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Experimental and Numerical Investigations on Floor-To-SpeedCore Wall Connections Under Fire Loading

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Abstract

Composite Plate Shear Walls/ Concrete Filled (C-PSW/CF), also referred to as SpeedCore walls, are being used as innovative shear walls in commercial high-rise buildings. C-PSW/CF offers various advantages such as modularity and construction schedule contraction. Elevated temperatures due to a fire event in buildings result in the deterioration of structural components' strength and stiffness. This phenomenon can lead to the failure of structural components. Studying the behavior of structural components at elevated temperatures and designing them properly will improve the fire safety of structures. The stability of SpeedCore walls under fire loading was investigated previously by the authors. In the current study, the authors focus on the floor-to-SpeedCore wall shear connections. These connections are designed to transfer gravity and diaphragm loads to SpeedCore walls. The elevated temperatures result in the development of combined additional forces and displacements within the connections. Thus, connections may fail during a fire event which may lead to the progressive collapse of structures. To analyze and design the floor system and connections, robust analysis methods are required to predict the generated deformations and forces due to elevated temperatures. Two connection configurations were developed to improve the strength and stiffness of connections. A test matrix is developed for studying the behavior of connections. A preliminary test was conducted on a full-scale floor-to-SpeedCore wall connection. The obtained experimental data was utilized to benchmark a detailed 3D FE model. Component-Based (CB) models simulate the response of connections using an assembly of springs where each spring simulates the behavior of an individual component of the connections (e.g., plate bearing and bolt shear). In the current study, the CB model was updated to simulate floor-to-SpeedCore wall connections. The updated CB model was benchmarked based on the obtained data from a detailed FE model of the connection. Further experimental and numerical studies will be conducted to study the behavior of floor-to-SpeedCore wall connections. Design guidelines will be developed based on the gathered data.

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1. Introduction

Composite Plate Shear Walls – Concrete Infill, also known as SpeedCore walls, are used in constructing high-rise buildings as a lateral load-resisting system. This wall system offers construction schedule contraction (40-50%) compared with the construction time using other wall systems. The cross-section of a SpeedCore wall comprises steel plates sandwiching plain concrete infill. Steel plates run along the length of the wall filled with concrete. Steel faceplates are connected through steel tie bars. Ties ensure the structural integrity of the system (Seo et al. 2016) and act as out-of-plane shear reinforcement (Bhardwaj and Varma 2017). SpeedCore walls are typically reinforced by boundary elements towards their ends which act as flanges. The steel plates are analogous to the primary reinforcement bar in conventional reinforced concrete construction. Fire events may occur during the lifetime of commercial or residential buildings. Fires in residential or commercial constructions can subject the structural elements to surface temperatures upwards of 2000 °F. The strength and stiffness of construction material degrade at elevated temperatures (fire loading). This phenomenon will lead to the degradation of the mechanical properties of materials, stability failure of structural components during a fire, and the progressive collapse of the structures.

The performance of SpeedCore walls under fire loading was investigated previously by Anvari (2022). The fire resistance (load capacity and rating) of SpeedCore walls was addressed using experimental, numerical, and analytical investigations. Typical SpeedCore walls, for example, with thickness greater than or equal to 24 in., story height/thickness ratio less than 10, and gravity load ratio less than 10%, have a fire-resistance rating greater than 3 hours without any fire protection. Walls with a story height/thickness ratio greater than 20, are recommended to have fire protection, at least on the exposed face.

Designing SpeedCore walls without any fire protection can be economical and efficient; however, it raises questions regarding the fire performance of the composite floor system and its connections to SpeedCore walls. Floor systems subjected to gravity loading and fire exposure undergo deformations (thermally induced and structural) that are restrained by the surrounding, interacting structure (Fischer et al. 2019). As a result, the complete system consisting of composite floors, SpeedCore walls, and wall-to-floor connections will be subjected to complex deformations and forces induced by these restraints and interactions.

A research project focusing on the behavior of composite floor systems to SpeedCore wall connections subjected to fire loading was initiated by the authors. The behavior of the connections under fire loading is being evaluated through experimental and numerical studies. Benchmarked numerical models will be developed to conduct parametric studies. The experimental and numerical results will be employed to develop design recommendations for the connections under fire loading.

2. Existing research

There is a lack of research-based studies on the behavior of floor-to-SpeedCore wall connections at elevated temperatures. Studies have been conducted on the behavior of steel beams-to-CFT columns and simple shear connections at elevated temperatures. An experimental study by Ding and Wang (2007) was conducted to investigate the fire effects on steel beams to concrete-filled tubular (CFT) columns using different types of connections. The joint types include fin plate, end plate, reverse channel, and T-stub. In each test, loads were applied to the beam, and then the structural assembly was exposed to the standard fire condition (ISO 834) in a furnace while maintaining the applied loads. In total, 10 tests were carried out on CFT assemblies (joints) Various modes of fracture in the connection regions were observed. However, there was no fracture in the connection during the cooling phase. The results of the study indicated that the steel beams were able to accommodate very large deflections. Therefore, steel beams can develop catenary action and survive very high temperatures with appropriate design and protection of the joint components.

Hu and Engelhardt (2012) conducted extensive experimental and numerical studies on the behavior of shear tab connection at elevated temperatures. The experiments included a series of tests on connection subassemblies at elevated temperatures. The assemblies included a beam, shear tab, and structural bolts. Tests on single plate connections were conducted by subjecting the connections to axial and inclined tension forces at elevated temperatures. Obtained results from inclined tension force tests showed that the connections experience a sequential failure under a combination of tension, shear, and rotation. A finite element (FE) model was developed and benchmarked using experimental data. The FE model was then used to conduct a series of parametric studies. The results showed that structural bolts are potentially more vulnerable than other connection components at high temperatures, as bolts lose more strength than structural steel with increasing temperature.

Agarwal and Varma (2014) investigated the progressive collapse failure of 10-story steel buildings subjected to design fire scenarios using FE analyses. Component-based model, developed by Sarraj (2007), was utilized to model the shear connections. Agarwal (2014) upgraded the component-based model to be able to model complete temperature-dependent coupled axial and shear force–deformation–moment–rotation responses. Their investigations concluded that gravity columns are the weakest link for the overall stability of steel-frame buildings during a fire event.

