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LOAD AND RESISTANCE FACTOR DESIGN OF COLD-FORMED STAINLESS STEEL

STATISTICAL ANALYSIS OF MATERIAL PROPERTIES AND DEVELOPMENT OF THE LRFD PROVISIONS

by

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1. INTRODUCTION

1.1 General Remarks

The "Allowable Stress Design" method has long been used for the design of steel structures in the United States.[1,2,3] Recently, the probability-based load and resistance factor design (LRFD) criteria have been successfully applied to the structural design of hot-rolled steel shapes and built-up members.[4,5,6] The AISI LRFD Specification is being developed as well for the design of structural members cold-formed from carbon and low alloy steels.[7-17] These design criteria can provide a more uniform degree of structural safety to achieve consistent reliability for different design situations. The probability-based design method is developed on the basis of the "Limit States Design" philosophy,[18-22] which is related to the ultimate strength and serviceability of the structural members and connections. In the United States, research work on probability-based design has focused primarily on the ultimate strength limit states because such limit states are clearly defined.

In order to update the 1974 edition of the AISI Specification and to develop the new LRFD Specification for cold-formed stainless steel structural members, a research project entitled "Load and Resistance Factor Design of Cold-Formed Stainless Steel" was initiated in July 1986 at the University of Missouri-Rolla under the sponsorship of the American Society of Civil Engineers (ASCE). This study was conducted by Shin-Hua Lin under the direction of Dr. Wei-Wen Yu. Dr. Theodore V. Galambos of the University of Minnesota is the ASCE consultant for the project.

The first phase of this study dealt with the revision of the 1974 edition of the AISI allowable stress design specification[3] for cold-formed stainless steel structural members and its commentary. Based on the reevaluation of previous test results obtained from the research projects conducted at Cornell University[23-27] and the current AISI specifications for the design of cold-formed stainless steel and carbon steel structural members,[2,3] a draft of the Proposed Allowable Stress Design Specification with Commentary has been prepared and published in the Third Progress Report.[30] This proposed ASCE Specification includes four types of austenitic stainless steels (annealed, 1/16-, 1/4-, and 1/2-Hard Types 201, 301, 304, and 316) and three types of ferritic stainless steels (annealed Types 409, 430, and 439). Following a careful review by the ASCE Steering Committee at its meeting held at the University of Missouri-Rolla on April 21, 1988, it was recommended that the proposed ASD Specification included in the Third Progress Report be submitted to the new ASCE Standard Committee for consideration.

The second phase of this project is to develop the new LRFD criteria for cold-formed stainless steel structural members. These criteria are to be developed on the basis of the first-order probabilistic theory by using only the mean values and coefficients of variation of load effects, material factors, fabrication factors, and professional factors. The development of load and resistance factor design criteria for cold-formed stainless steel structural members is being carried out at the University of Missouri-Rolla. The initial work included statistical analyses of mechanical properties and material thicknesses together with the calibrations of the proposed LRFD provisions by using the available test data.

1.2 Purpose of the Study

The purpose of the investigation reported herein was to obtain the statistical data on mechanical properties and thicknesses of stainless steels and to calibrate the proposed LRFD provisions based on the results of statistics. The strength limit state design was used in this study. The material and fabrication factors determined on the basis of the available statistics are presented. The selection of resistance factors and their corresponding safety indices obtained from calibrations are also discussed in this report.

1.3 Scope of the Study

The statistical analyses of mechanical properties and thicknesses are based on six types of stainless steels: Types 201, 301, 304, 409, 430, and 439. The results of statistical analyses are included in Section 2. These statistical values are used for selecting the material and fabrication factors, which are applicable for structural members and connections made by using austenitic and ferritic stainless steels.

For the purpose of formulating the procedures to develop the LRFD provisions, the required formulas are summarized in Section 3. They include 1) the basic theory of LRFD criteria, 2) the model of risk analysis, 3) the evaluation of resistance and load effects, and 4) the calculation of safety index and determination of resitance factors. The mean values and coefficients of variation of material factors as well as fabrication factors used in this study are also given in this section.

The test data obtained from previous Cornell research programs were used in the calibration of the proposed LRFD provisions. In addition to the Cornell data, References 38, 46, and 50 provide additional test results for this study. These tests were fabricated from austenitic and ferritic stainless steels. The calibration based on these test data deals only with the following subjects: 1) flexural members subjected to bending, 2) stub columns and compression members subjected to flexural buckling and torsional-flexural buckling, 3) welded connections, and 4) bolted connections. For flexural members subjected to lateral buckling, the calibration was not included in this report due to the lack of test data.

Sections 4 through 7 include calibrations of the proposed LRFD provisions for the aforementioned subjects. Resistance factors are recommended in these sections with due consideration given to their corresponding safety indices. Section 4 contains the calibrations of the proposed design formulas on bending strength of beams based on either initiation of yielding or inelastic reserve capacity approach. The calibration of the proposed design formulas for concentrically loaded compression members are based on stub column tests, and tests for flexural buckling and torsional-flexural buckling of columns as presented in Section 5. Sections 6 and 7 include the calibrations of the proposed design formulas on welded connections and bolted connections, respectively. Finally, conclusions are drawn and future studies are summarized in Section 8.

2. STATISTICS OF MECHANICAL PROPERTIES AND THICKNESSES FOR STAINLESS STEELS USED IN THE LRFD SPECIFICATION

The LRFD method is an improved approach for the design of steel structures because it involves probabilistic treatments for uncertain variables in different design situations. The theoretical basis of this design method, which is derived from the model of failure probability of structural safety, is included in Section 3.2 of this report. The LRFD criteria are based on the first-order probabilistic design approach, for which only mean values and coefficients of variation of variables are required. These variables reflect the uncertainties in mechanical properties, load effects, design assumptions, and fabrication.

In order to develop the LRFD criteria for cold-formed stainless steel structural members, statistical studies were conducted on mechanical properties (yield strength, tensile strength, and elongation) and thicknesses of stainless steels. The material property statistics obtained from this study are to be used as a basis of selecting the material factor, M, and the fabrication factor, F. These factors are discussed in Section 3.3 of this report.

The American Society for Testing and Materials (ASTM) is the basic source of stainless steel designations. It specifies the minimum values of yield strength and tensile strength of stainless steels as well as other mechanical properties. The ASTM specified mechanical properties have been adapted for the design of cold-formed stainless steel structural members.[3,30] These specified values are to be used in this statistical study.

The available test data used for the statistical analysis are the following types of materials: (1) austenitic stainless steels (Types 201, 301, and 304),[24,47-49] and (2) ferritic stainless steels (Types 409, 430, and 439).[31-34,43-45]

2.1 Austenitic Stainless Steels (Types 201, 301, and 304)

2.1.1 Yield Strengths

The specified yield strengths, F_y, for Types 201, 301, and 304 austenitic stainless steels are given in Table 1. These values are obtained from Ref. 30. The tested yield strengths of 1/4-Hard and 1/2-Hard Type 301 austenitic stainless steels are given in Table 2a. The test data used in this table were obtained from the research projects conducted at Cornell University and reported in Ref. 24. Table 2b includes the tested yield strengths of annealed and strain-flattened Types 201-2 and 304 austenitic stainless steels based on Refs. 47 and 48. The tested data included in Tables 2a and 2b are given for four different types of stresses, i.e., longitudinal tension (LT), transverse tension (TT), transverse compression (TC), and longitudinal compression (LC). In Table 2a, the tested yield strengths in transverse compression are the highest, while the values in the longitudinal compression are the lowest. Similar results can also be found in Table 2b. Additional tested yield strengths of 1/4-Hard and 1/2-Hard Types 201 and 301 austenitic stainless steels are presented in Table 2c, which were obtained from Ref. 49.

By using these specified yield strengths and the tested values discussed above, the yield strengths of Types 201, 301, and 304 austenitic stainless steels have been analyzed statistically. The ratios of tested to specified yield strengths are presented in Tables 3a, 3b, and 3c, which are based on the tested data given in Tables 2a, 2b, and 2c, respectively. The range of the specified yield strengths for these stainless steels varies from 30 to 120 ksi. The mean values and coefficients of variation of the ratios of tested to specified yield strengths are also presented in Table 3.

2.1.2 Tensile Strengths and Elongations

Table 4 presents the statistics on tensile strengths and elongations for Types 201, 301, and 304 austenitic stainless steels. The tested data used in this study were obtained from Refs. 24, 47 and 48, and 49 as given in Tables 2a, 2b, and 2c, respectively. The specified tensile strengths and elongations are based on the ASTM A666-84 Specification[41]. Accordingly, the mean values and coefficients of variation of the ratios of tested to specified tensile strengths and elongations are given in Tables 4a, 4b, and 4c. These tables are based on the source references discussed above.

2.2 Ferritic Stainless Steels (Types 409, 430, and 439)

2.2.1 Yield Strengths

The tested yield strengths for Types 409, 430, and 439 ferritic stainless steels are given in Table 5. The test data used in this study were obtained from Rand Afrikaans University in South Africa, (Ref. 32), Allegheny Ludlum Steel (Ref. 33), and Middelburg Steel and Alloys in South Africa (Refs. 43, 44, 45). The yield strength specified by ASTM for Types 409, 430, and 439 ferritic stainless steels is 30 ksi as given in Table 1.

It has been noted that for these ferritic stainless steels, especially for Types 430 and 439, the specified yield strength is excessively lower than the tested values as given in Table 5. In order to obtain a reasonable material factor on yield strength to be used in the LRFD criteria for cold-formed stainless steels, the adjusted values of yield strength for Types 409, 430, and 439 ferritic stainless steels are needed to reflect the tested results. The differences between the tested and specified yield strengths were discussed by members of the ASCE Steering Committee at the April 21, 1988 meeting held at the University of Missouri-Rolla. It was agreed that the yield strengths for Types 409, 430, and 439 ferritic stainless steels should be revised to more realistic values. Accordingly, the specified yield strengths have been adjusted on the basis of the test values. The ratios of the tested-to-specified yield strength for Types 409, 430, and 439 ferritic stainless steels are given in Table 6. It has been noted that for these stainless steels, most test data are given for transverse tension (TT), which is specified by the ASTM Standard.[42] From this table, it can be seen that the specified yield strength F_y of 30 ksi has been adjusted to 35 ksi for Type 409 in both transverse tension and compression (TT & TC). For Types 430 and 439, the specified yield strength of 30 ksi has been adjusted to 40 ksi for longitudinal tension and compression (LT & LC), and to 45 ksi for transverse tension and compression (TT & TC). Based on these modifications of the specified yield strength for Types 409, 430, and 439 ferritic stainless steels, the mean values and coefficients of variation of the ratios of tested to specified yield strengths are given in this table.

2.2.2 <u>Tensile Strengths and Elongations</u>

The statistics on tensile strengths and elongations for Types 409, 430, and 439 ferritic stainless steels are given in Table 7. The tested tensile strengths and elongations in longitudinal and transverse tension were obtained from the same coupon tests for yield strengths as given in Table 5. In Table 7, the specified tensile strengths are 55 ksi for Type 409, and 65 ksi for Types 430 and 439 ferritic stainless steels. The specified elongation is 22 percent for Types 409, 430, and 439.

Based on the results of the statistical study, the mean values and coefficients of variation of the ratios of tested to specified tensile strengths and elongations are given in Table 7. It should be noted that the ductility was measured by the permanent elongation in a 2 in. gage length of tensile coupon tests after fracture.

2.3 Thicknesses

Only a limited number of measured values are used for the statistical analysis on thicknesses of stainless steels. Table 8 lists the ratios of measured to nominal thicknesses on the basis of 309 test samples for austenitic and ferritic stainless steels. The mean value of these ratios is 0.982 with a coefficient of variation of 0.023. However, these values may not be actually representing the mean value of the thickness statistics because only a small amount of test data was used in this study. Additional test data are needed to determine the fabrication factors caused by the randomness of measured thicknesses of stainless steels.

The statistics on material thicknesses, flange width, overall depth, and inside bend radius for cold-formed carbon and low alloy steels have been studied in Ref. 8, which included a statistical analysis of more than 1400 measured thicknesses of carbon steel sheets. Due to the fact that the manufacture of cold-formed stainless steel sections is similar to that of cold-formed carbon steels, the mean value and coefficient of variation of fabrication factors reconmmended in Ref. 8 are equally applicable for the design of cold-formed stainless steel members. These values are discussed further in Section 3.3 of this report.

