東京理科大学「火災安全科学研究拠点」

Tokyo University of Science “Research Center for Fire Safety Science”

■研究成果概要報告書/ Report for Outline of Research Results

研 究 課 題 Research Topic		Structural Fire Performance of Earthquake-Damaged Cold Formed Steel Framed Walls	実 施 年 度 2016
研究代表者 Research Leader	所属 Affiliation	Worcester Polytechnic Institute (WPI)	
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１．研究の背景および目的/ Background and Aim of Research

Post-earthquake fire performance of buildings is a concern in earthquake prone zones across the globe. In recent years, there has been an increased use of cold formed steel (CFS) framed building assemblies in many countries, including the USA. CFS is known for its strength, durability, stability, sustainability, non-combustibility and cost effectiveness over conventional light wood-framed construction. Due to its wide advantages, cold-formed steel is used as a preferred material for construction in earthquake resistant structures. However, the performance of CFS framed structures in fire remains unknown. However, multiple tests have been performed on CFS wall frames in the recent past [1-7].

A project was successfully completed in summer 2016 with UC San Diego and WPI to investigate the earthquake and post-earthquake fire performance of CFS framed construction. A series of 7 seismic tests were conducted on the large outdoor shake table at UCSD on a 6-story cold-formed steel building. Given site restrictions, fire testing could not be conducted at a desired duration or until structural failure. In parallel to this effort, Individual CFS framed wall panel tests were conducted on damaged specimens at the National Fire Research Laboratory (NFRL) at NIST, Gaithersburg, MD to assess the structural fire performance of individual panel systems. However, for comparison purposes, the duration of fire was matched with the short-duration of the fire tests at the shake table site.

To complement those tests, WPI proposed to conduct CFS wall-floor configurations at Tokyo University of Science (TUS), using the *Multiple Horizontal Loading Full-Scale Furnace* (MHLFSF), which can support a compartment-size specimen with provision to impart structural loading. The application to utilize the TUS MHLFSF was accepted, and plans were developed to conduct tests in November 2016. While the original intent was to test specimens from the USA with induced damage, as representative of earthquake damage, this was ultimately not possible. First, the CFS panel supplier cancelled their participation late in planning; meaning specimens were not available for shipment to Japan. In addition, it was determined that the planned earthquake loading (motion-induced damaged) could not be developed at TUS. As such, it was decided to test a representative CFS panel assembly, constructed of Japanese materials fabricated close to US specifications, without induced damage, as this was appropriate to investigate the feasibility of structurally loaded full-scale fire test in MHLFSF.

[1] W. Chen, J. Ye, Y. Bai, and X.-L. Zhao, "Full-scale fire experiments on load-bearing cold-formed steel walls lined with different panels," *Journal of Constructional Steel Research,* vol. 79, pp. 242-254, 2012.

[2] W. Chen, J. Ye, Y. Bai, and X.-L. Zhao, "Improved fire resistant performance of load bearing cold-formed steel interior and exterior wall systems," *Thin-Walled Structures,* vol. 73, pp. 145-157, 2013.

[3] M. Feng and Y. Wang, "An analysis of the structural behaviour of axially loaded full-scale cold-formed thin-walled steel structural panels tested under fire conditions," *Thin-walled structures,* vol. 43, pp. 291-332, 2005.

[4] M. Feng and Y.-C. Wang, "An experimental study of loaded full-scale cold-formed thin-walled steel structural panels under fire conditions," *Fire safety journal,* vol. 40, pp. 43-63, 2005.

[5] S. Gunalan, P. Kolarkar, and M. Mahendran, "Experimental study of load bearing cold-formed steel wall systems under fire conditions," *Thin-Walled Structures,* vol. 65, pp. 72-92, 2013.

[6] P. Kolarkar and M. Mahendran, "Experimental studies of non-load bearing steel wall systems under fire conditions," *Fire safety journal,* vol. 53, pp. 85-104, 2012.

[7] L. Laím, J. P. C. Rodrigues, and L. S. da Silva, "Experimental analysis on cold-formed steel beams subjected to fire," *Thin-Walled Structures,* vol. 74, pp. 104-117, 2014.