3. Fire test

A series of tests will be conducted to study the behavior of floor-to-SpeedCore wall connections. The experimental study includes testing connections with two configurations under various loading directions and angles at ambient and elevated temperatures. The current section discusses the analyses used to study the history of the generated forces and rotations in the connection during a fire event, the developed test matrix, and a preliminary test on a floor-to-SpeedCore connection.

3.1 Loading

The elevated temperatures due to a fire event will result in the generation of a complex combination of forces and displacements within the structural components including connections. Nonlinear FE models can be developed to simulate and assess the performance of structures under fire and gravity loads. The generated forces and rotations within the connections during a fire event can be studied to ensure the connections can survive. Thus, the authors developed FE models of the fire tests conducted by the National Institute of Standards and Technology (NIST) to study the history of the generated forces and displacements in connections.

Two structural fire tests were conducted on two-story steel frame structures with composite floors by NIST. Fire loading (temperatures) was applied to the structural components of a compartment. In the current study, a structure-level FE model of the two-story structures was developed using

ABAQUS (Simulia 2016). The data reported data by NIST (Choe et al. 2022) was used to benchmark the structure-level FE models. The details of the modeling techniques and the results of the analyses are reported by Anvari et al. (2021).

The obtained data from the structure-level FE analysis were used to evaluate the forces and rotations in connections during a fire event as follows:

1. The increase in temperature of beams due to the fire exposure results in expansion and the development of the axial compressive forces in the cross-section of the beam. A compressive axial force was generated within the steel beam's cross-section at the early stages of fire tests. The maximum axial force occurred at an average connection temperature of around 500 ℃.
2. During the later stages of heating, the mid-span displacement of beams results in the rotation of the connections, while there is still a compressive force in the cross-section of beams. The mid-span displacement of beams increased (sagging) until the termination of fire tests.
3. The axial compressive force within the cross-section of the steel beam was reduced during the cooling phase. The contraction of the steel beams due to the temperature drop combined with the deflection of beams resulted in tensile forces acting at inclined angles in the connections. For the second test conducted by NIST – Choe et al. (2022b), tensile forces were generated during the cooling phase that led to the fracture of a connection.

The obtained data (loading histories) from the structure-level FE analyses were used to select the loading angle and direction for testing the floor-to-SpeedCore connection specimens.

3.2 Test matrix

Detailed 3D nonlinear FE models for floor-to-SpeedCore wall connections were developed by Anvari et al. (2021). The behavior of connections with various configurations was studied. The analyses showed that the stiffness of floor-to-SpeedCore wall connections can be improved significantly by using a reinforcing plate (RP) or a through-plate (TP) shear plate. To study the behavior of RP and TP floor-to-SpeedCore wall connections, the specimens will be loaded in various loading directions and angles based on the findings in section 3.1.

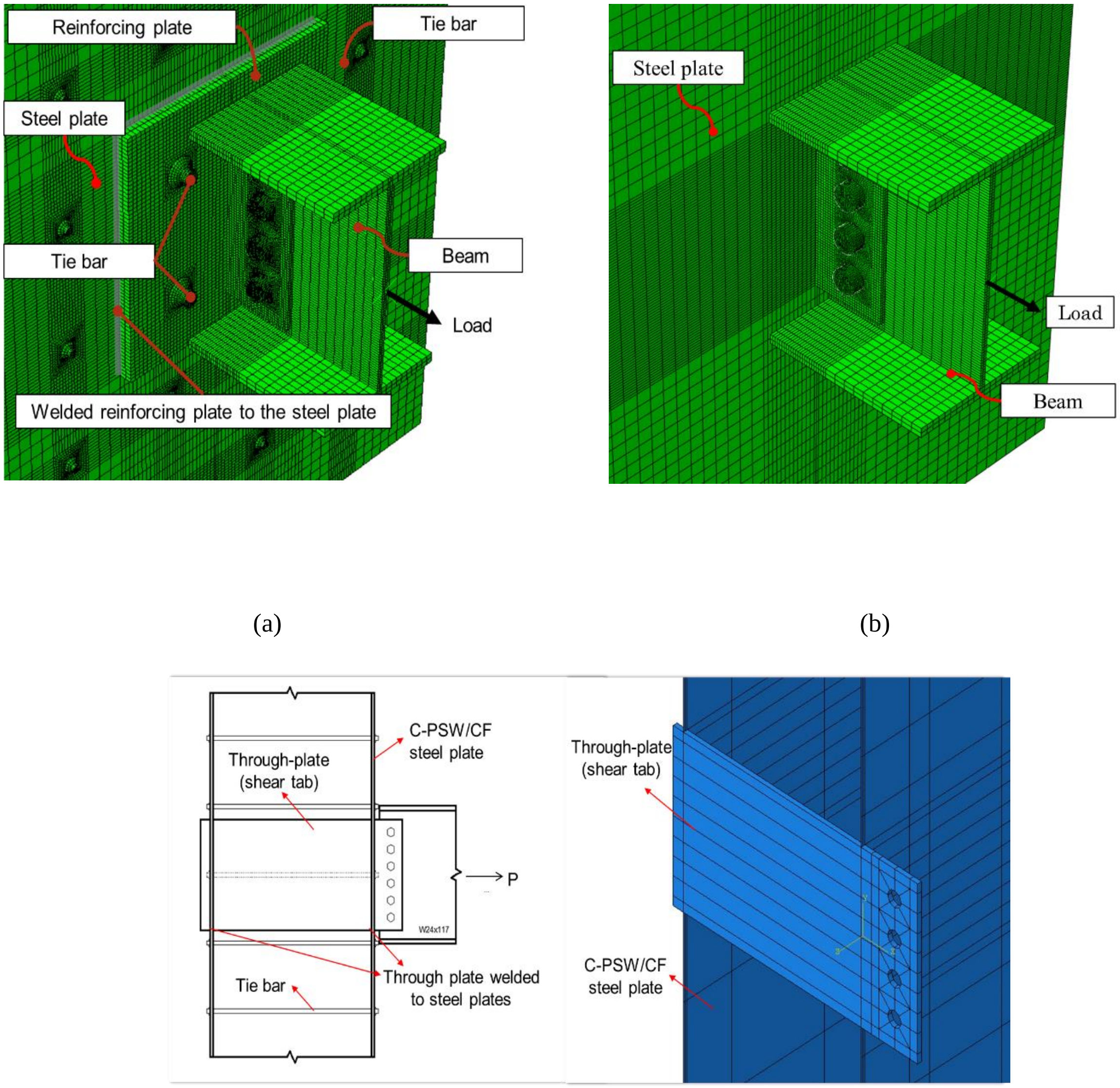
Table 1 presents the test matrix to experimentally study the behavior of floor-to-SpeedCore connections. The test matrix consists of floor-to-SpeedCore wall connections with three configurations, including RP, TP, and UP (unreinforced plate). Fig. 1 shows the details of the connection configurations. Specimens will be tested at ambient and elevated (500℃) temperatures, two loading directions (compressive and tensile), and two loading angles (0 and 30 degrees). The name of the specimens presents the connection configuration, connection temperature, loading angle (with respect to the horizontal line), and loading direction.

