Seismic design of multi-story cold-formed steel buildings: the CFS-NEES archetype building

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ABSTRACT

Lightweight cold-formed steel (CFS) framing is an effective building solution for low and mid-rise structures. However, systems level response and component contributions as well as their interactions such as those from lateral-load resisting systems, floor diaphragms, studs to track connections, etc., are not fully understood. Existing building codes for the CFS frame buildings are based solely on the stiffness of the lateral-load resisting frames and do not explicitly incorporate systems response. This paper presents the first-phase of a multi-year project aimed at generating knowledge and tools needed to increase the seismic safety of CFS frame buildings. The first phase of the study focuses on the design, instrumentation plan, and preliminary analysis of full-scale two-story CFS frame buildings that are tested on shake tables at University at Buffalo NEES Facility in the second phase. Design of the two-story CFS buildings incorporates a "state of the practice" ledger framing system that attaches floor and roof joists to the inside flanges of the load-bearing studs via a combination of track and clip angles. The instrumentation plan for the shake table tests is developed to capture both systems and component level response of the buildings. The preliminary analysis includes development of new modeling capabilities that incorporate cross-section limit states (local and distortional buckling) into frame analysis engines such as OpenSees to enable more accurate incremental dynamic analysis. This paper provides detailed design of a prototype CFS frame building and instrumentation plan for the shake table tests at Buffalo.

INTRODUCTION

Superficially similar to wood construction, lightweight cold-formed steel framing utilizes repetitive members in a manner as shown in Figure 1. The example, which utilizes platform construction and in-line framing, requires details that are by necessity significantly different from wood. For example, in wood construction direct bearing may often be utilized as a stiff load path, while in cold-formed steel framing, fastener deformations and local bending of the thin steel components must be taken into account. Differences in load path, the mechanics involved in energy dissipation, and governing limit states (e.g. local buckling) all require that cold-formed steel framing be uniquely treated and understood.

Common lateral force resisting systems (LFRS) for cold-formed steel construction consist of specifically detailed sheathed walls, strap bracing, and other systems. The two system-level load paths into the LFRS are: (1) the floor diaphragm, and (2) the load bearing wall along the same framing line as the LFRS. Conventionally one assumes the diaphragm and wall simply deliver forces to the shear wall, and collector elements are designed to enable this force transfer. However, the distribution of forces in an actual building (even ignoring non-structural components) can deviate from this idealization a great deal.
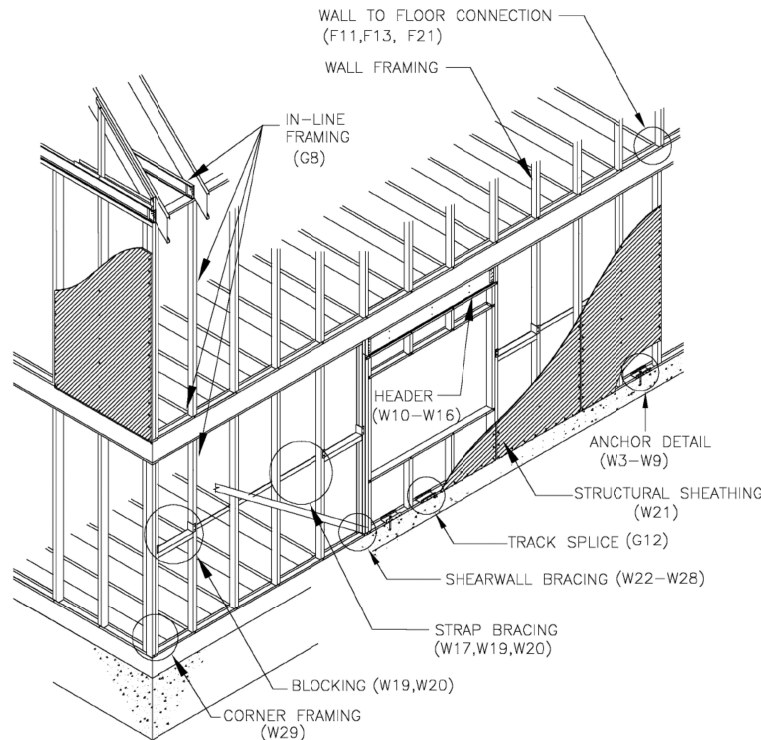

Figure 1. Typical framing details for multi-story cold-formed steel framed building (SFA 2000).

