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Towards Quantifying Beneficial System Effects In Cold-Formed Steel Wood-Sheathed Floor Diaphragms

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Abstract

Cold-formed steel wood-sheathed floor diaphragm system behavior is analyzed from a system reliability perspective. Floor systems consisting of oriented strand board (OSB), cold-formed steel (CFS) joists, tracks and screw fasteners are modeled using shell and spring elements in ABAQUS. (Dassault-Systems ())The models consider typical seismic demand loads, with careful treatment of light steel framing diaphragm boundary conditions and OSB sheathing kinematics, i.e., two sheets pulling apart or bearing against each other at an ultimate limit state, consistent with existing experimental results. The finite element results are used to build surrogate mathematical idealizations (series, parallel-brittle and parallel-ductile) for the critical system components. System reliability and reliability sensitivity, defined as the derivative of system reliability with respect to component reliability, are studied for these idealizations. These results represent mathematical upper and lower bounds to real system behavior, and are being used in ongoing research to codify beneficial diaphragm system effects.

Introduction

Residential and commercial buildings are made up of linked structural sub-systems – floor, roof, gravity walls, diaphragms, and shear walls as shown in Fig. 1. When these sub-systems are considered together, they have beneficial system effects that are typically not considered in component level design. Structural design codes almost exclusively consider component reliability and ignore system effects because (1) system reliability calculations are complicated; (2) system level experimental data, where

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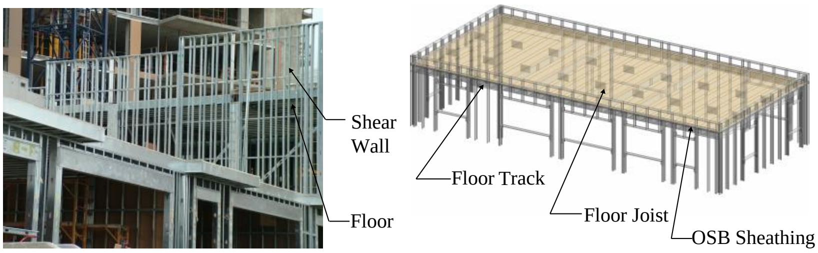
load sharing and force redistribution are explicitly tracked, does not exist; and (3) system level limit states and failure surfaces are challenging to conceptualize. The research presented in this paper begins to face this system reliability challenge with an analytically tractable system reliability calculation framework informed with computational studies.



(a) Typical light-steel framed building
courtesy: Mr. Don Allen, www.DSi-Engineering.com

(b) Floor diaphragm sub-system

Fig. 1: (a) Light steel framing and (b) wood sheathed floor sub-system

Challenges in structural modeling and probabilistic calculations for the system reliability problem are well documented, e.g., Moses 1982. Previous research to meet these challenges has largely focused on failure mode identification. These include enumeration-based approaches, for example the incremental loading method (Rashedi and Moses 1988) and the branch and bound method (Dey and Mahadevan 1998); simulation or hybrid-analytical/simulation approaches such as linear programming (Corotis and Nafday 1989), combined enumeration and adaptive importance sampling (Dey and Mahadevan 1998) and selective genetic algorithm search strategies (Shao and Murutsu 1999). These techniques model the structural system as a truss or a frame which can inaccurately represent behavior (Karamchandani 1990).

Building sub-system treatments with more sophisticated mathematical models have not received as much attention. System reliability and redundancy depend on material behavior, load and resistance statistics, load sharing relationships and damage level as demonstrated for parallel ductile and brittle systems (Hendawi and Frangopol 1994). System reliability treatments for series, parallel and series-parallel representations of geometrically non-linear elastic structures are also available (Imai and Frangopol 2000), with example applications to an elastic truss and a suspended structure, modeled as a series of parallel sub-systems (Frangopol and Imai 2000). (Series and parallel systems represent bounds on the structural component connectivity; failure occurs in series systems when the first component fails, i.e., low redundancy, and parallel systems when all components fail, i.e., high redundancy). These techniques were used for system reliability evaluation of suspension bridges, with specific application to the Honshu Shikoku Bridge in Japan (Imai and Frangopol 2002).