２．利用施設及び利用日/ Facility and Schedule

・ ●●装置 （2016 年--月--日 ～ --月--日）

・ ●●装置 （2016 年--月--日 ～ --月--日）

We utilized the Multiple Horizontal Loading Full-Scale Furnace (MHLFSF) at TUS. With an external dimension of 7 m (W) x 10 m (D) x 6 m (H), the MHLFSF is capable of offering an internal heating area of 3 m (W) x 4 m (D) x 3.5 m (H). This dominated the specimen size.
The overall test scheduled spanned over four weeks of November and early December 2016.

- The week of 11/07/2016 was used primarily for planning. A facility visit was undertaken for better understanding the feasibility of testing a full-scale test specimen and instrumentation. A meeting was held with the professional development company on 11/07/2016 to discuss the fabrication of test specimen. In the absence of standard cold-formed steel ready-made channel sections in Japan, a decision was made to produce studs, tracks and angle connectors (with the dimensions equivalent to standard US CFS sections) using 2.3 mm thick galvanized sheet steel. Also, the sheet steel used for sheathing and drywall panels was 0.8 mm in thickness. This week was also utilized for shop fabrication of the studs and tracks as well as redesigning the CFS frame to fit the actual furnace dimensions.

- During the week of 11/14/2016, a detailed instrumentation plan was worked out and the CFS materials were delivered to the furnace warehouse.

- The week of 11/21/2016 was scheduled for preparation of thermocouples and field fabrication of CFS wall and roof panels. The end of the week was used for mounting thermocouples alongside the specimen assembly.

- The week of 11/28/2016 was used for final assembly of wall panels, surface thermocouple mounting and preparation of loading block and the load-spreader frame. The full-scale CFS frame was slated for loading and testing on 11/30/2016 and 12/01/2016. However, the testing was delayed to 12/02/2016 due to a minor technical glitch with the gantry crane, which was essential to lift the test specimen into the large furnace. The crane was also used to tether the structural loading block in order to prevent the collapse of loading block and damage to the furnace floor.

