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Advanced modeling of cold-formed steel walls under fire

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Abstract

This paper discusses an advanced finite element model able to simulate the structural response of cold-formed steel walls during standard fire tests. The model includes experimental thermo-mechanical properties of materials, geometric imperfections, and temperature distributions on studs and sheathing boards. The model is capable of reasonably predicting the thermal bowing of walls, and estimating the shape, size and amount of joint openings between gypsum boards over time of fire exposure. Numerical results validated with experimental data indicate that the maximum out-of-plane displacements due to thermal gradients occur near the wall mid-height. Early in the heating process, joint openings develop on the exposed side of walls due to thermal bowing and contraction of gypsum boards at elevated temperatures, potentially altering the heat transfer and affecting the fire resistance of the entire system. Future work aims to utilize high fidelity modeling to study the response of load bearing cold-formed steel systems subjected to fire, and optimize their fire resistance.

1. Introduction

Understanding the behavior of cold-formed steel (CFS) wall assemblies at elevated temperatures is the main step towards the optimization of these systems. In essence, two main aspects motivate this work from the point of view of the industry. First, in repeated standard tests, it is observed that CFS wall assemblies underperform compared to wood systems at elevated temperatures

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with similar frame layout and gypsum boards. The CFS industry seeks more competitive solutions by providing similar or better fire resistance ratings compared to the wood industry, and this can be achieved by first understanding the behavior of CFS studs and their effect on the entire wall system. Second, sustainable (or green) building constructions seek a lighter footprint on the environment, and this can be achieved by optimizing (or reducing) the amount of materials used. In the design of fire-resistant structures, sustainability generally means reducing the thickness of gypsum boards. The simplest question is how can we reduce gypsum board thickness while maintaining or increasing the fire resistance of wall assemblies.

Currently, sequentially coupled thermal and mechanical models are used to study the response of structural members and systems under fire (Chen et al., 2013). The way this coupling works is unilateral, so that the outputs from the heat transfer analysis (e.g. temperature field) is used as an input for the structural analysis. Therefore, the heat transfer affects the structural response, but the structural response (e.g. deformations and damage) does not affect the heat transfer.

Through numerical analysis, this paper explores the development of thermally induced deformations that directly affect the heat transfer; therefore, supporting the argument that the structural response has a direct impact on the heat transfer over time. This implies that the fire resistance of CFS walls does not only depend on the thermal properties of gypsum boards, but also depends on the response of the CFS frame.

This paper aims to show that advanced modeling of CFS systems under fire is possible and could provide suitable results if realistic material models and other modeling parameters are taken into account. This study provides original insight on the development of thermal bowing of CFS walls and opening of joints between gypsum boards during standard fire tests. Numerical models are validated against experimental results from CFS walls in standard fire tests.

The following sections describe the parameters used in the finite element model, show the validity of the numerical results, and discuss the structural behavior of non-load bearing walls at elevated temperatures.

2. Modeling cold-formed steel partition walls in standard fire tests

This paper focuses on the response of non-load bearing walls used to avoid spread of fire and smoke between compartments. Usually, partition walls consist of CFS frames with equidistant vertical lipped channels (i.e. studs), and horizontal channels at the top and bottom (i.e. tracks).

The flanges of the studs are usually connected to the flanges of the tracks by screws or sliding/frictional connections. Gypsum boards enclose the CFS frame, and act as the main components to provide fire resistance. Wall components are illustrated in Figure 1.

2.1 Geometry and initial imperfections of CFS frame

A typical CFS wall geometry is considered in the analysis (Figure 2). The frame is 10 ft. (3.05 m) by 10 ft. (3.05 m), and has 6 lipped channel studs, and two channel tracks. The length of the tracks is 120 in. (304.8 cm), and the length of the studs is 119.25 in. (302.9 cm), since small gaps exist between the ends of the studs and the web of the tracks. The gaps measure 0.50 in. (1.3 cm) and 0.25 in. (0.6 cm) in the top and bottom, respectively (Figure 1-b). The centerline dimensions of web, flange and thickness of studs and tracks are 3.60 in. (9.14 cm), 1.23 in. (3.12 cm), and 0.0188 in. (0.478 mm), respectively. The centerline dimension of the lips of studs is 0.188 in. (0.48 cm).