2.4 Summary

The material property statistics included in Sections 2.1 and 2.2 of this report for austenitic and ferritic stainless steels are summarized in Table 9 for yield strength and in Table 10 for tensile strength and elongation. By using a total of more than 10,000 test data, the mean value of ratios of the tested to specified yield strengths is 1.149, and the coefficient of variation is 0.092 as given in Table 9. In Table 10, the mean values of ratios of the tested to specified tensile strengths and elongations are 1.178 and 1.434, respectively, with the corresponding coefficients of variation of 0.056 and 0.195.

Based on the aforementioned statistical results, the following mean values and coefficients of variation have been selected by judgmental decisions. These values are to be used as material and fabrication uncertainties for cold-formed structural members and connections made of austenitic and ferritic stainless steels.

$$(\sigma_y)_m = 1.10\ F_y\ , \qquad V_{\sigma_y} = 0.10$$

$$(\sigma_u)_m = 1.10\ F_u\ , \qquad V_{\sigma_u} = 0.05$$

$$t_m = t_s\ , \qquad V_t = 0.05$$

in which σ_y, σ_u, and t are actual values of yield strength, ultimate tensile strength, and thickness of stainless steels, respectively, while F_y, F_u, and t_s are the specified minimum values. The subscript m represents the mean value, and the symbol V stands for the coefficient of variation.

The mean value and coefficient of variation of material thicknesses discussed in the summary are adopted from Ref. 8 and are used for determining the fabrication factor for cold-formed stainless steels. Although these statistical values are larger than those given in Table 8, this assumption is considered to be appropriate because 1) only a limited number of sample tests are available, 2) the fabrication of cold-formed stainless steel sections is similar to that of cold-formed carbon steel, and 3) the proposed allowable stress design specification permits the delivered minimum thickness to be 95 % of the design value.

3. PROCEDURES FOR DEVELOPING LRFD PROVISIONS

In this Section, a detailed discussion on the development of the Load and Resistance Factor Design (LRFD) criteria based on the probabilistic approach is presented. The model of the failure probability of structural safety and performance is also included. The safety index β used as a relative measure of the safety for design is derived from the probability of failure. Separate resistance and load factors are to be applied to nominal resistance and specified loads to ensure that a limit state is not exceeded. These factors reflect the uncertainties of analysis, design, loading, material property, and fabrication. They are to be derived on the basis of the first-order probabilistic approach by using only the mean value and the coefficient of variation of random variables.

For the purpose of facilitating the steps used in the calibration of various design provisions, the following procedures have been formulated. All formulas used in this report for calibration are based on the "Ultimate Strength Limit" states, which are related to the structural failure or collapse of part or all of the structural members and connections. The information presented herein is based on previous research studies conducted for cold-formed carbon steel structural members (Refs. 7, 8, 15-17) and others (Refs. 18, 19).

3.1 Format of Load and Resistance Factor Design Criteria

The load and resistance factor design criteria for the combination of dead and live loads can be expressed in the following equation:

$$\phi R_n \geq \gamma_D c_D D_C + \gamma_L c_L L_C \tag{3.1}$$

The right side of the equation represents the effects of a combination of dead load, D_C, and live load, L_C; whereas, the left side relates to the nominal resistance, R_n, of a structural member; γ_D and γ_L are load factors associated with the dead load and live load, respectively; ϕ is the resistance factor, and c_D and c_L are deterministic influence coefficients, which transform the load intensities to load effects.

3.2 <u>Model of Risk Analysis</u>

It is assumed that the resistance, R, and the load effect, Q, are random variables because of the uncertainties associated with the inherent randomnesses. If these uncertainties are specified in terms of the probability density functions (probability distributions), then the measure of risk is the event of the probability of the "failure" (R<Q). Therefore, the equation for calculating the probability of failure of a structure is given as follows:[18]

$$P_F = P(\text{failure}) = P(R-Q < 0) \qquad (3.2)$$

in which R and Q are the random resistance and load effect, respectively. Figure 1 illustrates the probability distribution of variables R and Q. From this figure, it can be seen that failure may occur when the resistance of the structure is less than the load effect as indicated by the overlapping area of the curves.

To calculate the probability of failure, one requires knowledge of the distribution curves of variables R and Q. Although the correct distributions of R and Q are not known, it is convenient to prescribe the distribution of ln(R/Q) to be normal. Based on this probability distribution, the probability of failure can be expressed as follows:

$$P_F = P(\ln(R/Q) < 0) \qquad (3.3)$$

Equation (3.3) can be expressed by means of the cumulative lognormal distribution as follows:

$$P_F = P\left[U < -\frac{(\ln(R/Q))_m}{\sigma_{\ln(R/Q)}}\right]$$

$$= F_U\left[-\frac{(\ln(R/Q))_m}{\sigma_{\ln(R/Q)}}\right] \qquad (3.4)$$

$$= F_U(-\beta)$$

in which U is a standard variable with a zero mean and a unit standard deviation and defined as

$$U = \frac{\ln(R/Q)-(\ln(R/Q))_m}{\sigma_{\ln(R/Q)}} \qquad (3.5)$$

and $(\ln(R/Q))_m$ and $\sigma_{\ln(R/Q)}$ are the mean value and standard deviation of the natural logarithm of the ratio of R/Q, respectively,

and

$$\beta = \frac{\ln(R/Q)_m}{\sigma_{\ln(R/Q)}} \qquad (3.6)$$

In Eqs. (3.4) and (3.6), β is called the safety index, which sometimes called the "reliability index" is a relative measure of the safety for design. The higher the safety index, the smaller the probability of failure. By using the safety index, the probability of failure is simply obtained from the cumulative lognormal distribution as can be seen in Eq. (3.4). As shown in Fig. 2, the calculated probability of failure, P_F, based on Eq. (3.4)' is the area under the normal curve beyond β standard deviations from the mean. Due to the fact that the probability distribution of R/Q is not practically known, the mean value and coefficient of variation of variables R and Q are used as the estimated values. Thus, based on the statistics of variables R and Q, the safety index, β, calculated from Eq. (3.6) can be represented by the following equation:

$$\beta = \frac{\ln(R_m/Q_m)}{\sqrt{V_R^2+V_Q^2}} \tag{3.7}$$

in which R_m and Q_m are mean values of the resistance of the structure and the load effect, respectively, and V_R and V_Q are their corresponding coefficients of variation. Once the safety index is selected, the resistance factor, ϕ, can be determined accordingly.

3.3 Resistance

At the present, the allowable stress design method is used for cold-formed stainless steel structural members. The allowable load is determined by applying a factor of safety to the failure load. The factor of safety is determined on the basis of engineering judgment and past experience to ensure the safety of the structure. For cold-formed stainless steel design, the basic safety factors used for flexural members, compression members, bolted connections, and welded connections are 1.85, 2.15, 2.4, and 2.5, respectively. These factors of safety are relatively larger than those used for cold-formed carbon steel due to lack of experience for the design of cold-formed stainless steels.

In contrast to the traditional safety factor concept, the structural safety based on the LRFD criteria is achieved by the probabilistic theory instead of the judgment.

The resistance of a structural member, R, is assumed to be of the following form:

$$R = R_n MFP \tag{3.8}$$

in which R_n is the nominal resistance of the structural elements, and M, F, and P are dimensionless random variables reflecting the uncertainties in the material properties (i.e., F_y, F_u, etc.), the geometry of the cross-section (i.e., S_x, A, etc.), and the design assumptions.

The random variable M is called the "material factor" which is determined by the ratio of a tested mechanical property to a specified value. It is considered as a random variable because of the variation of mechanical properties of the materials. Based on the statistical analyses on mechanical properties for cold-formed stainless steels discussed in Section 2, the following mean values and coefficients of variation are recommended for the material factor in this study for structural members and connections made by using austenitic and ferritic stainless steels.

For yield strength of stainless steels

$$(\sigma_y)_m = 1.10\ F_y, \qquad V_{\sigma_y} = 0.10$$

For ultimate strength of stainless steels

$$(\sigma_u)_m = 1.10\ F_u, \qquad V_{\sigma_u} = 0.05$$

The fabrication factor F is a random variable which accounts for the uncertainties caused by initial imperfections, tolerances, and variations of geometric properties. This factor also reflects the differences between the designed and manufactured cross-sectional dimensions. Because a high degree of deviation on weld length and throat thickness is possible, a conservative value of variation of fabrication factor for welded connections is used in this study. Based on the statistical analysis of thicknesses of stainless steels discussed in Section 2 and the results used for cold-formed steel members,[8] the following mean values and coefficients of variation are recommended for the fabrication factor in the design of cold-formed stainless steel structural members and connections:

For stainless steel members and bolted connections

$F_m = 1.00, \qquad V_F = 0.05$

For stainless steel welded connections

$F_m = 1.00, \qquad V_F = 0.15$

These fabrication factors were also used in the development of the AISC LRFD criteria for hot-rolled steel structural members (Ref. 7).

The professional factor P is also a random variable reflecting the uncertainties in the determination of the resistance of structures. These uncertainties are included by the use of approximations in the simplification and idealization of complicated design formulas. The professional factor can be determined by comparing the tested failure loads and the predicted ultimate loads calculated from the selected design provisions. Thus, when the tested data are available, the professional factors are calculated by the ratios of the tested load to the predicted value. In this study, test data were collected from previous research work conducted at Cornell University and other institutions. The mean value and coefficient of variation of the professional factor for each design subject are evaluated and presented in subsequent sections.

After knowing the mean values and coefficients of variation of the material factor, the fabrication factor, and the professional factor, the mean resistance, R_m, can be determined as follows:

$$R_m = R_n M_m F_m P_m \tag{3.9}$$

in which M_m, F_m, and P_m are the mean values of M, F, and P, respectively.

By using the first order probabilistic theory and assuming that there is no correlation between M, F, and P, one finds that the coefficient of variation of the resistance, V_R, is

$$V_R = \sqrt{V_M^2+V_F^2+V_P^2} \quad (3.10)$$

in which V_M, V_F, and V_P are coefficients of variation of the random variables M, F, and P, respectively. For the resistance of the structure, the mean value and coefficient of variation can be obtained from Eqs. (3.9) and (3.10) as derived above.

3.4 Load and Load Effects

In this investigation, the discussion is limited to the gravity loads. The major load combination involving gravity loads is the dead load plus the maximum live load. This load combination governs the design in many practical situations and it is a particularly important case.

The load effect, Q, for a combination of dead and live loads is assumed to be the following form:

$$Q = c_D CD + c_L BL \quad (3.11)$$

where D and L are random variables representing the dead and live load intensities, respectively, c_D and c_L are deterministic influence coefficients, and B and C are random variables reflecting the uncertainties in the transformation of loads into the load effects. Based on the first order probabilistic theory, the mean load effect, Q_m, is

$$Q_m = c_D C_m D_m + c_L B_m L_m \quad (3.12)$$

in which, B_m, C_m, D_m, and L_m are the mean values of the random variables B, C, D, and L described above, respectively.

Consequently, the coefficient of variation of the load effects, V_Q, can be determined as follows:

$$V_Q = \frac{\sqrt{c^2_D C^2_m D^2_m (V^2_C + V^2_D) + c^2_L B^2_m L^2_m (V^2_B + V^2_L)}}{c_D C_m D_m + c_L B_m L_m} \quad (3.13)$$

where V_B and V_C are the coefficients of variation of random variables B and C, respectively, and V_D and V_L are the coefficients of variation of the dead and live loads.

If it is assumed that $B_m=C_m=1.0$ and $c_D=c_L=c$, the mean value and the coefficient of variation of load effects can be expressed as follows:

$$Q_m = c(D_m+L_m) \tag{3.14}$$

and

$$V_Q = \frac{\sqrt{(D_m V_D)^2+(L_m V_L)^2}}{D_m+L_m} \tag{3.15}$$

where D_m, L_m, V_D, and V_L are as defined above.

