Finite element analysis of steel shear frames with composite reinforced concrete infill walls and welded bolts as shear connectors

Pablo Uribe Barcenas[1], Marines Perez Ramirez[2], Carlos A. Bermudez Mejia[3]

[1]*Undergaduate student of the Dept. of Civil Engineering, Universidad Nacional de Colombia*
Sede Manizales, 17004, Manizales, Caldas, Colombia
puribeb@unal.edu.co
[2]*Phd candidate of the Dept. of Civil Engineering, Universidad Nacional de Colombia*
Sede Manizales, 17004, Manizales, Caldas, Colombia
mperezr@unal.edu.co
[3]*Professor of the Dept. of Civil Engineering, Universidad Nacional de Colombia*
Sede Manizales, 17004, Manizales, Caldas, Colombia
cabermudezm@unal.edu.co

Abstract. This paper presents a numerical study of the behavior of a composite structural system consisting of Steel Shear Frames with Reinforced Concrete infill Walls (SFRCW). The composite interaction is achieved using welded bolts as shear connectors along the steel frame–infill interfaces; welded bolts were used as shear connectors because they are frequently used in Colombia due to their ease of installation. The SFRCW system may be particularly appropriate for low-to-moderate-height structures. In addition, the steel shear frame will support gravity loads at the construction stage, allowing progress in height. The system can also be used to strengthen existing steel buildings. The relatively light steel frame constructed using shear connections maximizes the system's economy. This study compared the behavior of the SFRCW with columns acting in their weak and strong axes and with different numbers of shear connectors. It also compared the behavior of the bare steel moment frame, bare steel shear frame, and concrete wall.

Keywords: SFRCW, Composite structural system, Finite Elements Method (FEM), Infill wall, Welded bolts shear connectors.

1 Introduction

A composite shear wall consisting of a single bay wall encasing structural steel framing, where the concrete wall resists horizontal shear due to wind or earthquake while the structural steel columns resist the vertical overturning resistance. In some cases, the wall may be installed as shotcrete without encasing either the structural beam or the column. In this condition welded studs must be installed on both the beam and the column to transfer all forces at the perimeter of the shear panel as Viest IM [1] exposed. The reinforced concrete wall can be connected to the moment resisting frame through shear connectors and also to partially-restrained steel frame. Voghiatzis et al. [2] studied a composite structural system, which is formed by a partially-restrained steel frame with a reinforced concrete infill wall attached compositely to the steel frame around the perimeter of each wall panel (PRSRCW), offering a system for steel and composite buildings that are located in seismic zones. Such structures require a system capable of resisting or minimizing drifts -horizontal displacement- due to seismic loading and overturning moments. Additionally, the system offers rapid construction, lower cost and an easy maintenance in case of deterioration or local failures, by using both properties of a steel frame with shear connectors and a RC infill wall.

Similarly, Tong X [3] studies a composite structural system consisting of partially-restrained steel frames with reinforced concrete infill walls termed as the SRCW system. This research considers that the steel columns and beams serve as boundary members to resist gravity loads and most of the overturning moment due to seismic loading, while the reinforced concrete (RC) infill wall serves as a shear-resisting web. Also concludes, that the RC infills have the benefit of increasing the lateral stiffness dramatically as compared to a bare steel frame, thus avoiding excessive drift and reducing the seismic demands on the steel frames.

Therefore, the main idea of this article is to present a composite structural system consisting of Steel Shear Frames with Reinforced Concrete infill Walls (SFRCW). This system uses a typical steel frame with shear connections instead of a moment-resisting connection or partially-restrained connection between the beams and columns, providing to the system an economical and resource facility over similar systems non composite, while still offering sufficient strength to resist all service loads, including the gravitational and horizontal ones.

In this way, 3D Finite Element analysis were performed to evaluate the behavior of the components of the system; this includes studying the behaviour of the steel frame in both axes -the strong and weak axis under an horizontal displacement-. Subsequently, both models were analyzed under three scenarios. The first one, exclude the RC infill wall, allowing to evaluate the importance of the composite system, i.e. the bare steel frame. Following this, four simulations were conducted using the infill wall with a varying number of shear connectors (bolts) to evaluate the performance and requirements within the connectors and its relation to the infill wall stresses. Additionally, two simulations of the concrete walls were conducted to be compared.