Tests on RP/TP-20-0-C specimens represent the connections at the early stages of the fire event. At the beginning of the fire exposure, there is no significant deflection in the beam. The behavior of the wall-to-floor connections during the later stages of the fire exposure can be studied using the data on fire tests of RP/TP-500-30-C specimens. The behavior of the connections during the cooling phase will be studied using the data obtained from UP/RP/TP-500-30-T specimens.

Test setups were designed based on the loading angle. Electrical high-temperature ceramic fiber heaters will be used to heat the connections, a portion of the steel beam, and the surface of the SpeedCore wall specimen. Fire tests include two steps namely, (1) heating and (2) loading. In the first step of the fire tests, specimens will be heated to the target temperature. Then the temperatures of the specimen will be kept constant. Next, the displacements will be applied to the end of the beam until failure occurs.

Table 1: Proposed test matrix for wall-to-floor connections

Specimen	**Average Temperature (℃)**	**Loading Angle (deg)**	**Loading Direction**	**Objectives**
Reinforcing plate (RP)				
1 (RP-20-0°-C)	20	0°	Compression	Simulating expansion of beam at beginning of fire
2 (RP-500-30°-C)	500	30°	Compression	Simulating expansion and sagging of beam during fire
3 (RP-500-30°-T)	500		Tension	Simulating sagging and contraction of beam after fire (during cooling)
Through plate (TP)				
4 (TP-20-0°-C)	20	0°	Compression	Simulating expansion of beam at beginning of fire
5 (TP-500-30°-C)	500	30°	Compression	Simulating expansion and sagging of beam during fire
6 (TP-500-30°-T)	500		Tension	Simulating sagging and contraction of beam after fire (during cooling)
Unreinforced plate (UP)				
7 (UP-500-30°-T)	500	30°	Tension	Simulating sagging and contraction of beam after fire (during cooling)



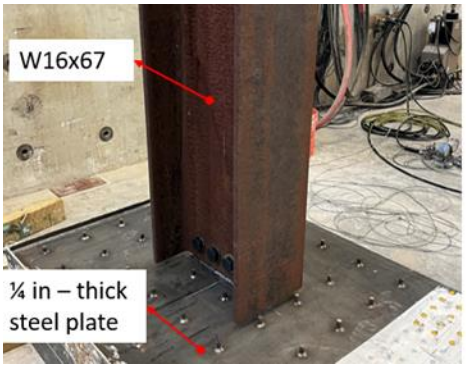
(a) (b)

(c)

Figure 1: Details of The Connection Configurations, (a) RP, (b) UP, and (c) TP

3.3 Preliminary test

A preliminary test was conducted on a floor-to-SpeedCore wall connection. The goal of preliminary this test was to evaluate the test setup performance during the test and improve it if needed, besides studying the behavior of the connection. A test was performed using a SpeedCore wall which had been used previously in a separate research project. The damaged part of the wall was only in the middle portion of the wall and the test was performed on the undamaged portion of the wall. Fig. 2 shows the size and dimensions of the beam and connection details. The connection includes a W16x67 steel beam connected to the SpeedCore wall. A 3/8 in-thick steel plate was directly welded to the SpeedCore wall. The weld size was 3/16 in. Four 1-in diameter bolts were used to connect the shear plate and W16x67.



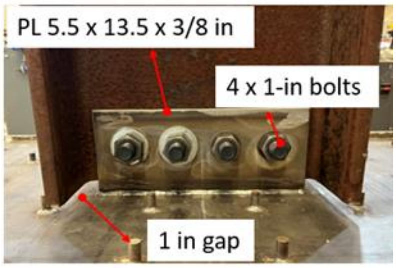


Figure 2: The size and dimension of the beam and connection components

Fig. 3 shows the details of the test setup. The test setup included a hydraulic jack that connected to the strong wall with an angle of $\pi/3$ with respect to the strong wall to apply inclined (30 deg) compressive or tensile forces to the end of the beam. The layout of the instrumentation is shown in Fig. 4. String potentiometers were used to measure the displacements of the beam and the steel plate of the C-PSW/CF specimen.

