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Impact of load combinations on structural reliability determined from testing cold-formed steel components

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ABSTRACT

The objective of this paper is to explore the impact of load combinations on the method used to assess the structural reliability of cold-formed steel components determined by testing. Chapter F of the AISI Specification (AISI-S100-07) provides a means to determined the resistance, ϕ or (safety, Ω) factor of cold-formed steel components by direct testing. The procedure uses the standard (United States) Load and Resistance Factor Design format, but simplifies the load side to a single load combination and single dead-to-live load ratio. The impact of this assumption on the resulting component reliability is the focus of this work. To complete the work the bias factors and variances for all loading conditions are established. In addition, a range of practical load ratios, for all loads, is assumed. 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. Design examples demonstrating the impact of current methods and the load combination dependent solution are provided.

1. Introduction

Broadly speaking, currently code-based reliability of structural components is handled through first order second moment-based reliability procedures that utilize target reliabilities and experimental or other simulation data to provide resistance factors for a given limit state. Extensive studies were performed to calibrate and arrive at the resistance factors in current use. For example, the resistance factors for the North American cold-formed steel specification [1] are developed in [2]. Chapter F of the AISI Specification (AISI-S100-07 [1]) provides a unique alternative to the prescriptive resistance factors. An engineer may instead perform tests, and from these tests and an assumed target reliability, directly determine the nominal strength as well as resistance, ϕ (or safety, Ω) factors for use in design.

Such a test-based reliability procedure provides a unique path to enable components for use in design. In cold-formed steel light steel framing, joist clip connections, shear wall hold downs, and numerous other components have followed this path. This path provides certainty for developers of new solutions in structural applications and at least in the experience of cold-formed steel design has positively impacted the creation of new products and shortened the time to market for such products.

A potential drawback of the test-based reliability procedure codified in Chapter F of AISI-S100 is that it may be oversimplified, resulting in either lost economy or lost reliability. Specifically, the use of a single load combination ($1.2D + 1.6L$) 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 $1.2D + 1.6L$ load combination, nor the assumed dead-to-live load ratio. This paper explores if the ϕ (or Ω) calculated from Chapter F is conservative, accurate, or unconservative.

Reliability, as implemented in AISI-S100 is embodied in Eq. F1.1–2:

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

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 target reliability, 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 AISI-S100 Commentary Eq. C-A5.1.1–2, as follows:

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

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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 AISI-S100 Chapter F with sample size effect included:

$$V_r = \sqrt{V_M^2 + V_F^2 + C_P V_P^2} \tag{5}$$

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

$$Q_m = c\sum Q_{mi} = c\sum B_i Q_i \tag{6}$$

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:

$$V_Q = \frac{\sqrt{\sum (Q_{mi} V_{Qi})^2}}{\sum Q_{mi}} = \frac{\sqrt{\sum (B_i Q_i V_{Qi})^2}}{\sum B_i Q_i} \tag{7}$$

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

$$\phi R_n = c\sum \gamma_i Q_i \tag{8}$$

Substituting Eqs. (3), (5), (6) and (8) into Eq. (2) results in:

$$\beta_o = \frac{\ln([M_m F_m P_m c(\sum \gamma_i Q_i)/\phi]/[c\sum B_i Q_i])}{\sqrt{V_M^2 + V_F^2 + C_P V_P^2 + V_Q^2}} \tag{9}$$

and then solving Eq. (9) for ϕ:

$$\phi = \frac{[\sum \gamma_i Q_i]}{[\sum B_i Q_i] M_m F_m P_m e^{-\beta_o \sqrt{V_M^2 + V_F^2 + C_P V_P^2 + V_Q^2}}} \tag{10}$$

which implies that the C_ϕ factor from Eq. (1) is

$$C_\phi = \frac{[\sum \gamma_i Q_i]}{[\sum B_i Q_i]} \tag{11}$$

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 the load combination case 1.2D + 1.6L with a load ratio L/D = 5, To demonstrate, consider Eq. (11):

$$C_\phi = \frac{[\sum \gamma_i Q_i]}{[\sum B_i Q_i]} = \frac{1.2D + 1.6L}{B_D D + B_L L} \tag{12}$$

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

$$C_\phi = \frac{1.2D + 1.6L}{B_D D + B_L L} = \frac{1.2 + 1.6 \times 5}{1.05 + 1.0 \times 5} = 1.52 \tag{13}$$

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

$$V_Q = \frac{\sqrt{\sum (B_i Q_i V_{Qi})^2}}{\sum B_i Q_i} = \frac{\sqrt{(B_D D V_D)^2 + (B_L L V_L)^2}}{B_D D + B_L L} = \frac{\sqrt{(1.05 \times 0.1)^2 + (1.0 \times 5 \times 0.25)^2}}{1.05 + 1.0 \times 5} = 0.21 \tag{14}$$

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.

Table 1
Coefficient of variations and bias factors.

	Dead	Live	Wind		Snow	Earthquake
			7-05	7-10		
V_{Qi}	0.1	0.25	0.37	0.37	0.26	1.38
B_i	1.05	1.0	0.92	0.575	0.82	α

2. Load combinations

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

ASCE7-05
(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 ASCE7. Note, the effects of these loads on the demands of a component, are the focus of this work. When the live load is less than 100 psf (common in cold-formed steel structures), the coefficient for live load in combinations (4), (5), and (6) is allowed to be 0.5 instead of 1.0. The effect of this exception is discussed later. In ASCE7-10, load combinations 5 and 7, which include wind load, are modified as follows:

ASCE7-10 Changes
(5) 1.2D + 1.0L + 1.0W + 0.5S
(7) 0.9D − 1.0W

3. 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.

Dead, Live, and Snow loads have a return period of 50 years based on ASCE7. This is equivalent to 2% probability of occurrence in a year. The bias factors available in the literature [3,5,6] for all these loads are based on the mean recurrence interval (MRI) of 50 years. The return period for Earthquake and Wind in ASCE7-10 is different and therefore an adjustment is required.

The determination of wind load has significantly changed form ASCE7-05 to ASCE7-10. The mean recurrence interval is now 700 years instead of 50 years. This causes the wind load coefficient of 1.6 in ASCE7-05 to change to 1.0 in ASCE7-10. In this study, the bias factor for wind load available in literature, which is for a 50-year return period, is adjusted (divided to 1.6) to account for this change in ASCE7-10 wind load.

Earthquake load in ASCE7, as developed in [7] has a different probability of occurrence to the other load types. In fact, the mean earthquake load in ASCE7 is based on a ground motion with 10% probability of occurrence in 50 years. This is equivalent to a return period of 475 years. This ground motion can be scaled to a ground motion with 50 years return period as follows [8].

$$S_i = S_{i10/50}\left(\frac{P_R}{475}\right)^n$$