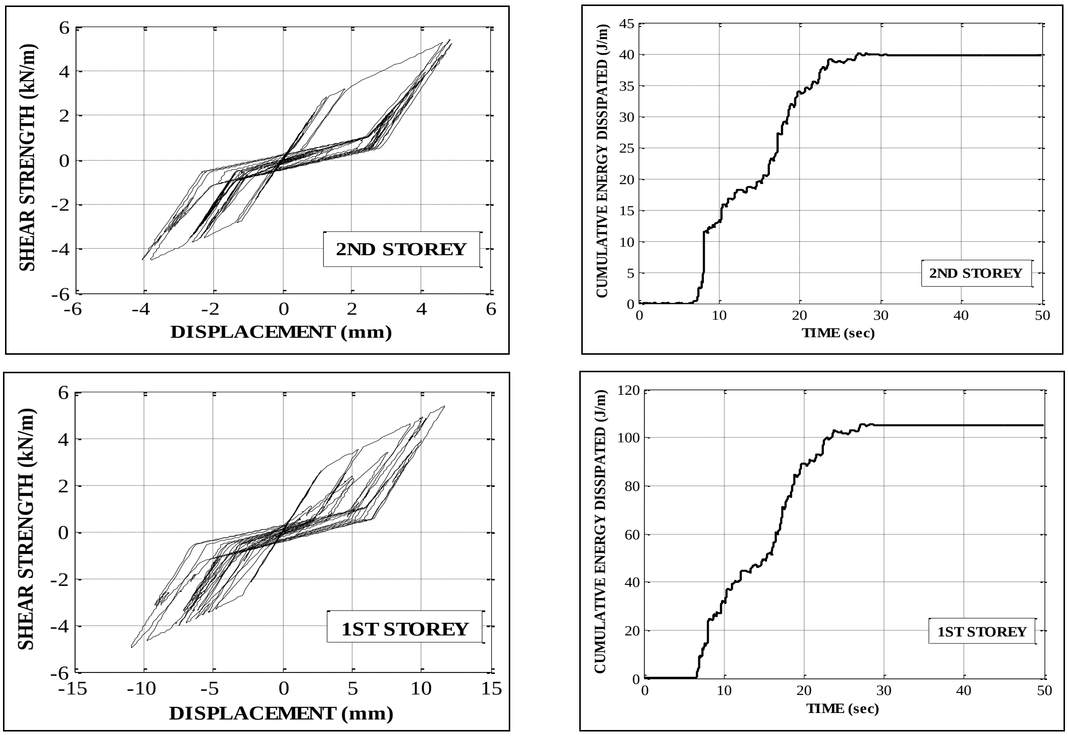
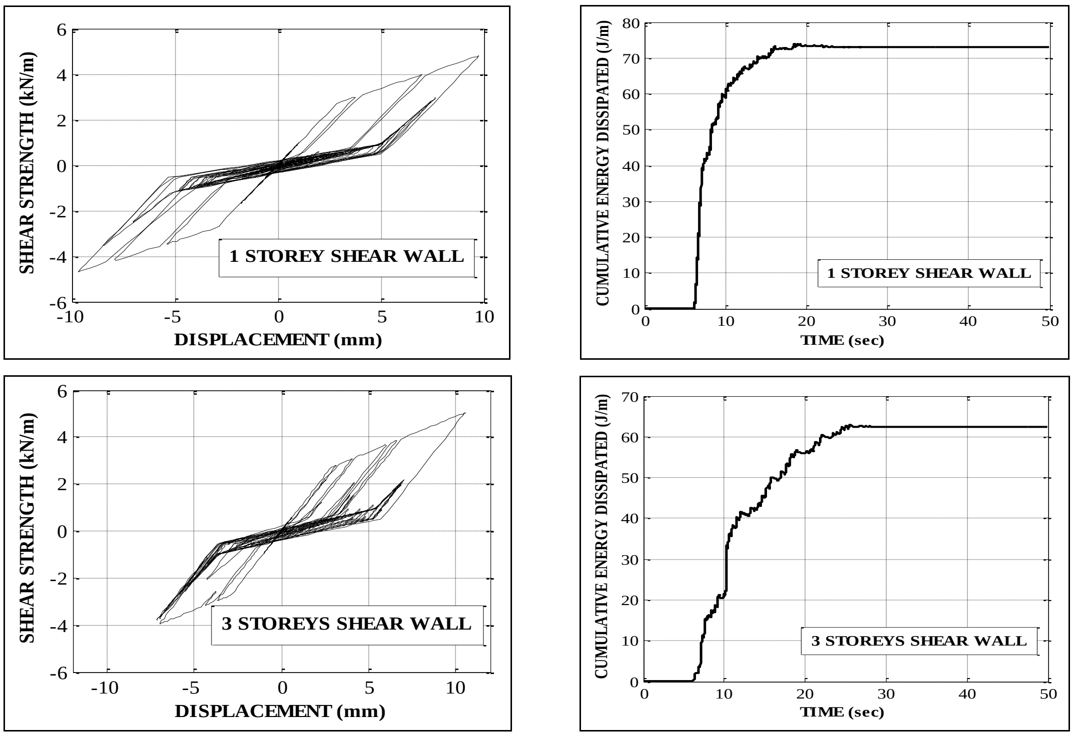