System factors, that increase or decrease nominal component resistance based on redundancy, are used in highway bridge superstructure design and load ratings (Ghosn and Moses 1998). The factors were calibrated to a lower bound on the difference between the system reliability index for a particular limit state and the most critical component reliability index, similar to the limit state-wise system reliability approach taken in this work. The methodology herein is new in that it is based on 'reliability sensitivity', defined as the change in system reliability per unit change in member reliability. This is the first step towards developing formal system reliability methods for building structural design that were impractical in 1988 (Galambos 1990) and still challenging today.

We consider the example of a CFS wood-sheathed floor diaphragm sub-system. The paper begins by introducing the wood-sheathed floor sub-system details and a high fidelity finite element model developed with careful treatment of kinematics and boundary conditions. System reliability idealizations (series, parallel-ductile and parallel-brittle) are coupled with finite-element modeling results that provide fastener force distributions and failure progressions. System reliability upper and lower bounds are approximated, along with their sensitivities to fastener capacity, providing valuable information to guide future design guidelines, for example, a lower number of fasteners in the field of the floor and more fasteners along the edges where the sheathing connects to the CFS framing.

CFS Wood Sheathed Floor Diaphragms

The specific sub-system under study is wood-sheathed cold-formed steel floor sub-systems experiencing in-plane shear demands under seismic loads. The components involved are: (1) OSB sheathing, (2) CFS floor joists, (3) CFS tracks, and (4) steel fasteners (screws) as shown in *Fig. 1(b)*. Existing literature on these sub-systems are summarized in Chatterjee et al. (2014). Key findings are repeated here to keep this work self-contained.

Only four monotonic wood-sheathed cold-formed steel floor diaphragm tests are reported in the literature (NAHBRC 1999). These tests indicated that system behavior is governed by fastener properties. Test detailing is shown in *Fig. 2*. 'Fastener group A' refers to fastener locations at which the sheets started pulling apart due to excessive flexural deformation, and 'Fastener group B' refers to fasteners that pulled through the sheathing as diaphragm shear accumulates near the fixed edges (lateral collectors).

The AISI-S100-12 commentary (AISI 2012) states that 'the dominant diaphragm limit state is connection related' which is consistent with the findings from these tests (AISI (2012). Available strength in shear as recommended in AISI-S213-07 (AISI 2007) is based on the National Design Specification for wood construction (ANSI/NFoPA 1991) which assumes all fasteners take the same shear force demand. Modeling described in the following sections demonstrate that this assumption is inconsistent with actual behavior.

