

Characterization of CFS Framed Diaphragm Behaviour

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**DEPARTMENT OF CIVIL ENGINEERING & APPLIED
MECHANICS**

TECHNICAL REPORT

***CHARACTERIZATION OF CFS FRAMED DIAPHRAGM
BEHAVIOUR***

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Abstract

Knowledge of the in-plane response to loading of cold-formed steel (CFS) framed diaphragm structures is essential for seismic and wind design. The information available specific to diaphragm design in the North American CFS design standards (AISI S240 & S400) is based on limited experimental work and the extrapolation of design methods developed for the wood industry. To address this shortcoming a test-based research project was performed in the Jamieson Structures Laboratory at McGill University focusing on the characterization of the behaviour under in-plane loading of CFS framed - wood sheathed diaphragms. This research was a complementary study to a research project involving the dynamic testing of CFS framed buildings, known as the CFS – NEES project. This Johns Hopkins University project involved full-scale two storey CFS framed buildings tested on a shake table under earthquake loading. Although the CFS – NEES project provided for the first time an insight into the seismic response of CFS structures, more information is required regarding the response of isolated diaphragm systems.

The research reported herein included diaphragm test specimens that were based on the floor and roof configurations used in the CFS - NEES Building; which were comprised of oriented strand board (OSB) sheathing screw connected to CFS C-Channel joists. The cantilever diaphragm test approach was followed and the specimen dimensions were chosen considering the AISI S907 Standard requirements. Four diaphragm configurations were selected, each of which was tested under in-plane monotonic and reversed cyclic loading, resulting in a total of eight test specimens. A self-reacting frame was initially designed and constructed as a test-setup in order to accommodate the 12'x 24' (3.66 m x 7.31 m) diaphragm specimens. It was demonstrated that screw size constitutes a decisive factor in the resulting diaphragm response. In addition, the fully blocked diaphragm configurations, i.e. where the edges of all sheathing panels are supported by an underlying CFS frame, exhibited a considerable increase in shear strength. The bare steel frame contribution to shear strength and stiffness was negligible. An effort to predict the shear strength and deflection of the diaphragm specimens was made using the information available in the AISI S400 Standard. However, the limited information provided in the aforementioned Standard prevented a meaningful comparison to be realized between the predicted design values and the measurements from the tests.

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1- Introduction

In recent years, there has been an increase in the construction of cold-formed steel (CFS) framed multi-storey residential and commercial buildings. Current code provisions addressing the seismic design of CFS framed structures (AISI S400, AISI S100, ASCE 7, CSA S136 and NBCC 2010) are based on the response of the bare steel shear walls, as the main lateral force resisting elements. Response modification coefficients R in the U.S., as well as the equivalent R_d and R_o seismic force modification factors in Canada, accounting for the ductility and over-strength, do not explicitly take into account the floor and roof diaphragms' contribution to the lateral resistance and dynamic response of the structure. At present in the AISI S400 Standard (2015), there is no Canadian design procedure available for diaphragms in CFS framed structures; and as for the US design provisions for diaphragms, there has been limited research behind their development. Moreover, the influence of the diaphragm's relative stiffness on the overall seismic response and transfer of forces in the structure has yet to be characterized and considered in design, i.e. of the diaphragm connection to the shear walls. Comparing with the design guidelines provided for the seismic design of structures by the hot-rolled steel and concrete codes, the design deficiencies of the CFS building design provisions become evident. As such, there exists a need for this shortcoming to be addressed in order to ensure the construction of better, safer and more economic CFS structures.

This technical report presents in detail the research project realized in the Jamieson Structures Laboratory at McGill University during the summer of 2015 aimed at the characterization of CFS framed - wood sheathed diaphragm behaviour under in-plane loading. It constitutes the first step of an ongoing research program that includes both experimental and numerical work with the purpose of improving design provisions for CFS framed diaphragms for use in Canada and the United States.