Load statistics have been analyzed in Ref. 35, where it was shown that $D_m=1.05D_n$, $V_D=0.1$, $L_m=L_n$, and $V_L=0.25$. It also indicated that the mean live load intensity equals to the code live load intensity if the tributary area is small enough so that no live load reduction is required. Substitution of the load statistics into Eqs. (3.14) and (3.15) gives

$$Q_m = c(1.05D_n/L_n+1)L_n \tag{3.16}$$

and

$$V_Q = \frac{\sqrt{(1.05D_n/L_n)^2 V_D{}^2+V_L{}^2}}{(1.05D_n/L_n+1)} \tag{3.17}$$

It can be seen that, in Eqs. (3.16) and (3.17), Q_m and V_Q depend on the dead-to-live load ratio. Previous research reported in Refs. 15 and 16 indicated that cold-formed members typically have relatively small D_n/L_n ratios. For the purposes of determining the reliability of the LRFD criteria for cold-formed stainless steel structural members, it is assumed that the dead-to-live load ratio of 1/5 (D_n/L_n = 1/5) be used in this investigation, and so that V_Q = 0.21.

3.5 Development of Load and Resistance Factor Design Criteria

The values of the reliability index β vary considerably for the different kinds of loading, the different types of construction, and the different types of members within a given material design specification. In order to achieve a more consistent reliability, it was suggested in Ref. 21 that the following values of β would provide this improved consistency while at the same time give, on the average, essentially the design by the new LRFD method as is obtained by current design for all materials of construction. These target reliabilities β_o for use in the AISC LRFD criteria are:

For basic case: Gravity loading, $\beta_o = 3.0$

For connections: $\beta_o = 4.5$

For wind loading: $\beta_o = 2.5$

Previous research on LRFD criteria for cold-formed carbon steel members[16] indicated that for the representative dead-to-live load ratio of 1/5 the target reliability index β_o may be taken as 2.5. A higher target reliability index of $\beta_o = 3.5$ was recommended for connections using cold-formed carbon steels. However, these target values may not be applicable for the design of cold-formed stainless steel because relatively higher safety factors have been used for cold-formed stainless steels as stated in Section 3.3. In order to maintain the consistency of structural safety used in cold-formed stainless steels, two target values of 3.0 and 4.0 are used in this study for members and connections, respectively.

In this report, the resistance factors, ϕ, are determined for the load combination of $1.2D_n+1.6L_n$, which is recommended in the American National Standard, ANSI A58.1-1982,[40] and is also used in Ref. 16 for cold-formed carbon steels. For practical reasons, it is desirable to have relatively few different resistance factors, and therefore the actual values of β will differ from the derived targets. By using the aforementioned load combination, Eq. (3.1) can be written as follows:

$$\phi R_n \geq c(1.2D_n+1.6L_n) \tag{3.18}$$

where c is a deterministic influence coefficient used to transform the loads into load effects. In order to determine the resistance factor, ϕ, for the LRFD criteria, the nominal resistance can be derived from the above formula as

$$R_n = (1.2D_n/L_n+1.6)cL_n/\phi \tag{3.19}$$

By assuming $D_n/L_n = 1/5$, Eqs. (3.19) and (3.16) can be written as follows:

$$R_n = 1.84(cL_n/\phi) \tag{3.20}$$

$$Q_m = (1.05D_n/L_n+1)cL_n = 1.21cL_n \tag{3.21}$$

The mean resistance, R_m, can be obtaineded by substituting Eq. (3.20) into Eq. (3.9).

$$R_m = 1.84(cL_n/\phi)\ M_m F_m P_m \tag{3.22}$$

Therefore, the ratio of R_m/Q_m is obtained from Eqs. (3.21) and (3.22) as follows:

$$\frac{R_m}{Q_m} = \frac{1.521}{\phi}\ M_m F_m P_m \tag{3.23}$$

By applying a proper resistance factor in Eq. (3.23) and by using Eqs. (3.10) and (3.17), the safety index, β, can be determined as

$$\beta = \frac{\ln((1.521/\phi)M_mF_mP_m)}{\sqrt{V^2_M+V^2_F+V^2_P+V^2_Q}} \tag{3.24}$$

Alternatively, based on Eq. (3.7) and by using $D_n/L_n = 1/5$, the ratio of R_m/Q_m can also be obtained from the following equation:

$$\frac{R_m}{Q_m} = \exp(\beta\sqrt{V_R{}^2+V_Q{}^2}) \tag{3.25}$$

By equating Eqs. (3.23) and (3.25), the resistance factor, ϕ, can be computed as follows:

$$\phi = \frac{1.521\ M_mF_mP_m}{\exp(\beta\sqrt{V^2_R+V^2_Q})} \tag{3.26}$$

4. DEVELOPMENT OF THE PROPOSED LRFD PROVISIONS FOR BENDING STRENGTH OF BEAMS

4.1 General Remarks

The objective of this section is to determine the safety index and the proper resistance factor for bending strength of flexural members by calibrating the proposed LRFD formulas. In this process, the mean values and coefficients of variation of the professional factors were obtained from the ratios of the tested ultimate moments to the predicted values for beams. Based on the formulas discussed in Section 3, the safety index can be computed. Accordingly, the resistance factor for flexural members is obtained from the computed safety index. Based on the test data on stainless steel beams subjected to bending, the calibrations of the proposed design provisions deal only with the nominal section strength of beams determined by either the initiation of yielding or the inelastic reserve capacity approach.

4.2 Proposed LRFD Provisions

The nominal bending strength of beams shall be calculated either on the basis of the initiation of yielding (Procedure I) or on the basis of the inelastic reserve capacity (Procedure II) as applicable. The effective section shall be used for both procedures to determine the sectional properties of beams. Due to the pronounced anisotropic characteristics in the cold-formed stainless steel beams, consideration must be given to the type of stress in compression or tension.

(1) Procedure I - Initiation of Yielding in Compression or Tension

The effective yield moment, M_n, based on the effective section and the yield strength shall be determined as follows:

$$M_n = S_e F_y \qquad (4.1)$$

where

F_y = Specified yield strength in compression, F_{yc}, or specified yield strength in tension, F_{yt} (Table 1)

S_e = Elastic section modulus of the effective section calculated with the extreme compression fiber at F_{yc} or the extreme tension fiber at F_{yt}, whichever initiates yielding first

(2) Procedure II - Inelastic Reserve Capacity

In order to utilize the available inelastic reserve strength of cold-formed stainless steel beams, new design provisions based on the partial plastification of the cross section are proposed in this study. Due to the lack of research data on cold-formed stainless steel members, the following design requirements are adopted from the AISI Specification (Ref. 2) for cold-formed carbon steels except that λ_1 and λ_2 are determined by the applicable compression stress (longitudinal or transverse) and the initial modulus of elasticity.

The inelastic reserve capacity of flexural members may be used when the following conditions are met:

(i) The member is not subject to twisting or to lateral, torsional, or torsional-flexural buckling.

(ii) The effect of cold forming is not included in determining the yield strength.

(iii) The ratio of the depth of the compressed portion of the web to its thickness does not exceed λ_1.

(iv) The shear force does not exceed $0.35F_y$ times the web area, hxt.

(v) The angle between any web and the vertical does not exceed 30°.

The nominal moment strength, M_n, shall not exceed either $1.25S_eF_y$ determined according to Procedure I or that causing a maximum compression strain of C_ye_y (no limit is placed on the maximum tensile strain), in which e_y is the yield compression strain = F_{yc}/E_o.

The coefficient C_y is the compression strain factor determined as follows:

(a) Stiffened compression elements without intermediate stiffeners

$C_y = 3$, for $w/t \le \lambda_1$

$C_y = 3 - 2\left[(w/t-\lambda_1)/(\lambda_2-\lambda_i)\right]$, for $\lambda_1 < w/t < \lambda_2$

$C_y = 1$, for $w/t \ge \lambda_2$

where

$$\lambda_1 = 1.11/\sqrt{F_{yc}/E_o} \quad (4.2)$$

$$\lambda_2 = 1.28/\sqrt{F_{yc}/E_o} \quad (4.3)$$

(b) Unstiffened compression elements

$C_y = 1$

(c) Multiple-stiffened compression elements and compression elements with edge stiffeners

$C_y = 1$

When applicable, effective design widths shall be used in calculating section properties. M_n shall be calculated considering equilibrium of stresses, assuming an ideally elastic-plastic stress-strain curve in compression and tension, assuming small deformation, and assuming that plane sections remain plane during bending.

(3) The effective widths, b, of compression elements used for calculating the effective sectional properties (S_e, A_e, etc.) are determined in accordance with the following design provisions:

(i) For uniformly compressed stiffened and unstiffened elements, the effective widths, b, shall be determined from the following formulas:

$$b = w \quad \text{when } \lambda \leq 0.673 \tag{4.4}$$

$$b = \rho w \quad \text{when } \lambda > 0.673 \tag{4.5}$$

where

w = Flat width as shown in Figs. 3(a) and 3(b)

$$\rho = (1-0.22/\lambda)/\lambda \tag{4.6}$$

$$\lambda = (1.052/\sqrt{k})(w/t)(\sqrt{f/E_o}) \tag{4.7}$$

k = 4.0 for stiffened compression elements supported by a web on each longitudinal edge

= 0.5 for unstiffened compression elements supported by a web at only one edge *

(ii) For webs and stiffened elements with stress gradient, the effective widths, b_1 and b_2, shall be determined from the following formulas:

$$b_1 = b_e/(3-\Psi) \tag{4.8}$$

For $\Psi \leq -0.236$

$$b_2 = b_e/2 \tag{4.9}$$

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* This k value is slightly larger than that used for cold-formed carbon steel sections (k = 0.43). Previous test results of cold-formed stainless steel members with unstiffened compression flanges indicated that the buckling coefficient can be taken as 0.85 for I-sections made by two channels connected back to back. In the 1974 Edition of the AISI Specification, the buckling coefficient was conservatively taken as 0.5 for unstiffened compression elements. This k value of 0.5 has been successfully used for determining the effective sectional properties of cold-formed stainless steel sections.

b_1+b_2 shall not exceed the compression portion of the web calculated on the basis of effective section

For $\Psi > -0.236$

$$b_2 = b_e - b_1 \tag{4.10}$$

where

b_e = Effective width b determined in accordance with Eqs. (4.6) and (4.7) with f_1 substituted for f and with k determined as follows:

$$k = 4+2(1-\Psi)^3+2(1-\Psi) \tag{4.11}$$

$$\Psi = f_2/f_1 \tag{4.12}$$

f_1, f_2 = Stress shown in Fig. 3(c) calculated on the basis of effective section. f_1 is compression (+) and f_2 can be either tension (-) or compression. In case f_1 and f_2 are both compression, $f_1 \geq f_2$

4.3 Selection of Resistance Factor for Nominal Bending Strength

In this study, a total of 17 Cornell beam tests were used for calibration. The cross-section of test specimens (hat sections) and the test setup used for the beam tests are shown in Fig. 4. The dimensions of test specimens are given in Table 11. Two types of austenitic stainless steels were included in this study. They are (1) annealed and strain flattened Type 304 (Series F and AS304F) and (2) 1/2-Hard Type 301 (Series H301F).

Table 12 lists the comparison of tested and predicted ultimate moments for the 17 beam test specimens. The tested ultimate moments of beams, M_{test}, are obtained from Refs. 23 and 24. The values, M_{pred}, represent the predicted ultimate moments. Also included in this table are the w/t ratios of the stiffened compression flanges and the yield strengths in longitudinal compression and tension, F_{yc} and F_{yt}, respectively.

All predicted ultimate moments, M_{pred}, were computed on the basis of initiation of yielding as given in Procedure I of Section 4.2. A computer program has been prepared for determining the predicted ultimate moments as given in Appendix C. The flow chart that gives basic steps in the computation of the nominal bending moment based on initiation of yielding is illustrated in Fig. 5. The predicted ultimate moments were also determined on the basis of the inelastic reserve capacity approach as given in Procedure II of Section 4.2. Because only two specimens (No. F-4 and F-5) were found to be applicable to use this method for determining the ultimate moment, the proposed inelastic reserve capacity approach would require further verification by using future tests. In Table 12, the predicted ultimate moments given in the parenthesis for the two specimens are based on the inelastic reserve capacity method. It can be seen that by using the partial plastification of the cross section for these two specimens, a better prediction can be achieved.