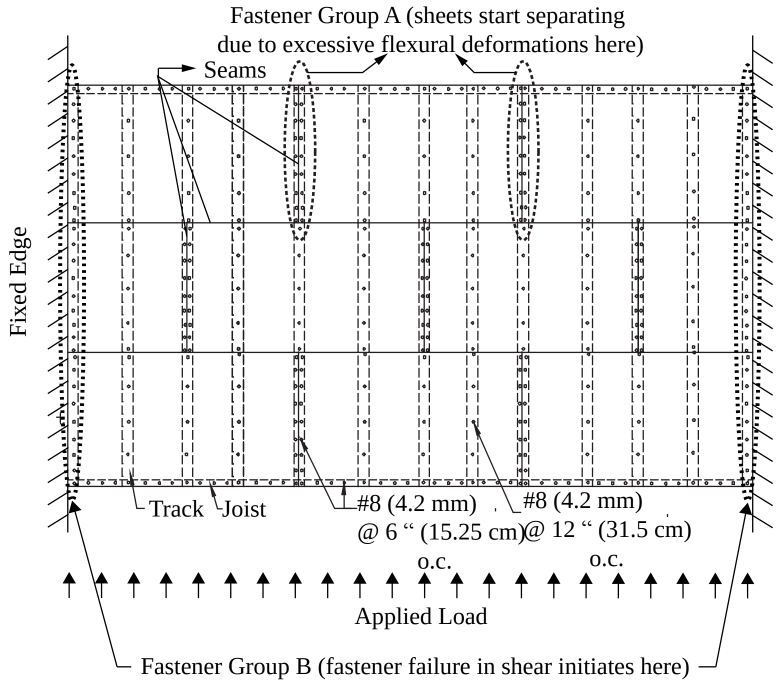


Fig. 2: Fastener failure locations in a wood-sheathed cold-formed steel diaphragm (adapted from (NAHBRC 1999))

Diaphragm Computational Modeling

A finite element model was developed using the commercial finite element program ABAQUS (Dassault-Systems 2014) to predict the behavior of the wood-sheathed cold-formed steel diaphragm. Members, elements and lateral load details are described in Chatterjee et al. (2014).

Joist, track and diaphragm descriptions are provided in *Table 1*. Joists and tracks are modeled as four-noded shell elements with reduced integration. Floor tracks are modeled as eight-noded shell elements with reduced integration and five degrees of freedom per node. The overall diaphragm size is 48 ft (14.6m) by 24 ft (7.3m) and contains smaller 8 ft (2.4 m) by 4 ft (1.2 m) OSB sheets connected together at seam locations by normal and tangential constraints (see *Fig. 3*). The panel seams are typically staggered in practice, however this stagger is not modeled here for simplicity. All materials are assumed to be isotropic and linear-elastic.

Table 1. ABAQUS model details

Component	**Section details (SSMA 2013)**	**Element size**
Floor joists	1200S250-97	6 in. (152.4mm)
Floor tracks	1200T200-97	6 in. (152.4mm)
OSB diaphragm	0.72 in. (18.3 mm) thick	6 in. (152.4mm)
Component	**Young's modulus**	**Poisson's ratio**
Floor joists	29000 ksi (200 GPa)	0.3
Floor tracks	29000 ksi (200 GPa)	0.3
OSB diaphragm	350 ksi (2.4 GPa)	0.3

Fasteners are spaced at 6 in. (15.25 cm) on-center along panel edges and 12 in. (30.5 cm) on-center in the field. Floor joists are spaced at 24 in. (61 cm) on-center. A distributed shell edge load with a total magnitude of 4.5 kips (20 KN) intended to simulate a seismic base shear (Madsen et al. 2011) is applied to the OSB sheathing (*Fig. 3*). A distributed shell-edge load is chosen over inertial forces across the whole diaphragm to simulate the NAHBRC tests (NAHBRC 1999) more accurately. The boundary conditions represent shear walls that are expected to be significantly stiffer than the diaphragm system.

