

Proceedings of the Annual Stability Conference Structural Stability Research Council St. Louis, Missouri, April 2-5, 2019

# An introduction to numerical modeling of composite plate shear walls / concrete filled (C-PSW/CF)

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# Abstract

Composite plate shear walls / concrete filled (C-PSW/CF) are being used as the lateral force resisting system for high rise buildings in the US and other countries. Individual walls are considered for low- to mid-rise buildings (less than 15 stories) and coupled composite core walls are considered for mid- to high-rise building (15 - 30 stories). When used as individual composite shear walls, the lateral resistance of C-PSW/CF is governed by the in-plane flexure and shear behavior, which is influenced by steel yielding, local buckling, concrete confinement, and the tie bar reinforcement ratio. When used as coupled composite shear walls, the lateral resistance of C-PSW/CF is governed by the in-plane flexure and shear behavior. This behavior under a combination of axial force, in-plane flexure, and shear. This behavior is influenced by the same parameters mentioned above along with the axial load level.

This paper briefly discusses results from experimental investigations conducted on a large-scale planar C-PSW/CF specimen subjected to axial compression and cyclic lateral loading. The paper also presents the development and benchmarking of detailed 3D nonlinear inelastic finite element models for the test specimen. The results from the experimental investigations and 3D finite element analyses are used to develop effective (phenomenological) stress-strain curves for the steel faceplates and the concrete infill of C-PSW/CF while accounting for the various complexities of behavior including steel yielding, local buckling, biaxial stress states, steel fracture, concrete confinement, composite action etc.

These effective stress-strain curves were implemented in 2D finite element models (using composite shell elements of ABQUS) and fiber element models (using OpenSEES). The effective stress-strain curves were used along with fiber elements (with deformation-based formulation) to predict the cyclic lateral load-deformation behavior of the C-PSW/CF specimens. The process developed in this paper is recommended along with the (idealized) effective stress-strain curves to model C-PSW/CF walls, for analyzing multi-story building structures for lateral load combinations including wind or seismic loads.

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# **1. Introduction**

High-rise buildings require proper lateral load resisting systems, especially in regions of high seismic hazard or sites with extreme wind. Composite plate shear walls / concrete filled (C-PSW/CF) are an excellent option for the lateral load resisting system due to their significant benefits such as modularity, construction schedule, and efficient structural performance (Wang et al. 2017, Shafaei 2017).

A typical C-PSW/CF is shown in Fig. 1. C-PSW/CF consists of structural steel modules that are filled with plain concrete. The steel modules consist of two faceplates that are connected to each other using ties; and may include some headed shear studs on the interior surfaces. The empty modules are pre-fabricated, transported to the site, assembled, and filled with plain concrete. The steel faceplates serve as the primary reinforcement, and composite action between the faceplates and concrete infill is achieved by the embedded ties (Shafaei et al. 2017, Sener and Varma 2014, Sener et al. 2015, and Wang et al. 2017).



Figure 1: A typical component of C-PSW/CF

Planar C-PSW/CF are typically used in the design of low- to mid-rise buildings (less than 15 stories) and coupled C-PSW/CF are used for mid- to high-rise buildings (15-30 stories). The lateral load resisting behavior of the planar C-PSW/CF is governed by the in-plane flexure and shear. However, the lateral load resisting behavior of the coupled C-PSW/CF is governed by a combination of axial load and in-plane flexure or axial force and shear. Steel yielding, local buckling, steel fracture, biaxial stress state, concrete confinement, and the tie bar reinforcement ratio have a direct influence on the behavior of planar and coupled C-PSW/CF, which should be considered in the analysis and design. An efficient procedure is needed for the analysis and design of multi-story C-PSW/CF, which can account all the mentioned complexities.

By contrast, there is a significant lack of knowledge regarding options for modeling the lateral load behavior and capacity of C-PSW/CF in multi-story buildings. A simple and relatively straightforward model that considers the various complexities of behavior of C-PSW/CF paves the way for the implementation of this system in the US and abroad.

