



Experimental and Numerical Analysis of Floor-to-SpeedCore Wall Connections Subjected to Fire Conditions

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Abstract

Composite Plate Shear Wall/Concrete Filled (C-PSW/CF), also referred to as SpeedCore walls, are being used as innovative shear walls in commercial high-rise buildings. These walls offer various advantages, such as modularity and construction schedule contraction. Elevated temperatures can deteriorate material properties during fire events in buildings, potentially leading to stability-related failure of structural components. Composite floors are connected to these walls through simple shear connections. The floor-to-wall connections will be exposed to elevated temperatures, which may result in connection failure and progressive collapse of structures. This paper presents the results of fire tests conducted on full-scale floor-to-wall connections and the numerical investigations for further studies. The specimens included steel beams connected to SpeedCore walls through simple shear connections. 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. Three types of floor-to-wall connections were tested: connections with through-plate, reinforcing plate, and unreinforced plate. The test matrix parameters included connection type, temperature, loading angle, and loading direction, based on results from previous numerical and experimental studies in the literature. The obtained experimental data was used to benchmark detailed 3D FE models. The results showed that regardless of temperature and loading angle, when the connection is subjected to tensile forces or an axial compressive force, bolt shear failure is the governing failure mode. Further numerical studies will be conducted to study the behavior of floor-to-SpeedCore wall connections at a system level, and design guidelines will be developed based on the gathered data.

1. Introduction

SpeedCore walls, also known as Composite Plate Shear Walls with Concrete Infill, are useful for building high-rise structures as they resist lateral loads. These walls significantly reduce construction time by 40-50% compared to other systems. A SpeedCore wall's structure includes steel plates with plain concrete infill, extending along the wall's length. Steel faceplates are linked via steel tie bars, maintaining the wall's structural integrity (Seo et al. 2016) and serving as out-of-plane shear reinforcement (Bhardwaj and Varma 2017). The ends of these walls are typically reinforced with boundary elements, functioning like flanges, while the steel plates act similarly to the primary reinforcement in traditional reinforced concrete. During a building's lifespan, fire

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events can heat structural elements to over 2000 °F, weakening the materials' strength and stiffness and potentially leading to structural failures and collapse.

Anvari (2022) explored the fire performance of SpeedCore walls, examining their fire resistance through experiments, numerical analyses, and analytical studies. For instance, walls thicker than 24 inches, with a story height/thickness ratio under 10 and a gravity load ratio below 10%, can resist fire for over three hours without additional protection. However, walls with a higher story height/thickness ratio are advised to have fire protection on exposed faces.

Designing SpeedCore walls without fire protection is cost-effective but raises concerns about the fire resilience of the associated composite floor systems and their connections. When exposed to gravity and fire loads, floor systems deform due to thermal and structural stress, influenced by the surrounding structure (Fischer et al. 2019). Consequently, the integrated system of composite floors, SpeedCore walls, and their connections faces complex deformations and stress.

This research investigates the response of composite floor systems and their connections to SpeedCore walls under fire. Experimental and numerical methods are being used to evaluate the behavior of these connections during fire. The study aims to develop an approach for performance-based fire resistance design of complete floor systems consisting of SpeedCore walls, composite floor slabs, and wall-to-floor connections and use the findings to propose design recommendations for such connections under fire conditions.

2. Summary of Existing Research

Currently, there is a notable scarcity of research on how floor-to-SpeedCore wall connections behave at high temperatures. While there have been studies on steel beams-to-concrete-filled tubular (CFT) columns and basic shear connections under fire conditions, research specific to SpeedCore connections is limited. Ding and Wang (2007) conducted an experiment to explore the fire impact on steel beams connected to CFT columns, using various connection types like fin plate, end plate, reverse channel, and T-stub. They applied loads to the beams and exposed the structure to standard fire conditions (ISO 834), observing different fracture modes in the connections but no failure during the cooling phase. Their findings indicated that steel beams could handle substantial deflections and, with proper design and connection protection, withstand high temperatures.

Selamet and Garlock (2010) used 3D finite element models to simulate simple connections in steel floor systems (absent concrete slabs) during fires. These simulations revealed potential failure modes such as bolt shear and shear-tab fractures during the cooling phase. Their research, which included benchmarking shear-tab connection models against Cardington experimental data, led to recommendations for altering typical steel building connections to enhance fire performance, including increasing the gap distance between the beam end and the connected member.