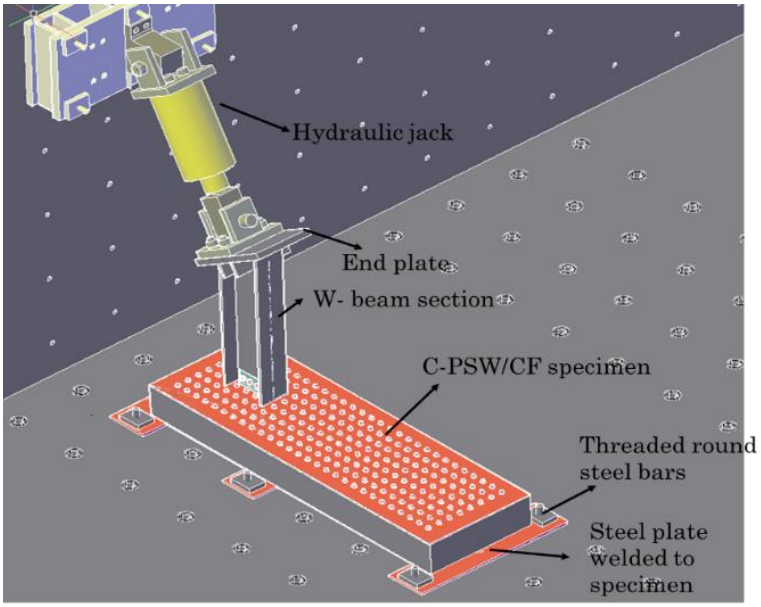


Figure 3: 3D CAD drawing of the test setup and the specimen

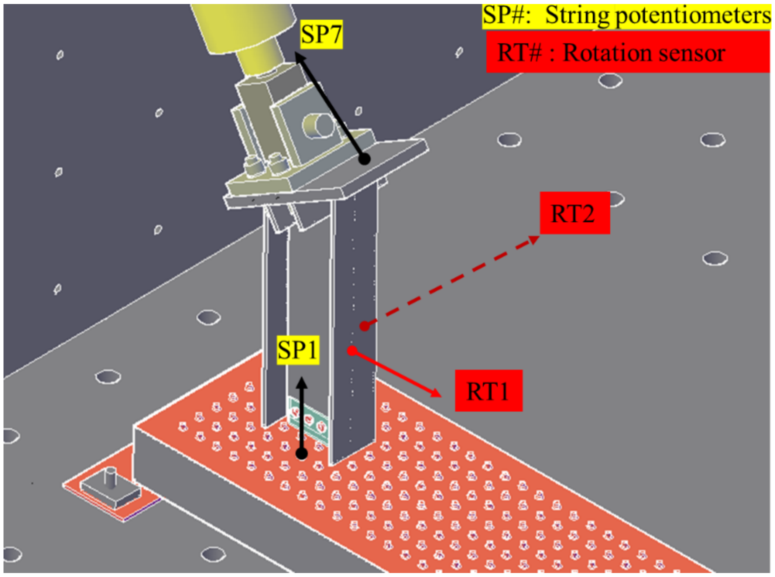


Figure 4: Instrumentations layout of the specimen

3.3.1 Observations

The connection was subjected to inclined tensile force with 30 deg. loading angle. Fig. 5 shows the force-displacement response of the connections and the connection after the test. Fig. 6 shows the failure modes observed during and after the test which were steel faceplate fracture, tie bars weld fracture, shear tab weld fracture, and shear tab bearing failure. The specimen was loaded to up 118 kips when a fracture initiated in the steel faceplate of the wall was observed. Then, the test was paused for inspection. Next, the connection was reloaded up to 120 kips when the faceplate fracture propagated further combined with tie bars welding fracture around the shear plate.

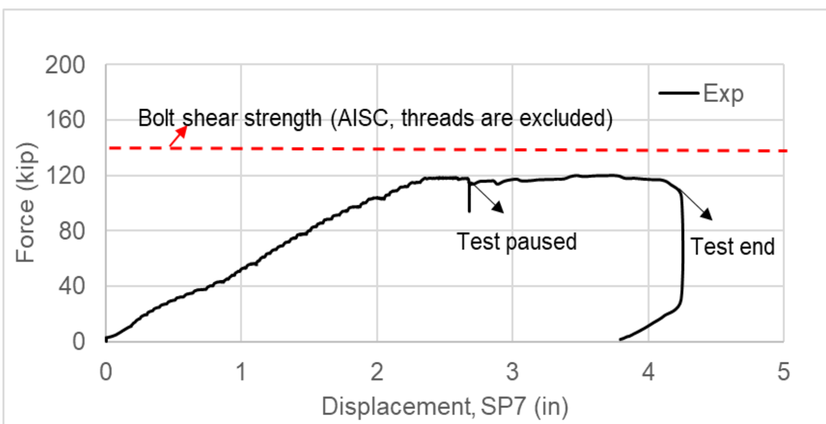


Figure 5: Connection response during the loading test (ambient)

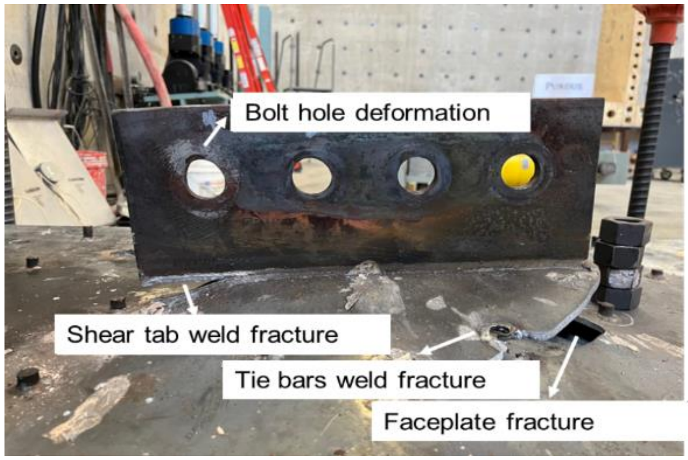


Figure 6: Failure observations during the loading test (ambient)

4. Development of 3D FE model

An FE model was developed to numerically simulate the behavior of the floor-to-SpeedCore wall connection for further investigations into the behavior of the connections. Thermal and structural models are needed to calculate the temperatures and displacements, respectively. For brevity, the development and benchmarking of the structural model are discussed herein. The development and benchmarking of the thermal model were discussed in depth by Anvari et al. (2022). The model was developed using ABAQUS (Simulia 2016). Fig. 7 shows the developed model and the details of the beam and the wall. The concrete, steel flange, web plates, and tie bars are modeled using solid elements (C3D8R) The models have all the degrees of freedom restrained at the post-tensioning plate holes (see Fig. 7)

A material damage model was defined in order to simulate the steel faceplate fracture in the wall. The damage model's parameters including damage initiation and damage evolution were specified based on experimental coupon tests' data. The dimensions of the coupon were obtained from ASTM E8 (2018) standard. Fig. 8 shows the comparison of stress-strain curves obtained from the FE analysis and the coupon test. A damage initiation strain equal to 0.276 was used.