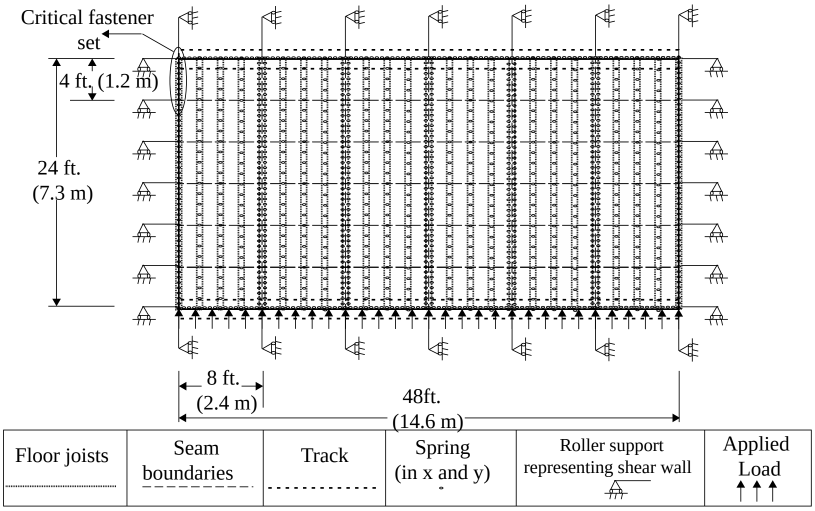


Fig. 3: ABAQUS Model Schematic

The fasteners are machine screws of diameter 4.2 mm (#8 screws). Fasteners connecting the OSB to tracks and joists are modelled as elastic-perfectly plastic (fully ductile) springs that have stiffness in 2 mutually perpendicular directions (parallel and perpendicular to the applied load). Spring sections are chosen over connector sections that fail under resultant loads for computational efficiency. Post-yield difference in system resistance between models with spring and connector elements is found to be of the order of 1%. The ultimate load of each individual spring is taken from values recommended in Peterman and Schafer (2013).

The fasteners along the left and right edges experience large shear demands parallel to the applied-load direction (‘Fastener Group B’ in *Fig. 2*). Panels on the tensile side of the system (away from the loaded edge) try to pull apart, opening the seams. Fasteners along the left and right edges (‘Fastener Group B’ in *Fig. 2*) are identified as the critical loading points in the system. For this study we focus on just the left edge of the top-left panel (‘Critical fastener set’ *Fig. 3*). Each fastener on this edge (total of 9 fasteners) is treated as a component. In reality, the whole ‘Fastener Group B’ contributes to system failure and the reliability treatments for this group have the same basic form as those discussed in this paper.

System Reliability Studies

The analysis of realistic structural systems consists of three major modeling parts: load modelling, material modeling, and system modeling. Structural systems or their sub-systems can exhibit two limiting cases of behavior: series and parallel. In a series system (*Fig.*4a), the failure probability (p_f) of the structure is defined by the probability that any one component fails and is given by

$$p_f = p(F_1 \cup F_2 \cup F_3 \cup ... \cup F_n) \quad (1)$$

where F_i represent the failure of sub-system i. The probability of failure in component i can be obtained in terms of the reliability index as

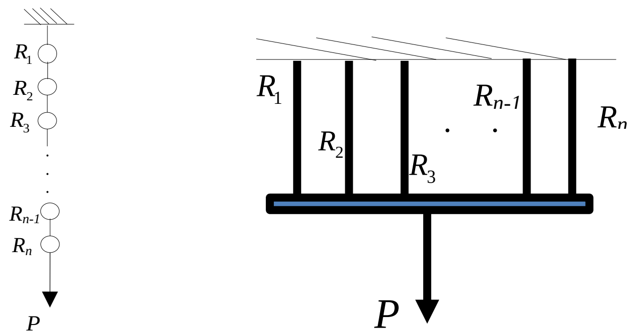
$$p_{f_i} = \Phi(-\beta_{component_i}) \quad (2)$$

Where Φ() is the standard normal cumulative distribution function (CDF). The component reliability can be written as

$$\beta_{component_i} = \frac{\mu_{R_i} - \mu_P}{\sqrt{\sigma_{R_i}^2 + \sigma_P^2}} \quad (3)$$

where μ_{Ri} and the μ_P represent the mean value of resistance and loading of component i respectively and σ_{Ri} and the σ_P represent the standard deviation of resistance and loading of component i respectively. The derivations above assume that the resistance and loading of the component are Gaussian variables. Appropriate transformation is required for treatment of non-Gaussian variables. For independent components, the system reliability can be described as

$$\beta_{system} = -\Phi^{-1}(-p_f) \quad (4)$$



(a) series system (b) parallel system

Fig. 4: Schematic plot of series system and parallel system

In a parallel system (*Fig.4*b), failure probability (p_f) is governed by the failure of all components and is given by

$$p_f = p(F_1 \cap F_2 \cap F_3 \cap ... \cap F_n) \quad (5)$$

The component reliability in a parallel system is the same as that in a series system. For a parallel system with ductile (ideal plastic) components, system reliability is

$$\beta_{system} = \frac{\sum_{1}^{n}\mu_{R_i} + \sum_{1}^{n}\mu_{p_i}}{\sqrt{\sum_{1}^{n}\sigma_{R_i}^2 + \sum_{1}^{n}\sigma_{p_i}^2}} \tag{6}$$

where μ_{Ri} and the μ_{Pi} represent the mean value of resistance and loading of component *i* respectively and σ_{Ri} and the σ_{Pi} represent the standard deviation of resistance and loading of component *i* respectively.