In the determination of the safety indices, the ratios of tested to predicted values are defined to be the professional factor. From Table 12, it can be seen that the mean value, P_m, and the coefficient of variation, V_P, of the professional factor are 1.189 and 0.0608, respectively, if the predicted ultimate moments for Specimens F-4 and F-5 are based on inelastic reserve capacity method. On the basis of the material and fabrication factors discussed in Section 3, it was decided that the following mean values and coefficients of variation be used in this study:

Material factor: $M_m = 1.10$, $V_M = 0.10$

Fabrication factor: $F_m = 1.00$, $V_F = 0.05$

Based on these mean values and coefficients of variation, the safety index can be computed accordingly.

The relationship between the safety index, resistance factor, and the ratio of D_n/L_n for stainless steel beams subjected to bending is shown graphically in Fig. 6. From this figure, it can be seen that based on the ratio of $D_n/L_n = 0.2$, the computed safety index is 3.04 if the value of the resistance factor is taken as 0.95. The safety indices computed for other ϕ values are also given in Fig. 6. As discussed in Section 3, the resistance factor shall be determined so that its corresponding safety index is larger than the target value. Based on the target safety index of 3.0 for cold-formed stainless steel structural members, the resistance factor of 0.95 ($\phi = 0.95$) is recommended for cold-formed stainless steel beams subjected to flexural bending.

4.4 Comparison of Safety Indices and Resistance Factors for Cold-Formed Carbon and Stainless Steel Beams

Recently, the LRFD provisions for cold-formed carbon steel structural members were reported in Ref. 16. The results of calibrations on bending strengths of cold-formed steel beams are given in Table 13, in which the safety indices β vary from 2.53 to 2.76 for sections with stiffened compression flanges if the resistance factor ϕ was taken as 0.95. This resistance factor was determined on the basis of $D_n/L_n = 0.2$ for a load combination of $1.2D_n + 1.6L_n$. As compared with the results given in Section 4.3 of this study, the safety indices determined for carbon steel beams are relatively lower than that used for cold-formed stainless steel flexural members although the same ϕ factor of o.95 is used for both cases.

5. DEVELOPMENT OF THE PROPOSED LRFD PROVISIONS FOR CONCENTRICALLY LOADED COMPRESSION MEMBERS

5.1 General

The calibrations presented in this section are based on the proposed design formulas to be included in the LRFD criteria. The formulas given in Section 3 of this report were used to determine the safety index and the corresponding resistance factor. Because only a limited number of tests[23,38,50] were available for this study, the calibrations of the proposed design provisions for concentrically loaded compression members are based on the stub column tests, and the tests for flexural buckling and torsional-flexural buckling of columns.

5.2 Proposed LRFD Provisions

The proposed LRFD provisions contain the following requirements for compression members, in which the resultant of all loads acting on the member is an axial load passing through the centroid of the effective section at the stress, F_n, defined in this section.

The nominal axial load shall be calculated as follows:

$$P_n = A_e F_n \qquad (5.1)$$

where

A_e = Effective area calculated at the stress F_n

F_n = The least of flexural buckling, torsional buckling, and torsional-flexural buckling stresses.

Due to the lack of test data for columns subjected to torsional buckling, the following design provisions used for this study are given only for columns subjected to flexural buckling and torsional-flexural buckling.

(1) For doubly-symmetric sections, closed cross sections and any other sections which can be shown not to be subject to torsional or torsional-flexural buckling, the flexural buckling stress, F_n, shall be determined by the following equation.

$$F_n = \pi^2 E_t/(KL/r)^2 \le F_y \tag{5.2}$$

where

E_t = Tangent modulus in compression corresponding to stress F_n, as determined from Eq. (A.9) of Appendix A

$$= E_o F_y/(F_y + 0.002nE_o(F_n/F_y)^{n-1}) \tag{5.3}$$

n = Constant, as determined from Eq. (A.7) of Appendix A

$$= \log(0.002/\epsilon_1)/\log(F_y/\sigma_1) \tag{5.4}$$

ϵ_1, σ_1 = 0.01 % offset strain and stress, respectively

F_y = 0.2 % offset yield strength

E_o = Initial modulus of elasticity

K = Effective length factor

L = Unbraced length of member

r = Radius of gyration of the full, unreduced cross section

(2) For singly-symmetric sections subject to torsional-flexural buckling, F_n shall be taken as the smaller of F_n calculated in Eq. (5.2) and F_n calculated as follows:

$$F_n = (1/2\beta)((F_{ex}+F_t) - \sqrt{(F_{ex}+F_t)^2 - 4\beta F_{ex}F_t}) \le F_y \tag{5.5}$$

where

$$\beta = 1 - (x_o/r_o)^2 \tag{5.6}$$

F_{ex} = Euler buckling stress about the symmetry axis (x-axis)

$$= (\pi^2 E_o/(K_x L_x/r_x)^2)(E_t/E_o) \tag{5.7}$$

F_t = Torsional buckling stress

$$= (1/(Ar_o)^2)(G_oJ+\pi^2E_oC_w/(K_tL_t)^2)(E_t/E_o) \qquad (5.8)$$

x_o = Distance from the shear center to the centroid along the x-axis

r_o = Polar radius of gyration of the cross section about the shear center

r_x = Radius of gyration of the cross section about the centroidal principal x-axis

r_y = Radius of gyration of the cross section about the centroidal principal y-axis

K_x,K_t = Effective length factors for bending about x-axis and twisting, respectively

L_x,L_t = Unbraced lengths of member for bending about x-axis and twisting, respectively

A = Area of full, unreduced cross section

G_o = Initial shear modulus

J = St. Venant torsion constant of the cross section

C_w = Torsional warping constant of the cross section

E_t and E_o are defined in Section 5.2(1).

The flexural buckling stress, F_n, in Eq. (5.2) was determined simply by using the tangent modulus theory. The torsional-flexural buckling stress, F_n, in Eq. (5.5) is calculated on the basis of Eqs. (5.7) and (5.8), in which the tangent modulus is determined at the torsional flexural buckling stress. The tangent modulus E_t used in these equations was computed by the modified Ramberg-Osgood Equation as given in Eq. (5.3). Due to the fact that the tangent modulus equation is a function of the buckling stress, the process for determining the tangent modulus corresponding to the stress F_n is iterative and tedious. For the purpose of simplicity, the flexural buckling stress and the torsional-flexural buckling stress are obtained from computer programs as given in Appendices D and E, respectively, in which the nonlinear iterations are included.

In the determination of the effective area A_e, the effective width, b, of compression elements used in this study shall be calculated in accordance with Section 4.2(3) of this report. For uniformly compressed stiffened and unstiffened elements, the effective widths, b, shall be determined in accordance with Eqs. (4.4) through (4.7) of this report.

5.3 Selection of Resistance Factor for Concentrically Loaded Compression Members - Based on Stub Column Tests

A total of 14 stainless steel stub columns having unstiffened and stiffened compression elements were obtained from previous Cornell studies.[23,24] The cross sections of these test specimens (I-sections and box sections) and the test setup used for the testing of stub columns are shown in Fig. 7. These stub columns were tested in the flat-ended condition between ends. The specimens were fabricated from annealed Type 304 and 1/2-hard Type 301 austenitic stainless steels. The dimensions of these test specimens are given in Table 14.

The tested failure loads, P_{test}, obtained from Refs. 23 and 24 and the predicted failure loads, P_{pred}, are listed in Table 15. The predicted failure loads, P_{pred}, are computed by the product of the yield strength in longitudinal compression of the material (F_{yc}) and the effective area (A_e) calculated on the basis of the effective width formula. This table also gives the ratios of w/t varing from 11 to 154.5. The comparison of the tested and predicted failure loads is indicated by the ratio of

P_{test}/P_{pred} as given in Table 15. The mean value of the P_{test}/P_{pred} ratios, P_m, is 1.265, and its coefficient of variation, V_P, is 0.06.

Based on the discussions presented in Section 3.3, the mean value and coefficient of variation of the ratios of P_{test}/P_{pred} were used as the professional factor in the determination of the nominal resistance of the stub column. The material factor and fabrication factor used for this study are: $M_m = 1.10$, $V_M = 0.10$, $F_m = 1.00$, and $V_F = 0.05$. On the basis of these mean values and coefficients of variation, the safety index can be determined by the formulas given in Section 3.

The relationship between the safety index, resistance factor, and the ratio of D_n/L_n for stainless steel stub columns is illustrated in Fig. 8. The safety indices are compared with four different resistance factors ranging from 0.85 to 1.0 with an increment of 0.05. From this figure, it can be seen that all computed safety indices for $D_n/L_n = 0.2$ are larger than the target value of 3.0. If the resistance factor is taken as 0.95, the computed safety index for $D_n/L_n = 0.2$ is equal to 3.40. For other ϕ factors, the computed safety indices for $D_n/L_n = 0.2$ are also shown in the figure. Based on this result, the resistance factor of 0.95 is recommended for the LRFD criteria for stainless steel stub columns.

5.4 <u>Selection of Resistance Factor for Concentrically Loaded Compression Members - Based on Flexural Buckling of Columns</u>

The test results of stainless steel columns used in this study were obtained from Refs. 23 and 38. The column specimens were fabricated from annealed and skin passed Type 304 austenitic stianless steels. The test specimens (I-sections and box sections) and the test setup used for column tests are shown in Fig. 9. These columns were tested in the pin-ended condition. Table 16 lists the dimensions and sectional properties of these test specimens.

For a total of 29 tests, the tested failure loads, P_{test}, the predicted loads, P_{pred}, and the ratios of P_{test}/P_{pred} are listed in Table 17. The tested failure loads were obtained from Refs. 23 and 38, while the predicted loads were calculated on the basis of the design equations as given in Eqs. (5.1) and (5.2). The tangent modulus, E_t, of the stainless steel used in this study is determined by the Modified Ramberg-Osgood formula[36,37] as discussed in the Appendix A. After substituting Eq. (5.3) for tangent modulus E_t into Eq. (5.2), it can be seen that the flexural buckling stress is a function of the stress itself. Because the process for determining the nonlinear equation to obtain the correct buckling stress is iterative and tedious, a computer program has been prepared to calculate the solution. This program is included in Appendix D of the report. Also included in this table are the slenderness ratios of columns (l/r) varying from 27.5 to 177, the computed flexural buckling stress (F_c), and the effective area of sections (A_e).

The ratios of the tested to predicted failure loads are used as the professional factor to compute the safety index for the flexural buckling of columns. Based on the results given in Table 17, the mean value of the professional factor, P_m, is 1.194, and its coefficient of variation, V_P, is 0.114. The material factor and the fabrication factor are the same as those used in Section 5.3, i.e., M_m = 1.10, V_M = 0.10, F_m = 1.00, and V_F = 0.05. Using the formulas given in Section 3, the safety index can be computed and the proper resistance factor can be determined readily.

Figure 10 shows the relationship between the safety index, resistance factor, and the ratio of D_n/L_n for stainless steel columns subjected to flexural buckling. The computed safety indices are compared with four different resistance factors ranging from 0.85 to 1.0 with an increment of 0.05. From this figure, it can be seen that the computed safety index (β = 3.05) is slightly higher than the target value for D_n/L_n = 0.2 if the resistance factor is taken as 0.90. A safety index of 3.26 can be achieved if the resistance factor of 0.85 is used. The safety indices computed for other ϕ values are also shown in Fig. 10. In order to be consistent with the LRFD criteria for cold-formed carbon steel sections (Ref. 17) and hot-rolled shapes (Ref. 6), the same resistance factor of ϕ = 0.85 is recommended for the LRFD criteria for stainless steel columns subjected to flexural buckling.

The conclusion discussed above for columns subjected to flexural buckling is drawn from a limited number of tests made of annealed and skin passed Type 304 stainless steels only. It may not be applicable for other types of cold-formed stainless steels. Additional tests are needed to justify the values recommended in this study.

5.5 <u>Selection of Resistance Factor for Concentrically Loaded Compression Members - Based on Torsional-Flexural Buckling of Columns</u>

The experimental study on torsional-flexural buckling strength of cold-formed stainless steel columns has been conducted by Van den Berg and Van der Merwe.[50] These tested results are used to compare with the predicted values that are determined by using the proposed LRFD provisions as given in Eq. (5.5).