4.1 Benchmarking

The response from the FE model was compared with the experimental data obtained from the test. Fig. 9(a) shows the comparison between the obtained data from the test and the FE model. The displacement in the graph represents the out-of-plane deformation at the location of SP1 (see Fig. 4). The estimated displacements had a good correlation with the obtained data from the experiment. In the FE model, failure displacement was slightly lower than in the experiment. In the model, the maximum displacement (failure) occurred at 0.58 in while the failure in the test occurred at 0.63 in. Plastic deformations occurred in the wall's plate which led to the steel plate fracture (see Fig. 9(b)). The deformed shape of the wall and shear plate at failure is compared in Fig. 9(b) and 9(c), respectively.

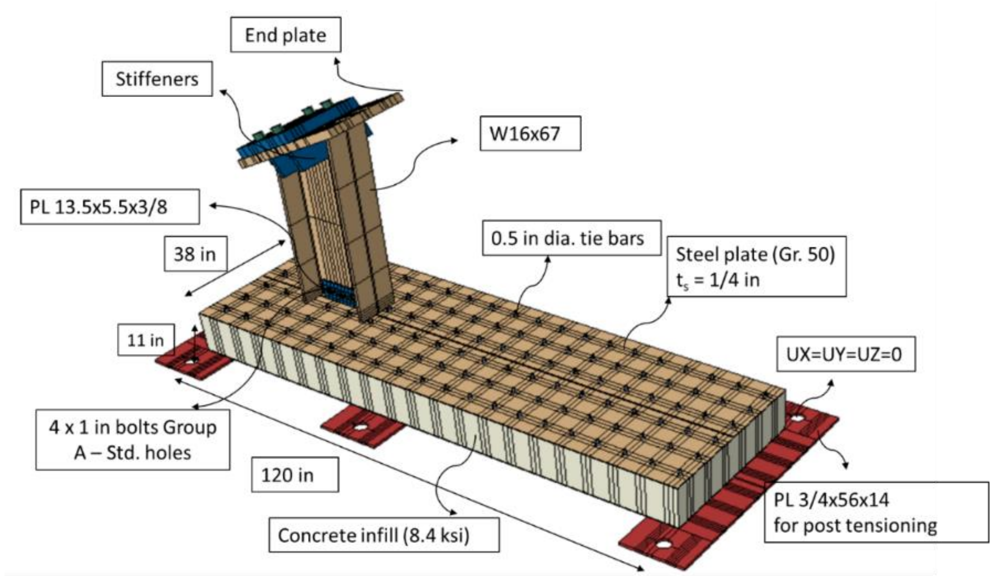


Figure 7: 3D model of the floor-to-SpeedCore wall connection

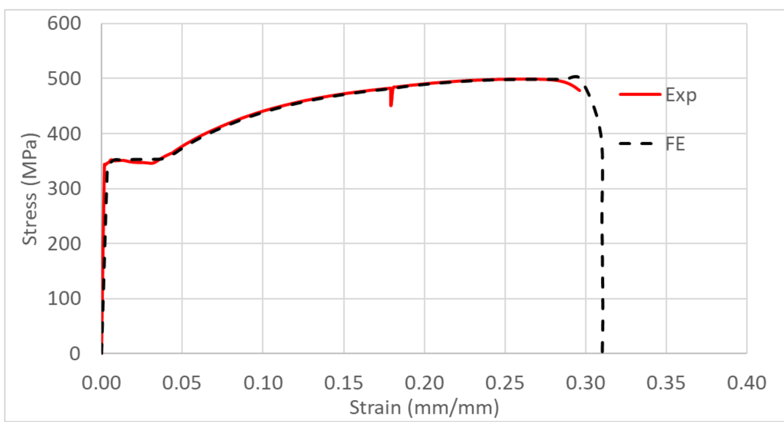
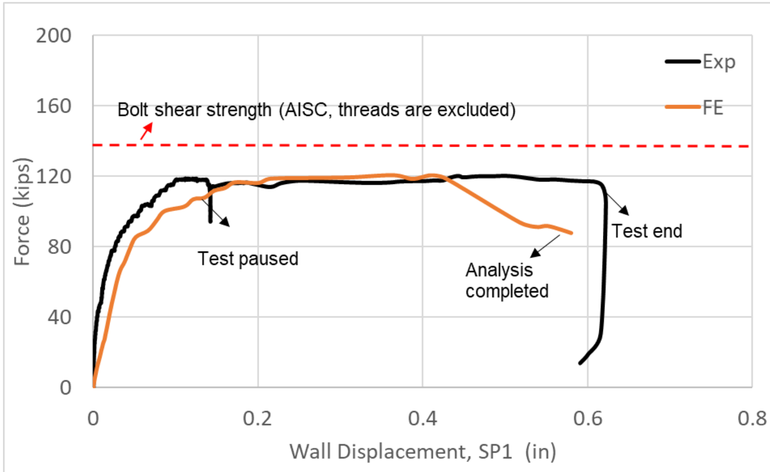
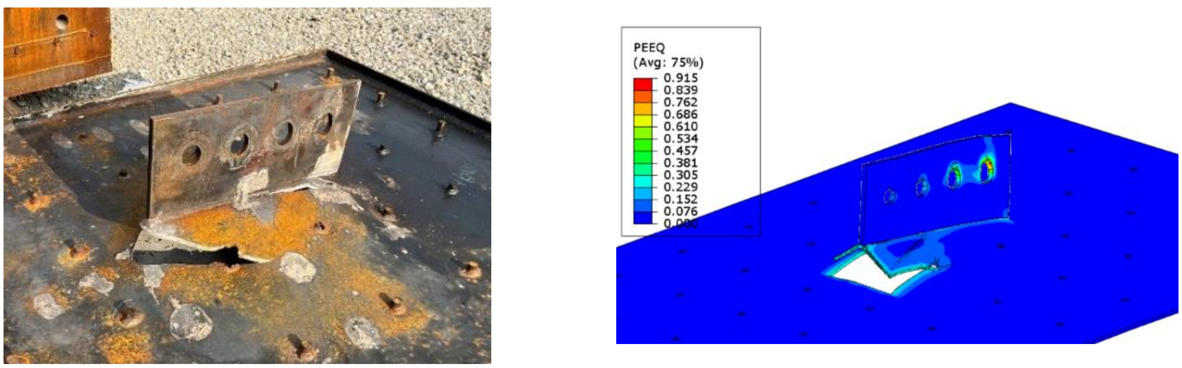