To date, research has focused on single-story LFRS (without gravity loads) in complete isolation from the larger system). Advancing seismic structural safety of lightweight cold-formed steel construction requires that the secondary systems, repetitively framed floors and walls, which are directly in the load path for the LFRS be understood in far greater detail.

To address the above research needs, a multi-year project was initiated at Johns Hopkins University and Bucknell University with a support from the National Science Foundation, George E. Brown, Jr. Network for Earthquake Engineering Program (CMMI-10-41578). The main objective of the project is to provide knowledge, technologies, and tools to enable performance-based seismic design and increase the seismic safety of lightweight cold-formed steel framed buildings. The project will include experimental and computational tasks as follows. The experimental tasks span from characterization of sub-systems to full-scale shake table tests at University at Buffalo NEES Facility. The computational tasks are broken into those related to high fidelity models, phenomenological models, and high efficiency beam models that incorporates the strength and stiffness reductions inherent in local and distortional buckling of thin-walled cold-formed steel cross-sections.

This paper presents the first-phase of the project focusing on the design and instrumentation plan of full-scale multi-story CFS frame buildings that are tested on shake tables at University at Buffalo NEES Facility in the second phase. Detailed design criteria and specifications of the multi-story cold-formed steel buildings as well as sensor arrangements in shake table tests are presented in this paper.

STRUCTURAL DESIGN OF MULTI-STORY CFS BUILDING

A multi-story prototype CFS frame building (referred to as CFS-NEES building) is designed for the investigation of seismic performance of light-framed structures using cold-formed steel cee-sections as the primary gravity load carrying elements with wood structural panel diaphragms and shearwalls as the primary lateral load resisting system. This section provides a background, detailed design criteria, and structural drawings of the CFS-NEES building.

Background and Related Research

The CFS-NEES building is intended to represent a typical structure in its class. To seek for the input on the-state-of-the-practice building design and construction, the project team requested experienced professional engineers to form an Industry Advisory Board (IAB). Currently, there are seven active members with diverse background in the IAB. Design of the CFS-NEES building is an outcome from hours of discussion between the project team and the IAB, and incorporates most of the important practical aspects that are of great interest for practitioners. Inputs from the IAB will be incorporated in construction, instrumentation, and experimental phases as well.

While this research makes the case that cold-formed steel requires separate treatment, this is not to say that related wood research has no bearing on the work proposed herein. In particular the CUREE-Cal Tech Woodframe project (www.curee.org/projects/woodframe) and the recently completed NEESWood project (jwv.eng.ua.edu/neeswood_reports.html) are important contributors to the overall state of knowledge for low-rise repetitively framed construction. In particular, the NEESWood shake table tests at UB-NEES (Filiatrault *et al.* 2007) form the basis for the whole building tests proposed herein and the related 3D modeling () demonstrates the current state of the art for modeling wood-framed construction.

Description of the CFS-NEES Building

The CFS-NEES building is a two-story office building that is assumed to be located in Orange Country, California. Figure 2 shows a three-dimensional view of the CFS-NEES building. Floor and elevation views of the building are shown in Figure 3. Dimensions of the CFS-NEES building are 15.2 m (approximately 50 ft) in long axis (east-west direction), 7.0 m (23.0 ft) in short axis (north-south direction), and 5.9 m (19.3 ft) in height. The height includes a 0.4 m parapet. These dimensions are determined based on the size of the dual shake tables at the University at Buffalo. The total mass of the CFS-NEES building is approximated 35.0 tons and it is also within the limit of the dual shake tables at Buffalo.