Gypsum boards are usually 4 ft. wide (1.22 m); therefore, several boards are used to cover each side of the CFS frame. In Figure 3, Board 1 is 2 ft. (0.61 m) wide, and Boards 3 and 4 are 4 ft. (1.22 m) wide. The thickness of gypsum boards is 0.61 in. (15.5 mm).

Initial imperfections are included in the stud model, following magnitudes recommended by Zeinoddini and Schafer (2012).

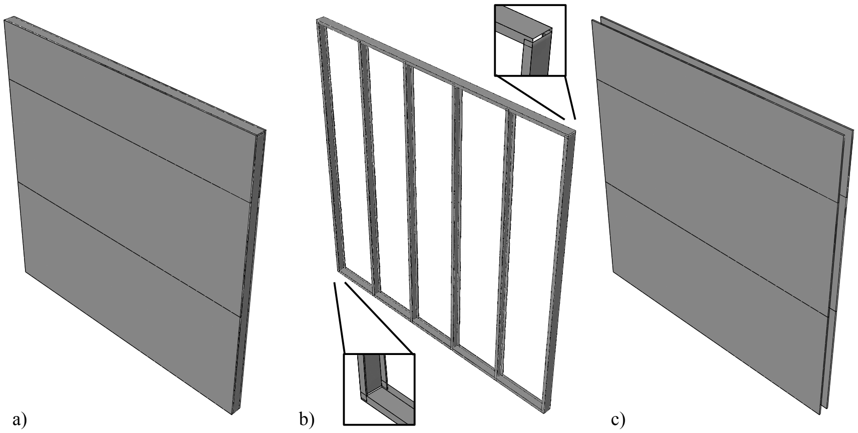

Figure 1: Components of a) wall model, b) CFS frame, and c) gypsum boards

In ABAQUS (ABAQUS 2013), quadrilateral shell elements with reduced integration and large-strain formulation "S4R" were used to model CFS members and gypsum boards. Studs and tracks consisted of 5656 and 8120 elements, respectively. Each portion of the studs and tracks (i.e. web, flange and lip) were discretized into 4 elements. Gypsum boards 2 and 3 were modeled with 360 elements each, while Board 1 was modeled with 180 elements. The boards on each side of the CFS frame were modeled similarly.

Connectors were modeled at screw locations, along the flanges of studs and tracks spaced 8 in. (20.32 cm) from screws, and 4 in. (10.16 cm) from board edges (Figure 4). Additional connectors on stud flanges were modeled 1 in. (2.54 cm) from board joints. Connectors were modeled as rigid beams, by tying nodes at the center of CFS flanges and adjacent nodes on the boards, within a radius of 0.07 in. (1.8 mm).

The web of the bottom track was restricted in its displacements, in all directions. The web of the top track was allowed to displace only in the vertical direction, to allow thermal expansion of studs. The web of the studs at the left and right sides of the wall were not allowed to displace in the in-plane horizontal direction. These boundary conditions intend to approximate actual displacement restraints during tests.