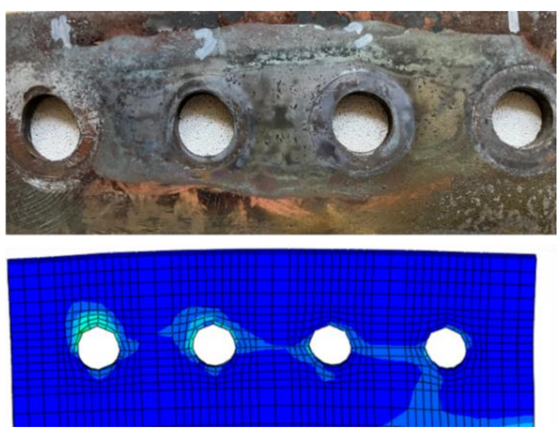
Figure 8: The comparison of the obtained results from the C-PSW/CF wall's coupon test and the FE model



(a)



(b)



(c)

Figure 9: The comparison of the obtained force-displacement response from the experimental studies and FE analysis with the damage model at ambient. (a) The comparison between the test data and the FE response, (b) steel plate fracture, (c) bolt hole deformation

5. Component Based (CB) models

FE models are needed to develop structure-level FE models to evaluate the overall response of structures under fire loading. The response of the connections can be predicted at ambient and elevated temperatures using CB models. CB models use an assembly of springs to model the different components of a connection including bolt shear, beam web bearing, and shear plate bearing capacities (see Fig. 10). The details of the development and validation of CB are reported by Anvari et al. (2021).

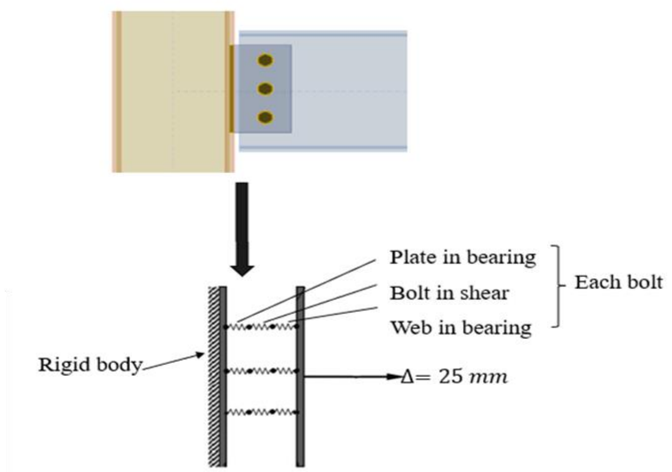
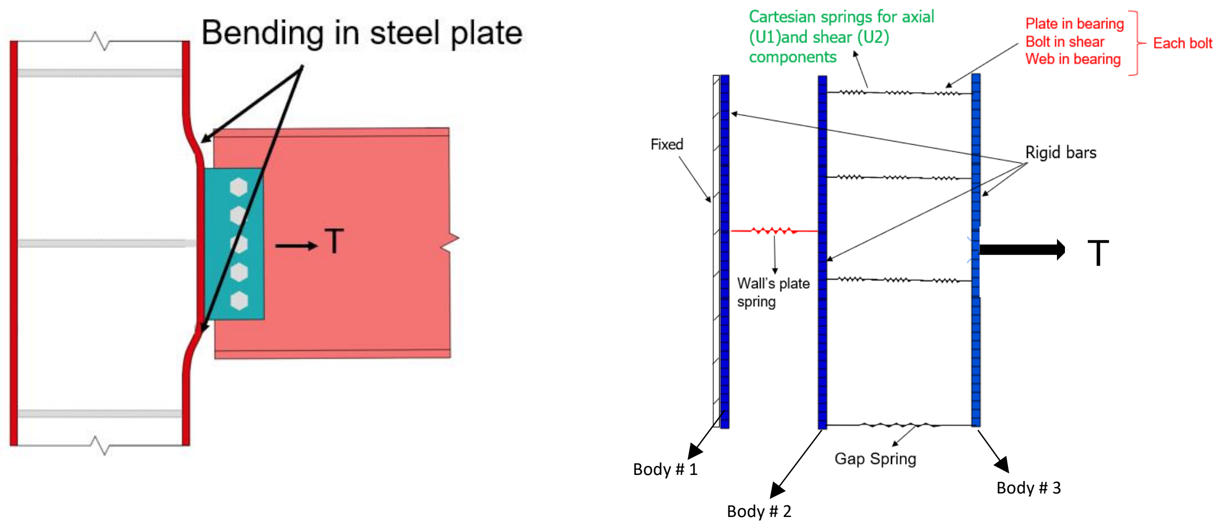


Figure 10: Schematic diagram of the model for a shear tab connection

5.1 SpeedCore walls' plate spring

A fixed connection (for the body on the left side) is assumed in the CB models developed by Sarraj (2007) and Agarwal (2014). For the floor-to-SpeedCore wall connections, the flexibility of the SpeedCore wall's steel plate can play a major role in the displacement-force response of the connections. Thus, some modifications to the current CB model are required to be able to simulate the floor-to-SpeedCore walls. Plastic out-of-plane deformations can occur in the SpeedCore wall's steel plate when a tensile loading is applied to the floor-to-SpeedCore connections (see Fig. 11(a)). The behavior of the steel plate can be highly nonlinear at elevated temperatures.

CB model uses an assembly of springs to simulate the behavior of the connections. (see Fig. 11(b)). The displacement-force response of the connections for shear tab and steel beam web in bearing and bolt shear can be simulated using the assembly of springs between bodies 2 and 3 in Fig. 11(b). In the current study, a spring is added to simulate the behavior of the SpeedCore wall's steel plate. The wall's plate spring is connected to the assembly in series, connecting bodies 1 and 2. This assumption is valid for axial loading only. However, a study is ongoing to improve the configuration when an inclined load is applied.



