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Modeling seismic response of a full-scale cold-formed steel-framed building

Jiazhen Leng [a,*], Kara D. Peterman [a,1], Guanbo Bian [a], Stephen G. Buonopane [b], Benjamin W. Schafer [a]

[a] Department of Civil Engineering, Johns Hopkins University, Baltimore, MD, USA
[b] Department of Civil and Environmental Engineering, Bucknell University, Lewisburg, PA, USA

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ABSTRACT

The objective of this paper is to present finite element modeling protocols and validation studies for the seismic response of a two-story cold-formed steel-framed building with oriented strand board sheathed shear walls. Recently, shake table testing of this building was completed by the authors. The building provides an archetype for modern details of cold-formed steel construction, and provides benchmarks for the seismic response of the building system, subsystem, and components. The seismic response of buildings framed from cold-formed steel has seen little study in comparison with efforts on isolated members and shear walls. Validated building-scale models are needed to expand our understanding of the seismic response of these systems. Finite element models corresponding to the archetype building during its various test phases are developed in OpenSees and detailed herein. For cold-formed steel framed buildings accurate seismic models require consideration of components beyond the isolated shear walls, e.g. the stiffness and capacity of the gravity framing is included in the model. Such decisions require model refinement beyond what is typically performed and details for completing this effort accurately and efficiently are described herein. In addition, nonstructural components, including exterior sheathing of the gravity framing, interior gypsum sheathing for the shear walls and gravity framing, and interior partition walls, are included in the building model based on nonlinear surrogate models that utilize experimental characterization of member-fastener-sheathing response. Comparisons between the developed models and testing for natural period, story drift, accelerations, and foundation hold-down forces validate the model. Performance of the tested archetype building is better than predicted by design or typical engineering assumptions. The model developed herein provides insights into how the building achieves its beneficial performance and will be used to further quantify the lateral resistance of each subsystem and the extent of their coupling. In addition, the protocols used to develop the model herein provide a first examination of the necessary modeling characteristics for wider archetype studies of cold-formed steel-framed buildings and the development and substantiation of seismic response modification coefficients.

1. Introduction

Buildings framed from cold-formed steel (CFS) are increasingly being specified due to their low cost, high material efficiency, short cycle times in manufacturing and construction, non-combustibility, and other factors. CFS-framed buildings typically consist of repetitive series of closely-spaced lipped channel CFS members: studs for walls, joists for floors; fastened together by screws and/or welds, and further stiffened with strap, sheet, or sheathing panels to resist applied loads. CFS framing is also used extensively in non-structural applications such as interior partition walls and exterior curtain walls, but this application is not the focus of the work herein. Research and design experience has grown for the use of CFS as the load-bearing system for gravity and lateral loads in buildings [1]. Modeling the seismic response of CFS-framed buildings is the subject of this paper.

The work presented herein is part of a multi-year research project to advance understanding of CFS-framed buildings in seismic events under the title: Enabling Performance-Based Seismic Design of Multi-Story Cold-Formed Steel Structures, funded by the U.S.

* Corresponding author at: Department of Mechanical Engineering, McGill University, 817 Sherbrooke Street West, Montreal, QC H3A 0C3, Canada.

E-mail addresses: jiazhen.leng@mcgill.ca (J. Leng), kdpeterman@umass.edu (K.D. Peterman), bian@jhu.edu (G. Bian), sbuonopa@bucknell.edu (S.G. Buonopane), schafer@jhu.edu (B.W. Schafer).

[1] Department of Civil and Environmental Engineering, University of Massachusetts Amherst, Amherst, MA, USA.

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National Science Foundation (NSF) and the American Iron and Steel Institute (AISI) and was formally a part of the NSF Network for Earthquake Engineering Simulation (NEES) research program, or in short CFS-NEES [2]. The central focus of the project was full-scale shake table testing and related modeling of a cold-formed steel ledger-framed building with wood structural panel shear walls and floors, known as the CFS-NEES building. Shake table testing of the CFS-NEES building was conducted in the laboratory of the University at Buffalo in the summer of 2013.

Design codes and standards for CFS-framed structures largely focus on component level design [3,4]. However, repetitively framed CFS buildings are recognized in seismic design [5] and supported with provisions for determining the capacity of the assumed lateral force resisting system (LFRS), e.g. shear wall, strap-braced wall, etc. [6,7]. The CFS-NEES testing provided the first experiments on the full-scale seismic system response for these structures. The CFS-NEES building exhibited stiffness and capacity far beyond that of the assumed LFRS, and suffered no permanent drift and only non-structural damage in testing up to maximum considered earthquake levels [8–10]. The testing demonstrated excellent performance, but also highlighted a significant knowledge gap between system performance and current understanding, which is predominately at the component level.

