Proceedings of the
Annual Stability Conference
Structural Stability Research Council
Nashville, Tennessee, March 24-27, 2015

Experiments on cold-formed steel sheathed studs at elevated temperatures

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Abstract

This paper aims to assess the stability of cold-formed steel studs at elevated temperatures through experimental methods. Short and intermediate-length studs braced with gypsum, fire-rated gypsum, and oriented strand board were subjected to compressive axial load and temperatures ranging from 20°C to 600°C. Compressive axial load was applied to the studs until failure occurred. Results show that the load-carrying capacity of the structural members lowers with increasing temperature, as the mechanical properties of cold-formed steel reduce, and the bracing provided by the sheathing degrades. Local and distortional buckling failures are observed in the cold-formed steel member. The stabilizing effect and increase of load-carrying capacity attributed to sheathing is eventually lost, and the behavior of the sheathed studs becomes similar to the behavior of unsheathed members. Direct Strength Method equations provided in AISI-S100-12 are used to predict the load-carrying capacity of the studs, then compared to experimental results to explore the feasibility of current design methods for performance-based fire design applications.

1. Introduction

Cold-formed steel (CFS) members are broadly used as framing components in non-load-bearing and load-bearing systems. Typical walls are assembled with thin-walled studs connected to top and bottom tracks through screws, and then sheathed with gypsum wallboards or oriented strand boards (OSB). In cases required by building codes, fire-rated gypsum boards are also used to sheath the cold-formed steel framing and to assist in mitigating the spread of fire and smoke among building compartments.

In general, sheathing provides (among other benefits) lateral restraint to CFS members at screw locations, potentially increasing their load-carrying capacity. Vieira (2011) investigated the behavior of sheathed CFS studs at ambient temperatures under compression and concluded that sheathing braces the studs, allowing only local buckling, by restraining distortional and global buckling modes. This beneficial effect was experimentally and analytically characterized, and translated into a design formulation to determine the strength of sheathed wall assemblies (Schafer 2013). The proposed method was validated for CFS systems at ambient temperature.

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In case of fire, the temperature of exposed assemblies increases producing a deterioration of the mechanical properties of structural and sheathing materials. Investigations on the behavior of stud-to-sheathing connections at elevated temperatures are limited in the current literature; consequently, the feasibility of a complete methodology for cold-formed steel system fire design has not yet been judged (Batista Abreu et al. 2014).

Gypsum wallboards consist of a core of pressed gypsum, enclosed by sheets of paper. At elevated temperatures, gypsum wallboards burn and suffer calcination, therefore decreasing the bracing stiffness provided to the studs. The deterioration process starts with dehydration of gypsum at about 100 °C (Gerlich 1995), when the void fraction of the material increases and its thermal conductivity drops (Rahmanian 2011). Then, at about 200 °C to 300 °C, the paper cover burns and thus the ability of the wallboard to remain integral progressively vanishes. During this heating process, the wallboard loses its structural strength (Cramer et al. 2003).

OSB is formed by blending rectangular wood strands and adhesives, then compressed in multiple layers. Besides burning and producing an enormous amount of smoke, the mechanical properties of OSB degrade at elevated temperatures. For example, OSB retains about 24% of its bending strength at 200 °C (Sinha et al. 2011).

In general, the response of sheathing determines the thermal response of CFS assemblies, and has a direct impact on the structural response of the system. For instance, the loss of lateral bracing may cause weakness in load-bearing members, influencing the stability of the structure. Aiming to understand response of sheathed studs under fire, this paper experimentally studies the behavior of single sheathed studs subjected to axial load, at elevated temperatures. The specimens studied are similar to those tested at ambient temperature by Vieira Jr et al. (2011).

2. Experimental setup

Specimens consisted of a single 0.60 m or 1.00 m long stud connected to 0.50 m long tracks. The studs were lipped channels with web, flanges, and lips nominally measuring 153, 43, and 13 mm, respectively; while the tracks were unlipped channel sections with similar dimensions. The thickness of all CFS sections was 1.55 mm.