The column specimens used in this study were fabricated from Types 304, 409, and 430 stainless steels. All these columns are hat sections as shown in Fig. 11a. Hinge-ended conditions were used for these column tests as shown in Fig. 11b. Table 18 lists the dimensions and sectional properties of these test specimens.

The tested failure loads, P_{test}, and the predicted loads, P_{pred}, for a total of 45 tests are listed in Table 19. The tested failure loads were obtained from Ref. 50, while the predicted loads were calculated on the basis of Eqs. (5.5), (5.6), and (5.7). It should be noted that the tangent modulus in Eqs. (5.7) and (5.8) should be determined at the stress causing torsional-flexural buckling, not flexural or torsional buckling. The tangent modulus, E_t, of the stainless steel used in this study is also determined by the Modified Ramberg-Osgood formula[36,37] as given in Eq. (5.3). A computer program based on the nonlinear iteration method has been prepared to determine the predicted torsional-flexural buckling stress of columns as presented in Appendix E of this report. The comparison of the tested and predicted loads is given by the ratios of P_{test}/P_{pred}. Also included in this table are the slenderness ratios of columns, l/r_y, varying from 11.0 to 202.0 and the yield strengths of column specimens.

The ratios of the tested to predicted failure loads are used as the professional factor to compute the safety index for the torsional-flexural buckling of columns. Based on the results given in Table 19, the mean value of the professional factor, P_m, is 1.111, and its coefficient of variation, V_P, is 0.074. The material factor and the fabrication factor are the same as those used in Section 5.4, i.e., M_m = 1.10, V_M = 0.10, F_m = 1.00, and V_F = 0.05. Using the formulas given in Section 3, the safety index can be computed and the proper resistance factor can be determined readily.

Figure 12 shows the relationship between the safety index, resistance factor, and the ratio of D_n/L_n for stainless steel columns subjected to flexural buckling. The computed safety indices are compared with four different resistance factors ranging from 0.85 to 1.0 with an increment of 0.05. From this figure, it can be seen that the computed safety index (β = 2.94) is slightly less than the target value for D_n/L_n = 0.2 if the resistance factor is taken as 0.90. However, a safety index of 3.17 can be achieved if the resistance factor of 0.85 is used. The safety indices computed for other ϕ values are also shown in Fig. 12. Based on this result, the resistance factor of ϕ = 0.85 is also recommended for the LRFD criteria for stainless steel columns subjected to torsional-flexural buckling.

5.6 Comparison of Safety Indices and Resistance Factors for Cold-Formed Carbon and Stainless Steel Columns

The results of calibration of the AISI design provisions for cold-formed carbon steel column members are summarized in Table 20. It can be seen that the safety indices computed for stub columns varies from 2.72 to 3.13, while for long columns subjected to different buckling modes, the safety indices varies from 2.39 to 3.34. For all cases given in Table 20, the resistance factor is taken as 0.85. This resistance factor was determined for D_n/L_n = 0.2 and on the basis of a load combination of $1.2D_n+1.6L_n$.

As compared with the results obtained from Section 5.3 of this report, it is noted that the safety indices and resistance factors used for stainless steel stub columns are relatively larger than those for cold-formed carbon steels. For cold-formed stainless steel columns subjected to flexural and torsional-flexural buckling, the safety indices obtained from Sections 5.4 and 5.5 of this report, respectively, are slightly larger than those used for cold-formed carbon steels. However, the same resistance factor of $\phi = 0.85$ has been selected for both cold-formed carbon steel and stainless steel columns subjected to flexural and torsional-flexural buckling.

6. DEVELOPMENT OF THE PROPOSED LRFD PROVISIONS FOR WELDED CONNECTIONS

6.1 General

In this section, calibrations are based on the proposed design formulas to be included in the LRFD criteria. The objective of this section is to determine the safety indices and the proper resistance factors for welded connections by following the procedures and the formulas given in Section 3 of this report. Based on the test results of welded connections obtained from previous Cornell research program[26] and Ref. 46, the investigation presented herein includes the calibrations of the proposed design provisions for groove welds and fillet welds.

6.2 Proposed LRFD Provisions

The welded connections shall be designed to transmit the maximum load in the connected member. Proper regard shall be given to eccentricity. The nominal failure loads , P_n, for groove welds in butt joints and fillet welds shall be determined from the following design provisions:

(1) Groove Welds in Butt Joints

The nominal load in tension or compression for a groove weld in a butt joint, welded from one or both sides, shall be determined by the following equation, provided that an effective throat equal to or greater than the thickness of the material is consistently obtained.

$$P_n = LtF_{ua} \qquad (6.1)$$

where

L = Welded length

t = Thickness of the thinnest welded sheet

F_{ua} = Tensile strength of the annealed base metal

(2) Fillet Welds

The nominal shear strength, P_n, on a fillet weld in lap or T-joints shall not exceed the following:

(i) For longitudinal loading:

$$P_n = (0.7 - 0.009\ L/t)\ LtF_{ua}, \quad \text{for } L/t < 30 \tag{6.2}$$

$$P_n = 0.43\ LtF_{ua}, \quad \text{for } L/t \geq 30, \tag{6.3}$$

$$\text{or } P_n = 0.75Lt_wF_{xx} \tag{6.4}$$

(ii) For transverse loading:

$$P_n = 0.75\ LtF_{ua}, \tag{6.5}$$

$$\text{or } P_n = Lt_wF_{xx} \tag{6.6}$$

where

L = Length of fillet weld

t = Thickness of the thinnest connected sheet

t_w = Effective throat = 0.707t

F_{ua} = Tensile strength of the annealed base metal

F_{xx} = Tensile strength of the weld metal

6.3 Selection of Resistance Factor for Welded Connections

6.3.1 Groove Welds in Butt Joints

A total of 10 as-welded groove welds obtained from Ref. 26 were used in this study. Typical groove welded specimens reported in Ref. 26 are shown in Fig. 13. The materials used for the tests are 1/4-Hard and 1/2-Hard Type 301 austentic stainless steel sheets. The welded length of test specimens is measured to be 0.5 inch. Table 21 lists the tested ultimate strength (F_{ult}), the average tensile strength of weld metal (F_{xx}), and the mechanical properties of annealed, 1/4-Hard, and 1/2-Hard

Type 301 base metals (F_{ua} and F_y) obtained from Ref. 26. In this case, the base metal thickness of test specimens instead of the as-welded thickness was used to calculate the ultimate strength of weldments. The comparison of the tested and predicted failure strengths of groove welds is given by the ratio of F_{ult}/F_{ua}.

In addition to test results obtained from Ref. 26, 33 test data on butt-joint welds reported in Ref. 46 were also included in this study. The test specimens were fabricated from 1/4-Hard Type 301 stainless steels. Tables 22 through 24 summarize the test results of butt welds by using Tungsten Inert Gas (TIG), Metal Inert Gas (MIG), and coated electrode welding processes, respectively. In these tables, F_y is the yield strength of cold-rolled metal, F_{ua} is the tensile strength of annealed base metal, F_{ult} is the tested ultimate strength of weldments, and F_{xx} is the average tensile strength of weld metal. The welded length used for these test specimens is taken as one inch. These specimens were tested in the as-welded condition, for which the weld reinforcement was not removed. However, the base metal thickness of test specimens was used to calculate the ultimate strength. The ratios of the tested to predicted failure strength, F_{ult}/F_{ua}, are also given in these tables.

For a total of 43 butt-joint welds obtained from Tables 21 through 24, the mean value of F_{ult}/F_{ua} is $P_m = 1.113$ and its coefficient of variation, V_P, is 0.084. These values are considered to be the professional factors, which were discussed in Section 3 of this report.

In order to determine the nominal resistance, the material factor and fabrication factor used in this study are taken as follows:

Material factor: $M_m = 1.10$, $V_M = 0.05$

Fabrication factor: $F_m = 1.00$, $V_F = 0.15$

The nominal resistance of groove welds is determined on the basis of the above values and the professional factor. Based on the formulas listed in Section 3, the safety index can be computed from a specified resistance factor and a ratio of D_n/L_n.

Figure 14 illustrates the variation of safety indices, β, with respect to the ratio of D_n/L_n for using groove welds. The computed safety indices are also plotted against four different resistance factors ranging from 0.55 to 0.7 with an increment of 0.05. It indicates that by using a resistance factor of 0.6, the computed safety index for $D_n/L_n = 0.2$ is equal to 4.13, which is larger than the target value ($\beta_o = 4.0$). However, a relatively low safety index of 3.84 can be achieved if the resistance factor is taken as 0.65. By comparing these results, a resistance factor of 0.60 ($\phi = 0.60$) is recommended for the development of the LRFD criteria for the design of welded connections using groove welds.

6.3.2 Longitudinal Fillet Welds

A total of 10 connection tests using longitudinal fillet welds were reported in Ref. 26. They were used in this report to calibrate the design formulas given in Eqs. (6.2) to (6.4). The test specimens were fabricated from two blanks, 4 in. x 20 in. (100 mm x 510 mm) and 5 in. x 20 in. (130 mm x 510 mm), as shown in Fig. 15a. The test blanks were sheared from 1/4- and 1/2-Hard Type 301 stainless steel sheets.

The tested failure loads, P_{test}, obtained from Ref. 26, and the predicted failure loads, P_{n1} and P_{n2}, are listed in Table 25. The predicted load P_{n1} was computed from Eqs. (6.2) or (6.3) to prevent the failure of sheet, while P_{n2} was determined by using Eq. (6.4) for preventing weld metal failure. The comparison of the tested and predicted failure loads of longitudinal fillet welds is given by the ratios of P_{test}/P_{n1} and P_{test}/P_{n2}. Also included in this table are the plate thickness (t), weld length (L), the tensile strength of the annealed base metal (F_{ua}), and the average tensile strength of the weld metal (F_{xx}).

From Table 25, it is noted that the mean values of P_{test}/P_{n1} and P_{test}/P_{n2}, which are referred to as the professsional factor, P_m, are 1.083 and 1.058, and the coefficients of variation, V_P, are 0.131 and 0.126, respectively. The material and fabrication factors used for this subject are similar to those used for groove welds, i.e., M_m = 1.10, V_M = 0.05 F_m = 1.0, and V_F = 0.15. Based on these values, the safety index can be computed by using the formulas given in Section 3 of this report. Then, the resistance factor is determined on the basis of the computed safety index and the ratio of D_n/L_n.

The variations of the safety indices versus the ratio of D_n/L_n for preventing sheet metal and weld metal failures of longitudinal fillet welds are shown graphically in Figs. 16 and 17, respectively. The safety indices are also plotted for four selected resistance factors varing from 0.50 to 0.65 with an increment of 0.05. From these two figures, it is noted that both computed safety indices for D_n/L_n = 0.2 are larger than the target value (β_o = 4.0) if the resistance factors are taken as 0.55 or less. However, if the resistance factors of 0.6 or higher are used for both cases, the safety indices are lower than the target value.

Accordingly, the resistance factor of 0.55 (ϕ = 0.55) is recommended for the LRFD criteria to prevent both sheet metal and weld metal failures of longitudinal fillet welds.

6.3.3 Transverse Fillet Welds

A total of 10 connection tests using transverse fillet welds were obtained from Ref. 26 and used in this study. The test specimens were made from two 4 in. x 20 in. (100 mm x 510 mm) blanks as shown in Fig. 15b. The test blanks were sheared from 1/4- and 1/2-Hard Type 301 austenitic stainless steel sheets.

The tested failure loads, P_{test}, obtained from Ref. 26, and the predicted ultimate loads, P_{n1} and P_{n2}, determined from Eqs. (6.5) and (6.6), respectively, are listed in Table 26. It should be noted that P_{n1} is the predicted load to prevent sheet failure and P_{n2} is the predicted ultimate load for weld metal. The comparison of the tested and predicted failure loads of transverse fillet welds is given by the ratios of P_{test}/P_{n1} and P_{test}/P_{n2}. The dimensions of plate thickness (t), weld length (L), and material properties are also included in this table.