３．実験方法・研究成果、および考察（申請時の計画に対する達成度合いも含む）

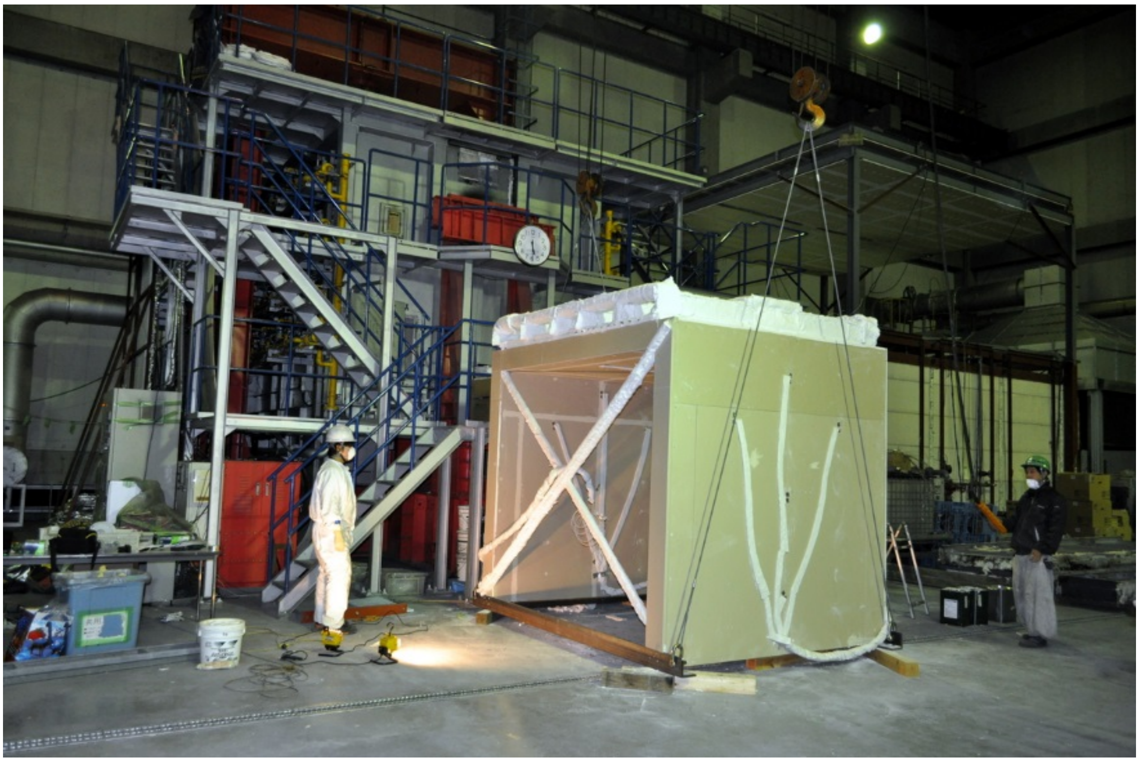
※継続課題の場合は，前年度との関係性，進展度合いについても記載すること。

/ Method, results, and conclusions (degree of achievement compare to application)

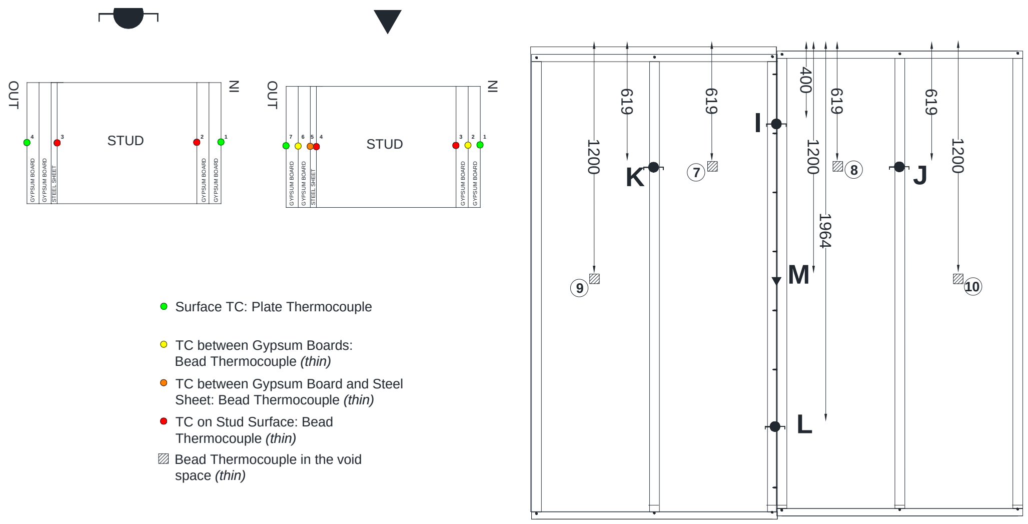
The full-scale test specimen was constructed from light-gauge cold-formed steel (CFS) frame. The assembly consisted of a CFS floor panel supported on two CFS wall panels. The assembly was provided with two cross-braces for adding structural stability and constructed over a simple platform made up of structural steel angles. This facilitated the easy lifting of specimen without compromising its verticality. Cold-formed steel framed construction represents a stud-and track system connected together using self-drilling, self-tapping sheet metal screws. The studs, tracks and joist sections were custom fabricated using locally available galvanized sheet steel bent to resemble standard US CFS sections (152.4 mm x 51 mm). It should be noted that the floor panels was fabricated using the same size tracks as studs. This is in contrast with the standard floor (or rim) track sections (254 mm x 51 mm). The CFS wall panels were built as shear walls, where one side of the sheathing consisted of a single layer of sheet steel (0.8 mm thick) adhered to 12.5 mm thick gypsum board using water-soluble adhesive. A second layer of 12.5 mm gypsum wallboard covered the base layer. 2 layers of 12.5 mm gypsum wallboard represent a 1-hour fire resistance rating.

