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Reliability analysis of welded and bolted connections in cold-formed steel sections

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Abstract

This article shows a study of the level of reliability of welded and bolted connections in cold formed steel members, for some limiting states, adopted by AISI and Brazilian codes. The aim of this study is the assessment of the reliability index β for a variation of the nominal live-to-dead load ratios as well as comparison of the value found considering different load combinations. The first order reliability method is used to calculate the reliability index β. In this study, reliability indices smaller than 3.5 were obtained, especially for bolted connections. Consideration of the model errors and FORM method, lead to significant reductions in reliability indices, which are found to be less than the recommended target reliability levels.

Keywords: cold-formed steel, reliability index, calibration, structural reliability.

1. Introduction

Welding and bolted fastening are the two most common types of connections in steel construction. These connections may be designed in accordance with the Limit State Design (LSD). In this method, separate load and resistance factors are applied to specified loads and nominal resistances to ensure that the probability of reaching a limit state is acceptably small. The same concept is also known as Load and Resistance Factor Design (LRFD) in the United States. The AISI Standard (2007) provides an integrated treatment of LRFD and LSD. The AISI LRFD strength prediction approach uses the following values for nominal live-to-dead load ratio (L_n/D_n), the load combination and the target reliability index (β_o): L_n/D_n = 5, 1.2Dn+1.6Ln, β_o = 3.5. For AISI LSD, the parameters used are: L_n/D_n = 3, $1.25D_n+1.5L_n$, β_o = 4.0. While the LRFD method is used in the United States and Mexico, Canada adopts the LSD method. It is to be noted that while the design philosophy used for LRFD and LSD is the same, the two methods differ in the load factors, load combinations, assumed live-to-dead load ratios and the reliability indices. The First-Order Second-Moment (FOSM) reliability analysis model was used for calibration of resistance factors used in the AISI Specification for cold-formed steel members.

This study shows a study of the level of reliability of cold-formed steel (CFS) welded and bolted connections, designed according to the Brazilian Standard (NBR 14762, 2010). The aim of this study is the assessment of the reliability index β for two different load combinations: (i) $1.2D_n+1.6L_n$ (AISI, 2007) and (ii) $1.25D_n+1.5L_n$ (AISI, 2007; NBR 14762, 2010), and two nominal live-to-dead load ratios (L_n/D_n) of 5 and 3 (AISI, 2007). Statistical data used for this study were obtained from the measured mechanical and sectional properties and from test-to-prediction ratios of the available experimental results. The results were compared with the target reliability index (β_o) of 3.5, the same levels used in AISI LRFD. Then, reliability indices were obtained for L_n/D_n ratio ranging 1 from 10, and compared with the results by FOSM method obtained from Brandão (2012). The First-Order Second-Moment (FOSM) and First-Order Reliability Methods (FORM) were used to assess the reliability indices.

2. Probabilistic methods

According to AISI (2007) and NBR 14762 (2010) the structural safety verification, for one particular reliability level, is done by the limit state concept. Reliability is the probability of a structure properly performing the functions for which it was designed over a given time. The structural reliability is normally evaluated using two measures (Ditlevsen and Madsen, 1996), related by equation:

$$P_f = \Phi(-\beta) \tag{1}$$

where β is the reliability index, P_f is the failure probability, and Φ represents the cumulative distribution of a standard normal variable.

In general, the failure probability can be determined using: accurate analytical integration, numerical integration methods, approximate analytical methods (like FORM and FOSM methods) and simulation methods.

Hasofer and Lind (1974) introduced the idea of the First-Order Reliability Method (FORM) in the early 70s in structural engineering. In its original form, the Hasofer-Lind method is applicable to problems with uncorrelated normal random variables. The corresponding reliability index is defined as the minimum distance from the origin of the reduced coordinate system to the performance function, and can be expressed as:

$$\beta_{HL} = \sqrt{(x'^*)^T (x'^*)} \tag{2}$$

where (x'^*) is the point of the performance function closest to the origin in reduced coordinates, named design point. In this definition, the original coordinate system $X=(x_1, x_2, ..., x_n)$ is transformed into a reduced coordinate system $X'=(x'_1, x'_2, ..., x'_n)$ according to Equation 3.

$$X'_i = \frac{X_i - \mu_{X_i}}{\sigma_{X_i}} \tag{3}$$

For nonlinear performance functions, the minimum distance calculation is an optimization problem, defined by β_{HL} minimization, with the constraint condition $g(x) = g(x') = 0$. It is possible to consider the correlation between random variables in the value of the reliability index. The FORM Method of Hasofer and Lind was further developed by Rackwitz and Fiessler (1976). Thus, for random variables with non-normal distributions, the Rackwitz-Fiessler method was used to transform the variable distribution into an equivalent normal distribution.