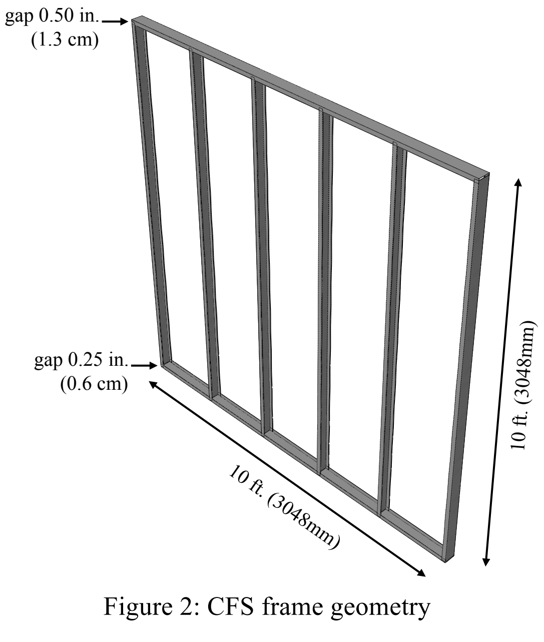

Figure 2: CFS frame geometry

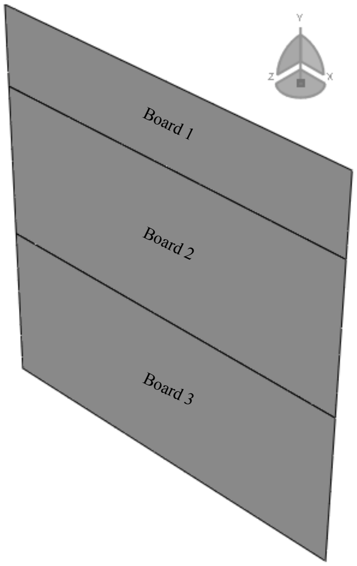

Figure 3: Gypsum boards layout

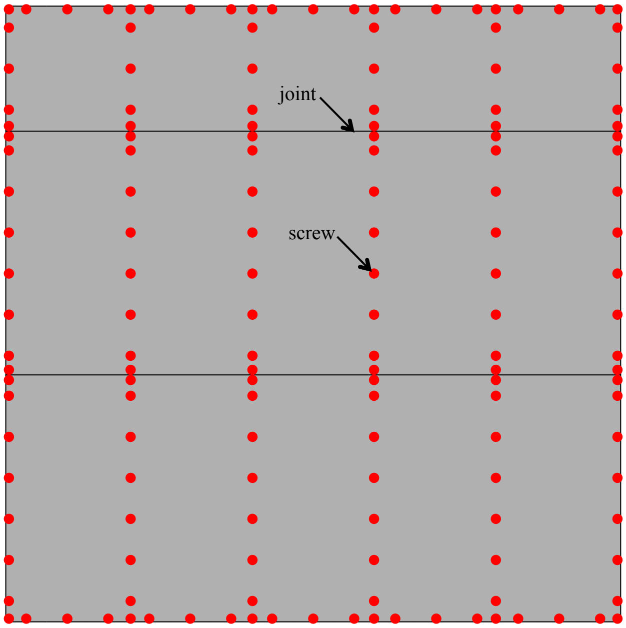

Figure 4: Gypsum boards and screw distribution in the model

2.2 Temperature distribution on CFS partition wall

Heat transfer analysis could be used to estimate the temperature distribution on the walls. However, models for heat transfer analysis found in the literature do not explicitly include the effect of structural response due to heat. Therefore, in this paper, time-temperature curves obtained experimentally were used.

During standard fire tests, the temperature of the furnace is controlled and the temperatures on the studs and gypsum boards can be measured (Figure 5). In the model presented herein, the temperature of the lips was assumed to be similar to the temperature of the flanges given that steel has a high thermal conductivity and the lips are small and thin. The temperature of the web of the studs was assumed to vary linearly, and it was obtained from the measured flange temperatures. The temperature distribution on the studs reflects the thermal gradient measured during test (Figure 6).

2.3 Mechanical properties of materials at elevated temperatures

The CFS material model used follows retention factors proposed by Batista Abreu (2015), assuming elastic modulus and yield stress at ambient temperature of 29500 ksi (203.4 GPa) and 33 ksi (228 MPa), respectively. The thermal expansion coefficient of CFS is 1.2×10-5 1/°C, and the Poisson's ratio is 0.3.

Retention factors for the mechanical properties and thermal expansion of gypsum are based on experimental results presented by Cramer, Friday et al. (2003). Retention factors for gypsum boards were fitted and extrapolated to 1000 °C. It was assumed a linear decay of the retention factors from 0.05 at 600 °C to 0.01 at 1000 °C. It implies that the elastic modulus of gypsum boards is negligible after 600 °C, as expected (Figure 7). It was assumed that gypsum is homogeneous, and has an elastic modulus at ambient temperature of 100 ksi (690 MPa), and Poisson's ratio equal to 0.3. The thermal expansion coefficient was assumed to remain constant -1.60×10^{-6} 1/°C after 400 °C (Figure 8).

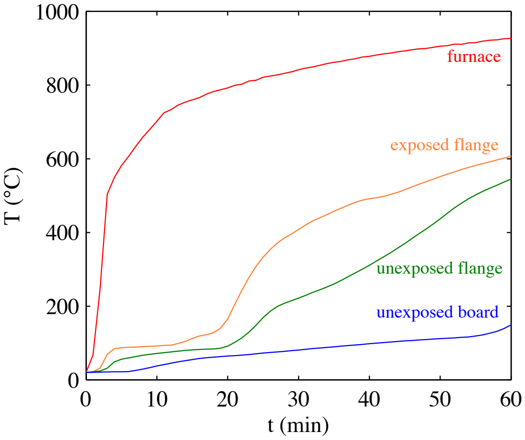

Figure 5: Measured temperature data in standard fire test (from proprietary data)