The test specimen is comprised of two wall panels connected to a floor panel. The dimensions of the specimens are carefully chosen to fit within the internal dimensions of the furnace. The overall wall panel dimensions were 2540 mm (W) x 2400 mm (H). The roof panel was also 2540 (W) x 2400 mm (D) in dimension similar to the wall panels. Each wall panel was a combination of two separate panels, joined at the center using fasteners The center connection represented a typical double stud connection

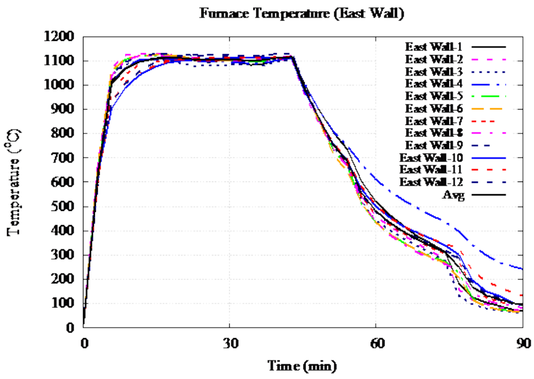
arranged back to back and fastened using sheet metal screws with a spacing of 300 mm o.c..
Structural loads are very important in fire tests as they may govern the failure of structural systems after the loss of their strength and stiffness in fire. Live loads are one of the major occupancy loads considered in designing the structure. However, in the event of fire, only 50% of live loads are considered in a structure. This is due to the fact that the live load in a structure is significantly reduced due to evacuation of the occupants. In the current test, 50% of the live load accounts to approximately 90 kg.m^2. This was achieved by means of a solid loading block placed on top of a secondary load spreader grid. The load spreader grid was constructed by orthogonal arrangement of cold form steel members. This supported a metal grillage, which facilitated the uniform distribution of load. This arrangement was protected from high temperature inside the furnace by covering them with ceramic fiber blankets. The loading block, which consisted of a stack of solid metal plates (30 kg each), was placed in the center of the roof over the load spreader. The loading block was tethered to the gantry crane to protect it from causing damage to the furnace floor due to collapse.

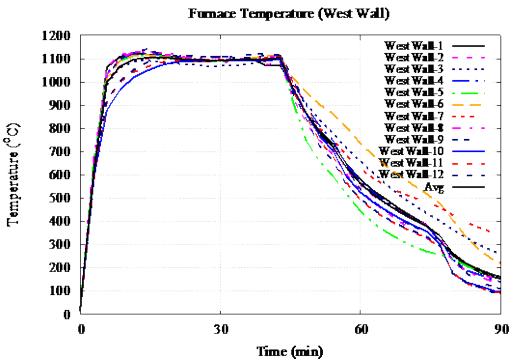


Temperature at various locations was the main parameter of measurement in the current test. The test frames was rigorously instrumented with Type-K thermocouples to measure the temperatures in various points of interest. Temperature was measured on the gypsum wall board surface, at different depths of the walls and diaphragm in between the components of the wall and diaphragm. Thermocouples were also inserted in the stud and joist cavities. Measuring temperatures at these locations will help in understanding the member temperature, which is an important parameter that determines the loss of structural capacity. The temperatures may also be used to validate the structure-fire and heat transfer modeling. 27 thermocouples were mounted on each wall: Wall A and Wall B (Total 54). 22 thermocouples were mounted on the diaphragm. Surface temperatures on each wall and the ceiling were measured using plate thermocouples. Each wall consisted of 10 surface thermocouples, 5 each on the interior and exterior face, whereas, the diaphragm was instrumented with only 6 plate thermocouples. Beaded wire thermocouples were used for all other locations. The center location on each panel was instrumented with thermocouples between all layers. An example of thermocouple layout is shown below.



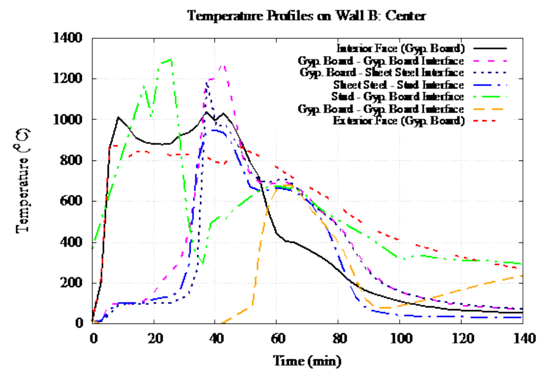
For this project, the two design fire curves considered were ASTM E-119 and the Hydrocarbon Fire Curve. The Hydrocarbon curve was deemed preferable for this study since a petrochemical fuel (n-Heptane) was used for fire tests conducted in UCSD. The duration of fire recommended was 60 minutes, followed by natural convective cooling achieved by opening the furnace doors..Given the materials used, the specimen was constructed to mimic 1-hour fire resistant construction, if tested against ASTM-E119. Exemplar furnace temperatures, developed during the testing, are shown below.