In the First-Order Second Moment (FOSM method), the information of the random variable distribution is ignored (Hsiao, 1989). The performance function is linearized by the first-order approximation of a Taylor series development, evaluated at the mean values of the random variables, using the statistical moments up to the second order (mean and variance values).

3. Performance function and statistical data

The performance function can be represented as follows:

$$g(.) = R_n MFP - (D + L) \tag{4}$$

R_n in this equation is the nominal resistance based on the model used to best predict the resistance, and on the nominal material properties and nominal geometric properties. M, F, P, D and L are random variables.

M and F (M defining "material" and F "fabrication") denote ratios of actual to nominal material properties and cross-sectional properties. The values for the mean and variation coefficient (V) were adopted in this study and were taken from Table F1 - Statistical Data for the Determination of Resistance Factor in AISI Specification (AISI, 2007).

The factor P is the ratio of test capacities, representing actual in-situ performance, to the prediction according to the model used. The modeling of the capacity is thus defined by P (P standing for "professional"). The tested failure loads for welded connections were obtained from McGuire and Peköz (1979), Teh and Hancock (2005) and Zhao *et al.* (1999), while the tested failure loads for bolted connections were obtained from Maiola (2004) and Sheerah (2009). The predicted values were computed according to the design formulas obtained from Brazilian Standard (NBR 14762, 2010), which are identical to the AISI (2007), for the analyzed cases. The Kolmogorov-Smirnov adherence test was used to assess the statistical adjustment of the PDFs to the data series of P. D is dead load, and L is live load. The statistics for these random variables in Eq. (4) are summarized in Table 1 (Ellingwood and Galambos, 1982; Ellingwood *et al.* 1980).

Load Type	Mean/Nominal	Coefficient of Variation	probability density function (pdf)
Dead Load (D)	$D_m/D_n = 1.05$	$V_D=0.10$	Normal
Live Load (L)	$L_m/L_n = 1.00$	$V_L=0.25$	Gumbel

Table 1
Dead and live Load statistics.

4. Reliability analysis

A total of 521 tests were used in this reliability analysis. The tested failure loads, were obtained from references previously mentioned. The predicted values were computed according to the design formulas in AISI Standard and Brazilian Standard. The number of specimens (n), mean values (P_m), and the coefficients of variation (V_p), and probability density functions (pdf) are listed in Table 2. The resistance factors, ϕ for AISI Standard and γ for Brazilian Standard, are also included in this table. The relationship between ϕ and γ in these cases is defined as follows: ϕ=1/γ.

4.1 Welded Connections

For welded connections, the reliability indices (β) computed for longitudinal and transverse loading are listed in Table 3. Herein, β was calculated for two different load combinations: (i) $1.2D_n+1.6L_n$ (AISI, 2007) and (ii) $1.25D_n+1.5L_n$ (AISI, 2007; NBR 14762, 2010), and two live-to-dead load ratios (L_n/D_n) of 5 and 3 (AISI, 2007). The FORM was used to assess the reliability indices. It can be seen that for all cases, the Reliability Indices β_{FORM} values are lower than the target of 3.5.

By using different γ factors for different cases, the values of β vary from 2.99 to 3.47 and the target β_o is 3.5. For Longitudinal Flare-Bevel Welds, by using the load combination (i) and L_n/D_n=5, the value of β was found to be 3.4, which is close to the target of 3.5.

Figures 1 to 5 show the reliability indices, which were obtained for L_n/D_n ratio ranging 1 to 10, and compared with the results from the FOSM method. The FOSM and FORM Methods were used to assess the reliability indices.

It is noted that the values obtained from the FOSM Method are higher than the values obtained from the FORM Method. By using the FOSM Method, values similar to Brandão (2012) were obtained. In general, the curves obtained for each of the cases are similar but with a gap between them.

By the calibration of the welded connections cases, with the target reliability index of 3.5, the load ratio L_n/D_n of 5 and the load combination (ii), resistance factors varying from 1.9 to 2.2 were obtained.

Table 2
Failure modes, statistical data and resistance factor.