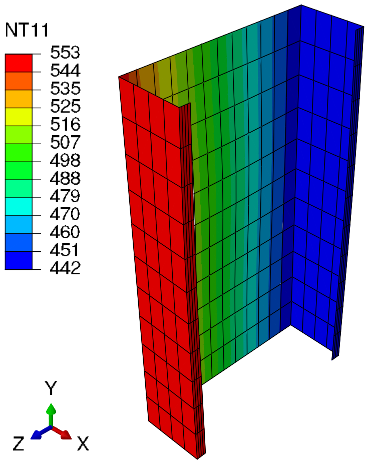

Figure 6: Temperature distribution on a CFS stud (°C)

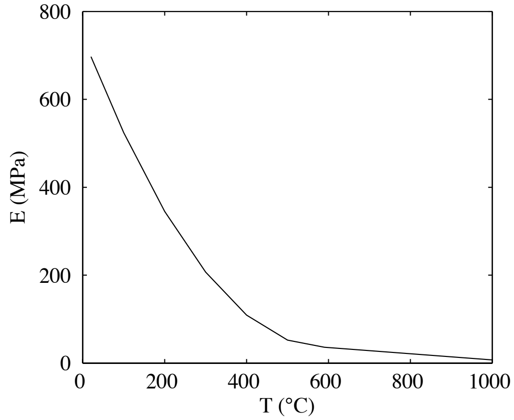

Figure 7: Elastic modulus of gypsum at elevated temperatures (1 ksi = 6.895 MPa)

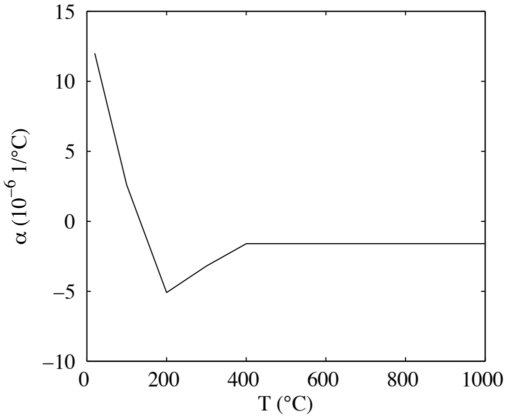

Figure 8: Thermal expansion coefficient of gypsum used in numerical models

3. Numerical results from finite element analysis

Stress distributions, thermal bowing and joint opening were the main outputs obtained from numerical simulations. It was observed that von Mises stresses on the CFS frame do not exceed the yield stress at ambient conditions (Figure 9). The stress distribution of a single stud is presented in Figure 10 to show that lower stresses are developed on the exposed flange compared to the unexposed flange due to higher temperature and therefore more pronounced material degradation on the former. Interaction of local and distortional buckling modes is observed, consistent with previous studies (Batista Abreu and Schafer, 2013).

The CFS frame bowed towards the furnace due to thermal gradients, causing larger thermal expansion on the exposed flanges compared to the unexposed flanges. Thermal bowing of the wall develops large out-of-plane displacement at mid-height (Figure 11).

Out-of-plane displacements on the unexposed side were obtained at the center of the wall, and at quarter-points at mid-height (both left and right). These values are compared against experimental data from two standard fire tests on CFS partition walls with similar geometry and materials (Figure 12). Relatively small displacements are observed before 20 minutes of exposure to a standard fire. Then, larger velocities are developed from 20 to 30 minutes, reaching a displacement peak between 45 and 50 minutes. Out-of-plane displacements tend to slightly decrease after the peak due to a reduction of the thermal gradient in the studs.