2- Background

One of the early researchers focusing on the diaphragm design for CFS structures was Lum (LGSEA 1998). Lum provided allowable design strength values for plywood sheathed CFS framed diaphragms using the National Design Specification (NDS 1991) formulas for the

fastener resistance and the methodology by Tissell and Elliot (2004) for wood framing to calculate the diaphragm's ultimate shear strength. These design values were originally included in Table C2-1 of the AISI S213 Standard (2007) and now are available in Table F2.4-1 of the new AISI S400 Standard (2015). CFS framed - wood sheathed diaphragm configurations were also tested by the National Association of Home Builders Research Center (NAHBRC 1999) and the individual fastener response was examined. Included in the test program were four 3.6x7.2m (12'x24') unblocked simple span diaphragm specimens with 18.3mm (23/32in) wood sheathing connected with #8 screws (152.4/304.8mm (6"/12") in spacing pattern) to CFS C-channel perforated joists (joist sections varied per two specimens). The loading protocol consisted of two monotonic loading cycles (loading, unloading and loading again towards one direction) before pushing the diaphragm to failure. The maximum load reached during the tests was 18.9 kN/m. Results showed that by multiplying the individual screw connection shear capacity with the number of fasteners along one end of the diaphragm provides a good estimate of the diaphragm's shear capacity. Valuable information on diaphragm seismic response is also provided by extensive experimental work on wood framed shear walls and diaphragms, e.g. Dolan and Madsen (1992), Tissell and Elliot (2004), and Brignola et al. (2012).

Moreover, during the last three years an ongoing major research program was being realised at Johns Hopkins University, entitled "Enabling Performance-Based Seismic Design of Multi-Story Cold-Formed Steel Structures" (Peterman 2014), involving full size two-storey CFS wood sheathed shear wall buildings tested under earthquake loading using the Network for Earthquake Engineering Simulation (NEES) equipment site (shake table) at the State University of New York (SUNY) at Buffalo in the USA (Figure 1). A full description of the criteria used for the design of the CFS shear walls and diaphragms of the test structure can be found in Madsen et al. (2011). The main parts of this research program were: (1) the investigation of the response of isolated CFS framed - wood sheathed shear walls and of the stud-fastener-sheathing connection under cyclic loading through experimental work, and (2) the characterization of the response and design of the overall CFS framed structure under seismic loading through the means of shake table tests and finite element modeling (Schafer et al. 2014). Isolated wood sheathed CFS framed shear walls were tested using monotonic loading and the CUREE (Krawinkler et al. 2000) loading protocol (Liu et al. 2012). In Leng et al. (2013), based on the aforementioned shear wall

testing (Liu et al. 2012), dynamic and non-linear response history analyses were conducted in order to simulate the response of the two-storey CFS framed building tested at Buffalo using OpenSees (McKenna 1997). The diaphragm was assumed to be rigid in the simulation because test information was not available with which to assign a more realistic in-plane stiffness.



Figure 1: CFS - NEES building (Peterman 2014)

The National Building Code of Canada (NRCC 2010) refers to the CSA S136 Standard (2007) for the design of cold-formed steel structures. In turn, CSA S136 refers to the AISI S213 Standard (2007) for the design guidelines of CFS framed structures under lateral loading. In the US the AISI S213 Standard is specified for the lateral design of CFS framed structures through the ASCE 7 and the building code under which the building is designed. AISI S213, now replaced by AISI S400, provides US design shear strength values for specific CFS framed diaphragm configurations (LGSEA 1998), while for any other diaphragm assembly it indicates that principles of mechanics must be employed for the shear strength calculation. The diaphragm deflection equation D2.1 included in the AISI S213 Standard is based on that derived for simply supported wood-framed diaphragms, with slight modifications making it applicable for steel-framed structures (Serrette and Chau 2003).