Case	Failure modes	References	n	P_m	V_P	pdf	γ	ϕ
	Welded Connections							
1	Longitudinal Fillet Welds (L/t<25)	McGuire and Peköz (1979), Teh and Hancock (2005) and Zhao et al. (1999)	51	0.93	0.11	Normal	1.65	0.60
2	Longitudinal Fillet Welds (L/t≥25)	McGuire and Peköz (1979), Teh and Hancock (2005)	29	0.80	0.11	Normal	2.00	0.50
3	Transverse Fillet Welds	McGuire and Peköz (1979), Teh and Hancock (2005)	79	0.98	0.11	Normal	1.55	0.65
4	Transverse Flare-Bevel Welds	McGuire and Peköz (1979), Teh and Hancock (2005)	56	1.00	0.15	Normal	1.65	0.60
5	Longitudinal Flare-Bevel Welds	McGuire and Peköz (1979), Teh and Hancock (2005)	30	0.90	0.13	Gumbel	1.80	0.55
	Bolted Connections							
6	Bearing (sheets)	Maiola (2004)	184	0.91	0.27	Lognormal	1.55	0.65
7	Bearing (angle and cannel sections)	Maiola (2004)	39	1.03	0.28	Lognormal	1.55	0.65
8	Spacing and edge distance	Sheerah (2009)	53	0.98	0.19	Gumbel	1.45	0.70

Table 3
Computed Reliability Index β for Welded Connections.

Case	(i) $1.2D_n + 1.6L_n$		(ii) $1.25D_n + 1.5L_n$	
	$L_n/D_n = 3$	$L_n/D_n = 5$	$L_n/D_n = 3$	$L_n/D_n = 5$
	Reliability Indices β_{FORM}			
1	3.18	3.13	3.05	2.98
2	3.32	3.27	3.19	3.12
3	3.12	3.07	2.99	2.92
4	3.27	3.23	3.15	3.09
5	3.47	3.40	3.33	3.24

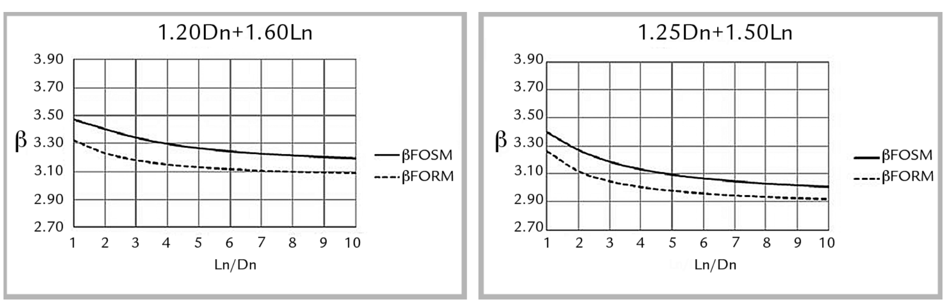

Figure 1
Reliability Index β vs. L_n/D_n ratio for Longitudinal Fillet Welds (L/t < 25).

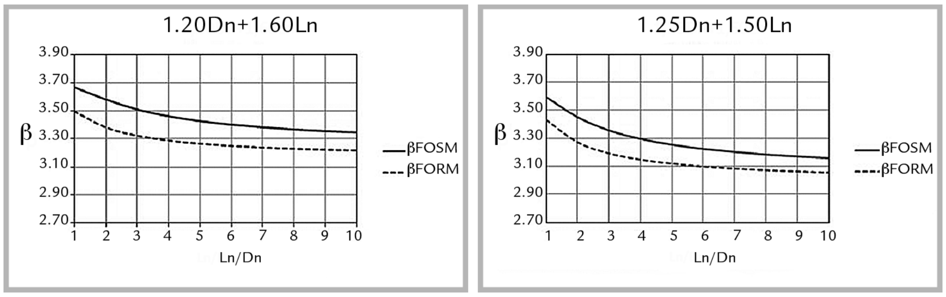

Figure 2
Reliability Index β vs. L_n/D_n ratio for Longitudinal Fillet Welds (L/t ≥ 25).

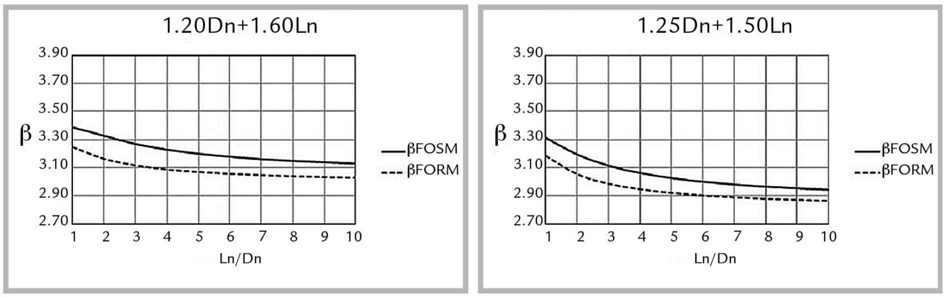

Figure 3
Reliability Index β vs. L_n/D_n ratio for Transverse Fillet Welds.