Design Criteria

Design of the structure was based on a site in Orange County, California. Gravity and lateral loads were determined per the 2009 edition of the International Building Code (IBC) based on this location. For member sizing, the "North American Specification for the Design of Cold-Formed Steel Structural Members", 2007 edition (AISI S100-07) was used. Member callouts were based on SSMA/SFIA criteria. Shearwall and diaphragm design was based on the "North American Standard for Cold-Formed Steel Framing – Lateral Design", 2007 edition (AISI S213-07). Wind and seismic forces were determined based on the location. For simplicity, and consistent with industry standards, allowable strength design (ASD) was used for members and connections not part of the lateral force resisting system (LFRS). For design of the LFRS, load and resistance factor design (LRFD) was used.
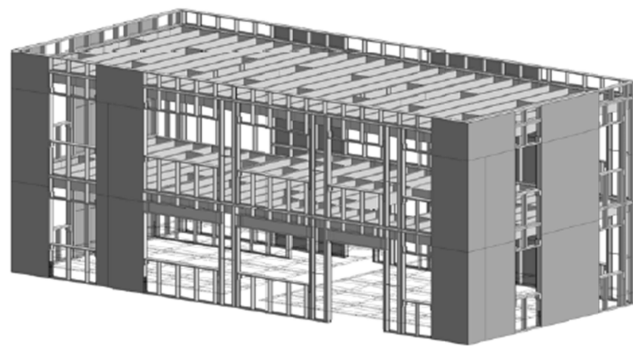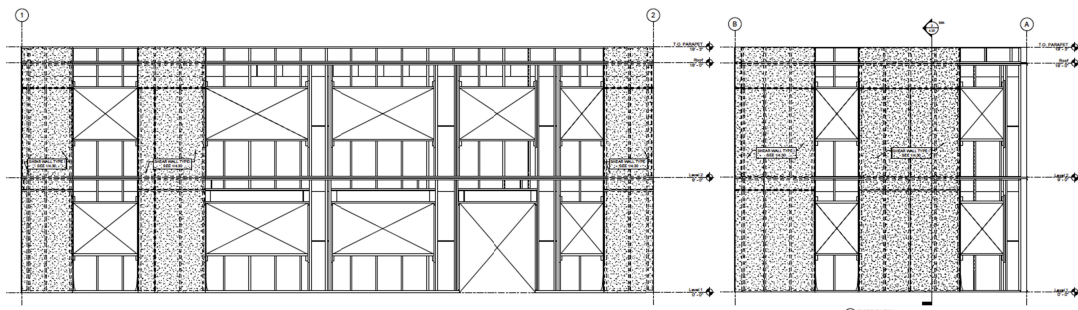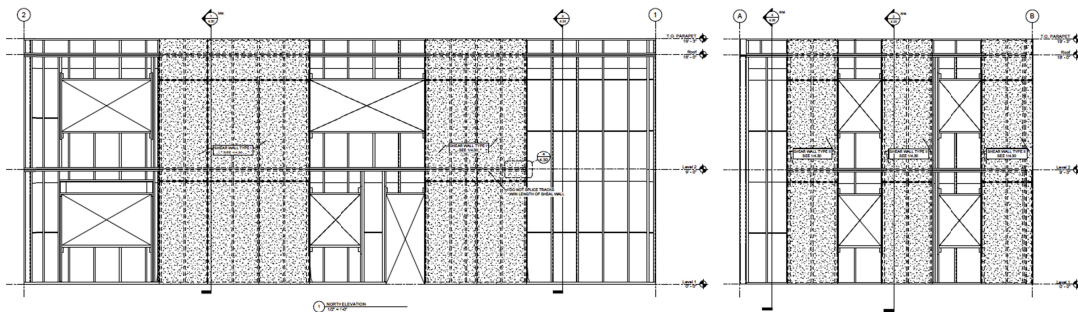