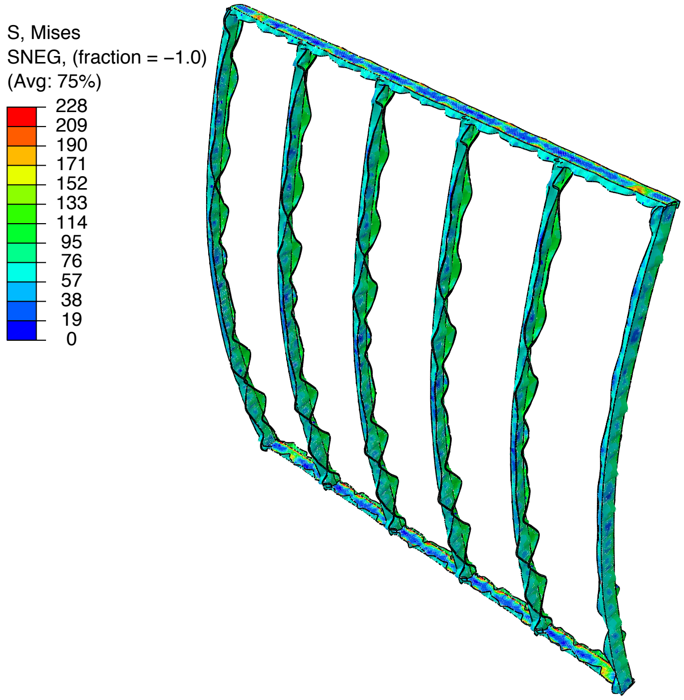

Figure 9: von Mises stresses (in MPa, 1 ksi = 6.895 MPa) developed in the CFS frame after 60 minute of fire exposure (scale 5:1)

Numerical models predict maximum out-of-plane displacements of 2.20 in. (56 mm), while 1.61 in. (41 mm) and 2.05 in. (52 mm) where measured in two similar tests. These results imply that the wall moves closer to the fire source (e.g. the furnace) as the thermal gradient increases. As the studs move the entire wall closer to the fire, the temperatures increase more dramatically. Therefore, the thermal response is undoubtedly affected by the structural behavior.

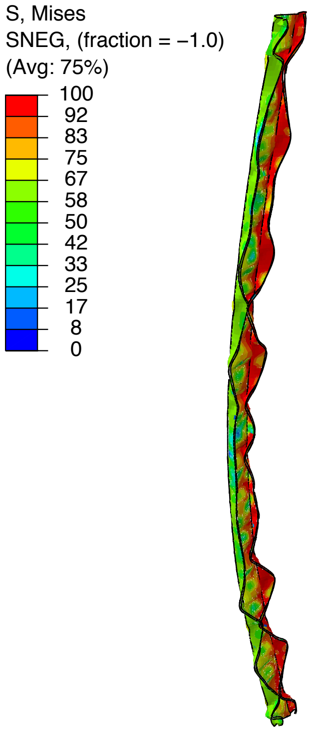

Figure 10: von Mises stresses in a CFS stud (in MPa, 1 ksi = 6.895 MPa) after 60 minutes of fire exposure (scale 5:1)

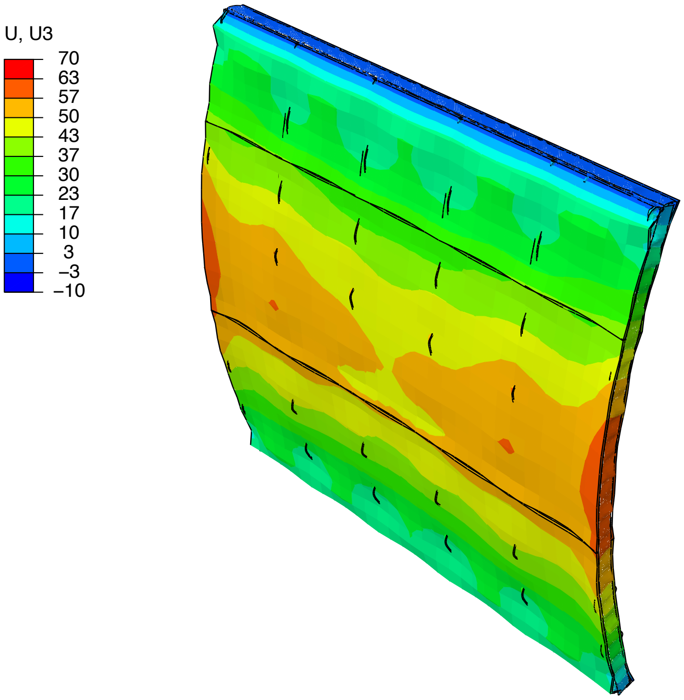

Figure 11: Wall out-of-plane displacements (mm, 1 in. = 25.4 mm) after 60 minutes of fire exposure (scale 5:1)