In this paper, an experimental study conducted on a large-scale planar C-PSW/CF is briefly presented. The tested C-PSW/CF was subjected to both axial compression and cyclic lateral loading. A detailed 3D nonlinear finite element model of the tested specimen was developed and benchmarked. The 3D finite element model explicitly accounts the various complexities in behavior of C-PSW/CF such as steel yielding, local buckling, biaxial stress states, steel fracture, concrete confinement, and composite action. Using experimental and numerical results, effective (phenomenological) stress-strain curves for the steel flange plates and infill concrete core are derived. Idealized effective stress-strain curves for the steel flange and infill concrete of C-PSW/CF are proposed. These curves can be efficiently used in 2D finite element models (composite shell elements) of fiber-based element model while analyzing multi-story buildings for lateral loads combinations.

## 2. Experimental Behavior of C-PSW/CF

This section covers an experimental investigation into C-PSW/CF subjected to both axial compression and cyclic lateral loads. A C-PSW/CF specimen, CW-42-55-10-T, with scale of 1:3 was fabricated and tested under 10%  $A_g f'_c$  axial compression load. Fig. 2 shows the details of cross section of CW-42-55-10-T. The specimen had a height and width of 10 ft. and 3 ft., respectively. The wall thickness (t<sub>sc</sub>) and steel faceplates thickness (t<sub>p</sub>) were 9 in. and 3/16 in., respectively, resulting in a reinforcement ratio ( $\rho=2t_p/t_{sc}$ ) of 42%. Steel tie bars with 3/8 in. diameter (d<sub>tie</sub>) and tie spacing (S<sub>tie</sub>) equal to 4.5 in. were selected to satisfy a tie reinforcement ratio ( $\rho_{tie} = \pi d_{tie}^2/S_{tie}^24$ ) of 0.55%.



Figure 2: Details of the C-PSW/CF specimen (CW-42-55-10-T)

Steel faceplates of the specimen were A572 Gr. 50 with a yield  $(F_y)$  and ultimate  $(F_u)$  strength of 59.1 and 68.5 ksi, respectively. The measured yield  $(F_y)$  and ultimate  $(F_u)$  stresses of the bars were 49.1 and 69.5 ksi. The compressive strength of concrete on the day of test was equal to 6508 psi; therefore, the constant axial compression load (P) of -210 kips was applied to the top of the specimen.

Fig. 3 illustrates a view of the test setup of the C-PSW/CF specimen subjected to axial compression load and lateral cyclic forces. The specimen was welded to the base plate of a reinforced concrete foundation, which is post-tensioned to the laboratory strong floor. The lateral loading was applied to the specimen using 100-kip actuators at 9 ft. above the base plate. Axial

compression load (P) was kept constant on the top of specimen using a 500-ton Enerpac ram and a swivel loading frame. Lateral loading protocol was in accordance with ATC-24 and included force- and displacement-control cycles.



Figure 3: Test setup of C-PSW/CF

The C-PSW/CF specimen, CW-42-55-10-T, showed linear behavior during the elastic cycles. Yielding of the steel flange plates initiated during  $1\Delta_y$ , when the lateral loads were 133 kips in the push and -126 kips in the pull direction. Local buckling of the flange plate was observed during the  $2\Delta_y$  cycles, as shown in Fig. 4. The local buckling of the steel flange plates took place between the first and second row of the flange shear studs (from the bottom).

At the first cycle of  $3\Delta_y$ , the maximum lateral load, 184.6 kips (in the push direction), was recorded. Fracture initiation in the south and north steel flange plates occurred during the next cycles of  $3\Delta_y$ . During  $4\Delta_y$  and  $5\Delta_y$  cycles, propagation of the fracture in steel flange plates and lateral load capacity degradation were observed. The south steel flange plate was totally fractured through at the first cycle  $6\Delta_y$  and the test was terminated. Fig. 5 depicts the lateral load-displacement response of the tested C-PSW/CF specimen. It should be noted the lateral displacement was corrected by removing the effect of elastic rotation of foundation and any slip at the base.