Figure 2. A 3-dimensional view of the CFS-NEES building.
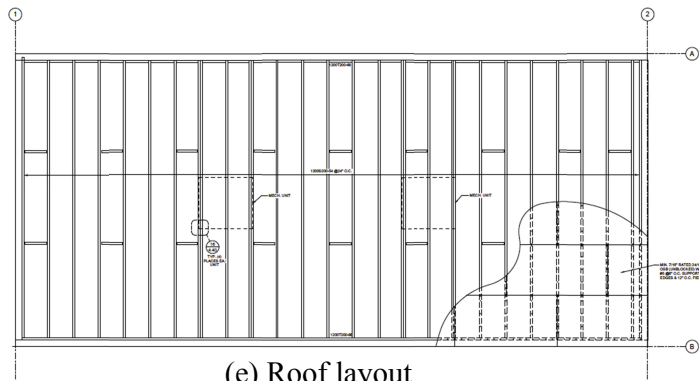
(a) South elevation

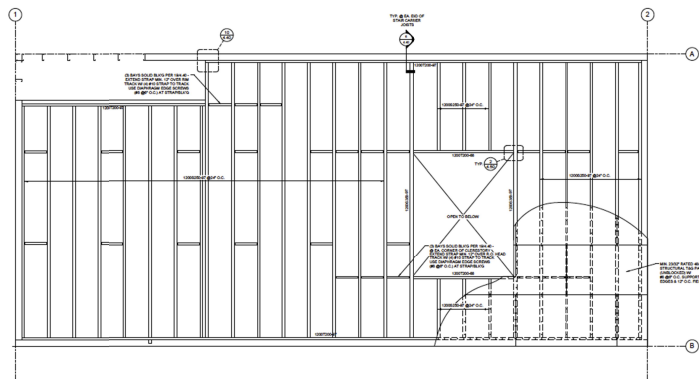

(b) East elevation

(c) North elevation

(d) West elevation

(e) Roof layout

(f) Floor-joists layout

Figure 3. Floor and elevation views of the CFS building.

Gravity System Design

Based on input from the IAB, a 'ledger framing' system was chosen rather than traditional platform framing. According to the IAB, ledger framing which attaches floor and roof joists to the inside flanges of the load-bearing studs via a combination of track and clip angles is currently the dominant method of construction. Studs are broken at the top of each floor level and capped with a track. Walls above are stacked on the lower wall top track (see Figure 4).
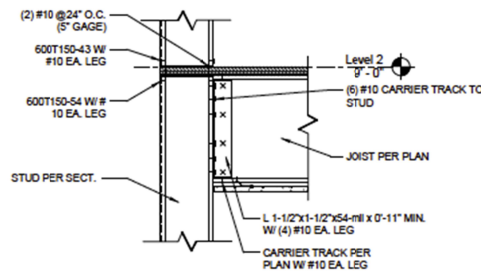

Figure 4. A schematic of ledger framing system.

Roof Joists

Roof joists were designed as simple span members with uniform loading. End rigidity of the attachment to the stud walls was not considered in the roof joist design. Design loads included 20 psf dead load, 20 psf live load and wind uplift per IBC requirements. Note that for the effective wind area associated with the joist spans for this building, maximum corner wind uplift was calculated at 14.1 psf and thus was not a significant concern in the design. Based on these loads and the deflection limit, 1200S200-54 joists at 24 inches on center were selected.

Because the web height-to-thickness for the selected joists exceeded 200, web stiffeners were required at member ends. Stiffening was accomplished with clip angles screwed to the joist and to the rim (ledger) track. This method transfers the reaction from the joist web to the support in direct shear rather than bearing, thus precluding web crippling failure in the joists.

Floor Joists

In addition to the standard 18 psf dead load to account for framing, sheathing, flooring and the like, a 15 psf partition load was included to account for partitions that may be moved at various times during the structure's life span. Based on the deflection limits of L/240 for total loads and L/360 for live loads, 1200S250-97 joists 24 inches on center were selected.

Load-bearing Walls

For a desired clear height of framing of 8'0" and 12" deep joists, studs were designed as 9 ft. in length. Code prescribed wind loads, when reduced for area, were less than

15 psf. As such, a slightly conservative value of 15 psf wind load was used for stud design.

