



## **Impact of Fabrication Tolerances on Cold-Formed Steel Section Properties, Stability, and Strength**

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### **Abstract**

The objective of this paper is to examine the impact of typical fabrication tolerances employed in the United States on the developed properties, stability, and strength, of cold-formed steel structural members. For a typical lipped channel cold-formed steel member the manufacturing process results in variations in the dimensions of the web, flanges, and lips. These dimensional variations lead to variations in the cross-sectional properties, the cross-sectional stability modes, and the resulting strength the section can develop. In the past, variations on the out-of-plane imperfection of member flats and out-of-straightness of member folds, and material strength properties have been studied; however, less attention has been paid to the impact of dimensional tolerances. Decisions to change current dimensional tolerances have significant financial impact for the manufacturers, but little in terms of the potential benefit for the performance is fully known. Using current United States dimensional tolerances and employing Monte Carlo simulation expected fabrication variation in a subset of common cold-formed steel lipped channel members are generated. The impact of dimensional tolerances on stability is studied, using the finite strip method (CUFSM) through generation of the axial and major-axis bending buckling load factors for local, distortional, and global buckling. The Direct Strength Method is used to track the impact of cross-section properties and stability onto the final predicted strength. This strength prediction provides means to investigate the fabrication factor currently used in Load and Resistance Factor Design in the United States. Sensitivity of the solution to correlation in the dimensional tolerances is also studied. Further, the impact of changes in current dimensional tolerances, are also studied. In the future, direct data on measured dimensional variations from as-formed sections can be employed to further understand expected variations in properties, stability, and strength. Understanding the importance of the dimensional tolerances and their impact on the structural performance provides crucial knowledge for future decisions on setting appropriate tolerances for cold-formed steel fabrication.

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## 1. Introduction

During the manufacturing process of cold-formed steel members, variations in the dimensions of the web, flanges, and lips (e.g.,  $h$ ,  $b_i$ , and  $d_i$  of Fig. 1) invariably occur, resulting in variations in the cross-sectional properties, the buckling loads, and the resulting capacity of the section. The effect that the tolerances have on the capacities, is not known, but it is an important knowledge, when deciding if the tolerances should be tightened or loosened – an issue that has a large impact in manufacturing.

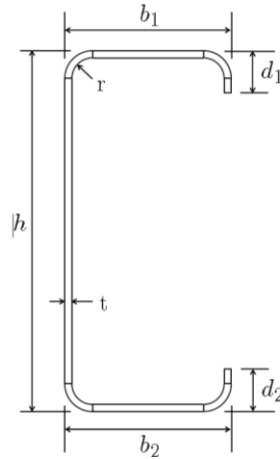


Figure 1: Example of lipped channel cross-section (600S200-54 shown) with dimension nomenclature.

AISI Specifications (AISI S220-15 and AISI S240-15) on cold-formed steel members are used to establish dimensional tolerances in the United States. The considered tolerances (for lipped channel profiles) are listed in Table 1.

Table 1: Tolerances for CFS stud members, applicable for both non- and structural members. (AISI S200-12).

|                        | Studs |        |
|------------------------|-------|--------|
|                        | [in]  | [mm]   |
| Web depth <sup>1</sup> | +1/32 | +0.79  |
|                        | -1/32 | -0.79  |
| Flange width           | +1/8  | +3.18  |
|                        | -1/16 | -0.159 |
| Lip Length             | +1/8  | +3.18  |
|                        | -1/32 | -0.79  |

1. The web depth is the inside dimension for studs.

The AISI Specification accounts for dimensional tolerances through the Fabrication factor ( $F$ ) in the standard Load and Resistance Factor Design (LRFD) formulation. In the LRFD formulation for each limit state the probability of failure is limited to a specified amount. This is achieved by insuring the random variable,  $R$ , that represents the resistance is a specific amount greater than the random variable  $Q$ , representing the load effect. The random variable for resistance  $R$  is generally expressed in the LRFD formulation as follows:

$$R = PMFR_n \quad (1)$$

Where  $R_n$  is the nominal predicted resistance typically formed from a closed-formed equation found in the Specification for a given limit state,  $P$  is the random variable known as the professional factor and accounts for the bias and variability in the  $R_n$  prediction equation,  $M$  is the material factor and accounts for the bias and variability in the material (typically the yield stress but also potentially the ultimate stress or other material factors depending on the limit states), and  $F$  accounts for the bias and variability inherent in fabrication of the member. For most limit states development of the prediction equation is the primary focus and a great deal of continual attention has been paid to  $R_n$  and  $P$  for a variety of limit states. Due in part to the need to have known ductility for seismic and blast design updated statistics related to  $M$  (particularly statistics on the yield stress) have been collected and employed in recent specifications.

AISI S100-12(2013) employs a mean fabrication factor and coefficient of variation of  $F=1.00$  and  $V_F=0.05$ , respectively. These values has been used since the introduction of LRFD to the AISI Specification in 1991. (Hsiao, et al., 1990) recommended these factors for  $F$  based on the work of (Rang, et al., 1979). The studies in Rang et al. based  $F$  on surveys of sheet thickness that reported a  $t_{mean}=1.05t_{nominal}$  and coefficient of variation  $V_t=0.05$ , see Table 2 and Fig. 2. Rang et al. recommended assuming  $t_{mean}=1.00t_{nominal}$  and  $V_t=0.05$  for future LRFD work due to the inclusion of provisions in AISI S100 that allow delivered  $t$  to be 95% that of the design  $t$ , which are still part of the Specification today.

Table 2: Statistics on thicknesses of steel sheets, strips and plates, from (Rang, et al., 1979).

| Ranges of the Ordered Thicknesses (in.)                       | Measured Thickness Ordered Thickness |        | No. of Samples |
|---|--------------------------------------|--------|----------------|
|   | Mean                                 | Cov    |                |
| Coated Steel Sheets, $t_s \leq 0.025$ in.                     | 1.0585                               | 0.0536 | 904            |
| Uncoated Steel Sheet, $t_s < 0.05$ in.                        | 1.0035                               | 0.0410 | 51             |
| Uncoated Steel Sheets, $0.05 \text{ in.} \leq t_s < 0.10$ in. | 1.0782                               | 0.0542 | 166            |
| Uncoated Steel Sheets, $0.10 \text{ in.} \leq t_s < 0.15$ in. | 1.0317                               | 0.0389 | 57             |
| Uncoated Steel Sheets, $0.15 \text{ in.} \leq t_s < 0.25$ in. | 1.0382                               | 0.0535 | 94             |
| Uncoated Steel Sheets, $t_s \geq 0.25$ in.                    | 1.0197                               | 0.0334 | 164            |
| All, 0.015 in.-1.0000 in.                                     | 1.0519                               | 0.0543 | 1,436          |

Details of the Rang et al. study are provided in Table 2. The sheet steel statistics may be modestly biased by the inclusion of coated steel sheets less than 0.025in (0.6mm), a thickness range that would be considered decidedly non-structural today, and  $t > 0.25$ in (6mm) a thickness rarely utilized in cold-formed steel structures today. Focusing on uncoated steel sheets between 0.05in and 0.10in (1.27mm and 2.54mm) results in  $t_{mean}=1.08t_{nominal}$ ,  $V_t=0.05$ , and the corresponding histogram of this data subset is provided in Fig. 2.