Hu and Engelhardt (2012) undertook detailed experimental and numerical studies on shear tab connections at elevated temperatures. Their tests on assemblies comprising a beam, shear tab, and structural bolts under axial and inclined tension forces at high temperatures showed sequential failures due to tension, shear, and rotation. Using the experimental data, they developed a finite element model for parametric studies, revealing that bolts are particularly vulnerable at high temperatures compared to other connection components.

Agarwal et al. (2014) investigated the progressive collapse failure of steel buildings subjected to design fire scenarios using finite element models of 10-story three-dimensional buildings. Component-based macro models were utilized to model the behavior of the shear tab connections used in the building design. The research concluded that gravity columns are the weakest link for the overall stability of steel-frame buildings during a fire. The results provided the motivation for experimental testing of a series of large-scale composite beams with simple connections.

3. Fire Tests

3.1. Test matrix

A series of tests was conducted to study the behavior of floor-to-SpeedCore wall connections. The experimental study includes testing connections with three configurations under various loading directions and angles at ambient and elevated temperatures. The analyses used to study the history of the generated forces and rotations in the connection during a fire event, the developed test matrix, test setup, loading and heating protocols, and a preliminary test on a floor-to-SpeedCore connection were discussed and reported by Alasiri et al. (2023). 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. In the current section, the results of the selected fire tests are discussed.

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 unreinforced plate (UP). Fig. 1 shows the details of the connection configurations. Specimens were tested at ambient and elevated temperatures (500°C), 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. The test on the TP-20-0°-C specimen represents 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 was studied using the data on the fire test of the RP-500-0°-C specimen. The behavior of the connections during the cooling phase will be studied using the data obtained from UP-500-30°-T and UP-300-30°-T specimens.

Test setups were designed based on the loading angle as discussed in Alasiri et al. (2023). Electrical high-temperature ceramic fiber heaters were used to heat the connections, a portion of the steel beam, and the surface of the SpeedCore wall specimen. Fire tests include two steps, (1) heating and (2) mechanical loading. In the first step of the fire tests, specimens were heated to the target temperature. Then the temperature of the specimen was kept constant. Next, the displacements were applied to the end of the beam until failure occurred.

Table 1: Test matrix for wall-to-floor connections

Specimen	Average Temperature (°C)	Loading Angle (deg)	Loading Direction	Objectives
Reinforcing plate (RP)				
1 (RP-500-0°-C)	500	0°	Compression	Simulating expansion of beam during fire
Through plate (TP)				
2 (TP-20-0°-C)	20	0°	Compression	Simulating expansion of beam at beginning of fire
Unreinforced plate (UP)				
3 (UP-500-30°-T)	500	30°	Tension	Simulating sagging and contraction of beam after fire (during cooling)
4 (UP-300-30°-T)	300	30°	Tension	Simulating sagging and contraction of beam after fire (during cooling)