Parallel systems with brittle components are more complicated compared to parallel ductile systems, and analytical solutions for cases with many components are not available. Therefore simulation-based approaches are used to calculate system reliability.

Series system reliability analysis

The fasteners on the left edge of the upper left panel ('Critical fastener set' in *Fig.*3) are considered as a series system with nine components. The resistance and loading on fasteners are treated as independent random variables. Resistance and loading are assumed to follow log-normal distributions (requiring transformations to apply Equations 3, 4 and 6). *Table 2* gives the loading and resistance statistics for the sub-system in which all fasteners are considered to be nominally identical.

Table 2 Stochastic coefficients for fastener resistance and loading

Parameter	Resistance, R_i (kips)		Demand , P_i (kips)		Scaled-up Demand, $2.74*P_i$ (kips)	
Fastener	Mean	Standard Deviation	Mean	Standard Deviation	Mean	Standard Deviation
1	0.473	0.082	0.067	0.014	0.185	0.507
2	0.473	0.082	0.046	0.010	0.138	0.378
3	0.473	0.082	0.048	0.010	0.143	0.392
4	0.473	0.082	0.049	0.010	0.147	0.403
5	0.473	0.082	0.050	0.010	0.150	0.411
6	0.473	0.082	0.051	0.011	0.153	0.420
7	0.473	0.082	0.052	0.011	0.155	0.425
8	0.473	0.082	0.053	0.011	0.159	0.436
9	0.473	0.082	0.050	0.010	0.150	0.411

The mean value of the loading information are taken directly from the ABAQUS finite-element model, based on applied loads in accordance with ASCE (2010); and the corresponding coefficient of variation (i.e., standard deviation divided by the mean) are derived in accordance with the provisions given in AISI (2012) and experimental results given in Peterman and Schafer (2013). Details of these derivations are discussed in Chatterjee et al. (2014).

The component reliability indices calculated using Eq. 3 are shown in *Table 3*. It can be seen that the minimum reliability index β for a component $(\beta_{component})$ is 7.24 which is far in excess of the target reliability of 3.5. Therefore an alternative loading scenario is studied in which the fastener demand loads are scaled up by a factor of 2.74. The corresponding loads are given in *Table 2* and the component reliability indices are shown in *Table 3*. The minimum component reliability index $(\beta_{component})$ is found to be 3.5. The series system reliability (β_{system}) using original ABAQUS results (design load) and the scaled up loading are 7.24 and 3.42, respectively. System reliability index under scaled up load is lower, indicating a lower safety margin compared to the design load scenario. The scaled up loading increases the demand on each individual, driving down $\beta_{component}$ and β_{system}.

Table 3 Component reliability index

Series system		
Parameter	Component-wise Reliability index β	
Fastener	Demand, P_i (kips)	Scaled-up Demand, $2.74{*}P_i$ (kips)
1	7.24	3.50
2	8.65	4.59
3	8.52	4.46
4	8.42	4.36
5	8.35	4.28
6	8.28	4.21
7	8.21	4.15
8	8.14	4.07
9	8.35	4.28

Parallel ductile system reliability analysis

Nine nominally identical fasteners (components) on the left edge of the top-left panel ('Critical fastener set' in *Fig.* 3) are considered as a parallel ductile system. The same assumptions regarding distribution of resistance and loading on the fasteners as provided in *Table 2* are used. The component reliability indices in the parallel system model are the same as those in series system. The system reliability using original ABAQUS results and the scaled up loading are 24.72 and 12.63, respectively. It can be observed that parallel-ductile system reliability index is much higher than that of series system, and likely highly unrealistic since fasteners do not have unlimited ductility.

