Aug 24th, 12:00 AM - Aug 25th, 12:00 AM

Improved Reliability Determination When Testing Cold-formed Steel Components

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Twenty-First International Specialty Conference on Cold-Formed Steel Structures
St. Louis, Missouri, USA, October 24 & 25, 2012

Improved reliability determination when testing cold-formed steel components

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Abstract

The objectives of this paper are to (a) determine the sensitivity of the reliability calculations in Chapter F of the AISI Specification (AISI-S100-07) to controlling load combinations and loading ratios, and (b) develop a more robust alternative for the use of Chapter F. To complete this study the bias factors and variances for all loading conditions are established. In addition, a range of practical load ratios is agreed upon. Parametric studies are performed to explore load case and load ratio dependency for use in the determination of the resistance factor, ϕ; specifically, the pre-factor term C_ϕ and the load variance term V_Q. The parametric studies are simplified into a table that provides load case dependent C_ϕ and V_Q factors. The table is recommended for use in Chapter F reliability analysis of new products.

Keywords: Reliability, cold-formed steel, load combinations, resistance factor.

Introduction

Chapter F of the AISI Specification (AISI-S100-07 [1]) provides a unique advantage for the cold-formed steel industry by providing codified reliability calculations for tested products. Neither hot-rolled steel, nor concrete, nor timber provides a direct, code adopted, means for manufacturers to determine the reliability of their product via testing. As a result, cold-formed steel enjoys much more certainty in how to proceed when bringing a new product to the marketplace. Further, the engineer is provided capacities as well as resistance (ϕ) or safety (Ω) factors that are intended to provide a consistent level of reliability for the new products when integrated with conventional member design. A drawback of the codified approach in Chapter F is that in some cases

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the process may be oversimplified, resulting in either lost economy or lost reliability. Specifically, the use of a single load combination (1.2*D* + 1.6*L*) and a single dead-to-live load ratio (*D/L* = 1/5), while convenient, may be in error. For example, common products such as hold-downs are not governed by the 1.2*D* + 1.6*L* load combination, nor assumed dead-to-live load ratio. This study investigates if the ϕ (or Ω) calculated from Chapter F is conservative, accurate, or unconservative.

Reliability as implemented in Chapter F is embodied in Eq. F1.1-2:

$$\varphi = C_{\varphi} M_m F_m P_m e^{-\beta_o \sqrt{V_M^2 + V_F^2 + C_P V_P^2 + V_Q^2}} \tag{1}$$

where C_{ϕ} is the calibration coefficient, M_m is the mean value of the material factor, F_m is the mean value of the fabrication factor, V_m is the coefficient of variation of the material factor, V_f is the coefficient of variation of the fabrication factor, β_0 is the reliability index, P_m is the mean value of the professional factor, C_P is a correction factor for sample size, V_p is the coefficient of variation for the test results, and V_Q is the coefficient of variation for the load effects. Eq. (1) originates, essentially, from Commentary Eq. C-A5.1.1-2 as follows:

$$\beta_o = \frac{\ln\left(R_m / Q_m\right)}{\sqrt{V_r^2 + V_Q^2}} \tag{2}$$

where, R_m is the mean resistance, Q_m the mean load effect (demand), and V_r is the coefficient of variation for the resistance. The derivation begins through introducing the notion of material (*M*), fabrication (*F*), and professional factors, (*P*), which connect the mean (subscript *m*) to the nominal (subscript *n*) via:

$$R_m = M_m F_m P_m R_n \tag{3}$$

and expands the coefficient of variation of the resistance as

$$V_r = \sqrt{V_M^2 + V_F^2 + V_P^2} \tag{4}$$

or for chapter F with sample effect:

$$V_r = \sqrt{V_M^2 + V_F^2 + C_P V_P^2} \tag{4a}$$

The mean demand is connected to the nominal loads as follows:

$$Q_m = c\sum Q_{mi} = c\sum B_i Q_i \tag{5}$$

where index *i* sums across all loads (e.g., D, L, W), *c* converts loads (e.g. 40 psf dead load) to load effects (e.g., compression force in a stud), and B_i is the bias factor between specified loads (Q_i) and mean loads (Q_{mi}).