At present, the AISI S400, NBCC 2010 and CSA S136 standards do not address the seismic design of wood sheathed / CFS framed diaphragms for use in Canada. Moreover, the existing R_d , R_o values used for the seismic design of CFS structures do not include the diaphragm's contribution. Similarly, the US response modification coefficients for CFS structures found in ASCE 7 do not explicitly account for the influence of the diaphragm. From the above-mentioned

literature, it is highlighted that, although a considerable number of studies exist for CFS framed shear walls, limited information is provided regarding the entire CFS framed building response including diaphragm flexibility and diaphragm-to-shear wall connection flexibility. Although, the AISI S213 Standard was replaced in 2015 by AISI S400 (2015) for seismic related design provisions and AISI S240 (2015) for wind related design provisions, no modifications with respect to diaphragm design were incorporated in these two new standards.

3- Objectives

The main objective of the research described in this report is to characterize the behaviour of CFS framed roof and floor diaphragms under monotonic and reversed cyclic in-plane loading. A secondary objective is to compare the measured test results with predictions of resistance and displacement determined from the existing provisions in AISI S400.

4- Scope

Given the complexity of diaphragm system behaviour under loading, due to the use of various configurations, different materials, non-linear fastener response, etc., in order for strength and stiffness properties to be established large-scale monotonic and reversed cyclic testing is typically required. To this end, a test-setup (self-reacting frame) was designed, fabricated and installed in the structures laboratory in order to conduct diaphragm tests. The design load for the frame was based on the maximum capacities of previous diaphragm and shear wall tests found in the aforementioned literature and the equipment available in the McGill structures laboratory (i.e. the actuator used).

Two diaphragm specimen configurations based on those used in the CFS - NEES building (Figure 1), as described by Madsen et al. (2011) and Peterman (2014), were selected for the experimental program described in this report. Two additional configurations were chosen to improve upon the response to loading offered by the original diaphragm construction. All diaphragm specimens were composed of oriented strand board (OSB) sheathing screw fastened to CFS C-Channel joists. The cantilever test approach was followed and the specimen dimensions 3.66 x 6.1m (12'x 20') were chosen in consideration of the AISI S907 Standard (2013) requirements. Each diaphragm configuration was subjected to a monotonic and a CUREE

reversed cyclic (Krawinkler et al. 2000) displacement controlled loading protocol, leading to the testing of a total of eight diaphragm specimens in the scope of this research project. In addition to a reporting of the testing and test results, this document contains a comparison between the measured shear strength values and the corresponding design values included in AISI S213 2007 / S400 2015, as well as a comparison with deflection estimates using equation C2.1 of the S213 Standard (Eq. E1.4.1.4-1 in AISI S400).

5- Description of Test-Setup and Specimens

This section contains a description of the diaphragm configurations that were tested and the loading protocols that were used; and further includes a brief description of the test-setup designed to accommodate the tests.

5.1 Test-Setup

The idea behind the construction of this prototype frame was to provide a test-setup that can accommodate both the current testing program included in this report and future experimental work on diaphragms. SAP2000 commercial software (CSI 2009) was relied upon in order to analyse and design the test frame. A self-reacting braced frame configuration was chosen comprised of three pin connected short beams, two long continuous beams and four pin connected braces. A conservative approach was followed to determine the design load, which was based on the capacities exhibited from CFS and wood shear walls and diaphragms of past experimental programs described in the literature review, as well as on the maximum capacities observed from sheathed CFS framed shear wall testing performed at McGill University (Branston 2004, Chen 2004, Boudreault 2005, Rokas 2005 and Blais 2006). The maximum load applied to the diaphragm specimens was predicted to be not greater than 200KN. The actuator chosen for this application has a tensile capacity of 450KN and compressive capacity of 650KN. It was decided to design the test frame based on the actuator's tensile capacity. A safety factor of 1.2 was implemented leading to a maximum load of 540KN considered for design, which is almost three times higher than the maximum diaphragm testing load observed in the literature. Based on the diaphragm specimens' plan dimensions, the overall frame dimensions were chosen to be 4.5x6.5m (15'x 22') (Figure 3). A uniform load of $540/6.1=88.5$ kN/m was applied in the