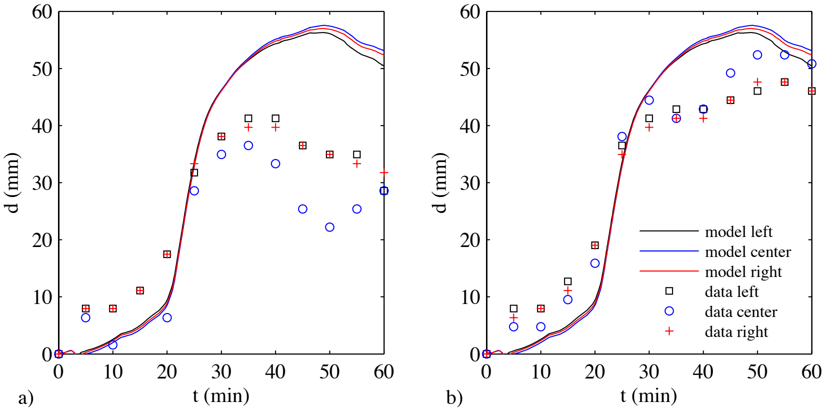

Figure 12: Wall out-of-plane displacements at mid-height (solid lines) compared against experimental data (markers) from a) test #1 and b) test #2 (obtained from proprietary manufacturer data, 1 in. = 25.4 mm)

During the heating process and subsequent thermal bowing of the studs, it is commonly observed that joints between exposed boards open up (Figure 13). After standard fire tests, joint openings on the unexposed side of walls are not visible, while they are evident between exposed boards (Figure 14). These openings could allow rapid passage of hot gases from the furnace to the wall cavity, consequently accelerating the heat transfer though the studs and unexposed boards, and therefore compromising the fire resistance of the system.

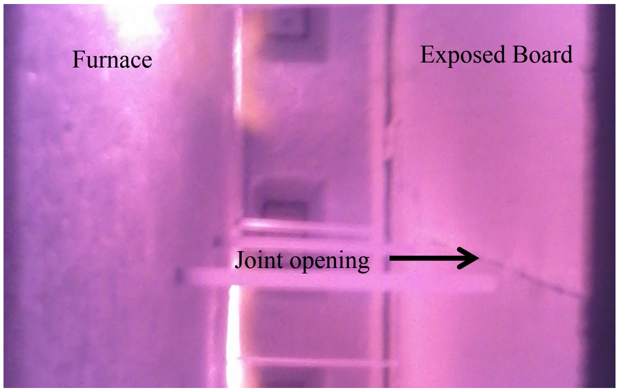

Figure 13: Joint opening on exposed side of a CFS wall during test

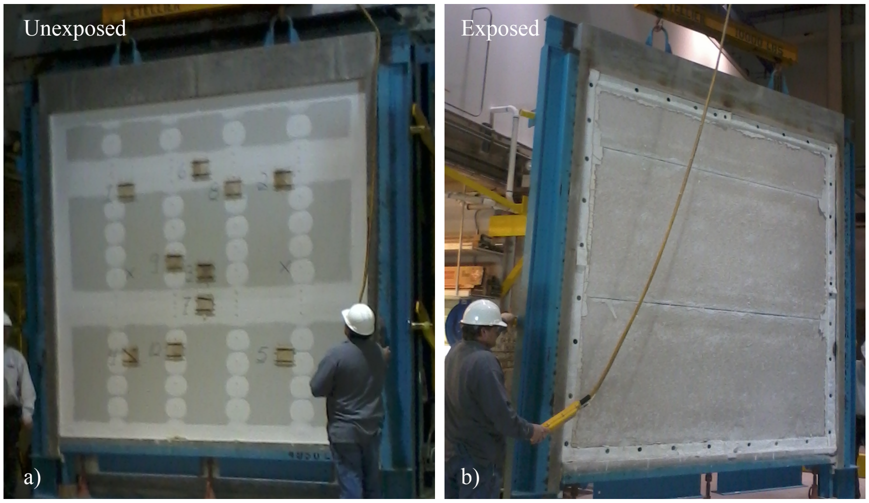

Figure 14: CFS wall after standard fire test, a) unexposed and b) exposed boards

Numerical results show that joint openings are developed between studs, as observed in standard fire tests. Joints do not open at their intersections with studs due to a larger concentration of screws in those regions. Maximum openings tend to occur midway between two consecutive studs (Figure 15).

Joint openings of about 0.039 in. (1 mm) wide are observed in the model at about 4 minutes of exposure to the standard fire curve. Maximum openings of about 0.197 in. (5 mm) wide are developed around 50 min to 60 minutes of fire exposure. According to the numerical results, the bottom joints may develop slightly larger joint openings after 20 minutes, compared to the top joints.