Studs above the 2nd floor platform were designed to carry wind load in combination with roof dead and live loads. Load combinations per ASCE 7-05 were used. The total gravity load of 440 lb/stud was used based on the roof joist reactions. Gravity loads were applied at the inboard stud flange, resulting in an end eccentricity of 3 inches to the center of the studs. Since walls will receive gypsum board sheathing on at least one flange, k for distortional buckling was taken as zero per CFSEI Technical Note G100-08. Based on these criteria, 600S162-33 studs at 24 inches on center were chosen.

Lower level walls were designed similarly to the upper level walls except that in addition to roof gravity loads, floor gravity loads were also considered. Basend on this, 600S162-54 studs @ 24 inches on center with discrete bridging at mid-height were chosen.

Lateral System Design

Because testing will be based on shake-table simulated seismic forces, the design of the lateral system focused on seismic design.

Lateral forces were determined based on mapped short period spectral response acceleration parameter, Ss, and mapped 1-second spectral response acceleration parameter, S1 for the location described previously. Site Class D was chosen as is typical for sites in the vicinity of this project. For the office occupancy chosen, IE = 1.0 was used.

Lateral resistance was provided by wood structural panel shearwalls. For this system, the following parameters were derived from ASCE 7-05 Table 12.2-1:

- Response Modification Coefficient, R = 6.5
- Overstrength Factor, 0 = 3
- Deflection Amplification Factor Cd = 4

The resulting base shear coefficient was calculated as Cs = 0.143.
From this base shear coefficient and the total seismic weight of 78 kips, the seismic base shear force is determined 11 kips.

The vertical distribution of the calculated shear was based on ASCE 7-05 section 12.8.3. The design shear forces at the roof and 2nd levels were determined to be roughly 6.5 and 4.5 kips, respectively.

Shear Walls

Based on the proposed location of windows and doors, shearwall locations were selected on each of the four perimeter walls. Both Type I and Type II shearwalls were investigated. However, for this structure, the Type II shearwalls did not, in the opinion of the investigators and the IAB, provide a significant benefit. As such, Type I shearwalls were selected throughout.

Based on the force distribution, shearwalls were selected per the procedures of AISI S213-07. OSB sheathing was selected on the basis of economy of OSB. The typical 2nd floor stud framing was specified as 33-mil, but in order to meet strength requirements 54-mil chord studs were selected. Also minimum 43-mil top and bottom track were specified. Therefore, shear values applicable to 43 or 54-mil framing members were used.

ASCE 7-05 Table 12.12-1 limits seismic story drift to 0.025hsx for the type of structure contemplated where hsx is the story height. Drift was determined based on AISI S213-07 Eq. C2.1-1 and found to be within this limit for each wall.

Shear Chord Studs

Shearwall chords were designed for load combinations per ASCE 7-05, section 2.3.2 including dead, live and both lateral and vertical seismic loads. Eccentric moment due to both gravity (ledger on inside face of stud) and seismic (shear panels on outside face of stud) loads were included. Chords were sized based on basic LRFD load combinations in addition to the strength requirements of AISI S213-07, C5.1.2. Chord stud strength was checked at the minimum of the amplified seismic load, or the maximum seismic load the system can deliver as allowed in AISI S213-07. Based on this analysis, two 600S162-54 back-to-back chords were selected for both the 1st and 2nd levels.

Ties and Hold-downs

For the 2nd floor ties, a strap system was chosen to transfer forces from the 2nd floor chords to the 1st floor chords. To avoid crushing the plywood that runs between the bottom track at the 2nd floor and the top track of the 1st floor, straps were sized for both compression and tension.

Shear Anchors

Transfer of 2nd floor shear forces to 1st floor shearwalls is accomplished via screw fasteners between the 2nd floor base track and the 1st floor top track. These fasteners pass through the 2nd floor diaphragm. As such, fasteners with spacing to match the edge fasteners for 2nd floor shearwalls were selected.