2 Finite Element Method - FEM

Fourteen finite element models were considered, divided into five main groups: CW (concrete wall), SF-SA (steel frame acting over the strong axis), SF-WA (steel frame acting over the weak axis), SCW-SA (steel concrete composite wall with steel frame acting over the strong axis), and SCW-WA (steel concrete composite wall with steel frame acting over the weak axis). In CW models, the width of the concrete wall was variable. In the SF models, the beam-column connection varied between a shear and moment connection, in order to represent the differences between both scenarios. Similarly, in SCW models, the compound action interaction was variable (0% - 100%), altering the number of shear connectors and the contact between the SF and CW systems. For more details, refer to table 1.

The general dimensions of the SF and SCW models are 1010 mm in width and 2523 mm in height, including a 38 mm thick base plate that provides fixed support condition for the structure.

Table 1. FEM Details and Results

Model Reference	Contact SF-CW	Total Numbers of Bolts	SF Connection	Stiffness [kN/mm]	Max. Force [kN]	Analysis time required [hr]
CW-SA	-	-	-	26.1	33.1	0.75
CW-WA	-	-	-	29.9	41.5	0.75
SF-SA-MC	-	-	Moment	1.01	48.4	0.58
SF-SA-SC	-	-	Shear	0.95	45.4	0.33
SF-WA-MC	-	-	Moment	0.46	26.3	1.0
SF-WA-SC	-	-	Shear	0.25	14.7	0.5
SCW-SA-100%	Tie	-	Shear	19.3	255.4	9.0
SCW-SA-22C	Hard-Frictionless	22	Shear	17.2	253.0	4.5
SCW-SA-16C	Hard-Frictionless	16	Shear	15.9	228.9	4.0
SCW-SA-0%	Hard	-	Shear	8.8	161.6	4.0
SCW-WA-100%	Tie	-	Shear	42.1	216.7	4.0
SCW-WA-22C	Hard-Frictionless	22	Shear	33.2	197.0	22.0
SCW-WA-16C	Hard-Frictionless	16	Shear	27.1	169.8	21.0
SCW-WA-0%	Hard	-	Shear	8.4	69.4	10.0

2.1 Modeling approach

Multiple 3D models were modeled with real dimensions for the beams and columns, and approximate measures of the concrete wall and bolts, which will be explained further. For this purpose, AUTOCAD 3D was used to draw the geometries, which were then exported to a Finite Element software as Abaqus V.21, allowing the drawing of a complex geometry.

This study evaluates the response of the model under a 10 cm (100 mm) displacement for the strong axis (SA) and a 5 cm (50 mm) displacement for the weak axis (WA) due to its modeling complexity. Both are applied to the upper zone of the left column, using a contact area similar to the dimensions of the beam-column contact zone. The analysis will be conducted using a Dynamic Implicit method for solving.

Beams and Columns: The columns consisted of HEA 100 steel section with a length of 2485 mm connected to beams that consisted of IPE 160. In the weak axis scenario, the columns were reinforced by placing stiffeners along their length at the same height as the connectors. Over the meshing process, a hexahedral solid element C3D8 was assigned for both instances according to Abaqus CAE User's guide, [4]with an approximate global size of 15 mm.

Concrete wall (CW): The concrete wall is 2165 mm in height, with different widths depending on whether the specimen is evaluated over its strong or weak axis. In the first scenario (SA), the width is 914 mm and in the second-one (WA) it is 1005 mm, in both the thickness of the wall is 80 mm. Also, the space occupied by the shear connectors was extracted from the total wall volume. A tetrahedral solid element C3D10 was assigned with an approximate global size of 40 mm. However, divisions were made approaching a refined mesh in the shear connectors zones.

Bolts: The bolts present a diameter of 20 mm (3/4") **SAE Gr. 2** with hexagonal heads, with a total length of 80 mm. In the software, a simplification was made by modeling the bolts without their hexagonal head, representing their total length as cylinders, avoiding divergence problems during the meshing process and in the contact zones as well, reducing the computational cost. Also, due to its cylindrical geometry a tetrahedral element C3D10 was assigned approaching a well refined mesh with an approximate global size of 8 mm.