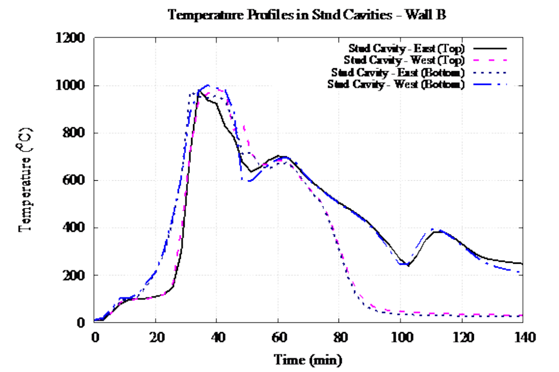


Results obtained by testing the cold-formed steel primarily consisted of temperature readings recorded by thermocouples instrumented at various locations of interest, as well as visual indication of failure modes and times to failure.

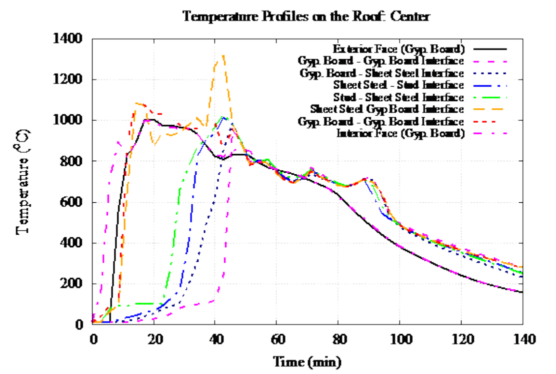
Representative temperature profiles from walls / wall cavities and ceiling / ceiling cavities are shown below. Individual temperature plots are specifically superimposed to compare the trends of heat transfer through the walls, which may then be corroborated with limited visual observations.



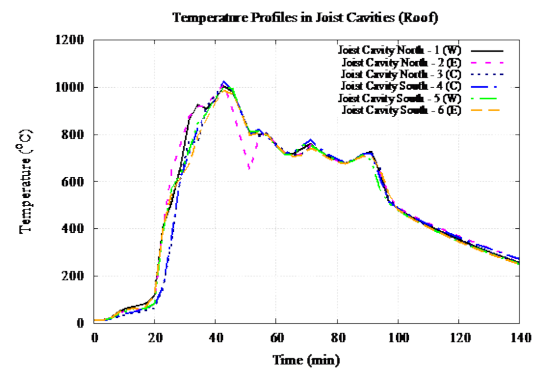
Temperature on Wall B: (a) Center *(Location H)*



Temperature on Wall B: (b) Stud Cavities



Temperature on diaphragm/roof: (a) Center



Temperature on diaphragm/roof: (b) Joist cavities

While difficult to see on this scale, gypsum wallboard started to fail within 10 minutes from the start of the test *(top left figure)*. This is further evident by the temperatures measured in stud cavities *(top right figure)*, where, a steep rise in temperature was observed following the loss of gypsum wallboard. A similar behavior may was observed in the roof panels, where the loss of gypsum board resulted in steep rise in temperature in the joist cavities. Catastrophic failure occurred around the 42-minute mark. The primary reason for failure was the yielding of connections at the wall to roof joint. The yielding of connections at high temperature was further pronounced by the failure of connections at the two individual panels, connected back to back. A quick post-fire investigation showed that the sheet metal screws did not completely shear off, but were bent and the screw holes had widened with occasional tearing. Thermomechanical buckling of steel studs and warping of sheet steel was also observed. Note again that the nominal fire resistance rating of this type of construction would be 60 minutes under an

ASTM E119 (standard) fire curve.

