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Design component and system reliability in a low-rise cold formed steel framed commercial building

B.H. Smith [a,*], S.R. Arwade [a], B.W. Schafer [b], C.D. Moen [c]

[a] Dept. of Civil & Env. Engg., University of Massachusetts, Amherst, MA 01003, United States
[b] Dept. of Civil Engg., Johns Hopkins University, Baltimore, MD 21218, United States
[c] Dept. of Civil & Env. Engg., Virginia Tech, Blacksburg, VA 24061, United States

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ABSTRACT

Target structural reliabilities are implicit in most modern design codes and yet efficiency of design and construction as well as the presence of constraints on the design space mean that structural components in a building system may have as-designed reliabilities that differ from the target reliabilities. This paper presents an investigation of this phenomenon through a detailed examination of the two story cold-formed steel framed building designed and tested as part of the CFS-NEES project and seeks to use this case study to elucidate features of the component and system reliabilities that may prevail in typically designed buildings. Specifically, for the gravity load system of the second floor and the lateral force resisting system the demand to capacity (D/C) ratios and reliabilities (β) are calculated. The results of these calculations illustrate the excess and highly variable D/C ratios and reliabilities that result from efficient design procedures. Since the ultimate goal of structural design is to ensure performance of the structural system at a target level of reliability the influence of excess and variable component reliability on reliability of the lateral force resisting system is examined by making assumptions about series and parallel-type interaction of the floor diaphragm and shear walls. Finally, discussion is presented about the role of load combinations and their associated coefficients of variation in determining component and system reliability in a cold-formed steel framed building. Future considerations include more robust, high fidelity, modeling of the system effects and evaluation of excess capacity and variability of reliability across suites of other building designs and structural systems such as roof trusses.

1. Introduction

Modern design approaches for buildings are based on underlying target reliabilities for each of the building's structural components. The target reliability, or probability of failure, varies between element types (e.g. connections are usually designed with a higher target reliability than members), often depending on how critical a particular component is to the performance of the overall building system. In a perfectly optimized structural design each component would be sized such that it exactly meets its target reliability. In practice, however, such fine-grained optimization is neither practical nor desirable for reasons including cost savings generated by consistency of member sizes within the building, commercial availability of members only in discrete size and shape increments, and the possibility that a given member is sized according to a serviceability rather than ultimate strength limit state. These factors combine to cause building designs to contain widely varying component reliabilities that may differ significantly from the target reliabilities. This variability of the as-designed reliabilities has implications for the overall structural efficiency of the building as well as for the overall reliability of the structural subsystems and systems such as shear walls, floor diaphragms, and gravity load-bearing walls that form a building. While the existence of these effects are known, especially relative to constructability, they have not, to the authors' knowledge been quantified for a realistically designed building, and a thorough understanding of the extent of excess and variable component and system reliability is required to improve upon reliability-based design practices.

The issues that affect the as-designed reliability are particularly acute for cold formed steel (CFS) structures, for which repetitive framing and a dense network of structural elements is typical, and which contain larger numbers of connections and fasteners

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* Corresponding author at: 223 Marston Hall, University of Massachusetts, Amherst, MA 01003, United States.

E-mail addresses: SmithBH@Members.ASCE.org (B.H. Smith), Arwade@UMass.edu (S.R. Arwade), Schafer@JHU.edu (B.W. Schafer), CMoen@VT.edu (C.D. Moen).

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than hot-rolled steel or reinforced concrete structures. It should be noted that the term 'as-designed' is used in this paper to describe the predicted reliability of the structural members as specified by the design engineer and that the 'as-built' reliability may differ significantly from the as-designed reliability due to myriad effects including member imperfection, construction misfit, and the influence of non-structural systems, among others.

Component design methodology has existed for cold-formed steel for some time, but it is only in the past 20 years that full-building solutions, notably integrating seismic design, have been developed for CFS. Since an initial characterization of wood sheathed CFS shear walls by Serrette et al. [1], research has focused upon experimental studies of shear walls [2], fasteners [3], and prototype buildings [4]. Numerical models [5] and complete seismic design procedures [6] have been developed, and the recent popularity of CFS residential structures in Australia and China have led to growing data on lateral force resisting systems for the material [7,8].

The positive or negative effects of having multiple interconnected structural components acting together is known as the system reliability. While research in system reliability has rarely focused specifically upon CFS, important contributions have included studies of load paths [9,10] as well as of redundancy, load distribution, and uncertainty in demands and capacities [11]. Among other things, this system reliability depends upon the load-deformation characteristics of each component acting together [12].