Figure10. Lateral response at each storey for six storeys shear wall: shear strength-displacement hysteresis and cumulative energy dissipated

The shear wall having a single storey, the strong reductions in the additional energy quantity after 15 sec of seismic loading (almost no energy added after this moment) as shown in Fig.11. However, shear walls having 3 and 6 storeys tend to dissipate the input energy throughout the entire accelerations of ground motion. Fig.11 shows evidence of the fact that the lateral response of different lateral load resisting systems depends not only on the seismic loading, but also on their model characteristics.



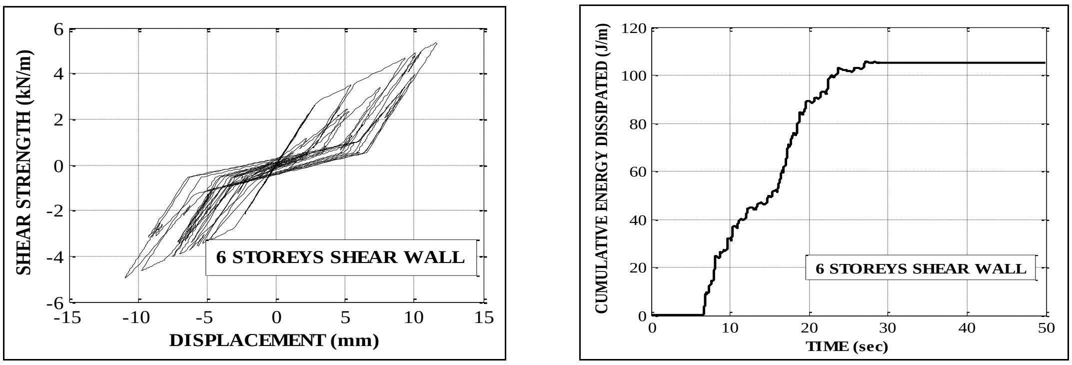


Figure 11. Lateral response at base storey for one, three, and six storeys shear walls: shear strength-displacement hysteresis and cumulative energy dissipated

The lateral displacement have four components: frame bending deformation due to the bending moment developed in the connections (HoldDown), the anchor bolt elongation (rigid rotation), displacement due to sheathing shear deformation, and displacement due to the chord studs shortening and elongation induced by compression and tension axial force (Fig.12). In general the SWP response includes all these four deformation and the dominant component is the shear deformation. Nevertheless, slender shear walls behave more in bending than in shear.