From Table 26, it can be seen that the mean values of P_{test}/P_{n1} and P_{test}/P_{n2}, which are referred to as the professsional factor, P_m, are 1.027 and 1.207, and the coefficients of variation, V_P, are 0.088 and 0.089, respectively. The material and fabrication factors used for this subject are the same as those used for longitudinal fillet welds, i.e., $M_m = 1.10$, $V_M = 0.05$, $F_m = 1.0$, and $V_F = 0.15$. Based on these values, the safety index can be computed by using the formulas given in Section 3 of this report. Similarly, the resistance factor is determined on the basis of the computed safety index and the ratio of D_n/L_n.

The variations of the safety indices versus the ratio of D_n/L_n for transverse fillet welds against plate failure are shown graphically in Fig. 18. The safety indices are compared with four different resistance factors ranging from 0.5 to 0.65 with an increment of 0.05. From this figure, it is noted that the computed safety indices for $D_n/L_n = 0.2$ are larger than the target value ($\beta_o = 4.0$) if the resistance factors are taken as 0.55 or less. Consequently, if the resistance factor of 0.6 is used, the safety index is lower than the target value.

For the study of weld metal failure of transverse fillet welds, the variation of the safety indices versus the ratios of D_n/L_n is shown in Fig. 19. The safety indices are also compared with four different resistance factors varying from 0.6 to 0.75 with an increment of 0.05. The computed safety indices for $D_n/L_n = 0.2$ are larger than the target value if the resistance factors of 0.65 or less are used as shown in Fig. 19. But the safety indices are to be lower than the target value if the resistance factors of 0.70 or higher are used in this case.

Based on the findings discussed above, the resistance factors (ϕ) of 0.55 and 0.65 are recommended for the LRFD criteria on transverse fillet welds against plate and weld metal failures, respectively.

6.4 Comparison of Safety Indices and Resistance Factors for Cold-Formed Carbon and Stainless Steel Welded Connections

For cold-formed carbon steels, the design provisions and the ϕ factor ($\phi = 0.9$) for groove welds in butt joints are the same as those used in the AISC LRFD criteria (Ref. 6). The nominal ultimate strength is determined on the basis of the yield strength of the base steel (Ref. 17). In this report, the ϕ factor is determined by using the design provisions discussed in Section 6.2(1), in which the nominal strength is based on the tensile strength of the annealed base metal. Due to the difference of design provisions, the resistance factor used for Ref. 17

for AISI cold-formed carbon steels is larger than that recommended in this report for cold-formed stainless steels.

The design provisions of cold-formed carbon steel welded connections have been calibrated for the subjects of arc spot welds and fillet welds. Table 27 summarizes the results of calibrations reported in Ref. 16. For longitudinal fillet welds, it can be seen that by using the resistnace factors of 0.55 and 0.6, the corresponding safety indices are 3.59 and 3.65 for two cases. The computed safety index is to be 3.72 if the resistnace factor of 0.6 is used for transverse fillet welds. These resistance factors were determined on the basis of $D_n/L_n = 0.2$ for a load combination of $1.2D_n+1.6L_n$.

Based on the above discussion, the resistance factors used for cold-formed carbon steel fillet weld connections are similar to those recommended for stainless steels. However, the safety indices obtained from Ref. 16 are relatively less than those computed in Section 6.3 for stainless steels.

7. DEVELOPMENT OF THE PROPOSED LRFD PROVISIONS FOR BOLTED CONNECTIONS

7.1 General

In this section, calibrations are based on the proposed design formulas to be included in the LRFD criteria. The objective of this section is to determine the safety index and the appropriate resistance factor for bolted connections. The procedures and the formulas of calibration given in Section 3 of this report are used in this section. Because only a limited number of test results were obtained from previous Cornell research program,[26] the investigation presented herein includes the calibrations of the design provisions for shear failure in connected parts, bearing, and tension failure of bolted connections.

7.2 Proposed LRFD Provisions

The design requirements for bolted connections discussed herein deal only with a) the minimum spacing and edge distance, b) bearing in bolted connection, and c) tension in connected parts. The design provisions for shear and tension strength in bolts are not included in this study due to lack of test data.

Bolted connections shall be designed to transmit the maximum load in the connected members. Proper regard should be given to eccentricity. The following design provisions for bolted connections are based on the consideration of shear failure in connected parts, bearing, and tension failure of connected sheets.

(1) Spacing and Edge Distance

The nominal shear strength of the connected part along two parallel lines in the direction of applied force shall be determined as follows:

$$P_n = teF_u \tag{7.1}$$

where

P_n = Nominal resistance per bolt

t = Thickness of the thinnest connected part

e = The distance measured in the line of force from the center of a standard hole to the nearest edge of an adjacent hole or to the end of the connected part

F_u = Tensile strength of the connected sheet in the longitudinal direction

(2) Bearing

The nominal bearing force per bolt shall be calculated by Eq. (7.2).

$$P_n = F_p dt \tag{7.2}$$

where

F_p = Nominal bearing stress for bolts with washers under both bolt head and nut is determined as follows:

(i) Single shear connections

$$F_p = 2.00F_u \tag{7.3}$$

(ii) Double shear connections

$$F_p = 2.75F_u \tag{7.4}$$

d = Nominal bolt diameter

t and F_u are as defined in Section 7.2(1).

(3) Tension in Connected Parts

The nominal tensile strength on the net section of a bolted connection shall be calculated as follows:

$$P_n = A_n F_t \quad (7.5)$$

where

A_n = Net section area

F_t = Nominal tension stress for connections with washers under both bolt head and nut is determined as follows:

(i) Single shear connections

$$F_t = (1.0 - r + 2.5\ r\ d/s)F_u \quad (7.6)$$

(ii) Double shear connections

$$F_t = (1.0 - 0.9r + 3r\ d/s)F_u \quad (7.7)$$

r = The force transmitted by the bolt or bolts at the section considered, divided by the tension force in the member at that section. If r is less than 0.2, it may be taken as 0.

s = Spacing of bolts perpendicular to line of stress. In the case of a single bolt, s = width of sheet.

d, t, and F_u are as defined above.

7.3 Selection of Resistance Factor for Bolted Connections

A total of 24 bolted connection tests were obtained from Ref. 26 and were used in this study to calibrate the design formulas as given above. The test specimens were fabricated from two blanks 4 in. x 20 in. (100 mm x 510 mm) of 1/2-Hard Type 301 austenitic stainless steel sheets. All specimens were made for single-row condition and tested in single shear connections (SS) or double shear connections (DS) as shown in Fig. 20. Washers were placed both under the bolt heads and the nuts.

Results of bolted connection tests indicated that four fundamental types of failure were observed as shown in Fig. 21, similar to those reported for cold-formed carbon steels.[39] These failure modes are briefly described as follows:

Type I - longitudinal shearing of the sheet along two parallel lines;

Type II - bearing or piling up of material in front of bolt;

Type III- tearing of the sheet in the net section;

Type IV - shearing of the bolt.

In some cases, combined modes of failure were exhibited.

The following calibrations of the design provision for bolted connections are based on the aforementioned failure modes except for Type IV due to lack of test data.

7.3.1 Type I -- Shear Failure

Only four bolted connections having shear failure were obtained from Ref. 26 and were used in this study. Table 28 lists the tested failure loads, P_{test}, and the predicted failure loads, P_{pred}, calculated according to Eq. (7.1) given in Section 7.2. The variant parameters of these test specimens are also included in this table. These four bolted connections were tested in single shear connection (SS) as shown in Fig. 20b.

From Table 28, it can be seen that the mean value of P_{test}/P_{pred}, which is reffered to as the professional factor, P_m, is 1.055 and the coefficient of variation, V_P, is 0.054. The material and fabrication factors used for bolted connections are taken as follows:

Material factor: $M_m = 1.10$, $V_M = 0.05$

Fabrication factor: $F_m = 1.00$, $V_F = 0.05$

Together with these values and the professional factor, the safety index can be determined by using the formulas given in Section 3 of this report.

The resistance factor is then determined on the basis of the safety index and the ratio of D_n/L_n.

Figure 22 illustrates the variation of safety indices, β, versus the ratio of D_n/L_n for bolted connections having shear failure. The computed safety indices are compared with four different resistance factors ranging from 0.60 to 0.75 with an increment of 0.05. From this figure, it was found that for $D_n/L_n = 0.2$ the computed safety index is larger than the target value ($\beta_o = 4.0$) if the resistance factor is taken as 0.70 or less. However, if resistance factor of 0.75 is used for this case, the safety index computed for $D_n/L_n = 0.2$ is 3.79, which is less than the target value. Based on this result, the resistance factor of 0.7 is recommended for the development of the LRFD criteria for bolted connections to prevent shear failure.

7.3.2 Type II -- Bearing Failure

A total of 13 test data were obtained from Ref. 26 and were used in this study. Among these test data, ten tests were bearing failure and three were combined bearing, shearing, and tearing failures. Table 29 lists the tested failure loads, P_{test}, and the predicted failure loads, P_{pred}, determined on the basis of the design formulas given in Section 7.2(2). The comparison of the tested and predicted failure loads is given by the ratio of P_{test}/P_{pred}. Also included in this table are the variant parameters of the test specimens.

From Table 29, it is noted that the mean value of the ratios of P_{test}/P_{pred} is $P_m = 1.018$ and its coefficient of variation, V_P, is 0.078. These values are referred to as the professional factor as discussed in Section 3.3. The fabrication factors used for this subject are the same as those used for Type I failure, i.e., $M_m = 1.10$, $V_M = 0.05$, $F_m = 1.0$, and $V_F = 0.05$. Based on these factors, the safety index can be determined according to the formulas given in Section 3, and the resistance factor is achieved accordingly.

The variation of the computed safety indices with respect to the ratio of D_n/L_n for bearing failure of bolted connections is illustrated in Fig. 23. The computed safety indeices are plotted for four selected resistance factors ranging from 0.55 to 0.70 with an increment of 0.05. From this figure, it is noted that the computed safety indices for $D_n/L_n = 0.2$ are larger than the target value ($\beta_o = 4.0$) if the resistance factors are taken as 0.65 or less. However, if the resistance factor is taken as 0.70, the safety index computed for $D_n/L_n = 0.2$ is 3.82, which is less than the target value. As a result, it is recommended that a resistance factor of 0.65 ($\phi = 0.65$) be used for the development of the LRFD criteria for preventing bearing failure of bolted connections.

7.3.3 <u>Type III -- Tension Failure</u>

Seven bolted connection tests having tension failure were reported in Ref. 26 and were used in this study. Table 30 lists the variant parameters of test specimens, the tested failure loads, P_{test}, and the predicted ultimate loads, P_{pred}, determined in accordance with the design formulas mentioned in Section 7.2(3). The comparison of the tested and predicted failure loads is given by the ratio of P_{test}/P_{pred}, which is referred to as the professional factor for determining the safety index.

From Table 30, the mean value of the ratio of P_{test}/P_{pred} is $P_m = 1.101$ and the coefficient of variation, V_P, is 0.098. Similar to the study of Type II failure, the material and fabrication factors are as follows: $M_m = 1.10$, $V_M = 0.05$, $F_m = 1.0$, and $V_F = 0.05$. Based on these factors, the safety index can be determined by the formulas given in Section 3 of this report. The resistance factor based on the computed safety index is achieved subsequently.

Figure 24 presents the variation of the computed safety indices, β, versus the ratio of D_n/L_n for tension failure of bolted connections. Because the safety index depends on the resistance factor, four selected resistance factors ranging from 0.6 to 0.75 with an increment of 0.05 have been used to compare the computed safety indices. From this figure, it was found that by using the resistance factors of 0.70 or less, the safety indices calculated for $D_n/L_n = 0.2$ are larger than the target value ($\beta_o = 4.0$). For $\phi = 0.75$, the computed safety indices for $D_n/L_n = 0.2$ is less than the target value. Based on this result, it is recommended that the resistance factor of 0.70 ($\phi = 0.70$) be used for the development of the LRFD criteria to prevent tension failure of bolted connections.