Also, we must note that the coefficient of variation of V_Q is load combination dependent which may be expressed as follows:

$$V_Q = \frac{\sqrt{\sum\left(Q_{mi}V_{Qi}\right)^2}}{\sum Q_{mi}} = \frac{\sqrt{\sum\left(B_i Q_i V_{Qi}\right)^2}}{\sum B_i Q_i} \tag{6}$$

For design (at maximum load) the design capacity is equated to the factored demand (to reach the desired target reliability):

$$\phi R_n = c\sum \gamma_i Q_i \tag{7}$$

Substituting Equations (3, 4a, 5, and 7) into Equation (2) results in:

$$\beta_o = \frac{\ln\left(\left[M_m F_m P_m c\left(\sum \gamma_i Q_i\right)/\phi\right] \Big/ \left[c\sum B_i Q_i\right]\right)}{\sqrt{V_M^2 + V_F^2 + C_P V_P^2 + V_Q^2}} \tag{8}$$

and then solving Eq. (8) for ϕ:

$$\phi = \left[\sum \gamma_i Q_i\right] \Big/ \left[\sum B_i Q_i\right] M_m F_m P_m e^{-\beta_o\sqrt{V_M^2+V_F^2+C_P V_P^2+V_Q^2}} \tag{9}$$

which implies that the C_ϕ factor is

$$C_\phi = \left[\sum \gamma_i Q_i\right] \Big/ \left[\sum B_i Q_i\right] \tag{10}$$

For more discussion on the above derivations refer to [2]. The current specified values for C_ϕ (1.52) and V_Q (0.21) in chapter F of AISI S100-07 are based on one load combination case (1.2*D*+1.6*L*) with a specific value for load ratio (*L*/*D*=5). To show this, first we specialize Equation 10 to this case:

$$C_{\phi} = \frac{\left[\sum \gamma_i Q_i\right]}{\left[\sum B_i Q_i\right]} = \frac{1.2D + 1.6L}{B_D D + B_L L} \tag{11}$$

From [3] the bias factors are known: B_D=1.05, and B_L=1.0. Further, assuming L/D=5 one obtains:

$$C_{\phi} = \frac{1.2D + 1.6L}{B_D D + B_L L} = \frac{1.2 + 1.6 \times 5}{1.05 + 1.0 \times 5} = 1.52 \tag{12}$$

Similarly, for V_Q, from [3] V_D=0.1 and V_L=0.25, therefore:

$$V_Q = \frac{\sqrt{\sum \left(B_i Q_i V_{Qi}\right)^2}}{\sum B_i Q_i} = \frac{\sqrt{\left(B_D D V_D\right)^2 + \left(B_L L V_L\right)^2}}{B_D D + B_L L}$$
$$= \frac{\sqrt{\left(1.05 \times 0.1\right)^2 + \left(1.0 \times 5 \times 0.25\right)^2}}{1.05 + 1.0 \times 5} = 0.21 \tag{13}$$

Given the large number of possible load cases and load ratios it is desired to explore the sensitivity of C_{ϕ} and V_Q. The statistics for the bias factors and coefficient of variation of the loads are largely available [3] and are utilized in the work presented here.

Load combinations

Based on ASCE7-05 [4] the following load combinations should be considered when designing structural members:

(1) *1.4D*
(2) *1.2D+1.6L*
(3) *1.2D+1.6L+0.5S*
(4) *1.2D+1.0L+1.6S*
(5) *1.2D+1.0L+1.6W+0.5S*
(6) *1.2D+L+0.2S+E*
(7) *0.9D-1.6W*
(8) *0.9D-1.0E*

where Dead (*D)*, Live (*L)*, Snow (*S)*, Wind (*W)*, and Earthquake (*E*) loads are defined in ASCE 7. Note, the effects of these loads on the demands of a component, are the focus of this work.