Although  $F$  is commonly understood to be related to the impact of fabrication on strength, and is generally introduced as being related to variability in section properties, the technical basis for  $F$ , at least in AISI S100 is Rang's sheet thickness survey from the 1970's, and judgment. This has served engineers and industry reasonably well, but certainly seems worthy of revisiting. In addition, it seems worthy to investigate variability in section properties and common integrated quantities, that enter the strength limit states such as  $A$  and  $I$  as well as  $P_{cr}$ ,  $M_{cr}$ , etc., in examining

$F$  and not just the thickness. With this approach a number of different limit states are addressed and sensitivity across limit states can be at least partially explored.

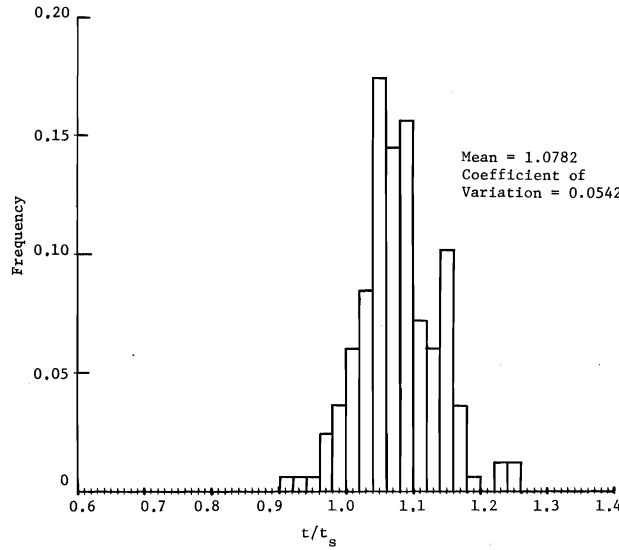


Figure 2: Histogram for thickness of uncoated steel sheets,  $0.05\text{in} \leq t_s \leq 0.10\text{in}$ , 166 samples, (Rang, et al., 1979)

It also seems logical, at least as a place to start, to use current manufacturing limits to develop these studies, although this assumes perfect quality assurance / quality control (QA/QC) and may need to be backed up by subsequent studies to demonstrate the truth of such a hypothesis it at least provides a direct look at the sensitivity under ideal current conditions. Since thickness enters into all the calculations it is a particularly important random variable in determination of  $F$ . However, it also complicates matters that AISI S100 continues to allow a delivered thickness that is 95% of nominal, so two scenarios are explored in the analysis herein:

- Assume underlying statistics remain the same as 1979, i.e.  $t_{mean} \sim 1.05t_{nominal}$  and the 95% rule in AISI S100 can be approximated simply by employing  $t_{mean} \sim 1.00t_{nominal}$  in the examination of  $F$ .
- Assume manufacturing of thickness has improved and thus the 95% rule in AISI S100 now has the impact of biasing thickness by 5% and employ  $t_{mean} \sim 0.95t_{nominal}$  in the examination of  $F$ .

In addition to establishing the mean for  $t$ , establishment of the variation and potentially bounds, assuming the presence of ideal QA/QC procedures, are also considered.

## 2. Methodology

Three CFS members (following U.S. nomenclature) and two different loading cases were considered for the investigation, resulting in a total of four different cases: The 600S200-54 profile subjected to both axial compression and major bending, the 362S162-68 member subjected only to axial compression, and the 1200S200-68 only to major axis bending (see Table 3). Monte Carlo simulations are used for generating the random un- and correlated variables of the cross-sections' dimensions, where a truncated normal distribution is used for describing the members, which are within the tolerances as detailed in the following.

Table 3: Design dimensions on the selected lipped channel CFS members in inches and millimeters. (Steel Framing Industry Association, 2007).

|             |                       |      | $h$   | $b$   | $d$   | $t$    | $r$    | $t_{min}$ |
|-------------|-----------------------|------|-------|-------|-------|--------|--------|-----------|
| 362S162-68  | Compression           | [in] | 3.62  | 1.62  | 0.5   | 0.0713 | 0.107  | 0.0677    |
|             |                       | [mm] | 91.95 | 41.15 | 12.7  | 1.81   | 2.72   | 1.72      |
| 600S200-54  | Compression + Bending | [in] | 6     | 2     | 0.625 | 0.0566 | 0.0849 | 0.0538    |
|             |                       | [mm] | 152.4 | 50.8  | 15.88 | 1.438  | 2.16   | 1.37      |
| 1200S200-68 | Bending               | [in] | 12    | 2     | 0.625 | 0.0713 | 0.107  | 0.0677    |
|             |                       | [mm] | 304.8 | 50.8  | 15.88 | 1.81   | 2.72   | 1.72      |

2000 members were generated for each cross-section and loading case, followed by an analysis of the cross-section, a Finite Strip analysis and the use of the Direct Strength Method for predicting the strength of each generated member. Finally, a statistical analysis of the results was executed.

The members are generated from un- or correlated truncated normal random variables, where the truncated normal distribution follows the tolerances in Table 1. Fig. 3a shows a histogram of generated random thicknesses which follow the truncated normal distribution. The analyses were also repeated with tolerances equal to half the size of the tolerances listed in Table 1. A final set of analyses were performed with a normal distribution, representing no quality control (all members are accepted) and a mean thickness equal to  $t_{mean}=0.95t_{nominal}$ , this is illustrated in Fig. 3b, where the red line indicates the nominal dimension. This final set is motivated by AISI S100's allowance of delivered  $t$  to be 95% of the design  $t$ .

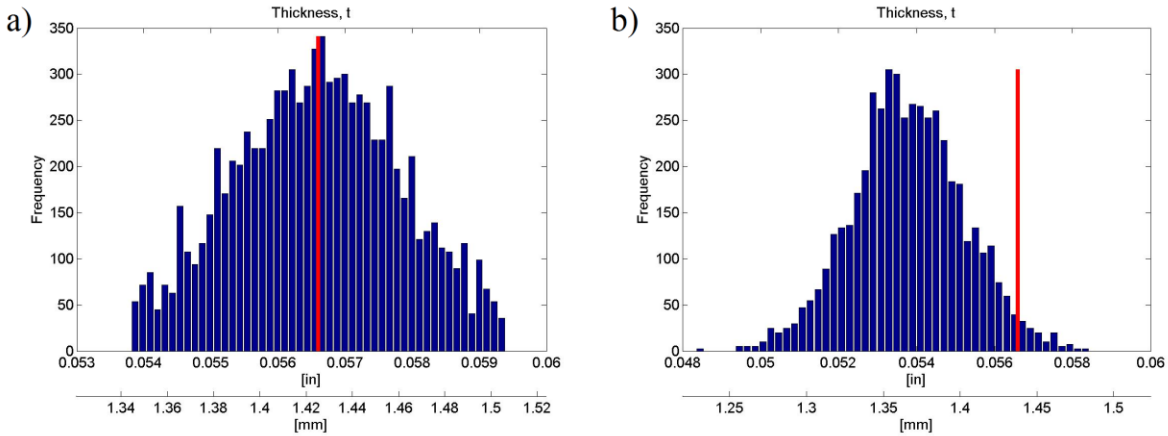


Figure 3: Histograms for the plate thickness in 600S200-54, a) as the truncated normal variable and b) as the normal variable with  $t_{mean}=0.95t_{nominal}$ .