Parallel brittle system reliability analysis

The parallel brittle system represents a compromise between the bounding behavior of the series and parallel ductile approximations. Direct simulation-based approach are used in the current study, because analytical solutions of component reliability and system reliability are not generally available. The same assumptions and distributions of resistance of fasteners as in *Table 2* are used. The failure rule is defined as follows: each fastener has a stiffness factor α_i and the load is distributed to each fastener with a linear distribution rule given by Eq. 6.

$$P_i = \frac{P\alpha_i}{\sum_1^n \alpha_i} \quad (6)$$

where P is the total load, and P_i is the load distributed on component i. The component will fail once the load reaches its resistance, and the total load on that fastener will be redistributed to the remaining components following the initial elastic load distribution (Eq. 6). One million samples of Monte-Carlo simulation are used. *Table 4* summarizes the system reliability results for all three cases. The parallel brittle system reliability estimates lie between the series and parallel ductile bounds.

Table 4 System reliability index

		Demand, P_i	Scaled-up Demand, $2.74*P_i$
Reliability index, β_{system}	Series	7.24	3.42
	Parallel ductile	24.72	12.63
	Parallel brittle	8.67	4.13

Reliability Sensitivity Analysis

The contribution of each fastener to the overall system reliability can be tracked through fastener reliability sensitivity analysis. The reliability sensitivity can be defined as the derivative of the system reliability with respect to the component reliability. A general solution of the fastener sensitivity is described as:

$$\frac{d\beta_{system}}{d\beta_{component_i}} = \frac{d\beta_{system}}{d\mu_{R_i}}\frac{d\mu_{R_i}}{d\beta_{component_i}} + \frac{d\beta_{system}}{d\sigma_{R_i}}\frac{d\sigma_{R_i}}{d\beta_{component_i}} \quad (7)$$

where β_{system} and $\beta_{component,i}$ represent the reliability index of the system and component *i*. Because the series system reliability index is a function of only the component reliability index, fastener sensitivity can be directly calculated as:

$$\frac{d\beta_{series}}{d\beta_{component_i}} = \frac{\prod_{1}^{n}\Phi\left(component_j\right)}{\varphi\left(\prod_{1}^{n}\Phi\left(component_j\right)\right)}\frac{\varphi\left(\beta_{component_i}\right)}{\Phi\left(\beta_{component_i}\right)} \quad (8)$$

where φ is the derivative of Φ. The reliability sensitivity in a parallel ductile system can be calculated using Eq. 9 in which sensitivity depends on faster reliability and mean fastener strength

$$\frac{d\beta_{parallel}}{d\beta_{component_i}} = \frac{\sqrt{\sigma_{R_i}^2 + \sigma_{P_i}^2}}{\sqrt{\sum_{1}^{n}\sigma_{R_j}^2 + \sum_{1}^{n}\sigma_{P_j}^2}} + \frac{\sqrt{\left(\sigma_{R_i}^2 + \sigma_{P_i}^2\right)^3}}{\sqrt{\left(\sum_{1}^{n}\sigma_{R_j}^2 + \sum_{1}^{n}\sigma_{P_j}^2\right)^3}}\frac{\sum_{1}^{n}\mu_{R_j} - \sum_{1}^{n}\mu_{P_j}}{\mu_{R_i} - \mu_{P_i}} \quad (9)$$

Since there is no analytical solution for β_{system} and $\beta_{component}$ in a parallel brittle system, Eq. 8 and Eq. 9 cannot be directly used for reliability sensitivity analysis in the parallel brittle system. A simulation-based approach and the general solution of sensitivity should be used, and computational cost is more expensive compared to that of a series system and parallel ductile system.