Diaphragms

Roof and floor diaphragms were designed for the higher of the maximum total roof shear and the minimum diaphragm shear required by ASCE 7-05, Eq. 12.10-2. Diaphragm capacity was determined per AISI S213-07, Table D2-1. On this basis, an unblocked minimum 7/16 inch OSB diaphragm with fasteners at 6 inches on center at supported edges and 12 inches on center in the field was selected for the roof. For the 2nd floor diaphragm, minimum 23/32 inch unblocked structural panels with fastening to match the roof were selected.

EXPERIMENTAL PROGRAM

The experimental program will include a series of component/subsystem tests at Johns Hopkins University and full-scale shake table tests at the University at Buffalo NEES Facility. The component/sub-system tests aim to provide information necessary for developing computational models, both high fidelity and reduced-order high-efficiency models. The full-scale shake table tests serve to provide a direct means to examine the interactions of the components, sub-systems, and systems that make-up a cold-formed steel framed structure. The tests also provide an important benchmark for validating the developed computational models: both the high fidelity and high efficiency models.

To capture the behavior of the CFS-NEES building in full-scale shake table tests for the above purposes, an instrumentation plan has been developed. Below is a brief summary of the instrumentation plan.

Instrumentation Plan for the Full-Scale Shake Table Tests

The goal of the instrumentation plan is to capture global and local responses of the CFS-NEES building in shake table tests. The global response herein mean fundamental dynamic response including natural frequencies, damping ratios, and mode shapes. Figure 5 shows an example accelerometer layout on the east-side wall. As shown in the figure, accelerometers are placed in all three directions to capture not only in the weak axis, but also in strong and vertical axes. The sensor layout plan will be further revised with nonlinear time-history analysis that has been currently in progress.

Instrumentation for the local response will be focused on the deformation and rocking of shear walls. Using fixed reference frames and string pots that are available at NEES@Buffalo, three-dimensional motion at several representative points will be measured. Using relative displacements and rotations at the point of interest from those globally measured point, deformation and rocking of walls cam be obtained. Uplifting forces at tie-downs will be also measured using load cells. Besides above transducers, high-resolution cameras and high-speed video recorders will be used to capture damage, cracking and failure of the structural and nonstructural members.
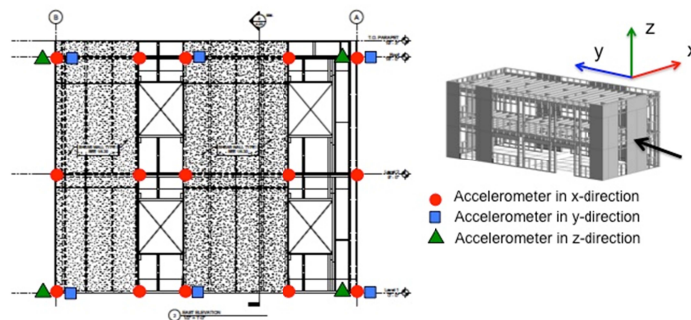

Figure 5. A sample accelerometer layout.

EDUCATION AND OUTREACH

In addition to the research activities, this project provides educational and outreach activities for undergraduate and K-12 students. Figure 6 shows a 1/12th-scale CFS-NEES building made of balsawood. This building was constructed by an undergraduate student at the Johns Hopkins University and a high school student at Baltimore Polytechnic Institute. Shake table tests were conducted at the Smart Structures and Hybrid Testing Laboratory at JHU to demonstrate dynamics of structures under random and earthquake loadings. Experimental results provided the students with data to study system identification techniques as well as damage detection techniques. More education and outreach activities will be offered from this project.

Figure 6. A 1/12th-scale CFS-NEES building made of balsawood.

CONCLUSIONS

This paper presented the first phase of the multi-year project that is aiming to generate knowledge needed to increase the seismic safety of CFS frame buildings. Detailed design criteria including designs of gravity and lateral systems were provided along with the instrumentation plan in the full-scale shake table tests at University at Buffalo NEES Facility. Results from the experimental and computational programs in this project will be made available to public as well as published in conference and journal papers.

ACKNOWLEDGEMENT

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