It is important to characterize the size and shape of joint openings because they play an important role in the heat transfer, and consequently affect the fire resistance of CFS walls. Joint openings allow the passage of hot gases (including smoke) and flames. The rapid temperature increase in the wall cavity leads to higher temperatures on CFS studs and a more pronounced degradation of their strength and stiffness. In consequence, studs develop larger thermal deformations. The rapid temperature increase in the wall cavity also affects the unexposed boards, and their ability to satisfy insolation and integrity criteria.

In general, models for heat transfer analysis of CFS walls found in the literature do not explicitly (or even implicitly) account for the effect of joint openings, and thermal bowing of studs. Calibrated thermal properties of gypsum are used to exaggerate the temperatures developed in a model that would assume not to deform or create joint openings. This limited approach based on arbitrary calibration of thermal properties has lead to dissimilar models proposed by different research groups.

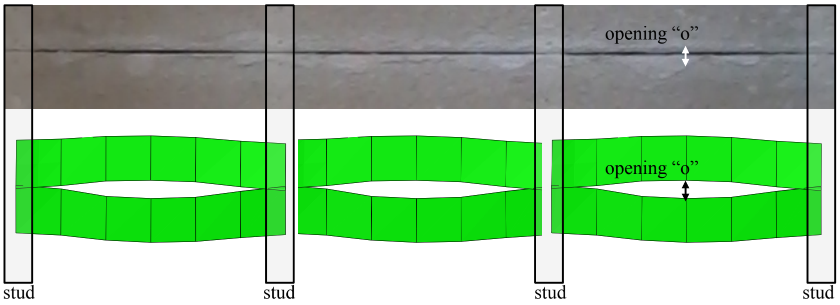

Figure 15: Joint opening observed in test and numerical model (scale 10:1)

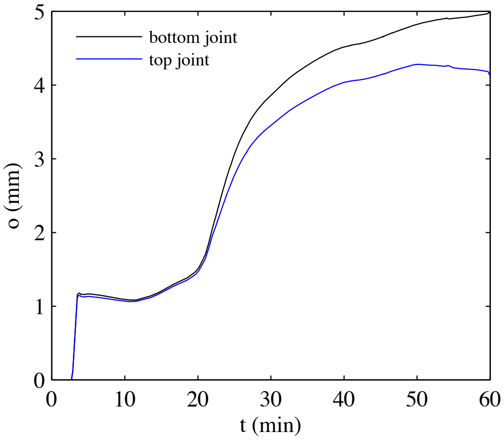

Figure 16: Maximum of joint opening width "o" developed at the bottom and top joints (1 in. = 25.4 mm)

The model proposed in this paper is capable of estimating the location, magnitude and shape of joint openings, as well as the thermal bowing of the wall over time of fire exposure. This information could be directly included in heat transfer analysis to generate accurate results without the need of significant calibrations of the thermal properties of materials.

4. Conclusions and future work

This paper presented an advanced finite element model to study the structural response of CFS walls exposed to the standard fire. The model includes temperature-dependent material properties, geometric imperfections of CFS members, connections between the CFS framing and sheathing boards, and experimental time-temperature curves. Thermal bowings obtained from numerical results were compared against experimental data, and were found reasonable.

It was observed that the structural behavior of CFS walls could alter the heat transfer in such systems. For instance, thermal gradients on the studs induce thermal bowing of the walls towards the fire source. Also, these thermally induced deflections and the contraction of gypsum boards lead to the opening of joints between exposed boards. Through these joint openings, the passage of hot gases and flames is possible. Both effects (i.e. thermal bowing and joint opening) impact the heat transfer and the fire resistance of CFS wall systems.

The model presented herein could be adapted to study the response of load-bearing walls at elevated temperatures. Therefore, future work will be dedicated to the analysis of load-bearing systems subjected to fire, through advance numerical modeling with the objective of understanding the response of load-bearing systems and optimize their fire resistance. The work provided herein establishes that such an approach is possible, and likely to provide useful predictions of fire and structural performance.

Future work in collaboration with the National Institute of Standards and Technology aims to enable fully coupled thermo-mechanical analysis of structural systems subjected to standard and real fires. The current model is able to estimate the structural response based on results obtained from heat transfer analysis. Furthermore, results from the structural analysis could be integrated in the heat transfer analysis to enhance the accuracy of the predictions.

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