The random variables are generated by the built-in random function in Matlab and then transformed to the proper distribution, followed by converting the dimensions to the input format for CUFSM (from outer dimensions to center line dimensions). The critical lengths for the local and distortional buckling mode for the member are found with cFSM, before the conventional CUFSM analysis for the actual member. The length for global buckling is chosen to be  $L_g=100$ in (2540mm) for all cross-sections and loading cases.

The capacity of each member is determined by the Direct Strength Method, before the statistical measurements are computed: average, standard deviation, fabrication factor, and the variance of the fabrication factor.

### 2.1 Truncated Normal Distribution

For simulating the dimensions as random variables a truncated normal distribution is assumed, where the mode of the distribution is set to be the design value. For all sets of the tolerances in AISI S220-15 and AISI S240-15 (see Table 1) the upper tolerance is always the larger one, therefore is the upper tolerance set to be the 99.5% percentile in the normal distribution. Fig. 4 illustrates the normal and the truncated normal distribution for the flange width  $b = 2\text{in}$  (50.8mm), where the nominal value equals the mode of the distributions and that the upper tolerance and the upper percentile coincide. Based on these definitions the lower percentile, corresponding to the lower tolerance, can be determined by Eq. ( 2 ).

$$percentile_{lower} = \Phi \left( \Phi^{-1}(99.5 \%) \frac{tol_{lower}}{tol_{upper}} \right) \quad (2)$$

where  $\Phi$  and  $\Phi^{-1}$  is the cumulative normal function and its inverse function, respectively, and  $tol$  is the tolerances. The standard deviation ( $\sigma$ ) for each distribution can be calculated from the upper percentile and tolerance:

$$\sigma = \frac{tol_{upper}}{\Phi^{-1}(99.5 \%) } \quad (3)$$

When generating the dimensions, the random values that are within the bounds (percentiles in the normal distribution) are accepted and values outside the bounds are rejected, thus the variables follow the truncated normal distribution. Histograms of the generated uncorrelated truncated normal variables can be found in Fig. 3a, 5a, 5c, and 5e.

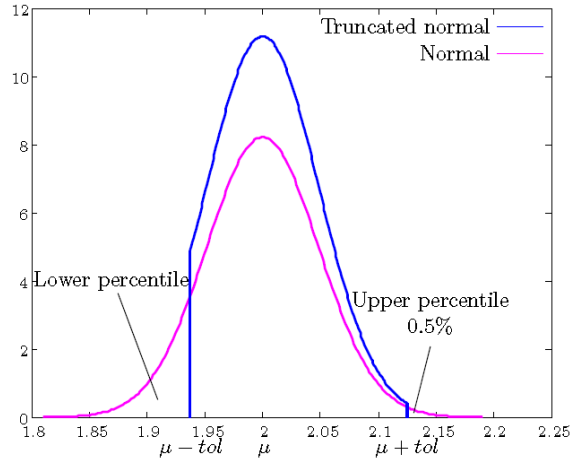


Figure 4: The truncated normal distribution for the flange width b.

A 99% interval is used to indicate the bound for the larger tolerance for all the dimensions expect for the thickness, where a 95% interval is used (the 99% interval is only retained when upper and lower tolerance are equal. The interval is only used to set the upper bound of the distribution). The minimum design thickness (see Table 3) is set to be the lower bound for the distribution of the

thickness, and the difference between design and minimum thickness is also set to be the difference between the design value and the upper bound.

For simulating the dimensions as correlated random variables a slightly modified approach is employed. The difference between the generated dimensions and the design values is set to be the random variable. The variations for each dimension are found by the same means as for the uncorrelated variables, the only change is that the mode of the distribution equals zero for the correlated random variables. Also correlation is considered by multiplication with the correlation matrix (see the section below). Dimensional variations of a member are accepted for subsequent simulation if the variation across all the dimensions are within the tolerances. The design/mean value is then added to the variations, providing the simulated dimensions as random, but correlated. Correlated truncated normal variables are illustrated as histograms in Fig. 5b, 5d, and 5f.

## 2.2 Correlation Matrix

In manufacturing, the coils a cold-formed steel member are folded from, are assumed to have no meaningful variation in their width. Based on this assumption and from engineering judgment the correlation matrix is set up with three predicted scenarios:

- mis-aligned sheet:  $h$ ,  $b_1$  and  $b_2$  would be perfect, but the  $d$ 's will be strongly negative correlated.
- the  $h$  roller is set too wide/narrow and the mistake will show up in the  $d$ 's, or
- lastly, a mistake will show up in the  $b$ 's, which the adjacent lip will compensate: so strongly negative correlation between  $b_1$  and  $d_1$ , and  $b_2$  and  $d_2$ .

Note, that the correlation matrix is set up as correlation between the variations from the design values, and not as correlation between the dimensions.

$$C = \begin{bmatrix} 1 & 0 & 0 & 0 & -1 & 0 \\ -1 & 1 & 0 & 0 & 0 & 0 \\ -0.5 & 0 & 1 & 0 & -0.5 & 0 \\ 0 & 0 & 0 & 1 & -1 & 0 \\ -1 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \quad (4)$$

where the rows and columns in the correlation matrix correspond to  $d_1, b_1, h, b_2, d_2$  and  $t$ , in that order.

## 2.3 Impact of employing correlated random variables for the dimensions

The dimensions were first generated as uncorrelated random variables. This is a standard statistical assumption, useful for comparison, but not realistic in practice. The dimensions generated as uncorrelated variables result in larger load estimates, for both buckling loads and final strength predictions when compared with the dimensions generated as correlated random variables. Estimates that are not believed to be realistic.