Bias factor and coefficient of variation

Five load types including Dead, Live, Snow, Wind, and Earthquake appear in the preceding load combinations. The bias factor (B_i) and coefficient of variation (V_{Qi}) for these load types are provided in Table 1.

Table 1: Coefficient of variations and bias factors

	Dead	Live	Wind	Snow	Earthquake
V_{Qi}	0.1	0.25	0.37	0.26	1.38
B_i	1.05	1.0	0.78	0.82	1.0

Earthquake load in ASCE 7, as developed in [5] has a significantly larger return period (2500 years) compared to the return period of other load types (50 years). Although current design directly compares earthquake load combinations to other load combinations this reflects current practice more than an attempt at risk neutral decision-making. The high variability of earthquake demands and the selection of different expectations for annual probability of failure greatly complicate the analysis. Therefore, although earthquake loads are included in this study, further investigation is needed.

Load ratios

To explore the sensitivity of the reliability analysis expected ratios between the loads must be determined. This is not the direct ratio of the load itself, but rather the load effect. Here, all load ratios are defined as the magnitude of the load effect of one load over the dead load effect (i.e., abbreviated as $\alpha_L=L/D$, $\alpha_W=W/D$, …). In a typical structure the load effect of dead and live loads are similar because they share a similar distribution and direction on the structure resulting in bending in the beams, compression in the columns, etc. As a result essentially the L/D ratio follows the magnitude of the L and D loads themselves. Self-weight plays a large role in this case and thus material standards generally adopted target L/D ratios based on ideas related to self-weight of members. For lateral loads the load effect is more complicated, within the same structure a W load creates high demands in some members and low demands in others – considering overall overturning W demands create load effects from tension to compression. Thus, W/D ratios vary greatly within a structure. In this study, motivated in part by [3, 6, 7], a uniform distribution is assumed for all load ratios ranging from 0 to 5 (Figure 1).

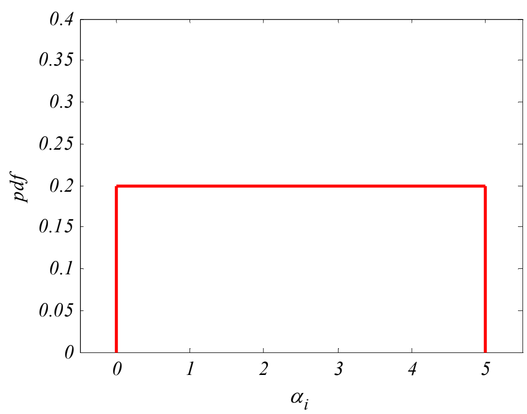

Figure 1: Probability distribution function for load ratios (magnitude of each load normalized by dead load)

Parametric study

A parametric study using Monte Carlo simulation is performed. The load ratios: α_L, α_W, α_S, α_E are modeled as independent uniform random variables over the interval 0 to 5. A realization of the α are created, and based on the resulting *L/D*, *W/D*, *S/D*, *E/D* the controlling load combination is determined. Based on the controlling load combination the values for C_ϕ and V_Q are found through Equations 6 and 10. The process is repeated for the desired number of samples.

Results

Monte Carlo simulation using 10,000 randomly generated load effects is performed for C_ϕ and V_Q. Results for the gravity load cases are provided in Figure 2 and the lateral load cases in Figure 3.