- For the SCW-SA-22C and SCW-WA-22C model, the bolts distribution consisted of 7 connectors placed along each column and 4 on the inner faces of each beam.
- For the SCW-SA-16C and SCW-WA-16C model, the bolts distribution consisted of 4 connectors placed along each column and 4 on the inner faces of each beam.

Steel plates: Exposed in figure 2.

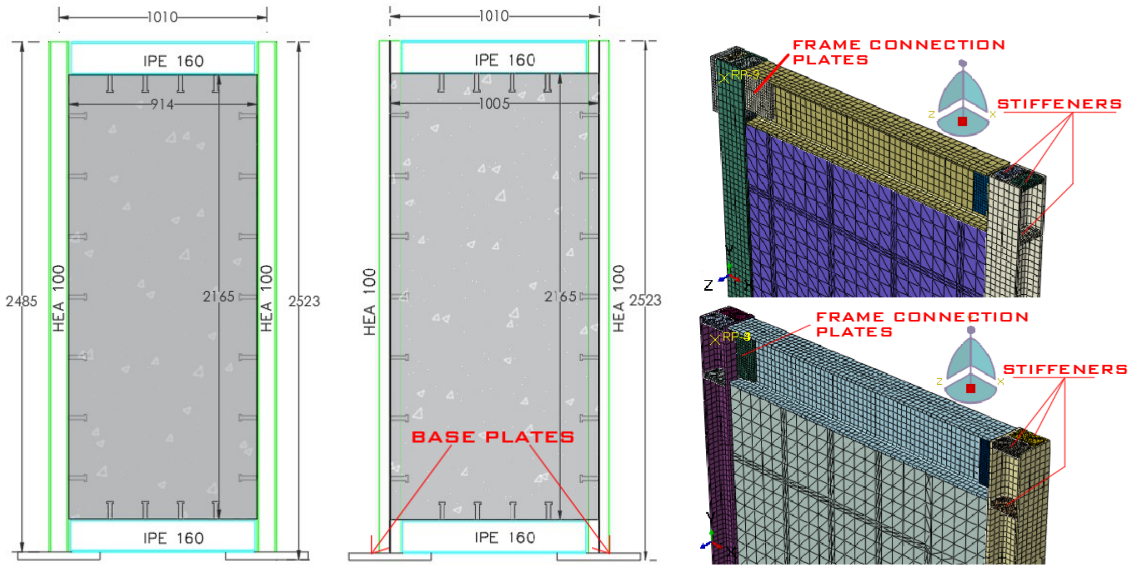
- Frame connection plates: For both the weak and strong axes, the connection plate was 12.7 mm (1/2") thick with different lengths according to each scenario. The simulation over the weak axis, required a 126 mm x 110 mm plate. In the strong axis scenario a 126 mm x 64 mm was required. The inner face of the frame connection plates was connected with a tie constrain to the beam web, and the surface to surface contact between the column and plate was also created using a tie constrain to simulate a steel frame shear connection. On the other hand, for the steel frame moment connection, the flanges of the beam were connected with a tie constrain to the columns in order to not allow a free rotation. For this instance a hexahedral solid elements C3D8 were assigned with an approximate global size of 6.3 mm.
- Base plates: A 38 mm (1 1/2") thick steel plate with 400x400 mm dimensions, was assigned based on the design calculation over the rotational forces that will affect the system. Hexahedral solid elements C3D8 were assigned with an approximate global size of 30 mm.
- Stiffeners: For this instance, the number of plates was different according to the scenario that was being simulated. In all cases, the stiffeners consist of a steel plate with a thickness of 12.7 mm (1/2"). Hexahedral solid elements C3D8 were assigned with an approximate global size of 3.2 mm.