(a) *(b)*

Figure 11: Schematic diagram of (a) representative of 3D floor-to-SpeedCore wall connection, and (b) the CB model for a shear tab connection of 3 bolts

A preliminary study was conducted to calculate the stiffness of the wall's plate spring at ambient conditions. Simple models were developed to model a portion of a SpeedCore wall using two configurations (see Fig. 12). These configurations include a steel plate and tie bars with and without concrete infill. The steel plate was modeled using shell elements (S4R) with a thickness equal to the wall's steel plate thickness (0.5 in). Symmetric boundary conditions were applied to the edges of the steel plate. Tie bars were modeled as springs with a stiffness equal to *EA/L* where *E* is the modulus of elasticity and was taken as 200 GPa for the steel plate and tie bars, *A* is the area, and *L* is the length of the tie bar. For the configuration with concrete, 2 in-thick concrete pad was modeled to account for the concrete infill's stiffness. The concrete compressive strength was taken as 40 MPa.

An axial tensile load was applied to an area equal to the length of the shear plate. The obtained force-displacement response from the simple models was compared with the obtained response from a detailed 3D FE simulation. A detailed 3D FE simulation was conducted for a floor-to-SpeedCore wall specimen with an unreinforced plate (UP) connection. UP with 4 bolts (A325), ¾ in diameter. The beam section size was W16x67 ($F_y = 345$ MPa) and was connected to $^3/_8$ in thick single plate ($F_y = 345$ MPa). Fig. 13 shows the detailed 3D connection model. The force-displacement response obtained from the simple models and the detailed 3D FE models were compared. Axial tension force was applied at ambient conditions for all cases.

Fig. 14 shows the comparison of the axial force vs displacement for the studied cases. UP-20-0-T represents the response obtained from the detailed 3D FE specimen model of the connection. "WS-steel" and "WS-steel & concrete" represent the obtained force-displacement response from the simple models without and with concrete infill, respectively. The obtained data from the simple models (WS-steel and WS-steel &concrete) are comparable to the obtained data from the detailed 3D model. The initial yielding in the steel plates occurred at 144 kN in both WS models.

The stiffness of the wall's plate spring was assumed to be (1) linear or (2) inelastic. For the linear option, the stiffness of the elastic region can be used as the stiffness of the wall's stiffness. Inelastic stiffness can be applied by using the force-displacement response as input for the wall's plate spring.