7.4 Comparison of Safety Indices and Resistance Factors for Cold-Formed Carbon and Stainless Steel Bolted Connections

The calibration of the AISI design provisions for cold-formed carbon steel bolted connections has been reported in Ref. 16. The computed safety indices β for shear failure in connected parts, tension, and bearing failures of bolted connections are summarized in Table 31. It indicates that by using $\phi = 0.6$ and 0.7, the safety indices vary from 3.61 to 3.90 for shear failure of bolted connections. For tension failure of bolted connections, the safety indices vary from 3.41 to 3.63 if the resistance factors are taken as 0.55 and 0.65. The computed safety indices vary from 3.43 to 4.06 with the resistance factors varying from 0.55 to 0.7 for bearing failure of bolted connections. These resistance factors were determined on the basis of $D_n/L_n = 0.2$ for a load combination of $1.2D_n+1.6L_n$.

Even though these safety indices are relatively lower than those computed for cold-formed stainless steel bolted connections, the resistance factors used for both cases are the same.

8. SUMMARY AND FUTURE STUDY

During recent years, the probability-based load and resistance factor design (LRFD) criteria have been developed for the structural design of hot-rolled steel shapes and cold-formed carbon steel members. In order to develop the new ASCE design codes for cold-formed stainless steel structural members based on the probabilistic approach, a research project entitled "Load and Resistance Factor Design of Cold-Formed Stainless Steel" was initiated in July 1986 at the University of Missouri-Rolla under the sponsorship of the American Society of Civil Engineers.

The first phase of this project dealt with the revision of the 1974 edition of the AISI allowable stress design specification for cold-formed stainless steel structural members and its commentary. The Draft of the Proposed Allowable Stress Design Specification with Commentary has been prepared and was published in the Third Progress Report dated January 1988. It was recommended by the ASCE Steering Committee that the propsoed ASD Specification with commentary included in the Third Progress Report be submitted to the new ASCE Standard Committee for consideration.

The second phase of the investigation is to develop the LRFD criteria for cold-formed stainless steel structural members. Since August 1987, progress has been made in the development of the load and resistance factor design criteria for cold-formed stainless steel structural members. The initial work included statistic studies of mechanical properties and material thicknesses as well as calibrations of the proposed LRFD formulas. This progress report contains the results of these investigations.

The tested mechanical properties and measured thicknesses for various types of stainless steels have been collected and evaluated statistically. The mean values and coefficients of variation of these test data are presented in Section 2. The recommended values of material and fabrication factors used for structural members and connections made by using austenitic and ferritic stainless steels are given in Section 3 of this report.

Because the LRFD criteria are based on the first order probabilistic theory, only mean values and coefficients of variation of load effects, material factors, fabrication factors, and professional factors are utilized. Detailed discussions on the development of the probability-based LRFD criteria are presented in Section 3 of this report. The professional factors used in the calibrations were determined on the basis of the test data collected mainly from previous research projects conducted at Cornell University and Rand Afrikaans University in South Africa. Based on the available test data, the proposed design provisions have been calibrated for bending strength of flexural members, stub columns, flexural buckling and torsional-flexural buckling strengths of compression members, welded connections, and bolted connections. For other design provisions, the calibrations were not possible due to the lack of test results. Table 32 lists the numbers of available test data used for calibrating the proposed LRFD provisions.

The computed safety indices, β, and the corresponding resistance factors, ϕ, determined from the calibrations of the proposed LRFD provisions are presented in Sections 4 through 7 of this report. These values are summarized in Table 33 for structural members and connections fabricated from austenitic and ferritic stainless steels. It can be seen that the computed β values for the ratio of $D_n/L_n = 0.2$ are larger than the specified target β_o values that were selected to be 3.0 and 4.0 for cold-formed stainless steel structural memebrs and connections, respectively. The mean values and coefficients of variation of the material factors, fabrication factors, and professional factors used for computing β values are also included in this table. It should be noted that the results discussed above are developed on the basis of a limited number of test data. Additional tests may be needed to justify the resistance factors recommended in this report.

With regard to the future study of the project, it is expected that the first draft of the LRFD specification for the design of cold-formed stainless steel structural members and connections with its commentary will be prepared in early 1989 and published in the Fifth Progress Report.

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APPENDIX A MODIFIED RAMBERG-OSGOOD EQUATION

A.1 Modified Ramberg-Osgood Equation

The stress-strain relationships for annealed and cold-rolled stainless steels are nonlinear and anisotropic. This leads to a relatively difficult design because the stress-strain curves can not be represented by a linear function. Thus, it is desirable to have an analytical expression for the study and design of stainless steel structural elements and members.

For the purpose of simplicity, the Ramberg-Osgood formula may be used to represent the stress-strain relationship. The original expression suggested by Ramberg and Osgood[36] is given as Eq. (A.1).

$$\epsilon = \sigma/E + K\,(\sigma/E)^n \tag{A.1}$$

where

ϵ = Normal strain

σ = Normal stress

E = Modulus of elasticity

K and n are constants which are evaluated through two secant yield strengths at slopes of 0.7E and 0.85E, respectively.

Based on the Ramberg-Osgood equation as given in Eq. (A.1), it can be shown that

$$K = \epsilon_1/(\sigma_1/E)^n \tag{A.2}$$

or

$$K = \epsilon_2/(\sigma_2/E)^n \tag{A.3}$$

and

$$n = \log(\epsilon_2/\epsilon_1)/\log(\sigma_2/\sigma_1) \qquad (A.4)$$

where σ_1 and σ_2 are the specified yield strengths and ϵ_1 and ϵ_2 are the specified strains. The modulus of elasticity, E, is regarded constant and equal to the initial value, E_o.

The Ramberg-Osgood formula was modified by Hill[37] in 1944 by using two offset yield strengths rather than the secant yield strengths because the former are commonly used. Hill indicated that the yield strength determined at the 0.2 % offset strain, i.e., F_y, may be used for determining the constant K. Thus, the constant K can be expressed as

$$K = 0.002/(F_y/E_o)^n \qquad (A.5)$$

Consequently, Eq. (A.1) can be written as

$$\epsilon = \sigma/E_o + 0.002\ (\sigma/F_y)^n \qquad (A.6)$$

in which

$$n = \log(0.002/\epsilon_1)/\log(F_y/\sigma_1) \qquad (A.7)$$

Although the 0.2 % offset yield strength in Eq. (A.7) seemed to be a common, reasonable choice, the remaining set of the offset stress and strain (σ_1 and ϵ_1) has not been uniquely decided. In this report, however, the constants of n have been determined on the basis of the 0.01 % offset strength because this value is well defined as the proportional limit of the material property. The following n values given in Table A1 are calculated by Eq. (A.7) on the basis of 0.2 % and 0.01 % offset stress and strain and may be used in the modified Ramberg-Osgood Equation for annealed and cold-rolled stainless steels.

TABLE A1

Coefficient n Used for the Modified Ramberg-Osgood Equation

Types of Stress	Types 201, 301, 304 & 316			Type 409	Types 430 & 439
	Annealed & 1/16-Hard	1/4-Hard	1/2-Hard		
Longitudinal Tension	8.31	4.58	4.21	10.77	8.43
Transverse Tension	7.78	5.38	6.71	15.75	14.13
Transverse Compression	8.63	4.76	4.54	15.76	14.30
Longitudinal Compression	4.10	4.58	4.22	9.70	6.25

A.2 Secant Modulus, E_s

Based on Eq. (A.6), the secant modulus, E_s, defined as the ratio of the stress and the strain, can be determined as follows:

$$E_s = \sigma/\epsilon$$
$$= E_o/(1+0.002E_o(\sigma^{n-1}/F_y{}^n)) \quad (A.8)$$

A.3 Tangent Modulus, E_t

The tangent modulus, E_t, which is defined as the slope of the stress strain curve in the inelastic range, is derived from the first derivative of the stress-strain ratio. Equation (A.9) gives the tangent modulus as a function of stress.

$$E_t = d\,(\sigma/\epsilon)$$
$$= E_oF_y/(F_y+0.002nE_o(\sigma/F_y)^{n-1}) \quad (A.9)$$

A.4 Plasticity Reduction Factor, η

The plasticity reduction factors used for the design of cold-formed stainless steel structural members can be obtained from the following equations, which are based on the secant and tangent moduli derived above:

For stiffened compression elements

$$\eta = \sqrt{E_t/E_o}$$
$$= \sqrt{(F_y/(F_y+0.002nE_o(\sigma/F_y)^{n-1})} \qquad (A.10)$$

For unstiffened compression elements

$$\eta = E_s/E_o$$
$$= 1/(1+0.002E_o(\sigma^{n-1}/F_y{}^{n})) \qquad (A.11)$$

For buckling stress of columns and lateral buckling stress of beams

$$\eta = E_t/E_o$$
$$= (F_y/(F_y+0.002nE_o(\sigma/F_y)^{n-1}) \qquad (A.12)$$

A.5 Comparison of Secant and Tangent Moduli Obtained from the Design Tables and the Modified Ramberg-Osgood Formula

For the design of cold-formed stainless steel structural members, the secant moduli, tangent moduli, and plasticity reduction factors are given in the Design Tables and Figures of the proposed ASCE allowable stress design specification.[30] These tables and figures were prepared on the basis of the actual stress-strain curves obtained from the test data for stainless steels. In this report, an attempt has been made to determine these design values by using analytical expressions. Based on the Modified Ramberg-Osgood equation with a proper constant of n, it appears that Eqs. (A.8) through (A.12) may be used for determining the secant modulus (E_s), tangent modulus (E_t), and the plasticity reduction factors for the purpose of simplicity.

The secant moduli in longitudinal compression obtained from the Design Table (Table A2 of Ref. 30) and Eq. (8) are compared in Table A2 for Type 304 annealed and Type 301 (1/4-Hard and 1/2-Hard) stainless steels. In addition, the tangent moduli obtained from the Design Table (Table A13 of Ref. 30) and Eq. (A.9) for the same materials are compared in Table A3. These materials were used for the calibration of the proposed design provisions in Sections IV.4 and V.4 of this report. In these two tables, all values computed from Eqs. (A.8) and (A.9) are given in parentheses. These comparisons indicate that the differences between the computed and tabulated values are small for most cases. The largest difference occurs at the "knee" of the stress-strain curve.

Based on Eqs. (A.8) and (A.9), the plasticity reduction factors can be determined by using Eqs. (A.10) and (A.11) for stiffened and unstiffened compression elements, respectively. Equation (A.12) is used for the design of columns subjected to flexural or torsional-flexural bucklings and beams subjected to lateral buckling. Because iterative processes are often used for the design of cold-formed stainless steel members, it would be convenient to use Eqs. (A.8) through (A.12) in the computer programs for the design of such members.

TABLE A2

Comparison of Secant Moduli in Longitudinal Compression Obtained from the Design Table and the Modified Ramberg-Osgood Equation

Stress (ksi)	Secant Modulus, E_s, ksi x 10^3		
	Type 304, Annealed	Type 301, 1/4-Hard	Type 301, 1/2-Hard
0	28.0 (28.0)	27.0 (27.0)	27.0 (27.0)
4	28.0 (27.9)	27.0 (27.0)	27.0 (27.0)
8	28.0 (27.5)	27.0 (27.0)	27.0 (27.0)
12	28.0 (26.4)	27.0 (26.8)	27.0 (26.9)
16	24.8 (24.3)	27.0 (26.5)	27.0 (26.8)
20	21.3 (21.5)	27.0 (26.0)	27.0 (26.5)
24	18.5 (18.3)	26.2 (25.0)	26.7 (26.1)
28		24.0 (23.8)	25.4 (25.6)
32		21.3 (22.2)	24.2 (24.9)
36		18.8 (20.3)	23.0 (24.0)
40		16.9 (18.1)	21.8 (23.0)
44		15.3 (16.0)	20.6 (21.8)
48		13.9 (14.0)	19.4 (20.6)
52		12.5 (12.0)	18.2 (19.2)
56			17.1 (17.8)
60			16.0 (16.4)
64			15.0 (15.1)
68			14.0 (13.8)

1 ksi = 6.895 MPa

Note: Values in the parentheses are calculated by using Eq. (A.8).