Stud and track flanges were connected with single screws #10 3/4” (19.1 mm) at each side, in both ends (Fig. 1-a). Therefore, the CFS studs were allowed to experience rotation about their minor-axis, reflecting partially-restrained end conditions. Regular gypsum boards (GYP), fire rated gypsum boards (FRG), or OSB were used as sheathing materials (Fig. 1-b). Gypsum boards were connected to CFS sections through #6 1-5/8” (41.3 mm) screws; although #8 1 15/16” (49.2 mm) screws were used for stud-to-OSB connections. The average thickness of OSB and gypsum boards (both GYP and FRP) was 11.5 mm and 12.7 mm, respectively.

Five configurations were studied according to the sheathing condition (or material used) at each side of the stud, and named as follows: BARE-BARE, OSB-OSB, GYP-OSB, GYP-GYP, and FRG-FRG. For instance, GYP-OSB denotes that the CFS stud was sheathed with gypsum board on one side, and oriented strand board on the other side.

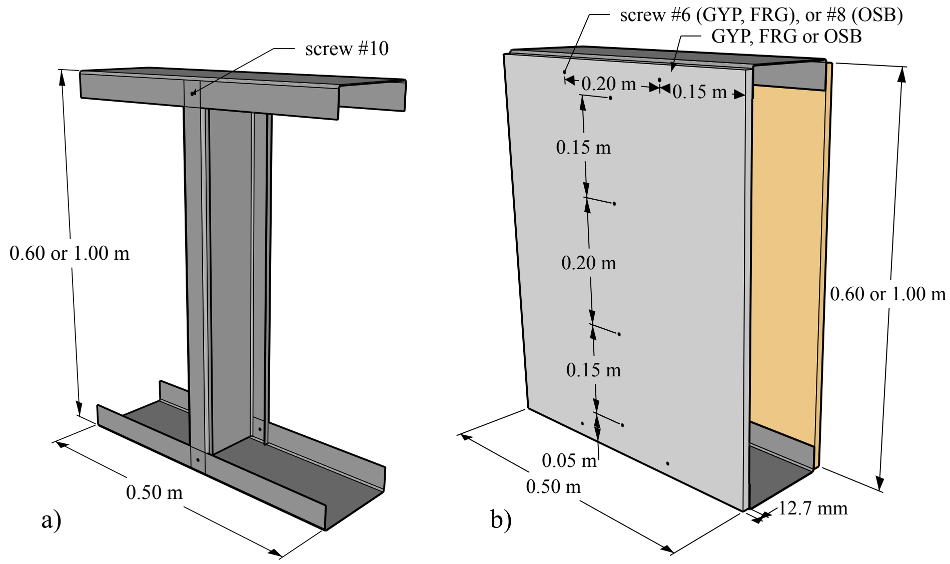

Figure 1: Sketch of a) bare and b) sheathed specimens

At room temperature (i.e. 20°C approximately), the average moisture content of OSB and gypsum (both GYP and FRG) was 3% and 12%, respectively. Bare specimens and specimens sheathed with (GYP or FRG) gypsum were tested at 20, 200, 400 and 600 °C. Specimens sheathed with OSB, either in one or two sides, were tested at 20, 100, 200 and 250 °C. In summary, CFS specimens with two stud lengths and five different sheathing conditions were tested at four temperatures levels. Therefore, a total of forty tests were completed.

After aligning the specimens in the structural testing frame (Fig. 2-a), an electric furnace was activated to set the temperature to a predetermined value (Fig. 2-b). The heating rate was defined as 10 °C/min, and the temperature of the furnace was controlled through type-K thermocouples. The temperature of the specimen was measured at three cross-sections: located at mid-height, 12.5 cm from the top of the top track, and 12.5 cm from the bottom of the bottom track. At each location, type-K thermocouples were attached to the middle of both flanges. Additionally, a type-K thermocouple was attached to the web center, at mid-height. In total, 7 thermocouples reported the temperatures of the steel studs. Thermal expansion was allowed during the heating phase of the experiment.

Once the temperatures reached the predetermined value and were stable for about 20 minutes, axial load was applied to the top of the specimen at a rate of 0.01 mm/sec. Two 153.0 mm wide, 304.8 mm long, and 12.7 mm thick steel plates were located on the web of the top track and under the web of the bottom track. These thick plates were used to transfer the load directly to the tracks and avoid direct bearing of the sheathing. The load was recorded through a load cell placed under the specimen, outside of the furnace. Two linear variable differential transducers (LVDTs) were used to measure the vertical displacement at the top of the specimen during the test. The temperatures of the load cell and LVDT was monitored with laser temperature sensors to guarantee they would not increase significantly over room temperature. Axial load was applied until collapse (Fig. 2-c).