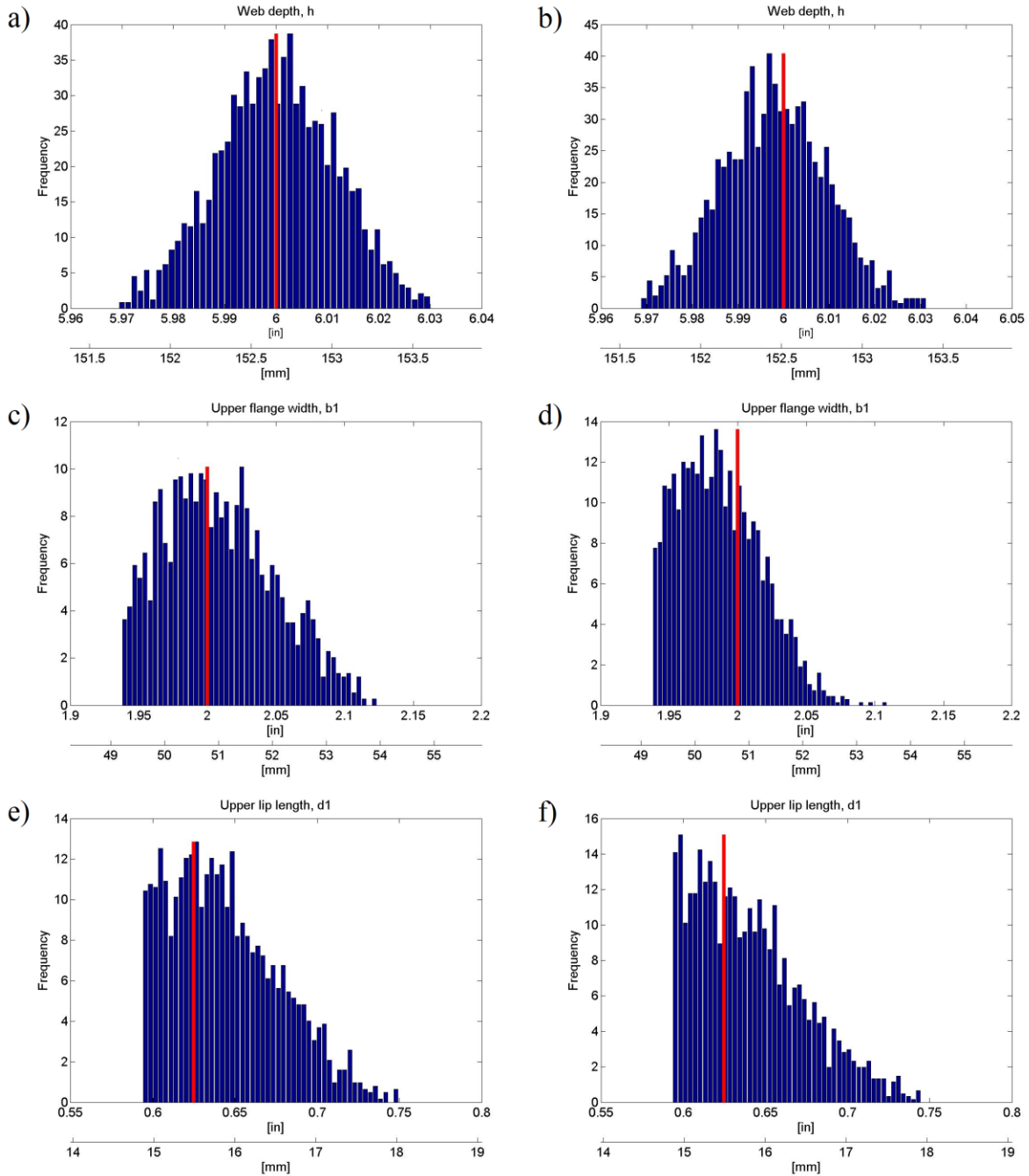


Figure 5: Histogram for the dimensions in the 600 S200-54 cross-section, which all follow a truncated normal distribution. a) uncorrelated variable for the web depth, b) correlated variable for the web depth, c) uncorrelated variable for the flange width, d) correlated variable for the flange width, e) uncorrelated variable for the lip length, and f) correlated variable for the lip length.

The correlated random dimensions differ from the uncorrelated random dimensions, as may be observed in Fig. 5, where the histograms for the un- and correlated random dimensions are shown next to each other. For the web depth, the mode of the distribution is shifted to the left for the correlated dimension, and the mean value is smaller than the design value. For the flange width, this shift is even more pronounced, where the mode of the distribution in the correlated random



dimensions are moved further to the left than for the same uncorrelated random dimension. Lastly, the shape of the lip length's distribution is changed from un- to correlated dimension: The histogram of the uncorrelated random lip length show the shape of a (strongly) truncated normal distribution, while for the correlated random lip length dimension the truncated normal distribution is not obvious. This is expected, as all the predicted manufacturing scenarios for folding mistakes that are used to define the correlation require correction in the lip length, and is why this dimension is strongly dependent on the realized length of the other dimensions. All considered, the correlated random dimensions are assumed to provide a better representation of reality and therefore are considered in the following.

#### 2.4 CUFSM

Finite strip analyses are used to compute the buckling loads, lengths and modes for the three defined buckling types: local, distortional and global buckling. The modes are illustrated in Fig. 6 and 7, for a 600S200-54 stud member in axial compression and bending about the major axis of the cross-section. The local buckling is characterized by the relatively short wavelength and buckling of individual plate elements, while the distortional buckling mode is when both translation and rotation of the compression fold line between flange and lip of the member occur. The wavelength of distortional buckling is generally in-between that of local buckling and global buckling. Global buckling is when a rigid body rotation or translation of the cross-section takes place. (Li & Schafer, 2010b).

The signature curve of a member is generated by CUFSM and describes the buckling loads as a function of the longitudinal half-wavelength of the buckled shapes. Curves for all four investigated situations are illustrated in Fig. 8, where several signature curves are plotted together to get the impression of the variations of the tolerances impact on members' buckling performance. The curves illustrated have a coarse discretization, but a finer one was used for the cFSM analysis around the local and distortional minima and only the coarse discretization is used for the CUFSM analysis to minimize the computational time and still provide information about the overall buckling load – half-wavelength performance.

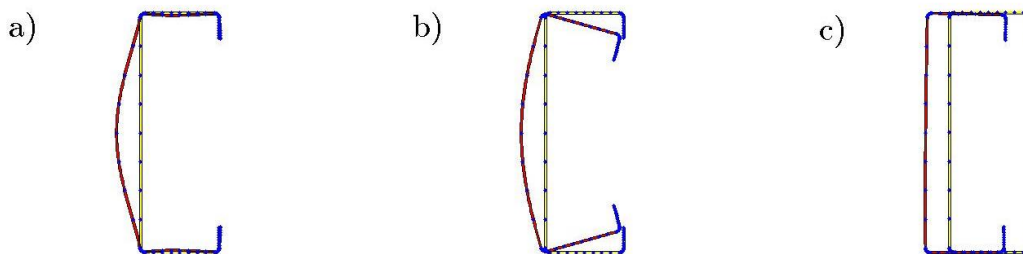


Figure 6: Buckling modes for 600S200-54 in axial compression, a) local, b) distortional, and c) global buckling