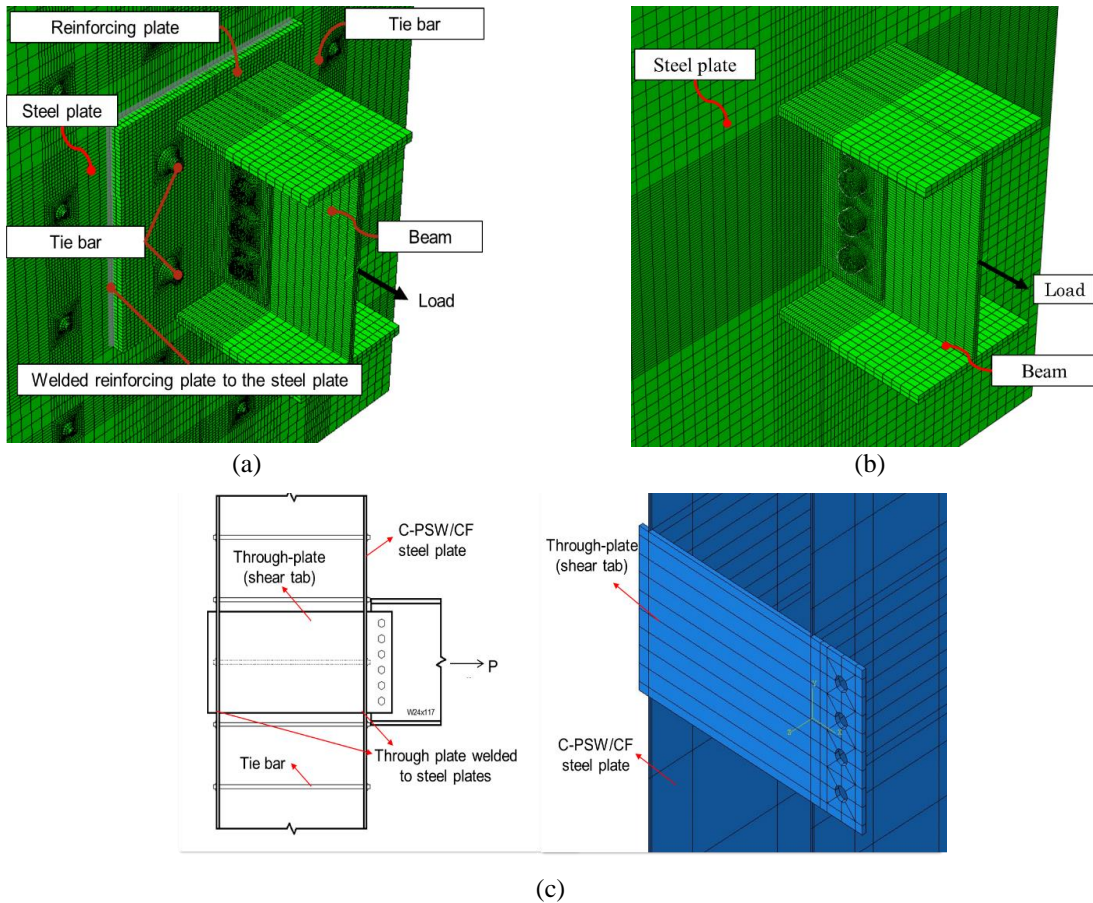


Figure 1: Details of The Connection Configurations, (a) RP, (b) UP, and (c) TP

3.2. Specimens

The wall-to-floor connection specimen includes a C-PSW/CF with simple shear connections welded to the exterior face of the C-PSW/CF. Fig. 2 shows a schematic drawing of a wall-to-floor connection specimen. The wall's cross-section is 457.2 mm x 1219.2 mm (18 in x 48 in) with two different heights of 1828.8 mm (72 in) and 2438.4 (96 in) for 0 rad and $\pi/6$ rad loading angles,

respectively. A steel plate thickness equal to 12.7 mm (1/2 in) was used to build the C-PSW/CF specimens. The tie bar spacing is equal to 304.8 mm (12 in). The connection parts (shear tab and bolts) were built based on the designed wall-to-floor connection with a W16x67 steel beam and 9.52 mm (3/8 in) shear tab, and four 19.05 mm (3/4 in) diameter bolts. The design of specimens was finalized based on numerical analyses.

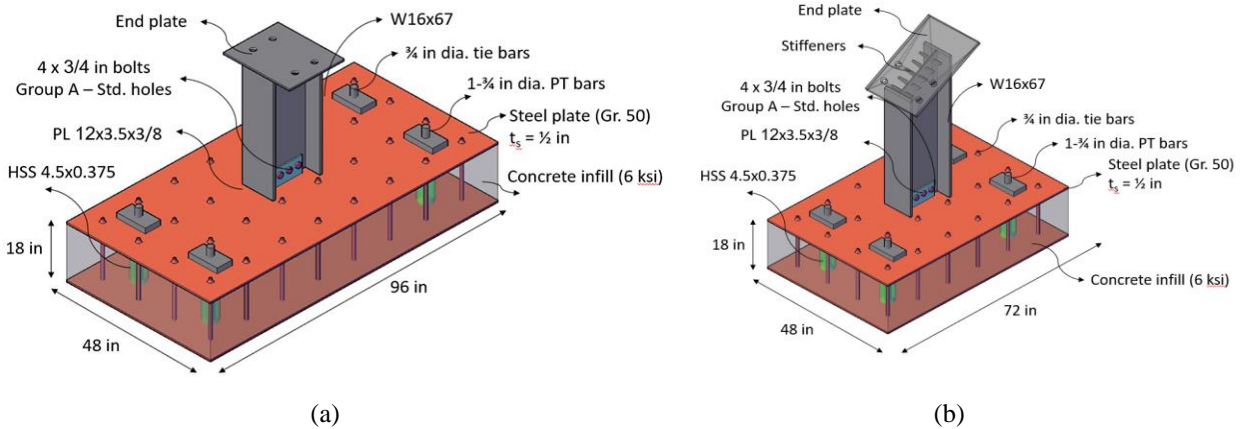


Figure 2: Wall-to-floor connection's specimens (a) zero rad (b) $\pi/6$ rad loading angle.