Figure 4: Local buckling of the south flange



Figure 5: Lateral Load-Displacement response of the C-PSW/CF specimen (CW-42-55-10-T)

#### **3. Finite Element Model**

A detailed 3D nonlinear finite element model (FEM) was developed using a commercial software program, ABAQUS, to investigate the behavior of C-PSW/CF. Fig. 6 shows the 3D finite element model of the tested C-PSW/CF specimen. The steel face plates were modeled using four-node shell elements with reduced integration (S4R). Eight-node solid elements with reduced integration (C3D8R) were selected for the infill concrete core. The tie bars were modeled using two-node beam elements (B31). Connector elements (CONN3D2) were defined at the connection between the steel faceplates and tie bars, considering the axial and interfacial shear response of the connection. The shear response of tie bars was specified using the model proposed by Ollgaard et al. (1971). Initial geometric imperfections were defined in the steel faceplates to trigger the initiation of local buckling.



Figure 6: Finite element model of the C-PSW/CF specimen

A nonlinear elastic-plastic material model, according to the results of tested steel coupons of the specimen, was considered for the steel faceplates, as shown in Fig. 7(a). The fracture failure of the steel material was defined using the ductile damage option of the ABAQUS software. In the ductile damage model: (i) the damage initiated at 18% equivalent plastic strain, (ii) the damage evolution was linear, and (iii) the fracture (element deletion) occurred at 25% equivalent plastic strain. Concrete damage plasticity (CDP) model was used for the infill concrete core. The uniaxial compression behavior of concrete was developed using confined concrete model proposed by Tao et al. (2013), as shown in Fig. 7(b). The CEB-FIP model (2010) was also used to specify the uniaxial tension behavior of concrete.



Figure 7: Material properties (a) steel stress-strain curve (b) Concrete stress-strain curve for compression

Fig. 8(a) shows the comparison of the experimental results of CW-42-55-10-T with the finite element model. There is a good agreement in numerical and experimental results, which indicates the complex behavior of C-PSW/CF can be reasonably and accurately predicted by finite element model. In the finite element model, the local buckling of the flange plates occurred between the first and second row of the flange shear studs from the bottom of the specimen, as shown in Fig. 8(b). The locations of local buckling of steel flange plates in both the finite element model and experiment were the same.



Figure 8: Finite element results: (a) Comparison of finite element model with experimental results (b) Local buckling of steel flange plates

# 4. Development of effective stress-strain curves

Detailed 3D finite element models are complex and take too much computational resources and time. There is much more interest in simple 2D finite element models that can reasonably model the behavior and conduct cyclic or seismic analysis much faster.

The effective uniaxial stress-strain relationships are used for 2D finite element models or fiber section analysis. The accuracy of a 2D finite element model or fiber-based finite element models to predict section capacity and behavior of C-PSW/CF is primarily dependent on the effective stress-strain curves. In this study, the effective stress-strain relationships for the steel flange plates (compression and tension flanges) and the compression infill concrete of C-PSW/CF were derived from the results of the 3D finite element model analysis. The development of effective stress-strain curves of C-PSW/CF follows (a) the fundamental behavior and failure mechanism (b) the conservative approach (c) the simplicity of their application in numerical models.

In accordance with experimental and numerical results, the steel flange plates and the compression concrete have a significant impact on the overall response of C-PSW/CF subjected to combined axial compression and lateral loads. The steel yielding, local buckling, biaxial stress state, steel fracture, composite action, and concrete confinement were taken into account in the development of the effective stress-strain curves. The results of detailed 3D finite element model of CW-42-55-20-T were used to develop the effective stress-strain curves for steel and concrete materials.

## 4.1 Effective stress-strain curves for the steel flange plates of C-PSW/CF

Fig. 8 represents the procedure used to develop the effective stress-strain curves for the steel flanges (both compression and tension). A row of elements at 18 in. above the base plate (above the plastic hinge) was selected and the effective principal stresses ( $\sigma_{11}$  and  $\sigma_{22}$ ) were extracted, as shown in Fig. 9. The effective strain of the plastic hinge was calculated dividing the average vertical displacement of selected elements through the lateral loading by the length of plastic hinge.