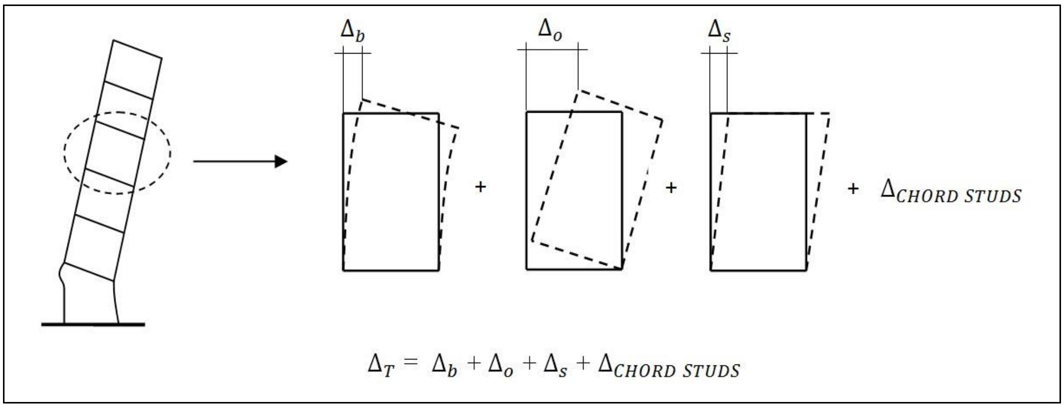


Figure 12. Components of SWP lateral displacement

Fig.13 shows Hold-Down anchor bolts' elongation histories located at the ground floor (0.00 m), 2nd floor (4.88 m), and 5th floor (12.20 m) for the shear wall composed of 6 SWPs (Fig.9).

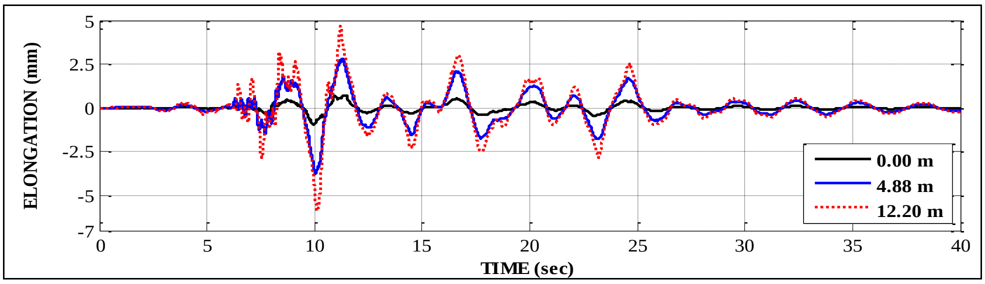


Figure 13. Hold-Down anchor bolt's elongation time histories at different height levels

Axial force histories developed at chord studs of the lowermost SWPs of the shear walls composed of 1 SWP, 3 SWPs, and 6 SWPs (Fig.9) are plotted in Fig.14 with maximum values: 6.49 kN, 17.61 kN, and 25.39 kN, respectively, which are well below the elastic buckling limit of the chord studs.

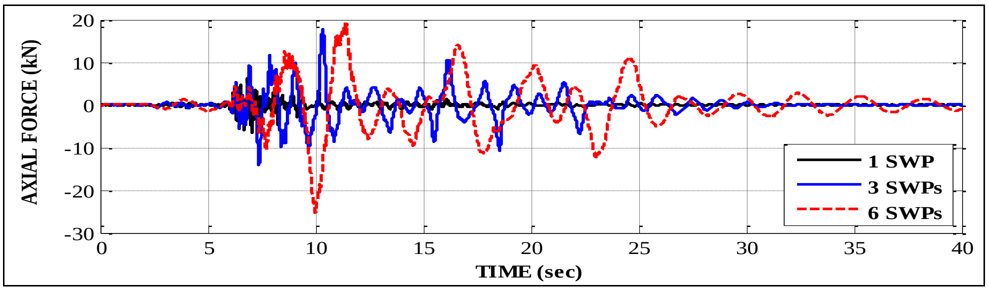


Figure 14. Chord studs' axial force time histories

CONCLUSION

This paper presents an analytical approach to predict hysteresis behaviour of a wood/steel sheathed CFS SWP with degradation criteria based on its physical and mechanical characteristics. Two analytical methods have been used for the assessment of the lateral strength and the correspondent displacement. A multi-linear envelop curve of the hysteresis loops based on the EEEP model was adopted. The model has been integrated into the finite element software OpenSees as a user-defined uniaxial material using a DLL written in C++ programming language. The efficiency of the modeling tip and the accuracy of the proposed model have been validated using available experimental data. The proposed model is used in non-linear dynamic analysis of multi-storey shear walls. The results showed that the walls' overall response is mainly dictated by the sheathing-to-framing connections configuration (fasteners arrangement). Parametric study on storey's number of the shear wall highlighted the fact that in addition to the inelastic bearing deformation of the steel sheathing and tilting of the fasteners, other mechanisms of energy dissipation took place with the increase of the storeys' number which leads to flexural deformation participation in the overall lateral behaviour of slender shear walls.

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