3.3. Fire test descriptions and results

The study conducted by Anvari (2022) explored the feasibility of using ceramic fiber heaters for applying heat to steel surfaces, as an alternative to traditional furnaces typically employed in fire tests. This involved conducting a trial fire test where these heaters were utilized to replicate the surface temperatures achieved in furnace-based fire tests, as documented in the existing literature. The results demonstrated a consistent alignment between the surface temperatures measured in the trial using ceramic fiber heaters and those reported for specimens heated in furnaces. Consequently, this research adopted ceramic fiber heaters as the method of choice for applying controlled temperatures to the specimens.

The temperatures on the surface and the through-thickness of the specimens were recorded. The axial and inclined displacements of the specimens were measured at different locations of the specimen. They were all part of a series of tests designed to evaluate the performance of different connection types under varying conditions, particularly in relation to fire incidents and temperature effects. A summary of the obtained peak load, the estimated strength using AISC specification (2016), the difference between the measured and the estimated strengths, and the failure modes is provided in Table 2.

Specimen 1 (TP-20-0-C): This test involved a through plate connection under ambient conditions, simulating beam expansion at the start of a fire. The load was applied axially in compression. Sensors measured displacement, deformation, and rotations. The specimen exceeded the estimated bolt strength capacity (123 kips vs. 113 kips calculated), resulting in bolt failure with limited bolt-hole deformation (about 1.5 mm). Fig. 3 shows the failed connection parts after the test. All the bolts failed at the same time, which showed that there was no load eccentricity applied to the specimen as seen in Fig. 3 (b). There was limited bolt-hole deformation observed upon removal of the specimen from the testing setup and was around 1.5 mm in the beam and the shear tab holes.

Specimen 2 (RP-500-0-C): This specimen was subjected to axial compression. The connection was heated to 500°C and then loaded to 75% of bolt capacity at the target temperature. The loading continued resulting in bolt shear failure at 84 kips. The temperature dropped from 500°C to 426°C at failure. Limited bolt-hole deformation was observed, and the actual force exceeded the AISC estimated strength.

Specimen 3 (UP-500-30-T): Fig. 4 shows the inclined force and the temperature-time history of the connection. This specimen was tested under tensile loading at 500°C. The peak force at failure was 64 kips at 489°C, with a maximum displacement of 6 mm in the wall's faceplate as seen in Fig. 5. This test showed a total large deformation before failure, and the connection capacity exceeded the AISC estimated strength.

Specimen 4 (UP-300-30-T): Similar to Specimen 3 but tested at a lower temperature (300°C), this specimen was subjected to inclined tensile loading. The test showed a sequential failure of tie bars at lower temperatures (278°C and 271°C) with significant deformation on the wall's faceplate. The peak force was 124 kips, exceeding the AISC estimated bolt strength.

Overall, each test provided valuable insights into the behavior of different connections under varying thermal and mechanical stresses, highlighting the impact of temperature on material strength, deformation, and failure modes. The results indicated discrepancies between measured and estimated bolt capacities, emphasizing the need for careful consideration of such factors in structural design, especially in fire scenarios.

Table 2. A Summary of the test results and the failure modes

Specimen	Peak load (kN)	AISC strength (kN)	Difference (%)	Failure Temperature (°C)	Failure modes
(TP-20-0-C)	551	493	11.7	20	Bolt shear
(RP-500-0-C)	377	354	6.5	416	Bolt shear
(UP-500-30-T)	287	265	8.3	489	Bolt shear
(UP-300-30-T)	124	100	24	278	Tie bar weld



(a)

(b)

Figure 3. The deformed parts of the connection after the test. a) beam web. b) bolts fracture.