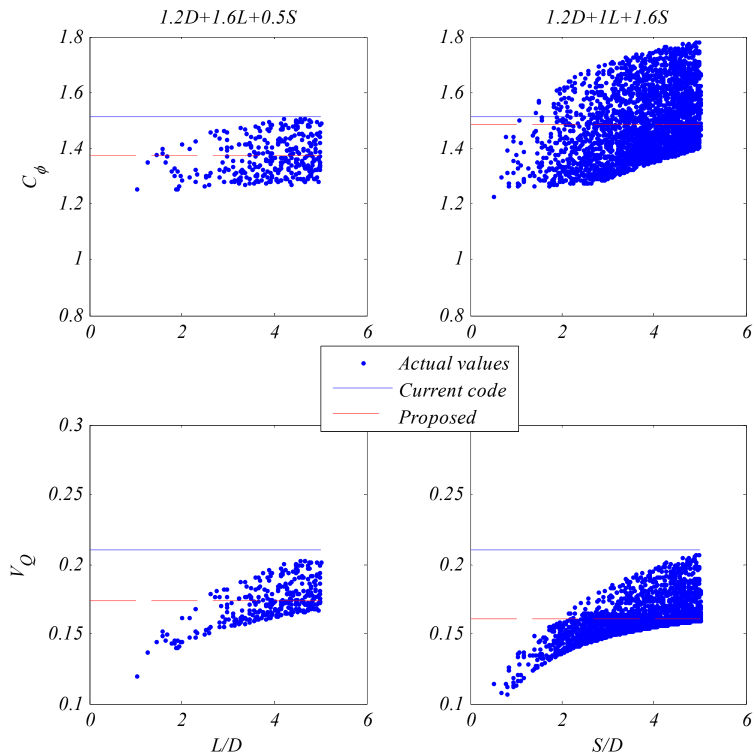

Figure 2: C_ϕ and V_Q in case with load combinations (3) and (4) controlling

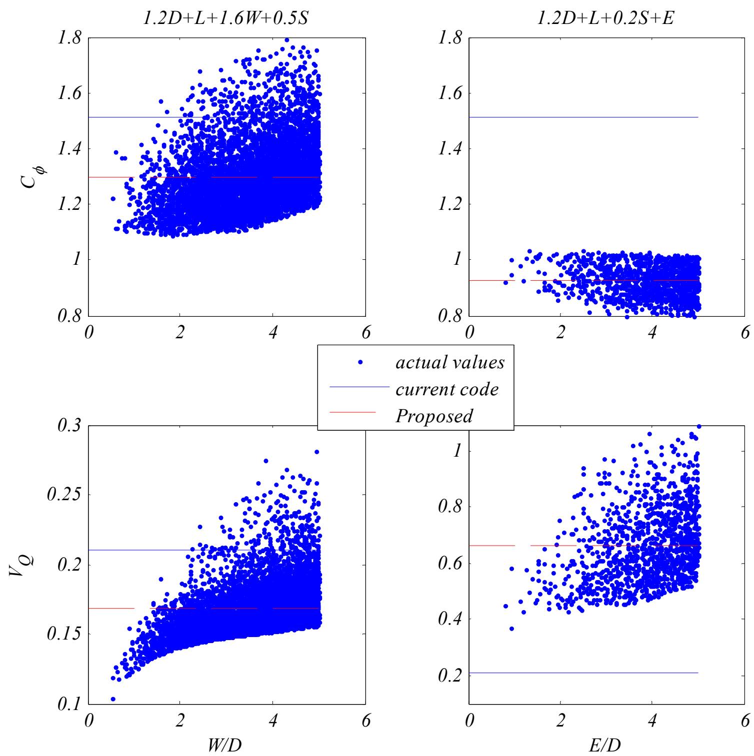

Figure 3: C_ϕ and V_Q in case with load combinations (5) and (6) controlling

Load combination (1) controls a member's design only when dead load is significantly bigger than all other loads. This case does not happen in any of the studied cases. However, it may be easily studied since the load ratios do not affect the calculations in this load case (There is only one load type). C_ϕ based on Eq. (10) is:

$$C_\phi = \frac{1.4D}{1.05D} = 1.33 \tag{14}$$

and

$$V_Q = V_D = 0.1 \tag{15}$$

Load combination (2) is smaller than load combination (3) as long as snow load exists. In the studied cases, the load ratios were generated randomly, therefore, snow load was never exactly zero. This means that load combination (2) is never the controlling case. This load combination is studied separately for varying *L/D* ratios and the results for C_ϕ and V_Q are plotted in Figure 4. As depicted, for *L/D* ratios at 5, which is the assumption in AISI-S100, the results for C_ϕ and V_Q match those specified in AISI-S100.