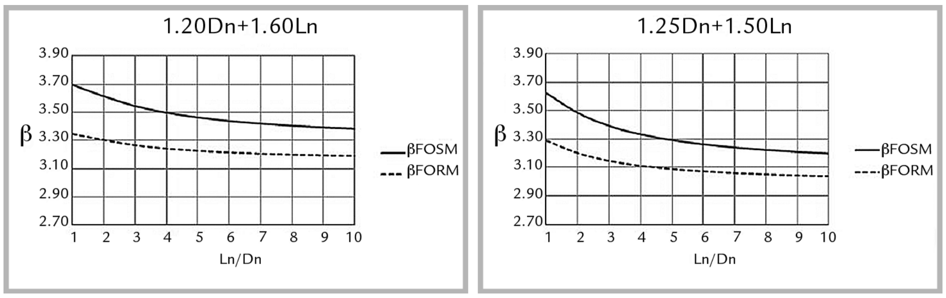

Figure 4
Reliability Index β vs. L_n/D_n ratio for Transverse Flare-Bevel Welds.

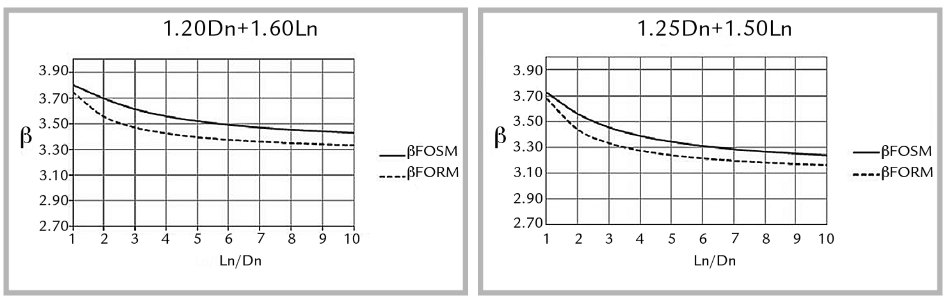

Figure 5
Reliability Index β vs. L_n/D_n ratio for Longitudinal Flare-Bevel Welds.

It is important to point out that only the data from McGuire and Peköz (1979) were used in the calibration of the applicable welded connection equations currently in AISI (2007). Detailed information can be found in Hsiao (1989), who used the FOSM Method. In that Reference, the load combination (i) and L_n/D_n ratio of 5 were adopted. In general, the values obtained by using load combination (i) and L_n/D_n ratio of 5 were satisfactory to the target of 3.5.

Another important aspect is the influence of professional coefficient (P) on the results. A sensitivity analysis shows that the random variable P, features an importance factor between 0.30 and 0.50, for the case analyzed.

4.2 Bolted connections

Table 4 shows results of the reliability indices β for bolted connections. Calculated was β for two different load combinations: (i) $1.2D_n+1.6L_n$ (AISI, 2007) and (ii) $1.25D_n+1.5L_n$ (AISI, 2007; NBR 14762, 2010), and two live-to-dead load ratios (L_n/D_n) of 5 and 3 (AISI, 2007). The FORM was used to assess the reliability indices.

Case	(i) $1.2D_n + 1.6L_n$		(ii) $1.25D_n + 1.5L_n$	
	$L_n/D_n = 3$	$L_n/D_n = 5$	$L_n/D_n = 3$	$L_n/D_n = 5$
	Reliability Indices βFORM			
6	1.99	2.01	1.93	1.99
7	2.15	2.18	2.09	2.11
8	3.01	2.95	2.86	2.79

Table 4
Computed Reliability Index β for Bolted Connections.

Figures 6 to 8 show the reliability indices, which were obtained for L_n/D_n ratio ranging 1 to 10, and compared with the results by the FOSM method. The FOSM and FORM Methods were used to assess the reliability indices. It can be seen that the FOSM Method produces results inferior to the FORM Method, although the FORM method is more accurate.

By using the FOSM Method, values similar to Brandão (2012) were obtained. As seen in the reliability analysis for welded connections, the curves obtained for each of the cases are similar but with a gap between them.