Figure 9: The procedure used to develop the effective stress-strain curves

Fig. 10 illustrates the extracted effective stress-strain curves for the steel flange in compression and tension. In accordance with 10(a), the principle stress along the flange plate,  $\sigma_{22}$ , reaches the yield stress and then remains approximately constant at the yield stress level. This elastic-plastic response of the compression steel flange is due to the local buckling of the flange plate. The principle stress,  $\sigma_{11}$ , in the 1-1 direction (transverse) is also negligible, which indicates there is no biaxial stress state effect in the flange plate.

As shown in Fig. 10(b), the principal stress along the tension flange,  $\sigma_{22}$ , reaches greater stress compared with the yield stress (F<sub>y</sub>) of 59.1 ksi. Additionally, the transverse principal stress (in the 1-1 direction) is noticeably high, that indicates the tension flange plate is in a state of biaxial stress. This state occurs because the tension flange plate undergoes longitudinal strain due to bending moment at the base, while it should also contract in the transverse direction due to Poisson effect. However, the infill concrete restrains the transverse shortening of flange plate, which results in the tension transverse stress (in the 1-1 direction). As the tension flange is in the state of biaxial stress state, both principal longitudinal and transverse stresses ( $\sigma_{11}$  and  $\sigma_{22}$ ) should be considered in calculation of the yield surface of the tension flange plate. As plotted in Fig. 10(b), the von Mises criteria results are similar the input stress-strain curve for the steel material.



Figure 10: (a) Principle stresses in the compression steel flange plate (b) Principle stresses ( $\sigma_{11}$  and  $\sigma_{22}$ ) and von Mises stress in the tension steel flange plate

In accordance with the derived effective stress-strain curves for the steel flange plates from the 3D finite element model, an idealized effective stress-strain relationship for steel flange plates of C-PSW/CF is proposed. As shown in Fig. 11, a uniaxial bilinear elastic-plastic behavior with plastic hardening is proposed for the tension flange. It is recommended the yield point of tension flange is increased by 10% to consider the effect of biaxial stress state. A uniaxial bilinear elastic-plastic is also proposed for the compression flange due to the local buckling. Additionally, considering a fracture initiation at ultimate strength with a linear fracture evolution is conservative.



Figure 11: Proposed uniaxial effective stress-strain curves for the steel flange plate of C-PSW/CF

#### 4.2 Effective stress-strain curve for the compression concrete of C-PSW/CF

The average axial stress ( $\sigma_{22}$ ) in the compression block was extracted from the 3D finite element model to develop the effective stress-strain curve for the compression concrete. Different sections of concrete in the plastic hinge were considered to understand the effect of local buckling on the concrete compression behavior. Fig. 5 shows the locations of the selected sections in the compression concrete for development of the effective stress-strain curves.



Figure 12: Locations of the selected layers in the compression concrete for the effective stress-strain curves

Fig. 13 depicts a comparison of the results of effective stress-strain curves in selected concrete sections with the input confined concrete behavior in Abaqus. As shown in the Fig. 13, the ascending branch of the extracted effective stress-strain curves for section 2, 3, and 4 are affected due to the initiation of local buckling of the compression steel flange. However, the ascending branch of section 1 follows the input stress-strain behavior up to the compression strength of concrete  $f'_c$ . In general, the post-peak ductility of concrete is considerably better than the input uniaxial stress-strain curve, which is due to the confinement provided by steel faceplates. According to the extracted effective stress-strain curves, the compression strength of concrete does not decrease below 60% of  $f'_c$ .



Figure 13: Comparison of extracted effective stress-strain curves of selected concrete layers with the input confined concrete behavior in Abaqus

The proposed uniaxial effective stress-strain curve for the compression concrete of C-PSW/CF is depicted in Fig. 14. The idealized compressive stress-strain relationship of concrete is developed using the ascending and descending branches of proposed concrete model by Tao et al. (2013). However, the ascending branch becomes constant at 60% of  $f'_c$ . It should be noted that using the descending branch proposed by Tao et al. (2013) is conservative, although the post-peak behavior of concrete is more ductile.