SAP2000 model on the side where the diaphragm was bolted while a roller support was placed in the location of the actuator restraining the x-direction degree of freedom. This support simulated the reaction force applied on the frame from the actuator. A maximum shear capacity of 50KN was assumed for the anchor rods to be used. However, most of the in-plane forces should be contained within the frame and not transferred to the strong floor; thus, four roller supports were implemented in the SAP2000 model restricting the y-direction while allowing the free movement of the frame in the x-direction as would be expected based on the applied loading. The frame sections were chosen so that the frame remains elastic throughout the testing process and has adequate stiffness to exhibit the minimum possible deformation. It was expected that the design was mainly based on maximum deformations allowed and not on member capacities; thus a limit of $L/1125$ (4mm or 0.157") was used, where $L=4.5\text{m}$ (15'). Figure 2 displays the test-setup.

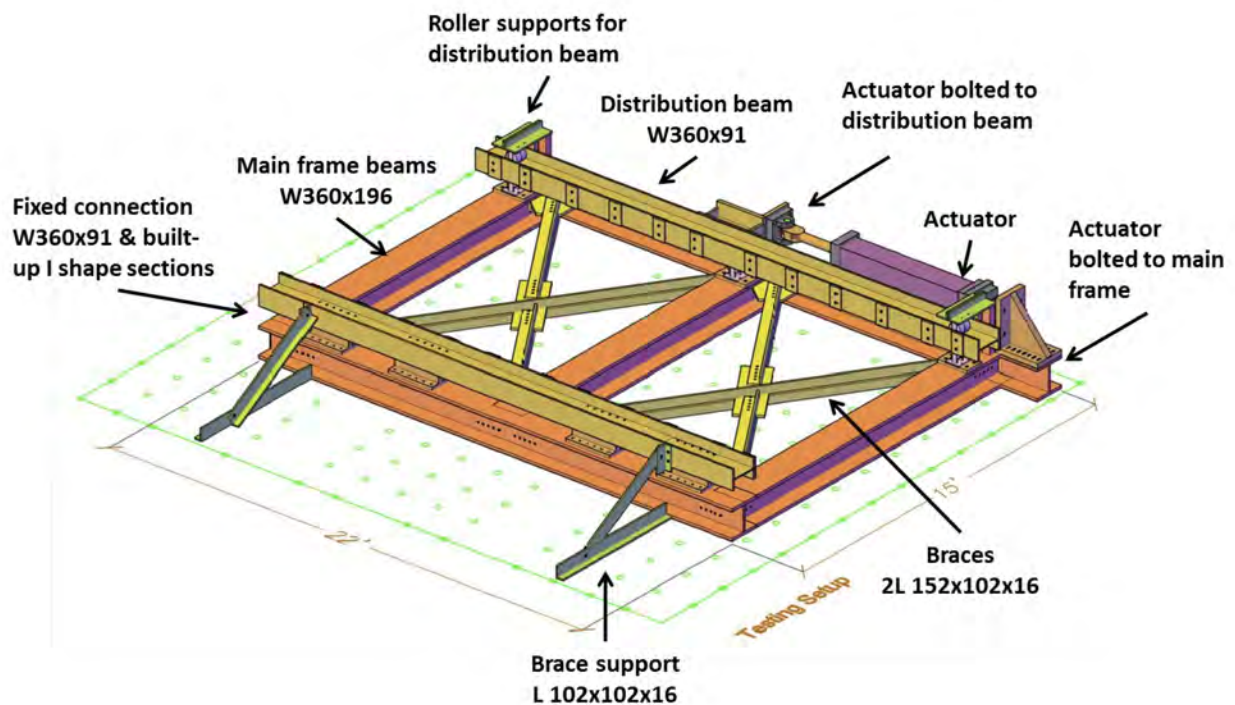
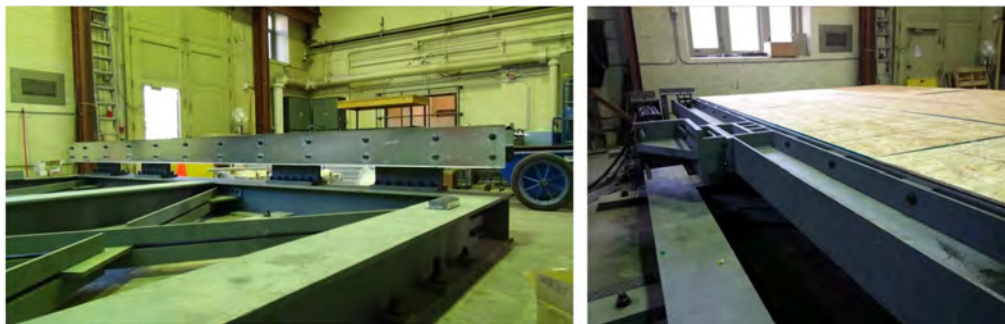