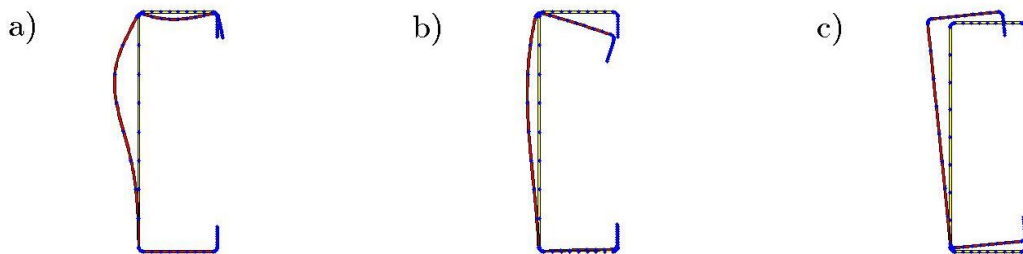


Figure 7: Buckling modes for 600S200-54 in major axis bending, a) local, b) distortional, and c) global buckling

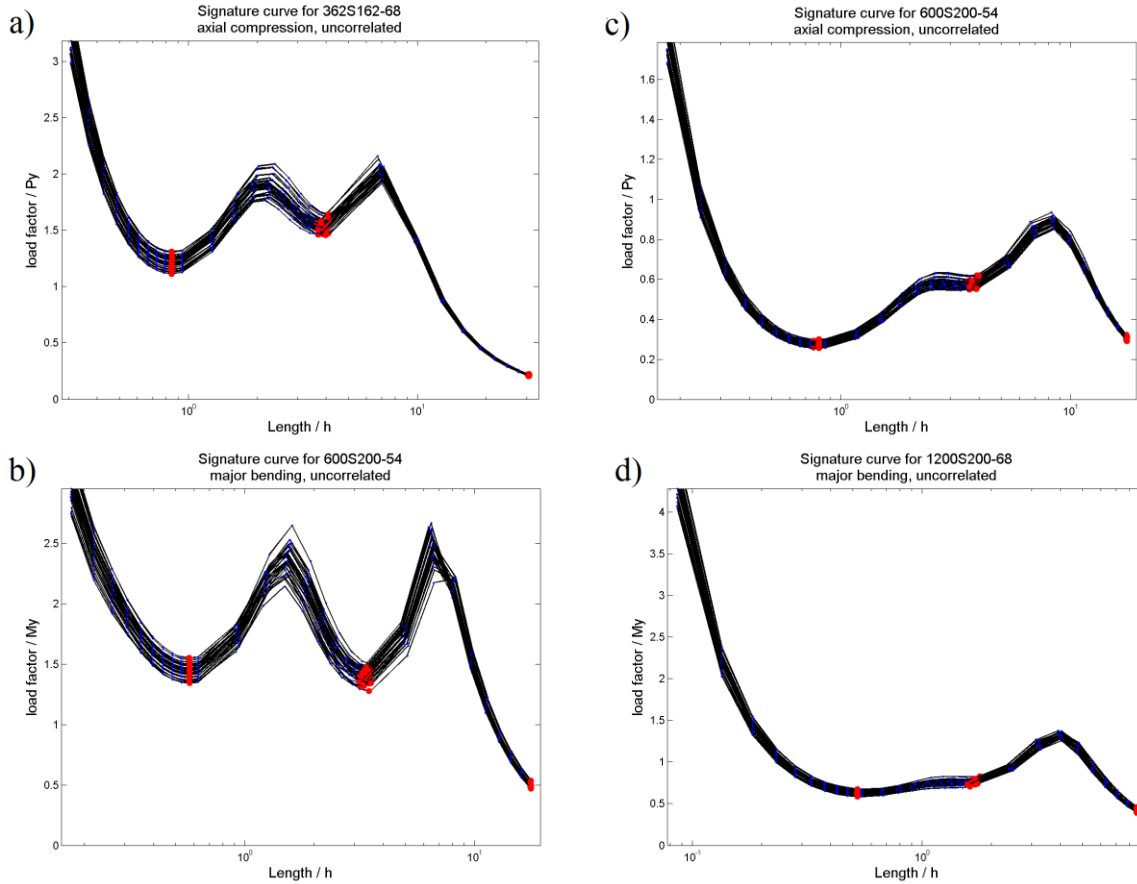


Figure 8: 30 signature curves randomly selected, showing the local, distortional and global buckling locations, a) 362S162-68 axial compression, b) 600S200-54 major bending, c) 600S200-54 axial compression, and d) 1200S200-68 major bending. All are found from uncorrelated variables.

## 2.5 cFSM

The local and distortional buckling loads and modes, can be identified by finding the minima on the signature curve from CUFSM. However, for some of the generated members there are no clear minimum for distortional or local buckling, and the algorithm could pick another location on the curve, resulting in the wrong data for the following statistical analysis. The error can be corrected manually, but 2000 members for each cross-section and loading case were performed in the analysis. Therefore, cFSM (constrained Finite Strip Method) was used to determine the critical length for local and distortional buckling (Li & Schafer, 2010a) followed by the conventional Finite Strip analysis, (Li & Schafer, 2010b).

When using cFSM a modified cross-section is used that has the same dimensions as the actual cross-section, but without any rounded corners. FSM is ran twice for each randomly generated cross-section, once with the cFSM model for determining the critical lengths for local and distortional buckling. cFSM gives one distinct minimum for each buckling mode, and leads to no uncertainty about the results. Then a FSM analysis at the identified lengths is completed to identify the exact buckling load (or moment) including the effect of rounded corners.

### 3. Results

#### 3.1 Generation of fabrication factors

In investigating the impact of randomness in the dimensions the following properties are considered: thickness ( $t$ ), gross area ( $A$ ), gross major-axis moment of inertia ( $I$ ); the following elastic buckling loads or moments: local ( $P_{crl}$  or  $M_{crl}$ ), distortional ( $P_{crd}$  or  $M_{crd}$ ), global ( $P_{cre}$  or  $M_{cre}$ ); and the following strengths: local-global ( $P_{nl}$  or  $M_{nl}$ ), and distortional ( $P_{nd}$  or  $M_{nd}$ ). For each property, elastic buckling value or strength, the simulated value is determined with random dimensions and divided that by the nominal value for the same property, buckling, or strength to form estimates of the fabrication factor,  $F$ , as a random variable. The subscript of  $F$  refers to the property ( $t, A, I$ ), elastic buckling value ( $crl, crd, cre$ ), or strength ( $nl, nd$ ) that is examined. Note, a single  $F$  value is used in the AISI-S100 Specification even though it is applied in a large variety of different limit states, thus a variety of scenarios for  $F$  are explored here.

The mean values for the various  $F$  are reported in Table 4 and the coefficient of variation in Table 5, all for the case of correlated random dimensions, but under different assumptions about QA/QC and the mean of the steel thickness. In addition, histograms for the buckling load factors are illustrated in Fig. 9 and the predicted strengths (local and distortional) in Fig. 10, for the correlated random variables with and without QA/QC for the 600S200-54 member in bending. The larger variations in the distortional and global buckling loads are noted in the figures, where both the intensity and range demonstrates the variations. The local loads have about the same variation, which can be noted from Table 5 and in Fig. 9a, 9b, 10a, and 10b. Additional detailed discussion follows in the subsequent sections.