Figure 14: Effective stress-strain curve for compression concrete

#### 5. Implementation of effective stress-strain curves

The proposed effective stress-strain relationships for the steel flange plates and the compression infill concrete were implemented in a 2D finite element model and fiber-based model.

#### 5.1 Application in 2D finite element model (ABAQUS)

The effective stress-strain curves developed for the steel flange plates and compression concrete core were implemented in a 2D finite element model of the tested C-PSW/CF specimen (CW-42-55-10-T). The infill concrete core and steel web plates were modeled using four-node composite shell section with reduced integration (S4R) and the steel flange plates were simulated by three-dimensional two-node truss elements (T3D2), as shown in Fig. 15.



Figure 15: 2D finite element model of the C-PSW/CF specimen, CW-42-55-10-T

The 2D finite element model had a height of 9 ft. and a width of 3 ft. The area of the truss element was equal to the area of the steel flange plate, and truss elements were tied to the composite shell elements. The composite shell section included 3 layers; 2 layers of steel web faceplates with 3 integration points and a layer of infill concrete in the middle with 7 integration points.

A comparison of 2D finite element model with the 3D model and experimental results are illustrated in Fig. 16. The comparison demonstrates the proposed idealized effective stress-strain curves for C-PSW/CF are conservative and valid for estimating the behavior.



Figure 16: A comparison of 2D finite element model with the 3D model and experimental results

# 5.2 Application in fiber-based model (OpenSees)

The effective stress-strain curves were also implemented in a fiber-based model. Using the opensource program OpenSees (McKenna et al. 2016), a fiber model of the tested C-PSW/CF was build using the effective stress-strain curves and test geometry. Due to limitations in available OpenSees steel material models, the yield strength was maintained at  $F_y$  in both tension and compression.

The fiber model used three 6 in. nonlinear fiber elements over the expected plastic hinge length (18 in.) then an elastic element along the rest of the height, as shown in Fig. 17(a). Nonlinear elements where assigned the section geometry and the effective stress-strain behavior. Elastic elements were assigned cracked transformed properties.

A comparison between the experimental results and fiber model showed the model to be a reasonable prediction of the behavior, as illustrated in Fig. 17 (b). Although the ultimate capacity is slightly under-estimated, the initial stiffness, cyclic deterioration, and unloading/reloading follow the experimental results well. Underestimating the ultimate capacity is expected because the steel material model did not include an increase in  $F_y$  in tension. Nevertheless, the close correlation of the behavior shows the effective stress-strain curves are able to accurately predict the cyclic behavior.



Figure 17: (a) The fiber-based model of the tested C-PSW/CF specimen (SW-42-55-10-T) (b) A comparison of experimental results with fiber-base model

## 6. Conclusions

This study represents the results of an experimental research conducted on a large-scale planar C-PSW/CF specimen subjected to both axial compression and cyclic lateral loads. Additionally, a detailed 3D nonlinear finite element model of the tested specimen was developed and benchmarked. The experimental and numerical results were used to develop effective (phenomenological) stress-strain curves for the steel flange plates and the compression infill concrete of C-PSW/CF.

The development of effective stress-strain curves was based on (a) the fundamental behavior and failure mechanism of C-PSW/CF (b) a conservative way (c) the simplicity of their application in numerical models. The proposed effective stress-strain curves consider various important parameters that influence the behavior of steel and concrete materials, for example, steel yielding, local buckling, biaxial stress states, steel fracture, concrete confinement, composite action etc. The proposed effective stress-strain relationships of this study can be efficiently used in 2D finite element model (composite shell elements) or fiber-based element model while analyzing multi-story buildings for lateral loads combinations.

## Acknowledgments

The project was supported by Charles Pankow Foundation (CPF Research Grant #06-16) and American Institute of Steel Construction (AISC). However, any opinions, findings, conclusions, and recommendations presented in this paper are those of the authors and do not necessarily reflect the view of the sponsors.

Specimen fabrication was donated by the Supreme Group. The authors acknowledge the contributions and support of Ron Klemencic and Brian Morgen from MKA Inc., Michel Bruneau and Emre Kizilarslan from the University at Buffalo, and the project advisory panel.

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