Figure 2: 3D representation of diaphragm test-setup

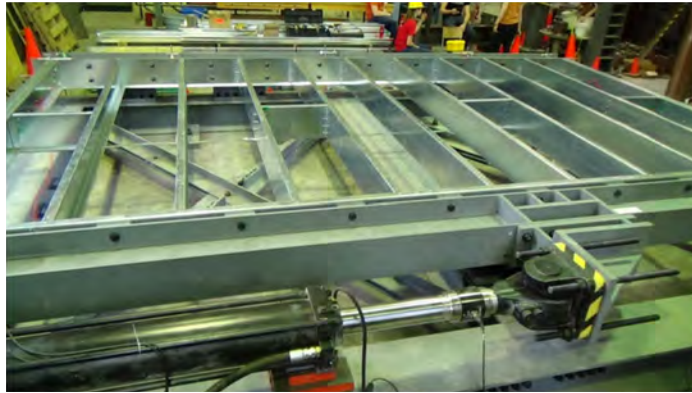
The frame sections were: W360x196 (W14 x 132) sections for the beams and 152x102x16 (6 x 4 x 5/8) angle sections with 25.4mm (1") spacing for the braces. A W360x91 (W14 X 61) load distribution beam was bolted to the actuator and the rim-joint of the diaphragm specimen in order to distribute the concentrated force from the actuator to the diaphragm. Rollers at the top and

bottom support the distribution beam in three locations (edges and middle). This roller system allowed in-plane rotation of the diaphragm (movement perpendicular to actuator) during the test. The actuator was in turn bolted to the main frame; however, each end of the actuator comprises a swivel mount which also allowed for in-plane perpendicular movement of the load distribution beam. An extra roller support was added under the actuator in the middle to account for the possible eccentric vertical loading on the distribution beam caused by the actuator's self-weight. A fixed connection was created on the other side of the frame by bolting four built-up I shape sections to the main frame and a W360x91 (W14 x 61) reaction beam, which was bolted in turn to the rim joist of the diaphragm specimen. Braces were also installed and connected to the strong floor to support the fixed connection against potential rotation during the test. It should be noted that the designed testing setup involved the diaphragm being connected in only two locations with hot rolled steel beams (fixed connection and distribution beam) without any extra steel elements supporting the CFS framing, as is the norm in classic metal panel cantilever tests. Figures 3 a, b, c, d, e & f depict the various connections and parts of the test-setup. It is worth mentioning that, during testing, the test-setup fulfilled its purpose as a self-reacting frame. Based on the instrumentation set in place as explained in Section 6, the in-plane forces were taken by the frame and not the anchor rods; further, there was no displacement observed by the test frame with respect to the strong floor throughout the testing process.



(a) Test frame

Figure 3: Test frame construction and connection details



(b) Test frame with specimen framing



(c) Roller supports of distribution beam



(d) Brace to main beams



(e) Fixed connection



(f) Actuator to distribution beam and main frame

Figure 3 (Continued): Test frame construction and connection details

5.2 Diaphragm Configurations

The experimental program consisted of two parts. The first part involved two main diaphragm configurations chosen based on the configurations used in the CFS - NEES building (Figure 1) for the floor and roof assembly, while the second part involved the same configurations with modifications. In total, eight tests were conducted, four with monotonic and four with reversed