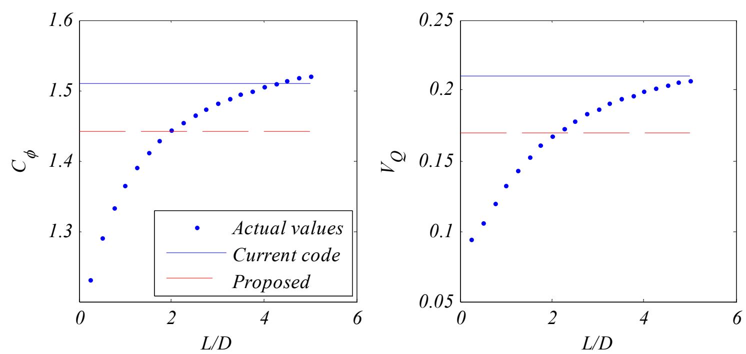

Figure 4: Cϕ and VQ in cases that load combination (2), 1.2D+1.6L controls

Load combinations (7) and (8) correspond to load effect reversal cases, i.e. cases in which wind or earthquake have a counteracting effect to the gravity load. These cases are studied separately and values for C_ϕ and V_Q are provided in Figure 5. For load effect reversal cases with low values of *W*/*D* (α_W) or *E*/*D* (α_E) this implies only a small load effect reversal (unlikely to control in design), and therefore more importance is given to higher values of *W*/*D* or *E*/*D* and the proposed C_ϕ and V_Q are chosen from these higher values. The proposed C_ϕ and V_Q are selected to be reasonably conservative.

For each load case the proposed values for C_ϕ and V_Q are tabulated in Table 2. These values are proposed for use in design.