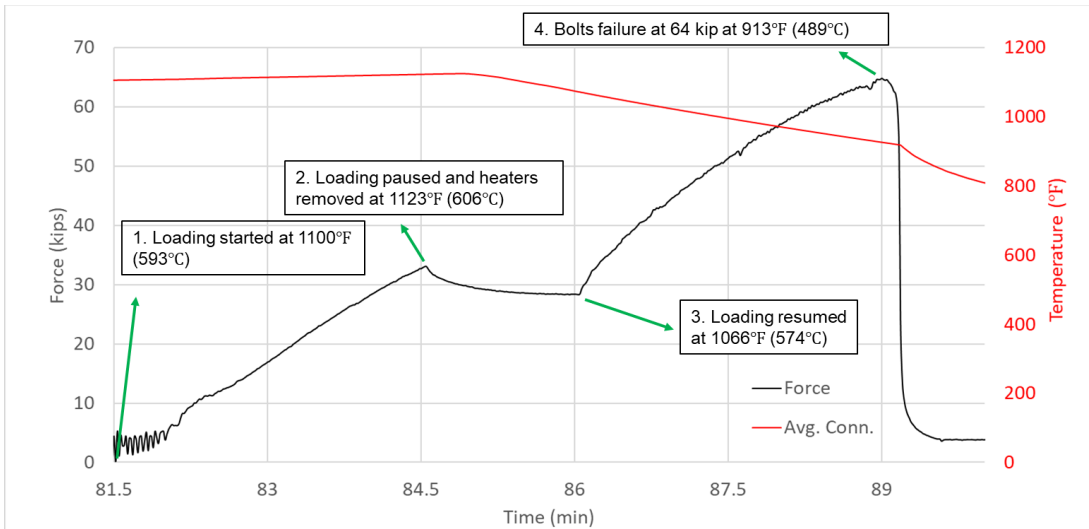
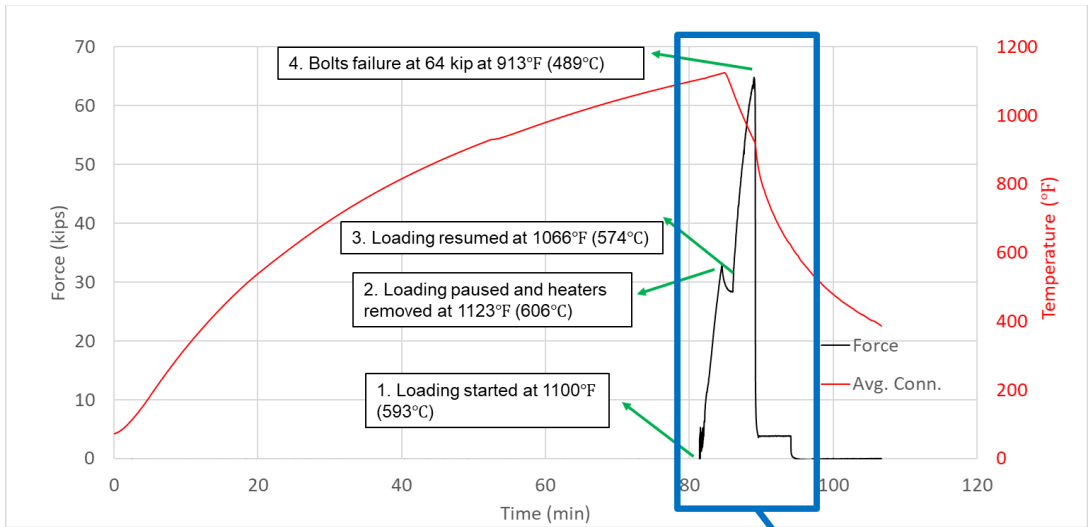