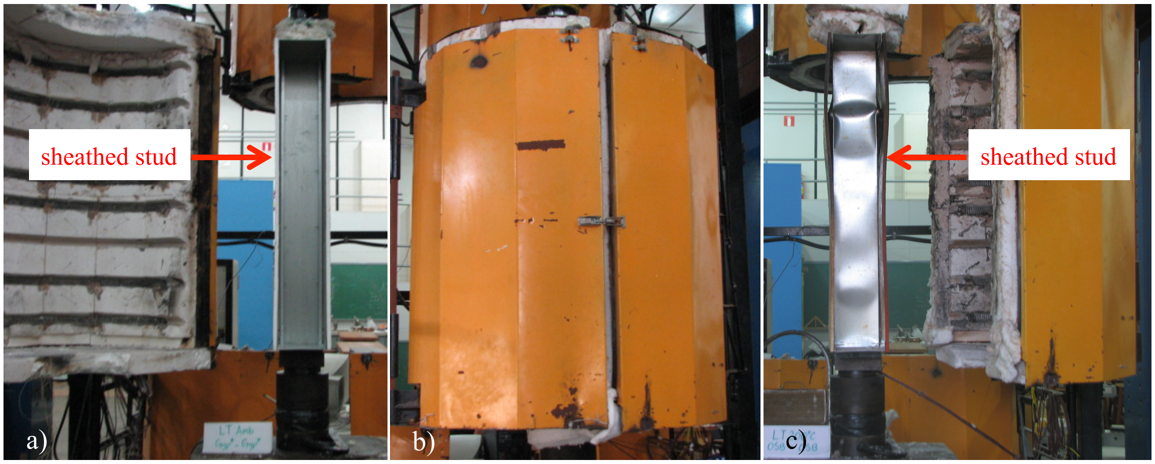

Figure 2: Experimental setup: a) sheathed specimen alignment before testing, b) electric furnace during testing, and c) sheathed specimen after testing

3. Results

Axial load and displacement of bare and sheathed specimens, at ambient temperature, are plotted in Fig. 3. Short members (i.e. 0.60 m long) show a slight variation of the peak load among bare and sheathed specimens (Fig. 3-a). For these short studs, the dominant failure mode corresponds to local buckling of the web. By adding sheathing, distortional and global buckling effects are restricted; however the local buckling of the web continues to govern the response. In contrast, intermediate-length specimens (i.e. 1.00 m long) exhibited an increased load-carrying capacity by adding sheathing, regardless of the sheathing material (whether it is gypsum or OSB). The response of the intermediate-length studs was governed by global-local interactions, and high participation of distortional buckling mode. Therefore, by adding sheathing and constraining the rotation of the flanges and minor-axis buckling, the capacity of the studs increased at least 15% compared to the bare case. Similar results were found by Vieira Jr et al. (2011).

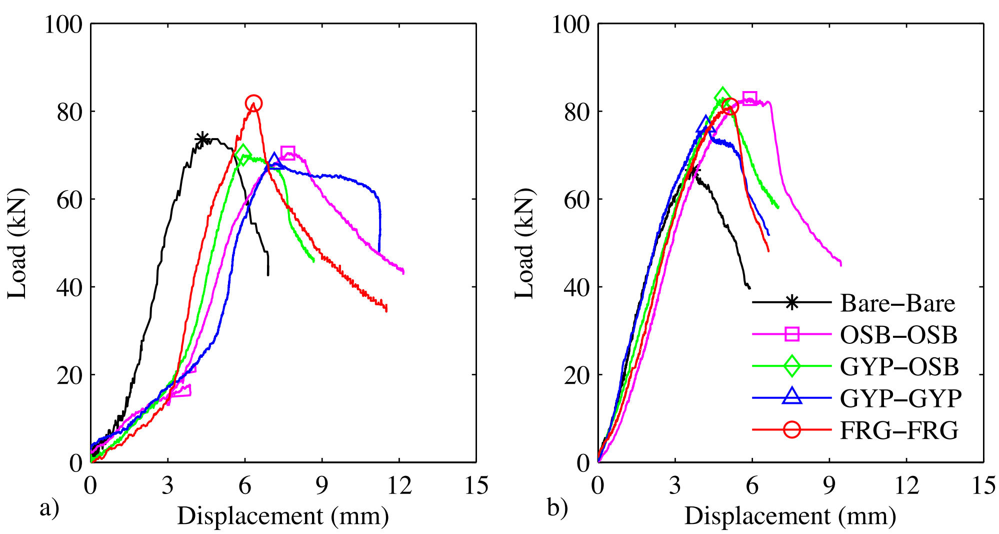

Figure 3: Axial load versus displacement of a) 0.6 m and b) 1.0 m long CFS studs at 20 °C