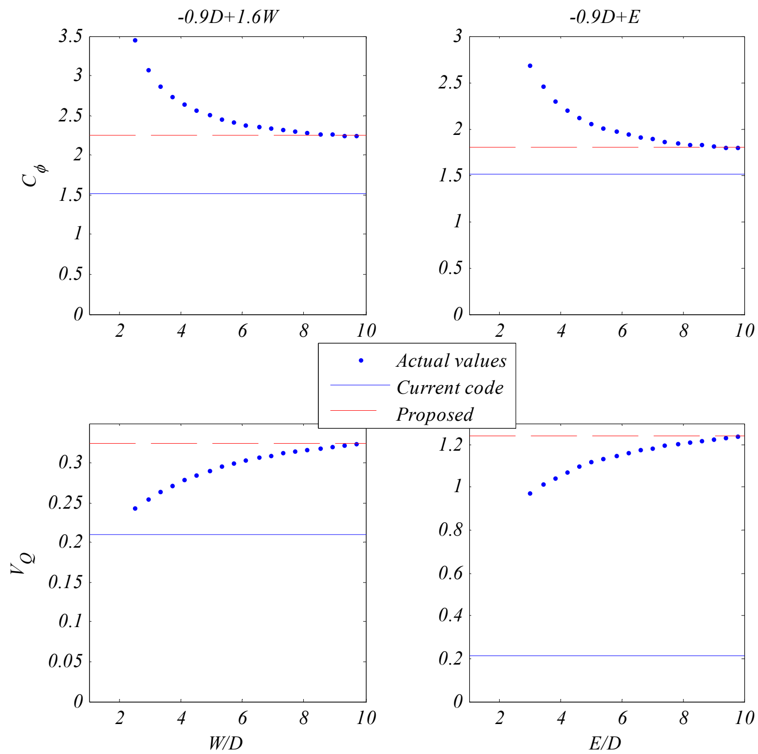

Figure 5: C_ϕ and V_Q in case of reverse load combinations

Table 2: Proposed values for C_ϕ and V_Q

	C_ϕ	V_Q
Current code values	1.52	0.21
1.4D	1.33	0.10
1.2D+1.6L	1.44	0.17
1.2D+1.6L+0.5S	1.35	0.17
1.2D+1.0L+1.6S	1.49	0.16
1.2D+1.0L+1.6W+0.5S	1.30	0.17
1.2D+1.0L+0.2S+1.0E	0.92	0.66
0.9D-1.6W	2.24	0.33
0.9D-1.0E	1.79	1.24

Note, for load combinations with load reversal asymptote values of C_ϕ and V_Q are selected (see Figure 5), for all other load combinations mean values are selected.

Example

In this section reliability determination based on AISI-S100-07 Chapter F is compared to modifications based on Table 2. The selected example is based on a CFSEI Technical Note illustrating the use of Chapter F for powder driven pins used in cold-formed steel connections that are not included in Chapter E of the specification [8]. In this case test results combined with a Chapter F analysis to calculate the resistance (safety) factor is used for these components. For a powder driven pin the following values have been used in CFSEI G100-07 to calculate the resistance factor (ϕ) from Eq. (1).

M_m=1.10

V_m=0.1

F_m=1.0

V_F=0.15

P_m=1.0

C_p=1.94

V_p=0.065

and based on the Chapter F, C_ϕ and V_Q are as follows:

C_ϕ=1.52

V_Q=0.21

Consequently, the resistance factor is determined as ϕ=0.60.

To compare this calculation to an actual case (i.e. with known demands), a hypothetical connection example in which powder driven pins replace self-drilling screws is explored. The example is chosen from the two-story ledger framed building designed for the CFS-NEES project (see calculation of loads on roof joists in Madsen et al. [9]). These connections are provided for a clip angle connecting the roof joists to the ledger as shown in Figure 6, the loading consists of pressure (p) from dead, live, and wind loads and concentrated live loads:

p_D = 20 psf

p_L = 20 psf

p_W = 14.1 psf

The demand in terms of shear on the connection is:

$$D = \frac{wl}{2} p_D,\ L = \frac{wl}{2} p_L + P_L,\ \mathrm{W} = \frac{wl}{2} p_W \tag{16}$$

where, w is the tributary width of the joist (24 in.), l is the length of the joist (22 ft) and P_L is a concentrated live load (150 lb). This results in a connection shear demand and the portions of the shear load due to dead, live and wind load are found as: D=440 lb, L=590 lb and W=310 lb.

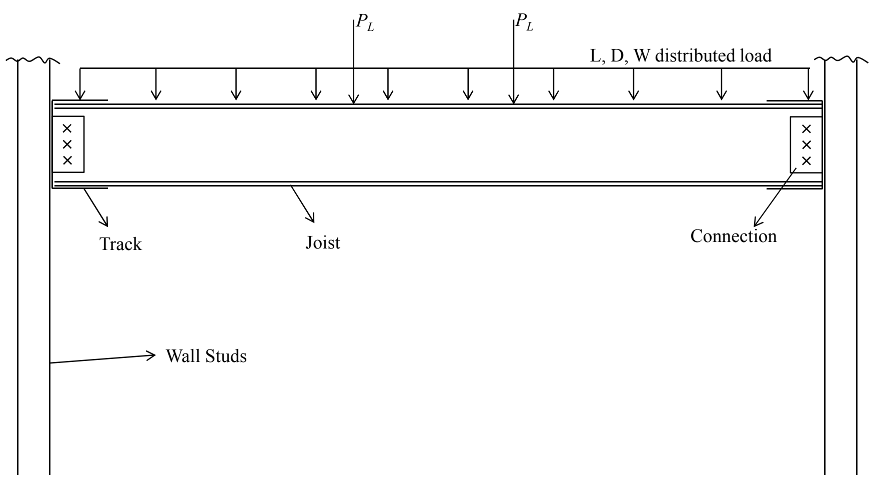

Figure 6: The example connection in which powder driven pins may be used

The controlling load combination is 1.2D+1.0L+1.6W. For this load case (without S) C_ϕ and V_Q may be calculated employing Eqs. (10) and (6):