2.2 Constraint types, interactions and restrictions

Over the modeling process, assigning boundary conditions, constraints and interactions are crucial to dictate how the system will perform during the analysis. This informs the software, how the elements are connected and the physical rules that need to be assigned by the user. First, the primary constrain used, was a *Tie* function, applied to all connections that, in a real model, could be attached by welded points. This was applied to the stiffeners, shear connections between beams and columns, the contact between the base-plates and columns, and to attach the shear connectors bolts with the steel frame. It was also applied in the bolts-head against the contact zone inside the RC infill wall to represent the connection effect produced by the bolts-head over this zone. Additionally, a tie connection was used in the 100% composite action model to represent the interaction between the steel frame and concrete wall.

The interactions were manually created with Hard Contact and Friction-less interactions. Both create a solid contact between surfaces, limiting movement between principal interactions, preventing parts from a possible trespassing between each other at the moment of applying the displacement load. The contacts were used between the surface contacts of the steel frame and the external faces of the infill RC wall, as well as the body of the shear connectors (bolts) and the inside surface of the concrete wall. Therefore, the friction incidence between both materials was ignored.

For restrictions, two principal boundary conditions were assigned. First, boundary encastre conditions were attached to the base plates, restricting all degrees of freedom (DOF) at the base. Second, to ensure the simulation takes place over the principal plane of the model and to avoid a rotation outside of its main plane, a restriction over the wall and columns displacements along the Z-axis was applied i.e. $U_z = 0$ in the models that exhibited rotation during the analysis. This displacement constraint prevents any rotation along the entire section about the Y-axis.



(a) SCW-SA Geometry (b) SCW-WA Geometry (c) FE details SCW-SA and SCW-WA

Figure 1. Details of SFRCW system

2.3 Material models

Concrete damage plasticity and perfect plasticity models were used for the concrete, steel, and bolts in the analysis. The material properties of concrete and steel were taken from nominal values and the properties of the bolts were taken from experimental results.

Frame steel:

The steel frames with stiffeners were modeled with **A572 Grade 50** steel with perfect plasticity. The parameters assigned are presented in Table 2.

Model	Parameter	Value
Density	Mass Density	7850 $\frac{kg}{m^3}$
Elasticity	Young Modulus	200000 MPa
	Poisson's Ratio	0.3
Plasticity	Yield Stress	345 MPa
	Plastic Strain	0

Table 2. Steel A572 Gr50 properties

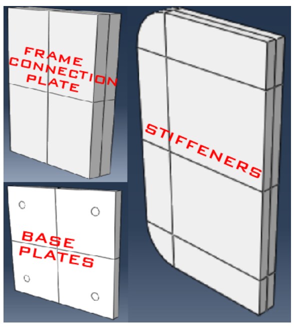


Figure 2. Steel plates used

Steel connectors (Bolts):

The shear connectors are made of a **SAE Gr. 2** steel bolt with a density of 7850 $^{kg}/_{m^3}$ and a Young Modulus of 200000 MPa according to its nominal values. The plasticity properties are the same as the concrete material exposed in Table 2 and for the Yield stress a **400 MPa** value was obtained according to the following laboratory results 3.

Table 3. Tensile strength laboratory results of a SAE Gr.2

Test	Area $[mm^2]$	Calibrated length $[mm]$	Max. Force [kN]	Max. Stress [MPa]	Yield Stress [MPa]	Roture Stress [MPa]	Area reduction [%]	Elongation [%]
A1	123.7	30.45	60.4	488.3	419.6	200.8	70.2	29.7
A2	123.7	30.00	59.2	478.2	410.4	219.2	70.2	29.3
Mean				483.3	**415.0**	210.0	70.2	29.5
Standard deviation				7.1	6.5	13.0	0	0.3
Variation [%]				1.5	1.6	6.2	0	1.0

Concrete:

The RC infill wall was modeled using a simple concrete, i.e., without reinforcement, to reduce convergence issues and computational cost. The concrete assigned presents a compressive strength (f'c) of **21 MPa** with properties established in the Colombian seismic code [5]. The concrete damage plasticity presented a perfect plasticity for both compressive and tensile behavior. The parameters assigned are presented in Table 4.