By increasing the temperature, the load-carrying capacity of the specimen decays due to degradation of the mechanical properties of CFS. Additionally, high temperatures alter the properties of the sheathing materials, consequently reducing their ability to brace the stud and constraint distortional and global buckling modes. Fig. 4 shows the case of intermediate-length CFS studs sheathed with FRG. Both stiffness and strength are considerably reduced with increasing temperature. For instance, the load-carrying capacity reduces to 30 % of its initial value, at 600 °C.

Short specimens showed comparable axial strength regardless of their sheathing conditions at every temperature (Fig. 5). The load-carrying capacity reduced mainly due to degradation of the steel. Intermediate-length studs showed higher capacity when sheathed at every temperature compared to the bare members, up to 600 °C (Fig. 6). However, the strength increase due to sheathing was observed to vary with increasing temperature.

Significant damage of the sheathing was noticed when increasing the temperature. The gypsum wallboards produced a noticeable amount of water steam and smoke after reaching 115 °C and 250 °C, respectively. The paper used to maintain the integrity of the gypsum was mostly burned at about 400 °C; therefore, at high temperatures, the sheathing capacity relied only on dehydrated and damaged gypsum. Smoke was observed after OSB reached 200 °C, approximately; and at 250 °C the amount of smoke was substantial.

Gypsum boards were significantly cracked after testing sheathed specimens at 600 °C. Results show that at 600 °C the difference between the strength of sheathed and bare specimens is small (Fig. 7).

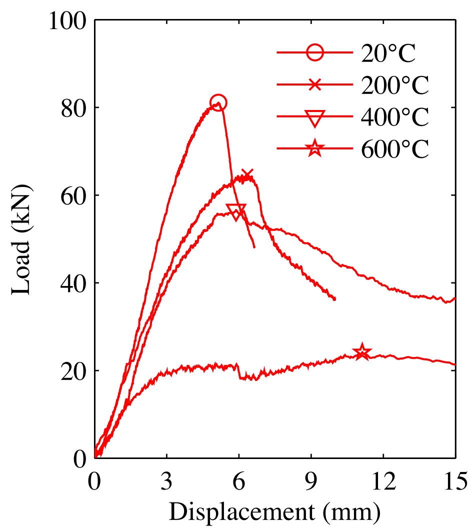

Figure 4: Axial load versus displacement of 1.0 m studs sheathed with fire-rated gypsum

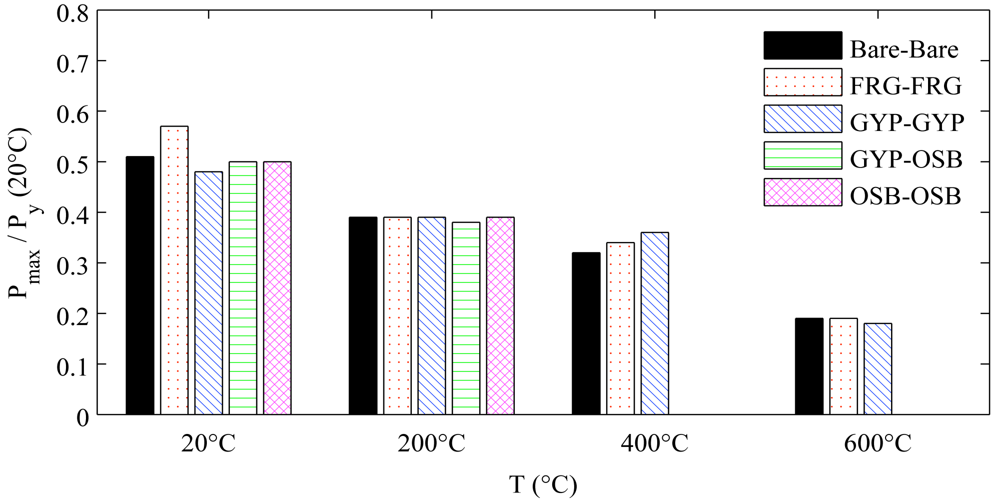

Figure 5: Normalized ultimate load of unsheathed and sheathed 0.6 m long studs with temperatures