Series system reliability sensitivity analysis

Series system reliability sensitivity analysis is performed using the same information as shown in the basic system reliability calculation. Direct calculated and normalized sensitivity results using the ABAQUS load and scaled-up load are displayed in *Table 5*. It is observed that the reliability of the first fastener (upper left corner) dominates the overall system reliability, as would be expected for a series system.

Table 5 Sensitivity analysis for series system

	Demand, P_i (kips)		Scaled-up Demand, $2.74*P_i$ (kips)	
Fastener	Sensitivity	Normalized sensitivity	Sensitivity	Normalized sensitivity
1	6.73E-12	1.00E+00	3.55E-03	1.00E+00
2	9.01E-17	1.34E-05	9.31E-06	2.62E-03
3	2.74E-16	4.08E-05	1.75E-05	4.92E-03
4	6.27E-16	9.31E-05	2.77E-05	7.80E-03
5	1.22E-15	1.81E-04	4.00E-05	1.13E-02
6	2.15E-15	3.19E-04	5.47E-05	1.54E-02
7	3.73E-15	5.54E-04	7.40E-05	2.08E-02
8	7.06E-15	1.05E-03	1.05E-04	2.94E-02
9	1.20E-15	1.79E-04	3.98E-05	1.12E-02

Table 6 Sensitivity analysis for parallel ductile system

	Demand, P_i		Scaled-up Demand, $2.74*P_i$	
Fastener	Sensitivity	Normalized sensitivity	Sensitivity	Normalized sensitivity
1	7.13E-01	1.00E+00	7.62E-01	1.00E+00
2	6.51E-01	9.13E-01	6.39E-01	8.39E-01
3	6.56E-01	9.20E-01	6.47E-01	8.49E-01
4	6.59E-01	9.25E-01	6.53E-01	8.5E8-01
5	6.62E-01	9.30E-01	6.59E-01	8.65E-01
6	6.65E-01	9.33E-01	6.64E-01	8.72E-01
7	6.68E-01	9.37E-01	6.69E-01	8.78E-01
8	6.71E-01	9.42E-01	6.75E-01	8.86E-01
9	6.62E-01	9.29E-01	6.59E-01	8.65E-01

Parallel ductile system reliability sensitivity analysis

Parallel ductile system reliability sensitivity analysis is summarized in *Table 6* with direct calculated and normalized sensitivity results using ABAQUS loads and scaled-up loads. In the parallel ductile system, the normalized sensitivity of each fastener are almost on the same order of magnitude from the load sharing that occurs in a parallel ductile system, and the first fastener, being the one with minimum $\beta_{component}$, has a slightly larger impact to the whole system reliability.

Parallel brittle system reliability sensitivity analysis

Parallel brittle system reliability analysis has been performed. Direct calculated and normalized sensitivity results using scaled-up load are displayed in *Table 7*. In parallel brittle system, the first fastener has about a 16% higher impact on the whole system reliability.

Table 7 Sensitivity analysis for parallel brittle system

	Scaled-up Demand, $2.74*P_i$	
Fastener	Sensitivity	Normalized results
1	2.33E+00	1.00E+00
2	2.00E+00	8.57E-01
3	2.01E+00	8.60E-01
4	2.02E+00	8.65E-01
5	2.02E+00	8.64E-01
6	2.01E+00	8.63E-01
7	2.02E+00	8.66E-01
8	2.03E+00	8.70E-01
9	2.01E+00	8.60E-01

Conclusions

Wood-sheathed cold-formed steel floor sub-systems were modeled using the finite element software ABAQUS, with careful treatment of boundary conditions and kinematics. On the basis of the finite element analysis results, parallel and series analytical models were developed for the most critical fasteners. System reliability and reliability sensitivity were evaluated for these models. These values represent analytical bounds to the actual reliability and reliability sensitivity of the overall model, which will be used to re-align target component reliability indices for these systems. The new indices can potentially be used to recommend revised resistance factors consistent with the target system reliability index. The revised factors are expected to improve design safety and efficiency for structural sub-systems.

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