Figure below shows the views from the viewport camera, which shows the separation of gypsum wallboards as early as 10 minutes into the test. Dehydrated gypsum boards showed a shearing failure originated near the fasteners. Dehydration was evident from visually observed numerous surface micro-cracks. Also, loss of bond between the gypsum wall board and sheet steel was observed, which is consistent with the CFS tests conducted in San Diego.

Figure below shows the collapsed roof panel and failure of the double stud connection.

Conclusions

While the original intent was to test specimens with simulated earthquake damage (motion-induced damaged), such damage was not possible to be developed TUS. Nonetheless, it was deemed appropriate to investigate the fire performance of undamaged CFS construction as a benchmark. In this regard, the tests were successful. Also, the MHLFSF facility at TUS was successfully found to enhance the capabilities for comprehensive, long-duration, full-scale structure-fire furnace tests to structural failure. A large data-set of temperatures through the wall is generated, which may be used to further validate the numerical modeling.

４．今後の展望（今後の発展性，見込み等についても記述）／ Future Perspectives

To collect additional data on fire performance of earthquake-damaged lightweight construction, an application for extending the joint usage research was submitted to TUS. The proposal was accepted. Year 2 of this project will involve assessment of multiple wall-diaphragm configurations of timber and cold-formed steel framed construction, which are firstly seismically-loaded (damaged) at the Building Research Institute (BRI) in Tsukuba, and then transported to Centre for Fire Safety Science and Technology at TUS-Noda Campus, where, the damaged specimens will be tested to failure under the load in the Multiple Horizontal Loading Full-Scale Furnace.

The specimens are envisioned to include at least one specimen each of the following: CFS construction fabricated to US standards, lightweight timber construction to US standards, CFS construction fabricated to Japanese standards (i.e., the Steel House), and lightweight timber construction to Japanese standard. If possible with timing constraints, two experiments on each system type will be tested. The specimens are to represent construction for residential housing.

The specimens have been designed so as to fit on trucks for transportation between BRI and TUS (Noda). Full-scale tests on assemblies are scheduled in the month of November/December 2017. It is envisaged that the wall and floor panels will be prefabricated and shipped to Japan (BRI) by the panel fabricator in the United States. The Japanese equivalent panels shall be fabricated and assembled at BRI by Professional Development Company. A series of 8 tests are scheduled from 11/06/2017 to 12/01/2017. Tentatively, the first two weeks will be utilized in simulated earthquake tests on traditional (or advanced) light-wood frame at BRI, thereafter followed by fire tests at TUS. One day is reserved for transporting the specimen from Tsukuba to Noda-Shi. Similarly, in the following two weeks, earthquake and fire tests on cold-formed steel frame will be carried out.

５．成果の公表状況（学会への発表，学術誌への投稿等を記述。予定も含む）/ Publishing (presentation, paper, etc. incl. plans in the future)

Since the tests are rather recently concluded, papers have not yet been prepared. However, it is planned to submit abstracts to the following conferences, which have proceedings, as well as to submit to a journal, such as Fire Technology or Fire Safety Journal. Planned conferences include the 2018 SFPE International Conference on Performance-Based Codes and Fire Safety Design, Structures in Fire (SIF), and the 2018 NFPA Annual Conference. It is planned to include the outcomes of the Year 2 testing as well.

６．経費の使用状況 / Usage of Budget

expendables・Meeting・Printing		Travel expense		Personnel expenses	
Contents	Cost	Contents	Cost	Contents	Cost
- Shipping Cost for Experimental Samples - Materials for experiment; e.g., flexible container bags - Glass Coating Thermocouples - Materials for Test Specimen - Disposal Fee of Test Specimen	2,608 10,585 68,040 693,360 160,920	- Air Fare - Accommodation	120,279 142,500	- Fees for Test Specimen Production and Support for Experiment	788,400
Subtotal	935,513	Subtotal	262,779	Subtotal	788,400
Burden of Tokyo University of Science / Total Yen 1,986,692					
Burden of / Total Yen					

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