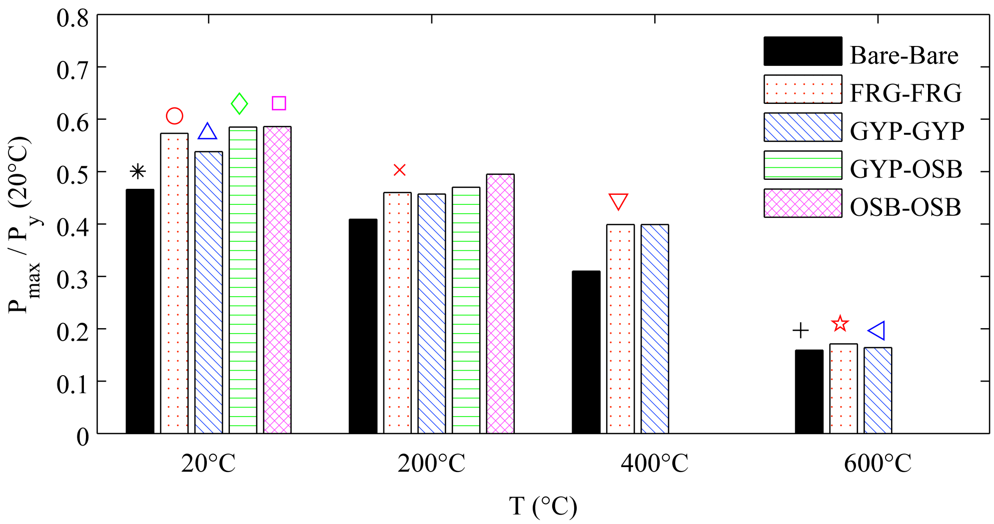

Figure 6: Normalized ultimate load of unsheathed and sheathed 1.0 m long studs with temperatures

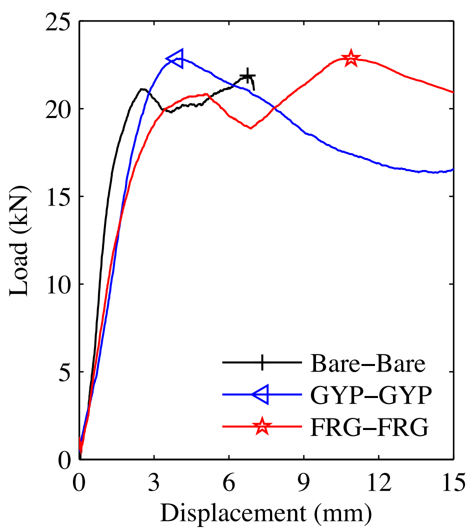

Figure 7: Axial load versus displacement of 1.0 m long studs at 600°C

4. Discussion

Although the load-carrying capacity of short studs governed by local buckling was not significantly improved by adding sheathing boards, the strength of intermediate-length members was improved. This improvement in strength tends to disappear as the sheathing board degrades with increasing temperature. Fig. 8 shows intermediate-length bare members after test, with noticeable deformations about the minor-axis, and localized deformations at mid-height. Similar sheathed studs at elevated temperatures show localized deformations at the ends and web buckling along the member, up to 400 °C. At 600 °C, the sheathed studs become "unsheathed" after a significant part of the gypsum spalls off; thus, both the bare and sheathed specimens show similar deformed shapes (Figs. 8-d and 8-h).

The normalized axial strength of intermediate-length studs is plotted in Fig. 9-a. The experimental results were fit, and then compared. A strength increase was predicted at several temperatures as the percentage of additional load-carrying capacity gained by the specimen when sheathed. Results are plotted in Fig. 9-b. The figure shows that the strength increase due to sheathing at ambient temperature is 20.0 % on average. This strength increase decays linearly with temperature down to 5.5 % at 600 °C. The regression line shown in Fig. 9-b provides an estimate of the strength increase due to sheathing with temperature. To quantify the lateral stiffness provided by the sheathing boards, additional tests were performed at high temperatures, similar to those completed by Vieira Jr and Schafer (2012) at ambient temperature. Future work includes the characterization of the lateral stiffness of sheathed CFS studs at elevated temperatures.