Figure 4. Inclined tensile force and average connection temperature history

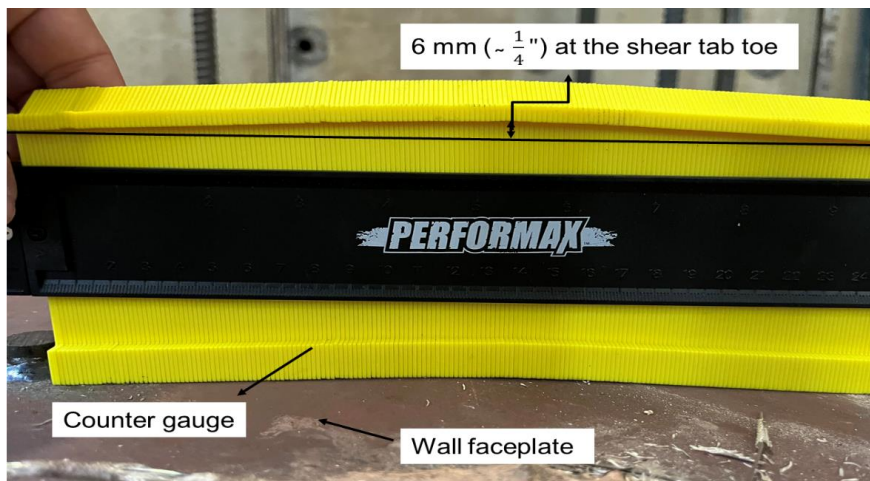


Figure 5. Wall's steel faceplate deformation after the test

4. Benchmarked Numerical Models

FE models were developed to numerically simulate the behavior of floor-to-SpeedCore wall connections, enhancing our understanding of these connections. Utilizing ABAQUS (Simulia, 2016), three-dimensional (3D) transient thermal and structural models were developed, enabling the calculation of temperatures and displacements. The models, incorporating temperature-dependent properties for both thermal and structural materials as per Eurocode 4 (2005), underwent sequential coupled thermal-stress analysis. These FE models were benchmarked against experimental tests detailed in Section 3, and fully replicated the specimens as depicted in Fig. 6. Every aspect of the connection, including the interaction between connection surfaces, was modeled.

The mechanical loading sequence, scale, and duration were replicated in the model, mirroring those in the specimen tests. The thermal heat transfer analysis encompassed both steel plates and concrete infill, with concrete infill modeled using the DC3D8 element and steel plates via the DS4 element. Structural models employed solid elements (C3D8R) to represent concrete, steel flanges, web plates, and tie bars. Constraints were applied at the post-tensioning plate holes, restricting all degrees of freedom. A detailed material damage model simulated potential specimen fractures, with parameters like damage initiation and evolution calibrated using data from experimental coupon tests, adhering to ASTM E8 (2018) standards. For comprehensive context, both the development and benchmarking of these models are elaborated in prior works by Anvari et al. (2021) and Alasiri et al. (2023). These validated models will be used to perform a parametric analysis of wall-to-floor connections under fire conditions.

The response from the FE models was compared with the experimental data obtained from the tests. Fig. 7 shows the comparison between the surface and mid-section temperature in the concrete of the test and the FE model for the specimen (UP-500°C-30T). The experimental surface temperatures were measured at 6.35 mm (0.5 in) from the concrete surface. Discrepancies in temperature, with the model indicating higher values than the test data, were attributed to unmodeled moisture loss in the concrete infill.

Fire loading induced expansion in all specimens, with average axial displacement histories illustrated in Fig. 8. The agreement between the FE model predictions and actual beam displacements from tests was good, particularly during the heating phase. Differences emerged primarily towards the end of the curves when mechanical loading was applied. Earlier bolt failure predicted in the FE model can be attributed to the possibility of having a higher temperature in the bolt shank which led to the failure. Fig. 9 showcases a comparison of deformed faceplates due to steel faceplate distortion near the shear tab toe, with both the test and model indicating similar wall deformation patterns. Notably, no wall faceplate fractures were observed or predicted.