Compared with experimental efforts, modeling the dynamic seismic response of CFS-framed building systems is less explored. Previous research has focused almost exclusively on modeling the assumed LFRS in isolation. For example, the authors modeled the oriented strand board (OSB) sheathed shear walls of the CFS-NEES building with elastic frame finite elements for the shear wall perimeter and nonlinear diagonal braces for the interior, calibrated to match cyclic shear wall tests [11,12] in OpenSees [13]. This phenomenological approach, where isolated shear walls are modeled such that they fit cyclic test data is the most common approach. Similar models have been adopted for CFS-framed steel sheet shear walls [14], corrugated steel sheet shear walls [15], wood sheathed shear walls [16] and walls sheathed with combinations of sheathing including plaster [17,18]. To estimate building seismic response these phenomenological shear wall models are then typically employed in 2D or 3D building models as the only component of the model available for resisting lateral load [11,12,14–18]. A recent notable exception is the model of a small prototype CFS building, completed in SAP 2000 that includes details beyond the isolated shear walls [19].

A higher resolution model, still implemented in OpenSees, for CFS-framed walls with sheathing has also been developed within the CFS-NEES effort [20]. This model employs cyclic data on the local stud-fastener-sheathing response and implements that data as nonlinear springs in a wall model where the members and sheathing are discretely modeled to predict the lateral wall response [21–23]. This method provides a means to predict the lateral cyclic wall response using only local cyclic fastener data, and is flexible enough to allow for different framing details, fastener patterns and spacing, etc. and is adopted herein as a surrogate model for predicting the cyclic performance of walls and floors that have not been explicitly tested as sub-assemblages, as detailed in Section 3.4.

System-level or full building models of the seismic response of CFS-framed buildings are rare, but comparable work in repetitively framed wood construction does exist. Wood-framed structures, which also feature lightweight designs and share common terminology, provide a useful prototype for needed seismic research in CFS-framing [10]. For example, van de Lindt et al. [24,25] modeled an archetype wood building using SAPWood and compared their numerical predictions with test results. Their nonlinear model condensed the response of floors into global translational and rotational degrees of freedom (DOF) smearing all details of the LFRS, but overall providing reasonable predictions. Advances have continued, including modeling a five-story residential light-frame wood building with discrete nonlinear phenomenological models for each shear wall and performing incremental dynamic analysis (IDA) to assess seismic response modification coefficient for use in design [26].

This paper presents the authors' efforts on high fidelity modeling and seismic analysis of the two-story CFS-NEES archetype building as detailed in the first author's dissertation [27]. Section 2 of this paper briefly overviews the design and construction of the CFS-NEES building. The assumptions, options, and details of the model development for each structural and nonstructural component of the building are addressed in Section 3. Section 4 provides validation of the models and comparison of time history analysis results with full-scale shake table tests. First natural period, story drift, acceleration, and axial force in shear wall hold-downs are selected as the metrics. The performance of the model is discussed, particularly from the perspective of its application in performance-based design evaluations and its use for IDA and the evaluation of seismic response modification coefficients.

2. CFS-NEES building design and construction

2.1. CFS-NEES building design

The CFS-NEES building was designed as a CFS-framed two-story office building for a high seismic zone in Orange County, California. The building was designed in accordance with the International Building Code (IBC) [28] and thus by reference the load standard ASCE 7 [5], the member standard AISI-S100 [3], and the lateral design standard AISI-S213 [6]. The building was professionally designed with input from an Industrial Advisory Board and the project team.

The design of the CFS-NEES building reflects current state-of-the-practice in CFS-framed construction. The CFS-framed gravity walls relied on an all-steel design philosophy, i.e. bridging is included between studs and sheathing is not considered as bracing. The CFS-framed floors used OSB sheathing and strap for bracing and were hung from the walls using ledger track. The assumed LFRS employs OSB-sheathed shear walls as well as the OSB-sheathed floor and roof. The resulting structural system is depicted in Fig. 1(a). Building dimensions were 15.2 m × 7 m × 5.8 m (49 ft − 9 in. × 23 ft × 19 ft − 3 in.). Additional non-structural features for the perimeter walls included exterior sheathing, exterior insulation finishing system, and interior gypsum. Architectural features also included interior partition walls and two staircases between the first and the second stories (resulting in two cutouts in the floor diaphragm), windows, and doorways as illustrated in Fig. 1(b). A detailed design narrative with complete calculations and drawings is available [29], and construction details of the specimen are also provided in [8].

A key feature of the building was the selection and use of ledger framing for the floor and roof system as advocated by the Industrial Advisory Board based on current practice. In ledger framing, the joists are hung from the top of the studs of the exterior walls via a ledger track and a clip angle, so the joists need not be aligned with the wall studs (see Fig. 2(a)). This framing type also provides a direct load path from the diaphragm to the top track of the walls, but the sheathing of the diaphragm has to be penetrated to allow the passing of a steel strap that connects shear wall chord studs across the floor, as shown in Fig. 2(a).

The selected seismic LFRS for the building was OSB sheathed shear walls. Per ASCE 7-05 [5] this resulted in a seismic response modification coefficient of $R = 6.5$, overstrength factor of $\Omega_o = 3.0$, and deflection amplification factor of $C_d = 4.0$. The seismic design