C_ϕ=1.25

V_Q=0.14

C_ϕ and V_Q are significantly different than the code's values. From Eq. 9 the resistance factor is found to be ϕ=0.58. The difference in ϕ is real, but small. For the same load case, the proposed approach (Table 2) predicts ϕ=0.57 which is more precise than the current Ch. F values. Several other load cases in the same basic demand range are examined and the resistance factors obtained from the proposed method (C_ϕ and V_Q of Table 2) are compared in Table 3.

Table 3: Comparison of current and proposed f factors for design example

Demands (lb)	Controlling load Combination	Actual	Current Ch. F		Proposed	
		ϕ	ϕ	%Error	ϕ	%Error
D=440 L=440 W=880	1.2*D*+*L*+1.6*W*	0.64	0.60	-6	0.57	-12
D=440 L=1100 W=440	1.2*D*+*L*+1.6*W*	0.55	0.60	+10	0.57	4
D=440 L=440 S=880	*1.2D+1.0L+1.6S*	0.69	0.60	-12	0.67	-3
D=440 L=2200 W=880	1.2*D*+*L*+1.6*W*	0.53	0.60	+15	0.57	8
D=440 W=2640	-0.9D+1.6W	0.74	0.60	-19	0.65	-12

Based on this example it is clear that load case dependent resistance factors (i.e. load case dependent C_ϕ and V_Q) have the potential to provide increased accuracy and in load reversal cases increased economy.

Potential variations for resistance factor:

The resistance (ϕ) factors of Table 3 provide potential variation in ϕ for specific examples. In this section the variation in expected ϕ based on 10,000 samples from the loading scenarios previously explored: L/D, W/D, S/D, E/D modeled as independent uniform random variables over the interval 0 to 5 is completed. With this study one can directly see the impact of adopting the proposed C_ϕ and V_Q on the resistance factor across all expected load cases. Table 4 provides the resulting statistics and Figure 7 visually summarizes the predicted ϕ and scatter.

Table 4: Resistance factor (ϕ) based on parametric study

Load Combination	Sample mean	Sample std. dev.	Current Ch. F	Proposed method	% Diff. from Ch. F
(1) *1.4D*	0.67	-	0.60	0.67	+12
(2) *1.2D+1.6L*	0.63	0.013	0.60	0.63	+ 5
(3) *1.2D+1.6L+0.5S*	0.59	0.015	0.60	0.59	- 2
(4) *1.2D+1.0L+1.6S*	0.66	0.043	0.60	0.66	+10
(5) *1.2D+1.0L+1.6W+0.5S*	0.57	0.032	0.60	0.57	- 5
(6) *1.2D+1.0L+0.2S+1.0E*	0.10	0.040	0.60	0.09	-85
(7) *0.9D-1.6W*	0.79	0.165	0.60	0.65	+ 8
(8) *0.9D-1.0E*	0.04	0.019	0.60	0.02	-97