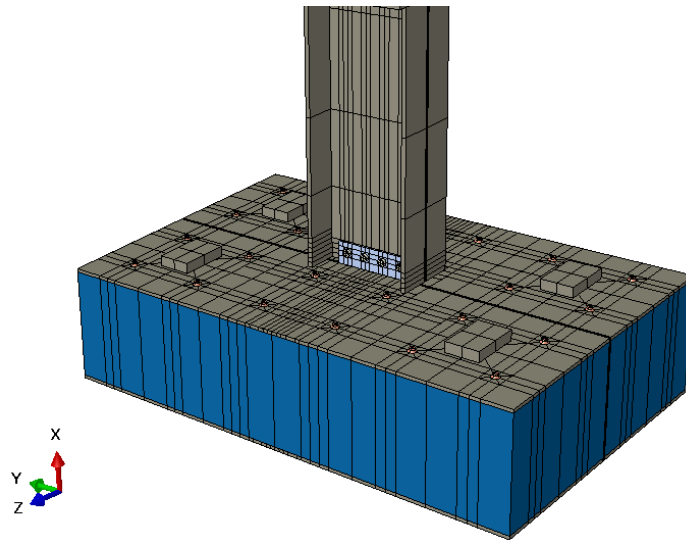


Figure 6. 3D FE model details for specimen

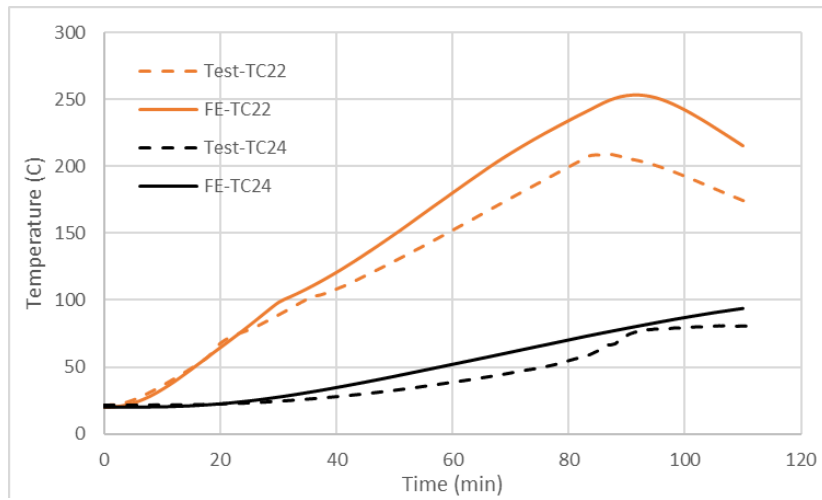
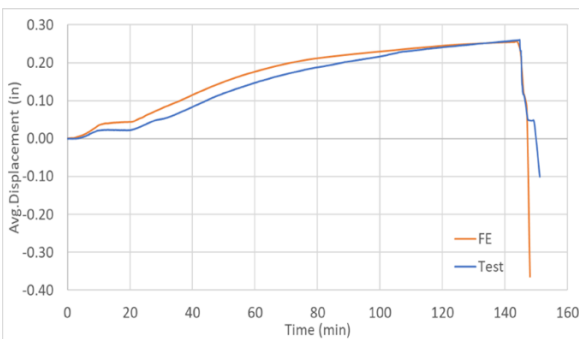
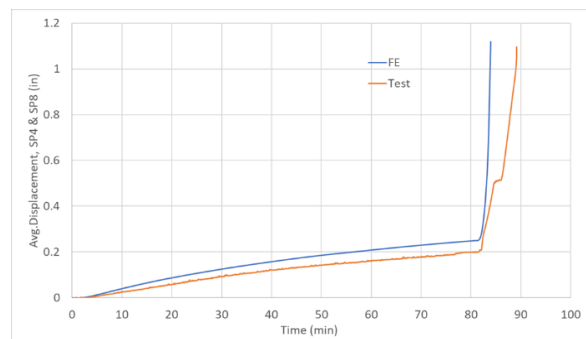


Figure 7. Comparison between the measured versus predicted temperature for the specimen (UP-500°C-30T)



(a) RP-500°C-0-C



(b) UP-500°C-30-T

Figure 8. Comparison of the average displacements of the predicted response from the test and FE models