Figure 8: 1.0 m long specimens after testing: bare studs tested at a) 20°C, b) 200°C, c) 400°C and d) 600°C, and studs sheathed with fire-rated gypsum tested at e) 20°C, f) 200°C, g) 400°C and h) 600°C

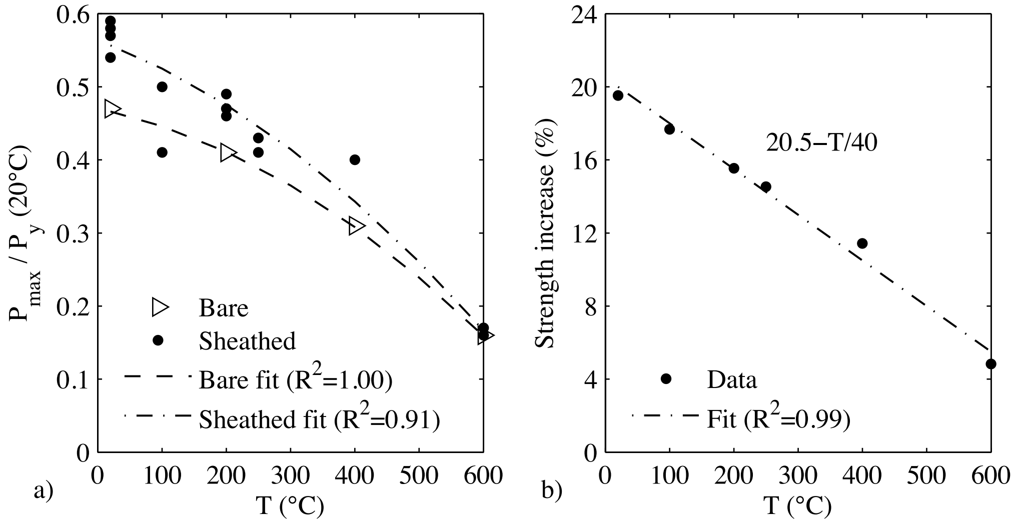

Figure 9: a) Degradation of the axial strength of bare and sheathed 1.0 m long studs, and b) loss of strength increase obtained through sheathing with temperature

The axial strength of bare studs was estimated through current Direct Strength Method (DSM) equations from AISI-S100-12 (Appendix 1), with temperature-dependent mechanical properties. The elastic modulus and yield stresses used for DSM calculations were obtained through tensile tests of CFS coupons cut from the web of lipped channels comparable to those used as studs, with dimensions shown in Fig. 10. Similar to Lee et al. (2003) and other researchers, the steady state test method was adopted, with a displacement rate of 0.003 mm/mm/min per ASTM E21-09. The observed elastic modulus (E) and yield stress (F_y) are shown in Table 1.

CUFSM was used to determine the elastic buckling loads needed for DSM calculations (Li and Schafer 2010). No sheathing stiffness was included in the finite strip model, since only bare members were modeled. The squash load was calculated as the product of the cross-sectional area of the stud and the yield stress at the temperature of interest.

Normalized axial strength of bare specimens are provided in Fig. 11 along with DSM predictions. In general, current DSM equations provide satisfactory and slightly conservative estimates; therefore, they are suitable for estimating the load-carrying capacity of CFS studs at uniform elevated temperatures (Heva 2008; Ranawaka and Mahendran 2009). However, adequate CFS mechanical properties should be used in the calculations.