The concrete damage plasticity parameters were assigned according to the Abaqus CAE User's guide. [4]

Table 4. 21 MPa concrete properties

Model	Parameter	Value
Density	Mass Density	2400 $\frac{kg}{m^3}$
Elasticity	Young Modulus	21538.106 MPa
	Poisson's Ratio	0.2
Concrete Damage Plasticity	Dilation angle	36
	Eccentricity	0.1
	$^{fb_0}/_{fc_0}$	1.6
	K	0.6667
	Viscosity Parameter	0.0001
Compressive Behavior	Yield Stress	21
	Inelastic Strain	0
Tensile Behavior	Yield Stress	2.1
	Cracking Strain	0

2.4 Results

Fourteen models were analyzed as shown in Table 1. This table presents the stiffness, maximum force and analysis time required for each model, allowing to visualize and compare the multiple results obtained during the simulations. Figure 3 displays the load-story drift curves for all models, with curves classified by colors, each representing a principal group.

As observed, the composite walls (SCW) reach highly resistance values compared to the steel frame (SF) and the concrete wall (CW) models. The curves that corresponding to the composite walls SCW-SA and SCW-WA in a 0% and 100% action models show resistance capacities ranging from 161.6 kN to 255.4 kN and a 69.4 kN to 216.7 kN respectively; and a stiffness capacity between 8.8 $^{kN}/_{mm}$ to 19.3$^{kN}/_{mm}$ and 8.4$^{kN}/_{mm}$ to 42.1 $^{kN}/_{mm}$. The SCW-WA group exhibits a wider range than the SCW-SA, reaching higher stiffness in the results likely due to the larger width of the RC wall dimensions in the weak axis scenario.