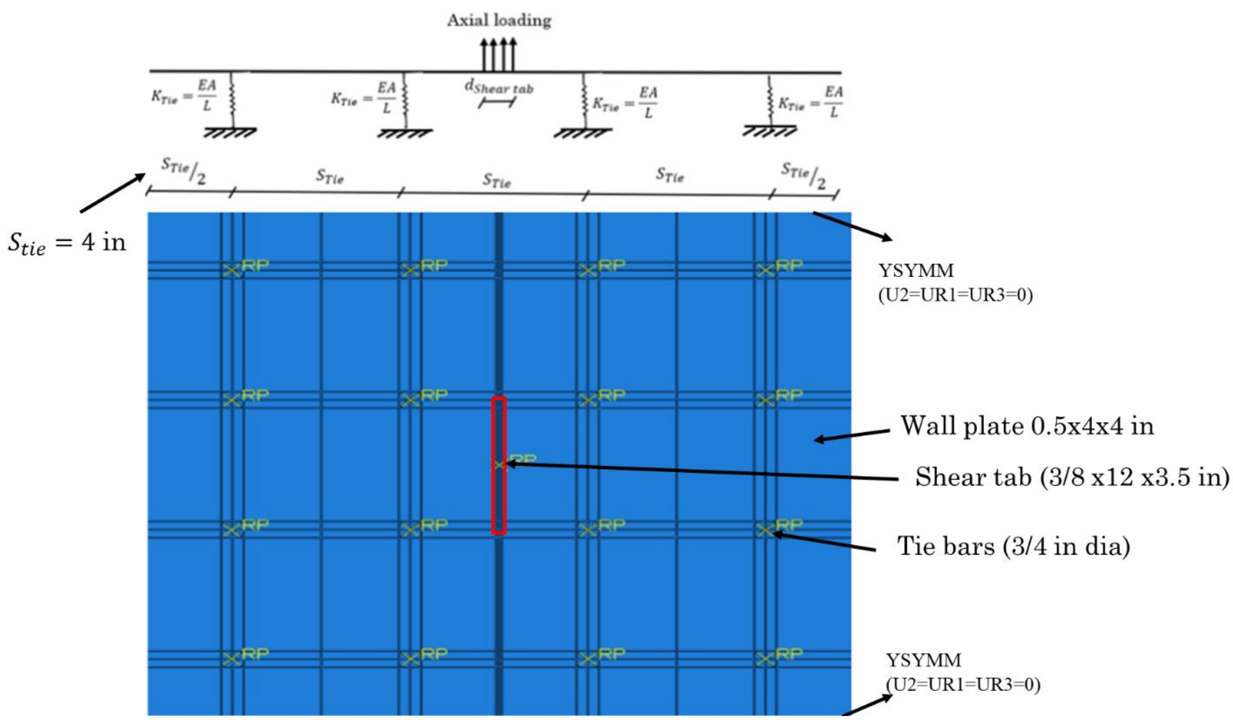


Figure 12: The wall's plate spring modeling techniques

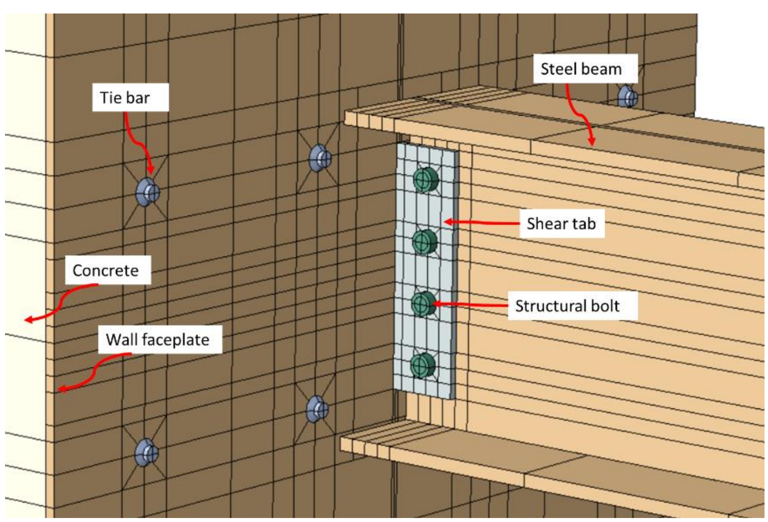


Figure 13: The detail of the connection model in the FE

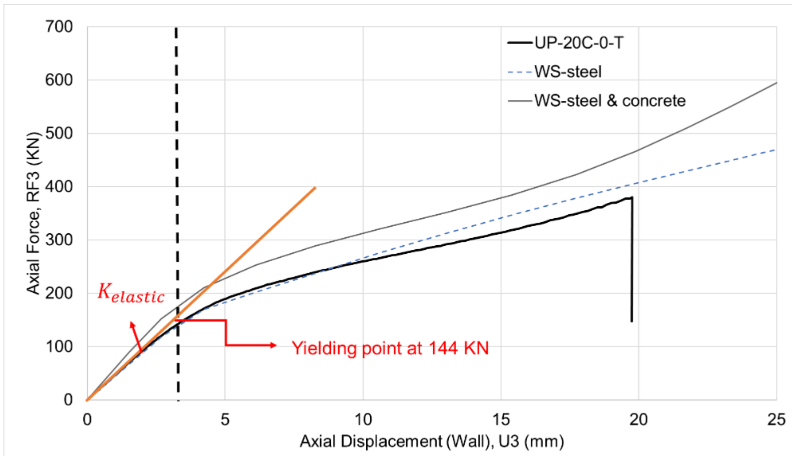


Figure 14: Comparison of the specimen model and the plate spring models

5.2 Benchmark the updated CB model

The obtained force-displacement response from the updated CB model with elastic and inelastic wall's plate spring (see Fig. 11(b)), was compared with the obtained response from the detailed 3D model of the floor-to-SpeedCore wall connection (see Fig. 13).

The obtained force-displacement curve from the detailed FE model of the connection (UP-20C-0-T-FE), the CB model without the wall's plate spring (CB- no plate spring), the CB model with the elastic wall's plate spring (CB-K-elastic), the CB model with the inelastic wall's plate spring (CB-K-inelastic), and the connection strength as per AISC *specification* (AISC, 2016) are plotted in Fig 15.

The effect of the wall's plate spring can be seen clearly in the figure when CB with no plate spring compared with other cases. The large differences show the necessity of accounting for the wall's plate flexibility for modeling floor-to-SpeedCore wall connections using CB models. CB model with the inelastic spring provides a comparable result to the response of UP-20C-0-T-FE. Bolt shear failure was predicted in all the models which agreed with the estimated strength by AISC *specification* (AISC, 2016).

The obtained data indicated that the CB model with an extra spring (wall's plate spring) can predict the response of a floor-to-SpeedCore wall connection with reasonable accuracy. The current configuration was benchmarked for the connections with tension force at ambient conditions. Further studies are required to improve the updated CB model for inclined forces.

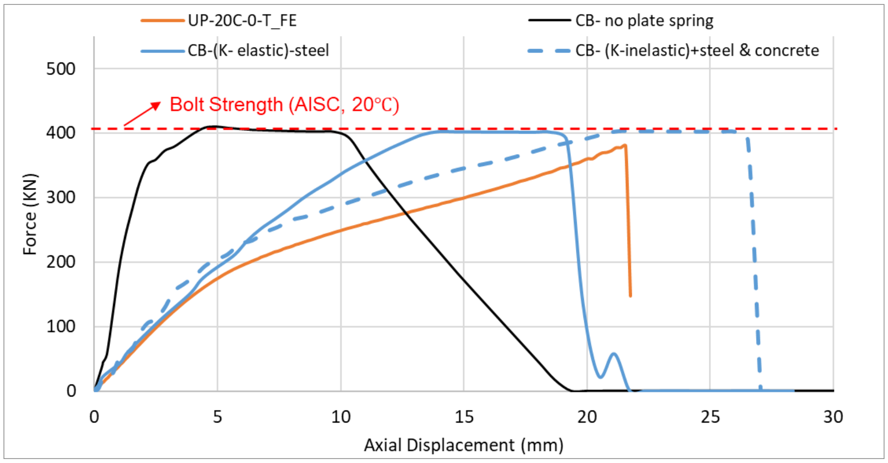


Figure 15: Comparison of detailed FE model and CB models at ambient temperature

6. Summary & Conclusion

This research aims to investigate the behavior of floor-to-SpeedCore wall connections. Based on obtained data from the member and structural-level numerical analyses, the history of the generated forces and displacements within the structural components were studied during various phases of a fire event. The authors developed two connection configurations to improve the stiffness of the SpeedCore's steel plate stiffness at elevated temperatures. An experimental test matrix was presented to study the behavior (force-displacement) of the connections during various phases of a fire event. The test matrix includes tests with various connection details, loading angles, loading directions, and temperatures.

The test data will be used to (i) evaluate the behavior of the floor-to-wall connections during heating and cooling phases, (ii) benchmark numerical models for 3D FE analysis to conduct parametric studies, and (iii) CB models for modeling connections to conduct system-level analyses.

A preliminary test was conducted to get initial insight into the behavior of the floor-to-SpeedCore wall connections at ambient conditions. A detailed 3D FE model was developed and benchmarked using data from the preliminary test. The CB model was improved to account for the flexibility of the SpeedCore walls' steel plates. The updated CB model (with the wall's plate spring) was benchmarked using the obtained data from the detailed FE model.
In the next step of the studies, the obtained data from the experimental studies will be used to improve and benchmark the CB based models. Parametric studies will be conducted using structure-level models to study the overall behavior of structures under fire loading. The obtained data will be used to develop knowledge-based design guidelines for floor-to-SpeedCore wall connections under fire loading.

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