Table 4: Mean fabrication factors

|                                    |             |         |       | Properties |       |           | Elastic Buckling |           |          | Strength |  |
|------------------------------------|-------------|---------|-------|------------|-------|-----------|------------------|-----------|----------|----------|--|
|                                    |             | loading | $F_t$ | $F_A$      | $F_I$ | $F_{crl}$ | $F_{crd}$        | $F_{cre}$ | $F_{nl}$ | $F_{nd}$ |  |
| with<br>QA/QC $t = 1.0t_{nom}$     | 362S162-68  | axial   | 1.000 | 1.001      | 0.996 | 1.005     | 1.017            | 0.986     | 1.002    | 1.005    |  |
|                                    | 600S200-54  | axial   | 1.000 | 1.000      | 0.998 | 1.005     | 1.016            | 0.978     | 1.002    | 1.007    |  |
|                                    | 600S200-54  | bending | 1.000 | 1.000      | 0.998 | 1.003     | 1.020            | 0.996     | 0.997    | 1.002    |  |
|                                    | 1200S200-68 | bending | 1.000 | 1.000      | 0.999 | 1.003     | 1.010            | 0.995     | 0.998    | 1.001    |  |
| without<br>QA/QC $t = 0.95t_{nom}$ | 362S162-68  | axial   | 0.950 | 0.952      | 0.953 | 0.860     | 0.890            | 0.924     | 0.920    | 0.931    |  |
|                                    | 600S200-54  | axial   | 0.950 | 0.951      | 0.952 | 0.860     | 0.894            | 0.916     | 0.917    | 0.923    |  |
|                                    | 600S200-54  | bending | 0.950 | 0.951      | 0.952 | 0.859     | 0.894            | 0.948     | 0.915    | 0.925    |  |
|                                    | 1200S200-68 | bending | 0.950 | 0.951      | 0.952 | 0.861     | 0.888            | 0.949     | 0.915    | 0.922    |  |

#### 3.2 Correlated members with QA/QC

Consider in Table 4 and Table 5 the first, optimistic case, where QA/QC is perfect (no sections outside the dimensional tolerances are allowed) and  $t_{mean}=1.00t_{nominal}$  even with the application of the 95% delivered thickness provision. The examined fabrication factors all are close to 1.0. The cross-sectional properties exhibit almost no bias (mean close to 1.0) and have small variation, approximately 2%. The elastic buckling properties also have small bias (mean  $F$  close to 1.0) but slightly larger variation, 3 to 7%. Local and distortional buckling have bias slightly greater than 1 and variation from 5 to 7% while global buckling has bias slightly less than 1 but a smaller variation near 3%. The predicted strength in local-global interaction or distortional mechanisms also has bias near 1.0 and a variation of approximately 4%. For the scenario of perfect QA/QC and  $t_{mean}=1.00t_{nominal}$  the existing  $F_m=1.0$  and  $V_F=0.05$  continue to appear justified.

Table 5: Variation of the fabrication factors

|                                    |             | Properties |       |       |       | Elastic Buckling |           |           | Strength |          |
|------------------------------------|-------------|------------|-------|-------|-------|------------------|-----------|-----------|----------|----------|
|                                    |             | loading    | $V_t$ | $V_A$ | $V_I$ | $V_{cr1}$        | $V_{crd}$ | $V_{cre}$ | $V_{nl}$ | $V_{nd}$ |
| with QA/QC<br>$t = 1.0t_{nom}$     | 362S162-68  | axial      | 0.023 | 0.022 | 0.021 | 0.068            | 0.055     | 0.025     | 0.037    | 0.031    |
|                                    | 600S200-54  | axial      | 0.022 | 0.022 | 0.021 | 0.067            | 0.052     | 0.026     | 0.038    | 0.035    |
|                                    | 600S200-54  | bending    | 0.022 | 0.022 | 0.021 | 0.067            | 0.052     | 0.026     | 0.038    | 0.035    |
|                                    | 1200S200-68 | bending    | 0.022 | 0.022 | 0.021 | 0.067            | 0.064     | 0.036     | 0.035    | 0.032    |
| without QA/QC<br>$t = 0.95t_{nom}$ | 362S162-68  | axial      | 0.026 | 0.025 | 0.025 | 0.070            | 0.066     | 0.033     | 0.041    | 0.037    |
|                                    | 600S200-54  | axial      | 0.025 | 0.025 | 0.025 | 0.069            | 0.061     | 0.034     | 0.042    | 0.041    |
|                                    | 600S200-54  | bending    | 0.025 | 0.025 | 0.025 | 0.072            | 0.113     | 0.056     | 0.040    | 0.049    |
|                                    | 1200S200-68 | bending    | 0.026 | 0.025 | 0.025 | 0.073            | 0.100     | 0.055     | 0.042    | 0.051    |

### 3.4 No QA/QC and assumption of manufacturing at the thickness limit

Table 4 and Table 5 also provide consideration of a second more pessimistic scenario where the dimensions follow narrow distributions but QA/QC is not perfect and it is possible to have violations of the tolerances and where the allowance for 95% delivered thickness has become embedded in the material delivery process resulting in  $t_{mean}=0.95t_{nominal}$ . The impact on the fabrication factor,  $F$ , is profound under this set of assumptions. The cross-sectional properties now all exhibit a bias consistent with 0.95, i.e. linear with the bias in  $t$ . The elastic buckling bias factors are more deeply effected exhibiting results that are nearly proportional to  $0.95^3$  for local buckling,  $0.95^2$  for distortional buckling, and 0.95 for global buckling. The elastic buckling variability is as high as 11%. The bias in nominal strength is not as significant as elastic buckling, but worse than the cross-section properties and equal to approximately 0.92 with a variation of about 4%. Under this scenario  $F=0.95$  and  $V_F=0.05$  would be justified.

### 3.4 Additional scenario: consideration of tighter tolerances

An additional scenario is considered with perfect QA/QC,  $t_{mean}=1.00t_{nominal}$  and the tolerance of Table 1 tightened to half of their current values. The results, provided in Table 6 indicate that in such a scenario  $F=1.00$  and  $V_F=0.03$  would be justified. With this one can observe that the tolerances do impact the fabrication factors, but based on the previous analysis determining the true distribution of thickness,  $t$ , is likely the most important factor for  $F$ .