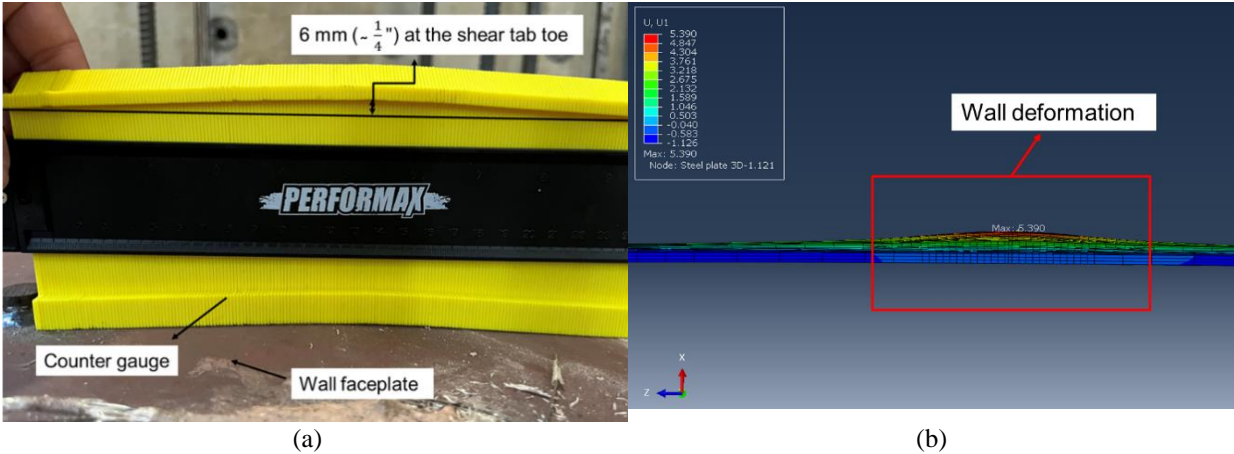


Figure 9. Comparison between the measured and the predicted wall faceplate deformation for UP-500°C-30-T

5. Summary and Conclusions

In this study, three connection configurations were developed to enhance the strength and stiffness of structural connections. These configurations included the UP, RP, and TP connections. These connections were tested under both ambient and elevated temperature conditions. Key parameters, including temperature, displacement, and rotational movement, were meticulously measured using thermocouples, string potentiometers, and inclinometers, respectively. The findings indicated a significant influence of steel faceplate flexibility on connection behavior. A notable observation across all test specimens was the prevalence of bolt failure as a common mode of failure, irrespective of temperature conditions or specific connection details. In most tests, the peak forces recorded surpassed the estimated capacities based on AISC specifications. Additionally, to gain a comprehensive understanding, 3D FE models incorporating more parameters were developed for a deeper evaluation of the behavior of these connections. These models were benchmarked against experimental data to validate their accuracy in predicting the thermal gradient and temperature histories of the connections. Comparative analysis between experimental results and FE model predictions demonstrated a high degree of correlation, affirming the model's reliability. Notably, the model proficiently anticipated the failure mechanisms observed during the experiments, including the deformation of the wall faceplate (prying action) and the fracture of structural bolts in the shear-tab connections. This level of predictive accuracy is crucial for understanding and improving the structural integrity of such connections.

The following conclusions were drawn from the current study:

1. The structural bolts are potentially more vulnerable than other connection components. Bolts lose more strength than structural steel at increasing temperatures, leading to bolt shear failure as the dominant mode across various temperatures and loading angles. This failure occurs under both tensile and axial compressive forces.
2. In UP specimens, the prying deformation of the wall faceplate suggests that this deformation in shear connections is preferable to the fracturing of the shear-tab connection. This type of deformation allows the steel beam to contract while avoiding brittle failure.
3. The behavior and failure modes of the specimens were notably influenced by temperature fluctuations during the heating phase and after heater removal.

4. Using AISC Specification equations, modified for elevated temperature effects on material strengths, generally provided reasonable calculations of connection capacity for all the tested specimens, indicating their efficacy in estimating connection strength.
5. The infill concrete did not have any effect on the failure type or failure time since the observed failure modes were bolt shear and beam-to-wall contact in all tests.
6. Floor-to-SpeedCore wall connections can be modeled with a sequentially coupled thermal-structural 3D FE model to predict the connection deformation and total displacement vs. time response. The results showed very good agreement between the measured and the predicted data.

6. Future Work

The authors are currently conducting parametric studies using the models benchmarked in this study. These models aim to assess the performance of connections across a range of parameters not previously examined in experiments. These parameters include bolt size, target temperature, loading angles, and direction. The outcomes of these analyses will be meticulously reviewed, and additional specimens may be tested to encompass a broader spectrum of parameters. Moreover, advanced numerical investigations are planned to replicate the behavior of entire structures (system level) under both ambient and elevated temperatures. This system-level analysis will integrate detailed component-based models for the connections, focusing specifically on the prying behavior of the steel faceplate in composite walls under varying temperature conditions. The insights gained from both experimental and numerical studies will inform the development of knowledge-based design guidelines for floor-to-SpeedCore wall connections subjected to fire loading.

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