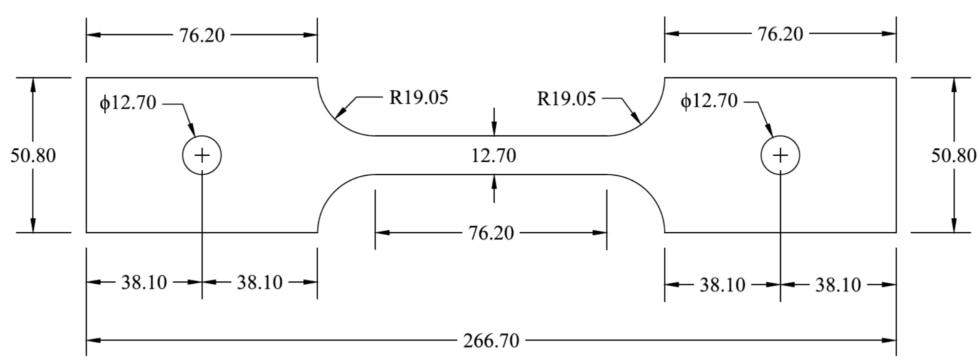

Figure 10: Dimensions of CFS coupon for tensile test (mm)

Table 1: CFS mechanical properties

Temperature (°C)	E (GPa)	F_y (MPa)
20	187	365
200	154	308
400	117	216
600	72	99

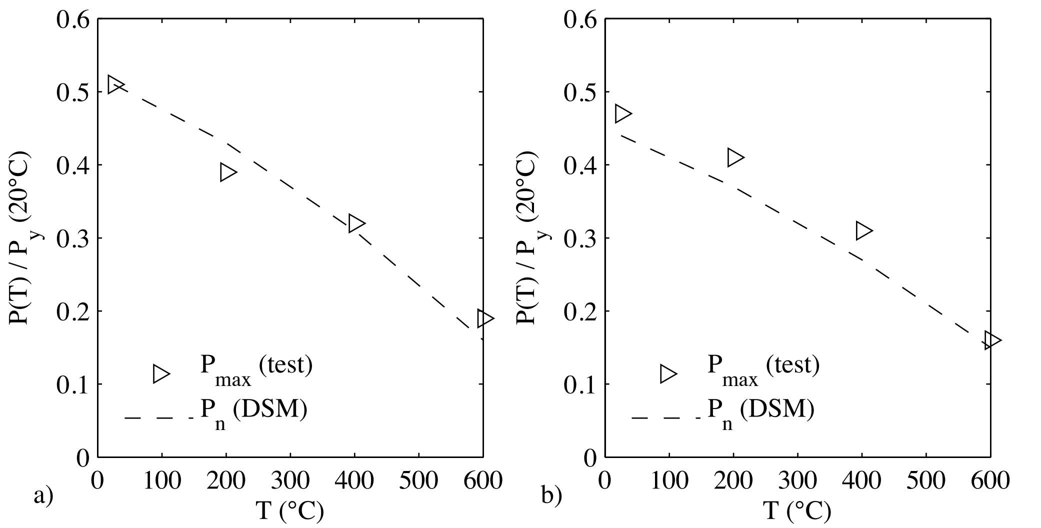

Figure 11: DSM predictions versus experimental results for a) 0.6 m and b) 1.0 m long bare studs

Future work includes the experimental and analytical characterization of temperature-dependent lateral stiffness of sheathed CFS studs to estimate their axial strength at elevated temperatures, and therefore contribute to enable the performance-based fire design of CFS walls.

5. Conclusions

This paper studied the response of short and intermediate-length cold-formed steel bare and sheathed studs at elevated temperatures, up to 600°C. Sheathing materials included oriented strand boards, regular gypsum boards, and fire-rated gypsum boards. Experimental results show that sheathing potentially increases the axial strength of thin-walled studs, especially when distortional and global buckling modes have significant participation in their structural response. While temperature increases, cold-formed steel mechanical properties degrade, and the impact of sheathing bracing in the strength and stiffness of studs decays. Therefore, initially sheathed studs respond similar to bare studs at high temperatures. Current Direct Strength Method equations along with empirical temperature-dependent mechanical properties were found suitable to estimate the load-carrying capacity of cold-formed steel studs at uniform elevated temperatures. Therefore, current design methods seem promising for performance-based fire design of cold-formed steel structures. Future work includes the characterization of stud-to-sheathing connections, particularly focusing on local fastener and global diaphragm stiffness.

Acknowledgements

The authors acknowledge the technical assistance provided by Luciano Passos in the laboratory at University of Campinas, Brazil. Also, the authors thank Simpson Strong Tie for donating the screws used in the tests, Constalica-Soufer for donating the cold-formed steel studs and tracks, and Fundo de Apoio ao Ensino, à Pesquisa e à Extensão (FAEPEX) and Fundação de Amparo à Pesquisa do Estado de São Paulo (FAPESP) for their financial support.

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