By proceeding to the calibration of the cases of bolted connections, with the target reliability index of 3.5, the load ratio L_n/D_n of 5 and the load combination (ii), the resistance factors 2.47, 2.24 and 1.82 are obtained for cases 6, 7 and 8, respectively. The high values of cases 6 and 7 are justified by the high dispersion of the variable P, shown in Table 2.

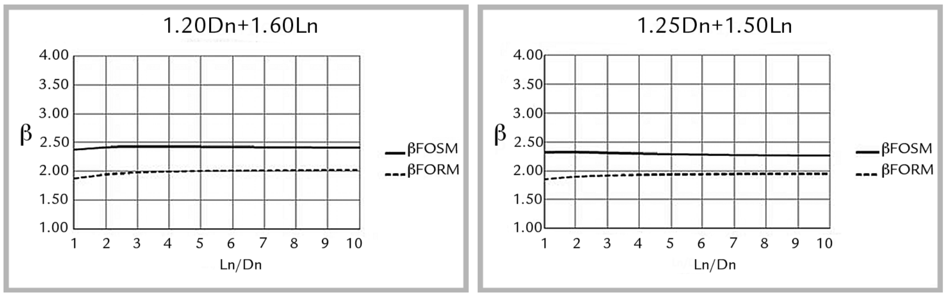

Figure 6
Reliability Index
β vs. L_n/D_n ratio for Bearing (sheets).

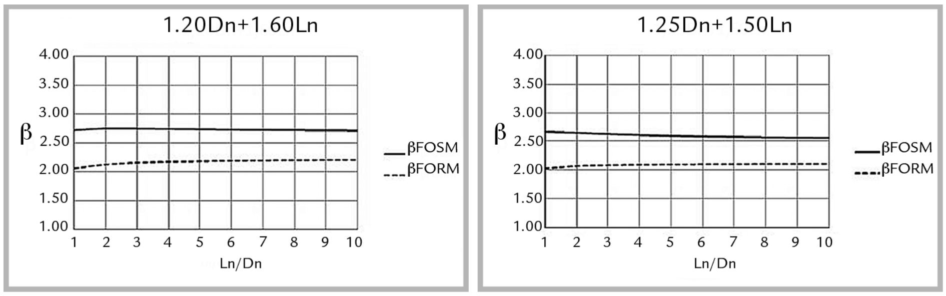

Figure 7
Reliability Index β vs. L_n/D_n
ratio for angle and channel sections.

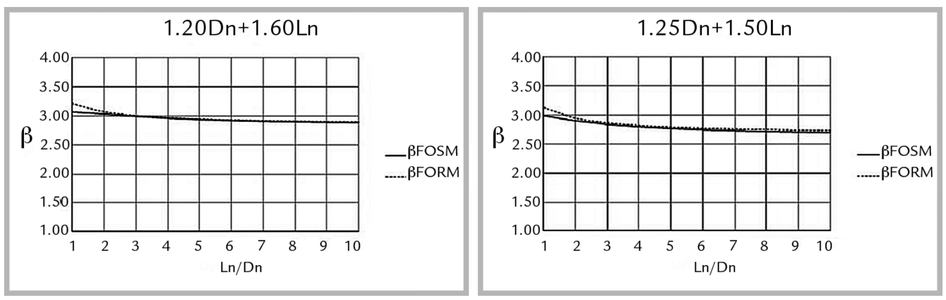

Figure 8
Reliability Index β vs. L_n/D_n
ratio for Spacing and edge distance.

5. Conclusions

The AISI LRFD strength prediction approach uses the following values for nominal live-to-dead load ratio (L_n/D_n), the load combination and the target reliability index: $L_n/D_n = 5$, $1.2D_n+1.6L_n$, $\beta_o = 3.5$. By calibration, resistance factors were determined for the load combination $1.2D_n+1.6L_n$ to approximately provide a target β_o equal to 3.5 for connections.

The reliability analysis of welded and bolted connections for thin sheets and cold-formed steel members designed by AISI and Brazilian codes are described herein. The FORM and FOSM Methods were used to calculate the reliability index β. In this study, obtained were reliability indices smaller than 3.5, especially for bolted connections. Consideration of model errors and the FORM method lead to significant reductions in reliability indices, which are found to be less than the recommended targeted reliability levels.

Through calibration of the standard for welded and bolted connections in cold formed steel members, using the usual load combination of the Brazilian code, the possibility of adjusting the resistance factors to a value close to 2 was verified.

It is suggested that the Brazilian code should to be adjusted in the near future. In this context, it is appropriate to show the importance of the test database to obtain the statistics of professional coefficient (P). Given the excessively low reliability indices, special attention should be taken to theoretical models of stress tolerance in bolted connections.

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