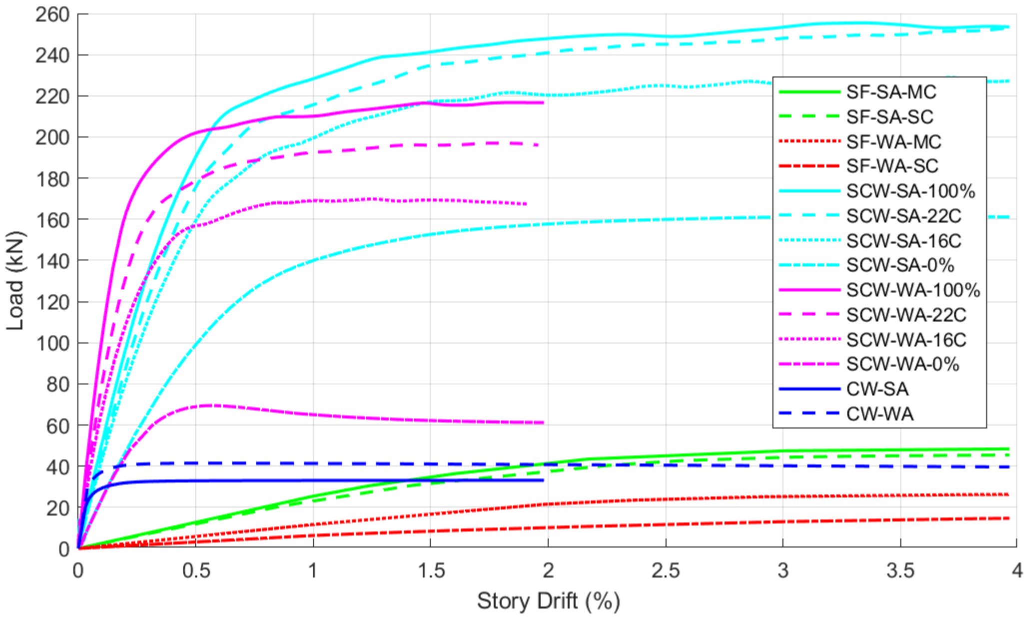


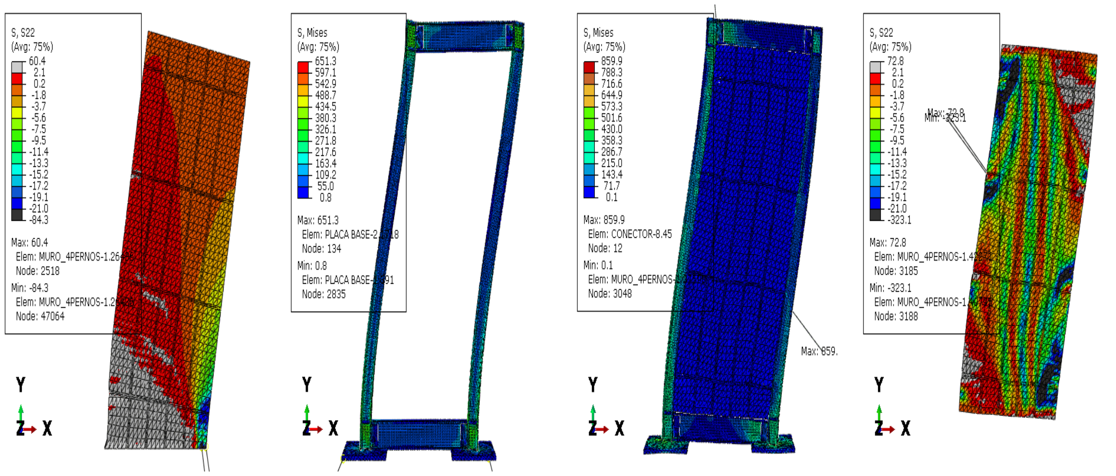
Figure 3. Data results adjusted - Load (kN) vs Story Drifts (%)

The difference in behavior between the walls is observed in the CW-SA and CW-WA models. In the weak axis scenario, the concrete wall reaches higher stiffness and resistance capacity compared to the strong axis, with increases of 15% and 25% respectively.

In the same way, the maximum allowable drift according to the Colombian seismic code [5] is 1% for all systems except the masonry-ones. In the steel frame (SF) cases, the system's behavior remains in the elastic zone, while the concrete wall (CW) models reached a plastic zone, indicating possible permanent damage. On the other hand, the composite wall (SFRCW) reached a hardening zone with the possibility of entering the plastic zone. Therefore, for designs where lateral stiffness is crucial over resistance, the composite wall system with partial or total action could be a great alternative.

The Figure 4 presents an example of the deformed conditions and stresses observed in different strong axis models. The figure 4(a) refers to the concrete wall, showing its longitudinal (compressive and tensile) stresses. Figure 4(b) displays the Von Misses stresses for the steel frame over the strong axis with a shear connection, where the higher values are located in the connection zones of the steel base plates and at the beam-columns interaction. Then, figure 4(c) shows the Von Misses stresses distribution over the composite wall (SFRCW) system over the strong axis with 16 connectors, where a distribution of stresses is observed throughout both columns. Finally, figure 4(d) refers to the same system as the previous one, displaying the longitudinal stress (S22), where the tensile and compressive zones are easily observed.

On the other hand, the analyzed models present various simplifications compared to the real specimen model, allowing to realize a complete analysis with lower computational cost and running time. Even with multiple non-linearities, complex interactions and a large number of elements -due to a refined mesh-, the maximum time required was around 22 hours. This approach, enabled the show of accurate and realistic results without the necessity of a complex model, which could present higher analysis time and computational cost over the scenarios exposed on table 1.



(a) CW-SA (S22) (b) SF-SA-SC (Von Mises) (c) SCW-SA-16C (Von Mises) (d) SCW-SA-16C CW (S22)

Figure 4. Deformed shapes and Stresses

3 Conclusions

Simplified FE models have been made to study the behavior of composite wall systems (SFRCW) comparing these to steel frames and concrete walls behavior. Details of the modeling used in the FEA were discussed, leading to the following conclusions:

- Evaluating the story drift curves of the composite wall systems (SFRCW) over the weak axis, it is observed that using 22 shear connectors (bolts) is sufficient to achieve a close behaviour of a 100% compound action. Therefore, it is acceptable to proceed to the next investigation step, where the SCW-SA-22C and SCW-WA-22C simulations will be compared with experimental results from real models that will be tested in a controlled environment under incremental and cyclic loads, as part of this research project at Colombia's National University.
- A simplified model of a composite wall systems (SFRCW) could be used to achieve accurate and realistic results while minimizing computational and resource costs, making it an effective method for pre-design steps. However, the numerical model has not yet undergone the validation process and, as a result, the model may expose unrealistic results until the real models are tested. Nevertheless, the preliminary results indicate a realistic behavior and are expected to be validated through experimental test in the next stage of this research.

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