Table 6: Fabrication factors and variation of the fabrication factor for dimensions with half the tolerances.

|       |             | Properties |       |       | Elastic Buckling |           |           | Strength |          |
|-------|-------------|------------|-------|-------|------------------|-----------|-----------|----------|----------|
|       |             | loading    | $F_A$ | $F_I$ | $F_{cr1}$        | $F_{crd}$ | $F_{cre}$ | $F_{nl}$ | $F_{nd}$ |
| $F$   | 362S162-68  | axial      | 1.001 | 0.998 | 1.002            | 1.009     | 0.993     | 1.001    | 1.003    |
|       | 600S200-54  | axial      | 1.000 | 0.999 | 1.002            | 1.009     | 0.989     | 1.001    | 1.004    |
|       | 600S200-54  | bending    | 1.000 | 0.999 | 1.001            | 1.010     | 0.998     | 0.998    | 1.001    |
|       | 1200S200-68 | bending    | 1.000 | 1.000 | 1.001            | 1.005     | 0.997     | 0.999    | 1.001    |
| $V_F$ | 362S162-68  | axial      | 0.011 | 0.011 | 0.034            | 0.027     | 0.012     | 0.018    | 0.016    |
|       | 600S200-54  | axial      | 0.011 | 0.011 | 0.033            | 0.026     | 0.013     | 0.019    | 0.018    |
|       | 600S200-54  | bending    | 0.011 | 0.011 | 0.033            | 0.032     | 0.018     | 0.018    | 0.016    |
|       | 1200S200-68 | bending    | 0.011 | 0.011 | 0.034            | 0.031     | 0.019     | 0.019    | 0.018    |

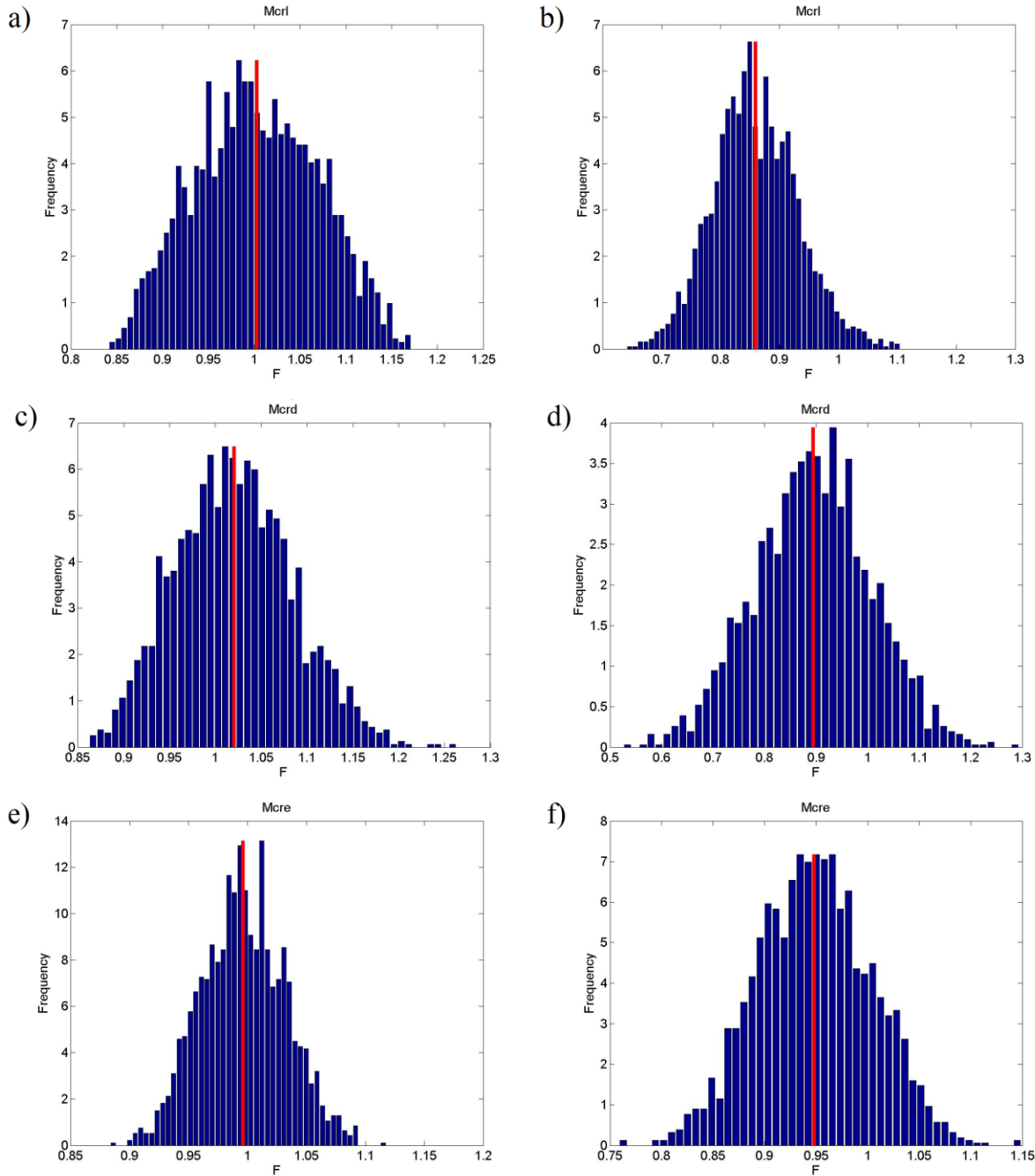


Figure 9: Histograms for the fabrication factors for the buckling moments in the 600 S200-54 cross-section. Red line indicating the mean fabrication factor from Table 4. a) local buckling moment for the truncated normal correlated variable, b) local buckling moment for the normal correlated variable without QA/QC, c) distortional buckling moment for the truncated normal correlated variable, d) distortional buckling moment for the normal correlated variable without QA/QC, e) global buckling moment for the truncated normal correlated variable, and f) global buckling moment for the normal correlated variable without QA/QC.