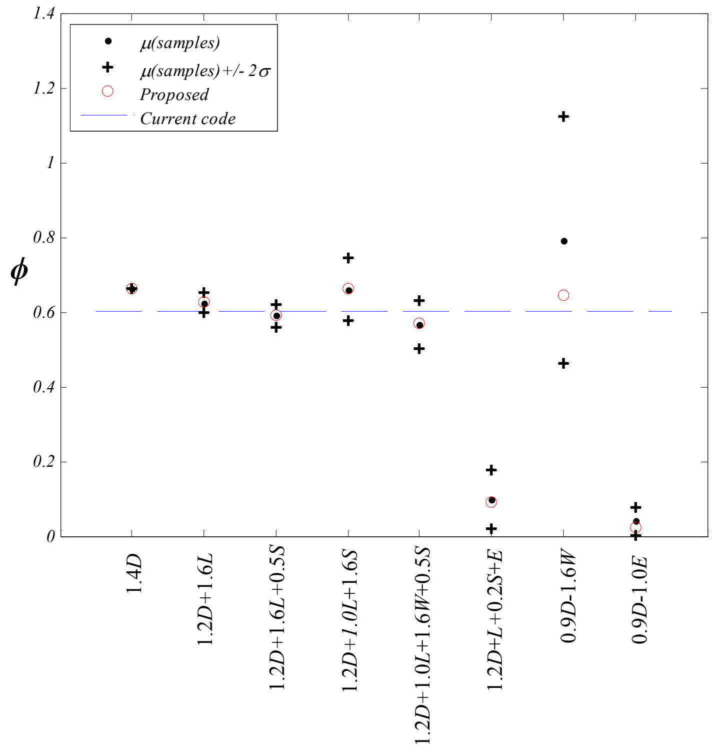

Figure 7: Comparison of resistance factors obtained from parametric study with those based on the current Ch. F of AISI-S100 and those based on proposed C_ϕ and V_Q as given in Table 2.

For load combinations 2, 3, and 5; i.e., when *L* or *W* are dominant the change in ϕ is ±5% and likely not great enough to be significant. For load combinations 1 and 4 when *D* and *S* are dominant the change is +10% to +12% and it may be economically advantageous to adopt the correct load combination. For load combination 7, when *W* is causing a load reversal, the reliability factor determined using the proposed C_ϕ and V_Q is +8% higher suggesting for devices that only see tension due to wind load reversal additional economies may be gained through this correction. For earthquake (E) load combinations the statistical basis is too different to provide meaningful results (as previously discussed).

Discussion

The uniform C_ϕ and V_Q from AISI-S100 Chapter F are generally conservative and do a reasonable job of covering the majority of load ratios for the determination of the resistance factor (ϕ). The major exception is seismic load combinations, but these follow a different design basis and should be treated separately. Additional work on seismic load combinations is needed.

Determining the governing load case for a tested product can be challenging; however, if the product function is specific and thus the governing load combination clear then additional economies may potentially be realized through load combination dependent C_ϕ and V_Q. This conclusion is sensitive to the load ratios studied, and here a rather brute force approach is utilized with uniform load ratios. A more robust method would examine archetype buildings and structures and determine the expected loads on key components. Such a study would be beneficial for a focused assessment of the developed C_ϕ and V_Q.

Conclusions

A parametric study is performed to evaluate the accuracy of the current codified procedure for the determination of the reliability of tested cold-formed steel products via AISI S100-07 Chapter F. The effect of different load combinations and different load ratios on key load dependent parameters (C_ϕ and V_Q) utilized in developing the component resistance factor (ϕ) is investigated. For most load combinations expected C_ϕ and V_Q differ significantly from the specified values in AISI-S100-07 Chapter F. However, in many cases the inaccuracies in C_ϕ and V_Q are counter-acting and the resulting resistance factor is within ±5% of AISI-S100-07. However, when dead or snow load dominates or wind load reversal occurs modest improvements in economy (~ +10% on ϕ) may be realized through the more accurate C_ϕ and V_Q. These conclusions do not apply to seismic load combinations, which are under a different design basis. The developed C_ϕ and V_Q are recommended for use in developing resistance factors.

Acknowledgements

The authors would like to thank Bruce Ellingwood for his discussions related to this work. The authors would like to thank the American Iron and Steel Institute and the Steel Deck Institute for partial funding that led to this work. Any opinions, findings, and conclusions or recommendations expressed in this publication are those of the author(s) and do not necessarily reflect the views of the American Iron and Steel Institute or Steel Deck Institute.

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