The CFS-NEES project (part of the larger NEESR-CR project) [13] funded by the US National Science Foundation, presents a unique opportunity to investigate the as-designed component reliabilities of a low-rise CFS building designed according to the latest US design codes. As part of the project a full-scale shake table test of a two-story CFS building was conducted at the NEES@Buffalo site at the University at Buffalo of the State University of New York. The performance of the building during the shake table test indicated that the as-designed (and as-built) components, subsystems and systems performed well in excess of design specifications. Specifically, the building was subjected to a full proof test at design gravity load levels and was then subjected to simulated design basis (DBE) and maximum considered (MCE) earthquake excitations with the full gravity load in-place. The building performed well in excess of design expectations at these load levels, exhibiting greater strength and stiffness than anticipated by the design [14,15]. While these results clearly indicate that the demand-to-capacity (D/C) ratios of all system components were less than one, there is no viable way to extract component D/C ratios from a full-scale building test. A detailed discussion of the methodology and results from the shake table testing is outside the scope of this paper, and the interested readers are referred to other publications from the CFS-NEES project for such information [14–16]. The primary importance of the CFS-NEES building to this work is that it provides a thorough, openly available CFS building design that has been proof-tested under design gravity and seismic loads. Such performance indicates substantial reserve strength in the components, or significant parallel system or load sharing behavior among components and subsystems that is not accounted for in component-based design. Furthermore, the CFS-NEES building utilizes the repetitive framing typical of CFS constructions and the project therefore provides an opportunity to assess component and system reliabilities for a repetitively framed structure.

This paper presents calculation and discussion of the as-designed demand-to-capacity (D/C) ratios and reliabilities for the structural components of the CFS-NEES building. The D/C ratios are included in the paper because they are more directly connected to the code checks performed during design than are the reliabilities. D/C ratios can be computed based on factored (D_f/C_f) or unfactored (D_u/C_u) values of the demand and capacity. D_f/C_f can be easily interpreted relative to the key value of $D_f/C_f = 1$, at which the component exactly meets the design check and therefore would also be expected to exactly meet the target reliability implicit in the code. Unfactored values D_u/C_u are also included here to indicate the amounts of relative safety margin provided by code factors. There are subtleties in the computation of D_u and C_u primarily associated with the variety of load combinations that may control a given component design, and in some cases assumptions have been made to allow computation of unfactored quantities. Detailed procedures are presented in the following sections. Once values of D and C are computed, component reliabilities for the factored, β_f, and unfactored, β_u cases can be computed by making appropriate assumptions about the variances and distributions of D and C or the ratio D/C itself. Some key limitations of the paper are that it treats a single building rather than an ensemble of building archetypes representative of the current building stock, and that it uses approximations for the coupling of the building systems to arrive at overall system reliabilities.

The remainder of this paper is organized as follows: first the general characteristics of the CFS-NEES building are reviewed; second, the detailed methods used to compute D, C, and the resulting values of β are described; third, the results of those calculations are presented, followed immediately by discussion of those results; fifth and finally, preliminary analysis of the effect of component reliabilities on building system reliability is presented. The paper closes with a summary of conclusions.

2. General characteristics of the CFS-NEES building

The CFS-NEES building (Fig. 1) was professionally designed by Rob Madsen of Devco Engineering with input from the CFS-NEES research team led by one of the authors (Schafer) and from an Industry Advisory Board comprised of experienced cold-formed steel engineers in the U.S. and Canada. The design was intended to reflect current practice. The building has a rectangular floor plan dimensions of 15.1 m × 6.97 m [49 ft–9 in. × 23 ft] and a total height of 5.83 m [19 ft–3 in.]. The lateral force resisting system consists of total shear wall lengths of 6.06 m [20 ft] (in 2 shear walls), 3.73 m [12 ft–4 in.] (in 3 shear walls), 4.47 m [14 ft–9 in.] (in 2 shear walls), and 4.85 m [16 ft] (in 3 shear walls) along the north, south, east and west sides of the building, respectively.

The second floor acts as a diaphragm to distribute lateral loads to the shear walls. The floor is ledger-framed, i.e., a ledger track is installed on the inside face of the wall studs and the floor joists are attached to this track with clip angles. Stud and joist spacing are not equal in ledger-framing. The top of joist and top of wall are at the same elevation. Oriented strand board (OSB) sheathes the floor and runs through to the outside edge of the walls providing direct diaphragm transfer between the floor and top track of the walls. The building uses OSB sheathed shear walls for the lateral force resisting system, corresponding to a response modification factor (R) of 6.5 per ASCE 7-05 [18]. The building was designed for Orange County, CA (site class D) with a total seismic weight of 350 kN [78 kips]. Resulting shear forces, calculated by the Equivalent Lateral Force method [18], are 20 kN [4.5 kips] for the second floor and 29 kN [6.5 kips] for the roof. A design narrative, complete calculations, and full drawings are available for the building [13,17].

In this paper, a total of 131 component design checks are examined in detail. These relate to the second floor gravity system and the sets of shear walls along each side of the building. Table 1 defines the component groups with the corresponding number of components in each group. The design check on the shear walls acts as both a check on the capacity of the sheathing boards and