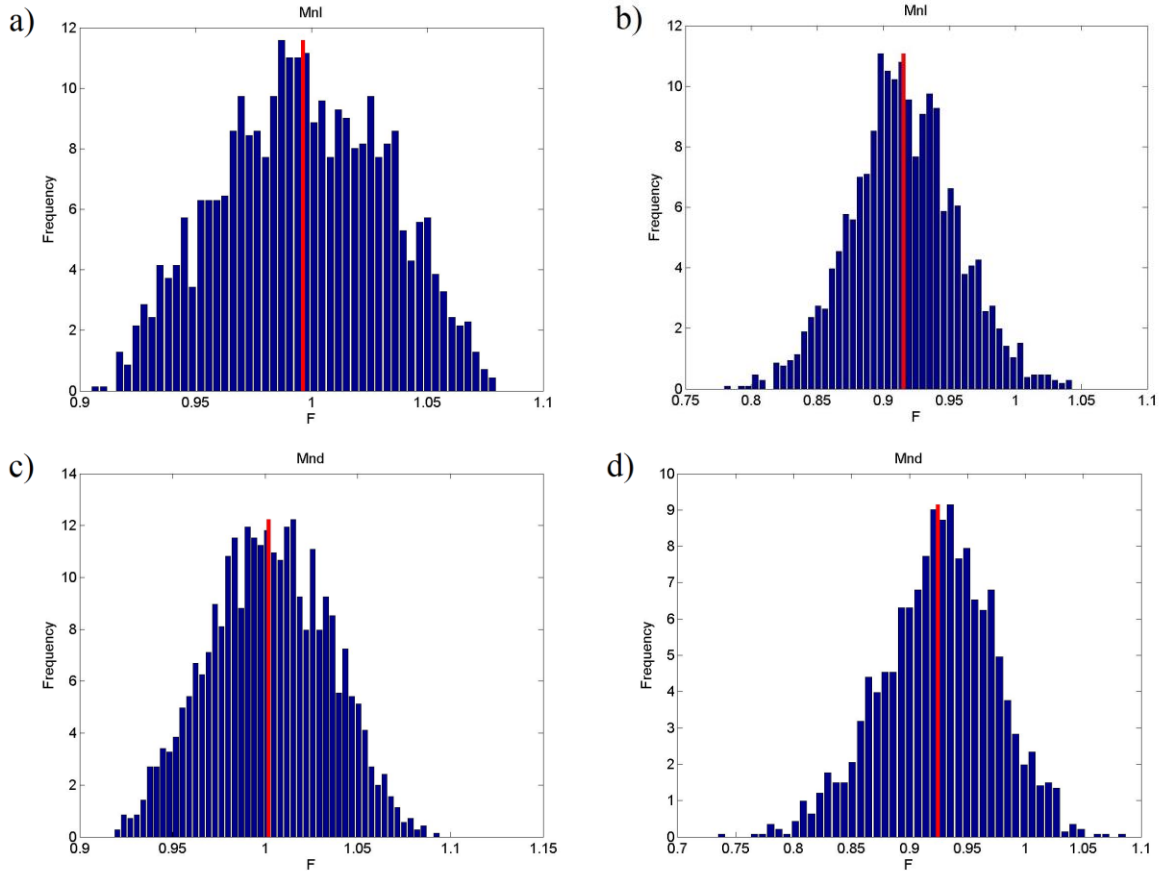


Figure 10: Histograms for the fabrication factors for the predicted moments in the 600 S200-54 cross-section. Red line indicating the mean fabrication factor from Table 4. a) predicted local moment for the truncated normal correlated variable, b) predicted local moment for the normal correlated variable without QA/QC, c) predicted distortional moment for the truncated normal correlated variable, and d) predicted distortional moment for the normal correlated variable without QA/QC.

#### 4. Discussion

Recent studies by (Zhao & Schafer, 2015) highlight that the distribution of the lips, in particular, do not follow a normal distribution (i.e., are non-Gaussian) see Fig. 11. Due to the roll-forming process the lip lengths may often be smaller than permitted. Thus, without perfect QA/QC it should be assumed that members with out-of-tolerance dimensions may be used on the construction site. This is consistent with recent measurements on as-formed members by Zhao and Schafer (2015). This highlights the importance of the tolerances and of processes to insure that the tolerances are adhered to in fabrication.

Recently, measurements on fifty-eight nominally identical 600S137-54 specimens were completed by (Torabian, et al., 2015). All the measured thicknesses are below the design value, and they have an average equal to 0.99 of the design value. Recall, that the results from (Rang, et al., 1979) had a  $t_{mean}=1.05t_{nominal}$  and a variance  $V_F=0.05$ . It was prudent in the original LRFD to reduce  $F$  to 1.00 (i.e.,  $t_{mean}=1.05t_{nominal}$ ). New studies are needed to determine current values of these statistics, but preliminary evidence exists that suggests it may be less than 1.0 and ultimately this would need to be reflected in  $F$  and the LRFD calibrations throughout the Specification.

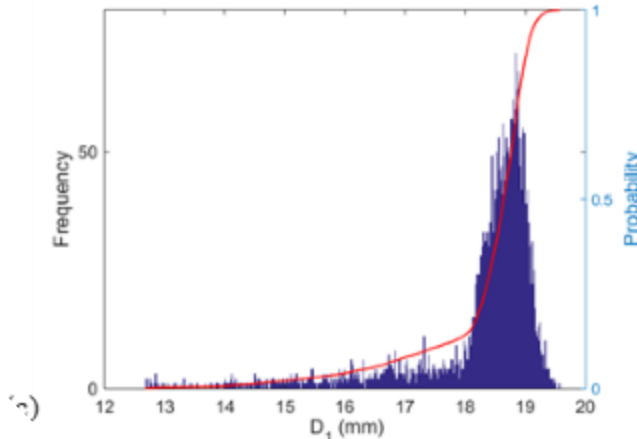


Figure 11: Histogram of lip lengths of 19 Z-sections, from Zhao and Schafer (2015)

### *Future work*

Information on the tolerances is useful, but ultimately the delivered dimensions are of primary interest. It would be useful to do a dimension survey on actual CFS members so the state of current variations could be utilized in future studies.

Preliminary calculations were performed to investigate the effect of out-of-flatness for the web and out-of-straightness angles between the web/flanges and flanges/lips on the buckling loads. The results are sensitive to these variables. The impact these additional tolerances have, beyond the dimensional tolerances investigated here, should be explored in the future.

Formal thickness studies on delivered uncoated steel thickness across a variety of members, manufacturers, etc. would be beneficial for establishing and potentially improving the reliability of cold-formed steel members.

Quality assurance / quality control measures are in place in the industry. It would be useful to review these measures from the standpoint of determining how they insure the dimensional tolerances and potentially provide assessment and recommendations on current practice.

## **5. Conclusions**

In the United States the reliability of cold-formed steel members is established through the use of Load and Resistance Factor Design (LRFD), e.g. see AISI-S100. In addition to considering the bias and variability of any limit state prediction equations used, and the material strength, LRFD also accounts for the variability of the fabrication process. Since the inception of LRFD in 1991 the fabrication variability has been based on a sheet steel thickness study from the 1970's combined with engineering judgment. This paper investigates a more formal approach to establishing the bias and variability in the LRFD fabrication factor. Three common cold-formed steel lipped channel cross-sections are studied where the dimensions of the cross-sections are considered as random variables based on tolerances in current use. A correlation structure is established for the dimensions based on assumed manufacturing difficulties and correlated random dimensions are generated for the three cross-sections. Cross-sectional properties, elastic buckling loads, and predicted strengths are studied for the simulated cross-sections with correlated random dimensions. If current tolerances are enforced and the mean thickness of uncoated sheet steel is

assumed equal to the design thickness then LRFD fabrication factors in current use in AISI-S100 are found to be consistent with the study results. However, if tolerances are not perfectly maintained and if the AISI-S100 provision that allows for delivered sheet steel thickness to be 95% of design thickness has caused the mean delivered thickness to be 95% of the design thickness then the current fabrication factors may be unconservative. Tightening tolerances can improve the performance, but thickness is the most important random variable for determining the LRFD fabrication factor accurately. An up to date study on delivered sheet steel thickness would supply the information necessary to update the current LRFD fabrication factor.

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