TABLE A3

Comparison of Tangent Moduli in Longitudinal Compression Obtained from the Design Table and the Modified Ramberg-Osgood Equation

Stress (ksi)	Tangent Modulus, E_t, ksi x 10^3		
	Type 304, Annealed	Type 301, 1/4-Hard	Type 301, 1/2-Hard
0	28.0 (28.0)	27.0 (27.0)	27.0 (27.0)
4	28.0 (27.8)	27.0 (27.0)	27.0 (27.0)
8	28.0 (26.1)	27.0 (26.8)	27.0 (26.9)
12	28.0 (22.4)	27.0 (26.2)	27.0 (26.6)
16	16.7 (17.3)	27.0 (24.9)	27.0 (26.0)
20	12.5 (12.6)	27.0 (22.8)	27.0 (25.0)
24	9.5 (8.9)	17.0 (19.9)	26.0 (23.6)
28	7.0 (6.3)	13.5 (16.7)	20.0 (21.9)
32	4.6 (4.5)	11.3 (13.5)	17.2 (19.9)
36		9.7 (10.7)	15.2 (17.7)
40		8.4 (8.4)	13.7 (15.6)
44		7.2 (6.5)	12.4 (13.5)
48		6.3 (5.1)	11.0 (11.6)
52		5.5 (4.0)	9.8 (10.0)
56			8.8 (8.5)
60			7.7 (7.3)
64			6.8 (6.2)
68			6.0 (5.4)

1 ksi = 6.895 MPa

Note: Values in the parentheses are calculated by using Eq. (A.9).

APPENDIX B NOTATION

The following symbols are used in this report:

A = Area of the full, unreduced cross section

A_e = Effective area

A_w = Cross-sectional area of the thinner welded part

B = Random variable reflecting the uncertainties in the transformation of live loads into live load effects

b = Effective width

C = Random variable reflecting the uncertainties in the transformation of dead loads into dead load effects

c_D, c_L = Deterministic influence coefficients translating load intensities to load effects; subscripts D and L denote dead and live loads, respectively

C_w = Torsional warping constant of the cross section

D = Random variable characterizing dead load

D_c = Specified dead load intensity

D_n = Specified dead load

d = Diameter of the bolt

E_o = Initial modulus of elasticity

E_s = Secant modulus

E_t = Tangent modulus

Elong = Elongation (measured value)

e = Edge distance measured from the center of the hole to the end of the connecting member

e_{min} = Minimum edge distance from edge

F = Random variable representing uncertainties in fabrication

F_m = Mean value of fabrication factor

F_n = Nominal buckling stress

F_p = Nominal bearing stress for bolts with washers under both bolt head and nut

F_t = Nominal tension stress for connections with washers under both bolt head and nut

F_t = Torsional buckling stress

F_u = Tensile strength of the connected sheet in the logitudinal direction

F_y = Yield strength

F_{cr} = Critical buckling stress

F_{ex} = Euler buckling stress about the symmetry axis (x-axis)

F_{ua} = Tensile strength of the annealed base metal

F_{ult} = Ultimate strength of groove weldment

F_{xx} = Tensile strength of the weld metal

F_{yc} = Yield strength in compression

F_{yt} = Yield strength in tension

f = Actual stress in the compression element

f_b = Permissible compressive stress for local distortions

G_o = Initial shear modulus

J = St. Venant torsion constant of the cross section

K = Effective length factor

K_x, K_t = Effective length factors for bending about x-axis and twisting, respectively

k = Buckling coefficient

L = Random variable characterizing live load; unbraced length of member

L_c = Specified live load intensity

L_n = Nominal specified live load

L_x, L_t = Unbraced lengths of member for bending about x-axis and twisting, respectively

M = Random variable characterizing the uncertainties in material strength

M_n = Nominal bending moment

M_{pred} = Predicted ultimate moment

M_{test} = Tested ultimate moment

n = Coefficient used for modified Ramberg-Osgood equation

P = Random variable reflecting the uncertainties in design assumptions

P_F = Probability of failure

P_n = Nominal force

P_{pred} = Predicted failure load

P_{test} = Tested failure load

Q = Load effect

R = Member resistance

R_n = Nominal resistance of a structure member

r = Radius of gyration

S_e = Effective section modulus of reduced section

S_f = Section modulus of unreduced, full section

s = Spacing of bolts perpendicular to line of stress

T_n = Nominal tension force on the net section of a bolt

t = Thickness of the thinnest connected part

t_s = Specified minimum thickness

t_w = Effective throat

U = Standard variable with a zero mean and a unit standard deviation

$V_{(x)}$ = Coefficient of variation of random variable x; V denotes the coefficient of variation

w = Flat width of compression element

$(x)_m$ = Mean value of random variable x; subscript m denotes mean value

x_o = Distance from the shear center to the centroid along the x-axis

β = Safety index

β = $1 - (x_o/r_o)^2$

β_o = Target safety index

γ_D = Dead load factor

γ_L = Live load factor

σ = Normal stress

σ_u = Actual value of tensile strength

σ_y = Actual value of yield strength

$\sigma_{\ln(x)}$ = Standard deviation of the natural logarithm of variable x

ϵ = Normal strain

ϕ = Resistance factor

η = Plasticity reduction factor

μ = Poisson's ratio

λ = Slenderness factor

APPENDIX C

COMPUTER PROGRAM USED FOR THE PREDICTION OF THE NOMINAL BENDING MOMENT BASED ON THE INITIATION OF YIELDING

```
5  REM ******************************************************************
10 REM  THIS PROGRAM IS USED TO CALCULATE THE NOMINAL BENDING MOMENT OF
15 REM  A HAT SECTION WITH OR WITHOUT LIPS ON THE BASIS OF INITIATION
20 REM  OF YIELDING. SEE DESIGNATION OF SYMBOLS IN FIG. 25(a) FOR
21 REM  BEAM DIMENSIONS.
22 REM ******************************************************************
25 REM
31 LPRINT "**** Flexural Member Design - Hat Sections ****"
32 REM
33 PRINT " **** Flexural Member Design - Hat Section ****"
34 LPRINT
35 INPUT "Specimen Name"; T$
36 LPRINT "Specimen ..." T$
37 LPRINT
38 PRINT "The cross-sectional dimensions of hat section"
39 LPRINT "The cross-sectional dimensions of hat section:"

40 REM "Read the cross sectional dimensions of the hat section."
45 DIM ELE(10), Y(10), LY(10), LYY(10), I1(10)
50 INPUT "Hat-section Stiffened Lip Length, D1, Bottom Flange Length,
   FL, Web Length, D2, Bend Radius, R, Top Flange Length,BL,
   and Thickness, T ="; D1, FL, D2, R, BL, T
70 PRINT "D1=" D1 "F=" FL "D2="D2 "R=" R "B=" BL "T=" T "(in.)"
71 LPRINT "D1=" D1 "F=" FL "D2="D2 "R=" R "B=" BL "T=" T "(in.)"
75 INPUT "Maximum Experimental Moment ="; MT
76 LPRINT "Maximum Experimental Moment =" MT "(in.-kip)"

80 REM " Determine properties of vertical corners"
90 R1 = R+T/2: U = 1.57*R1: C = .637*R1
98 LPRINT
100 REM "calculate the nominal section strength based on initiation of
    yielding"
110 INPUT "Fy(Yield Strength in L.C.), Fyt(in L.T.), Eo(elasticity),
    SF(safety factor)";FY,FYT,EO,SF
112 PRINT "Fy(L.C.)=" FY "ksi,  Fy(L.T)=" FYT "ksi,  Eo=" EO "ksi,
    S.F.=" SF
113 LPRINT "Fy(L.C.)=" FY "ksi,  Fy(L.T)=" FYT "ksi,  Eo=" EO "ksi,
    S.F.=" SF
114 LPRINT
115 INPUT "The Plasticity Reduction Factor for Stiffened element="; PRF
116 LPRINT "The Plasticity Reduction Factor for Stiffened element=" PRF

120 REM " Check the web element and assumed web fully effective
130 DWEB = D2-2*(R1+T/2)
140 IF DWEB/T > 200 THEN PRINT "h/t exceed the maximum (h/t)=200" ELSE 150
150 PRINT "Web is o.k. and is assumed fully effective"
151 LPRINT "Web is o.k. and is assumed fully effective"
```

```
160 REM "check the compressive flange, i.e.; check lumda <= 0.673?'
170 W = BL-2*(R1+T/2)
180 IF W/T > 500 THEN PRINT "w/t exceed the maximum (w/t)=500"
182 INPUT "assumed compressive stress in top fiber, f=";F
183 LPRINT "Assumed that the compressive stress in top fiber is=" F "(ksi)"
184 IF F = 999 GOTO 1000
190 LUMDA = (1.052/2)*(W/T)*((F/(PRF*EO))**.5)
192 LPRINT "lumda=" LUMDA
195 PRINT "lumda=" LUMDA
200 RO = (1-.22/LUMDA)/LUMDA
210 IF LUMDA <= .673 THEN B=W ELSE B=RO*W
224 LPRINT
225 PRINT "Effective width of the compressive flange=" B
226 LPRINT "Effective width of the compressive flange=" B "(in.)"
227 LPRINT
228 LPRINT
229 L1=0: L2=0: L3=0: L4=0
230 REM "calculate the section properties, i.e.; Ycg, Ix"
240 REM "Prepare the tabel that include the values of element no.
250 REM  effective length, distance from top fiber, LY, LYY, I1"
260 IF D1=0 THEN ELE(1) = 0 ELSE ELE(1) = (D1-(R1+T/2))*2
270 IF D1=0 THEN ELE(2) = U*2 ELSE ELE(2) = U*4
280 IF D1=0 THEN ELE(3) = (FL-(R1+T/2))*2 ELSE ELE(3) = (FL-(R1+T/2)*2)*2
290 ELE(4) = DWEB*2
300 ELE(5) = B
310 ELE(6) = U*2
320 Y(1) = D2-(R1+T/2)-ELE(1)/4
330 Y(2) = D2-(R1+T/2-C)
335 Y(3) = D2-T/2
340 Y(4) = D2/2
350 Y(5) = T/2
360 Y(6) = R1+T/2-C
362 PRINT "Element No","Effective L","     y","     Ly","    Lyy"
363 PRINT "  ", "     (in.)", "     (in.)", "  (in.**2)", "(in.**3)"
364 LPRINT "Element No","Effective L","     y","     Ly","    Lyy",
    "    I'"
365 LPRINT " ** ", "     (in.)", "     (in.)", "  (in.**2)", "(in.**3)",
    "(in.**4)"
366 LPRINT
370 FOR I=1 TO 6
371 L1=L1+ELE(I)
380 LY(I)=ELE(I)*Y(I)
381 L2 = L2+LY(I)
390 LYY(I) = LY(I)*Y(I)
391 L3 = L3+LYY(I)
400 IF I=1 OR I=4 THEN I1(I) = 2*((ELE(I)/2)**3)/12 ELSE I1(I)=0
401 L4=L4+I1(I)
409 PRINT I,
410 PRINT USING " ####.####   " ;    ELE(I),    Y(I),    LY(I),    LYY(I)
411 LPRINT I,
412 LPRINT USING " ####.####   " ; ELE(I), Y(I), LY(I), LYY(I), I1(I)
```

```
420 NEXT I
421 LPRINT
430 PRINT "Sum",
431 PRINT USING " ####.####   "; L1,
432 PRINT "  ",
433 PRINT USING " ####.#### ";L2,L3
434 PRINT
436 LPRINT "Sum",
437 LPRINT USING " ####.####   "; L1,
438 LPRINT "  ",
439 LPRINT USING " ####.#### ";L2,L3,L4
440 LPRINT
441 LPRINT "(** : 1=Lips, 2=Bottom Corners, 3=Bottom Flange, 4=Webs,
    5=Top Flange, and 6=Top Corners.)"
445 LPRINT

447 REM "Determine the netural axis from top fiber"
450 YCG = L2/L1
455 YT=D2-YCG
456 FT=F*(YT/YCG)
457 PRINT "Yt=" YT "(in.)" "      Ycg=" YCG "(in.)"  "      Ft(try) =
    " FT "(ksi)"
458 LPRINT "Yt=" YT "(in.)" "      Ycg=" YCG "(in.)"  "      Ft(try) =
    " FT "(ksi)"
465 IF YCG>=YT GOTO 475
467 IF FT<FYT THEN GOTO 475 ELSE IF ABS(FT-FY) >=.1 THEN GOTO 182 ELSE
    GOTO 475
475 PRINT "The compressive stress is=" F "(ksi)" ",and the corresponding
    stress in tension fiber is = " FT "(ksi)"
476 LPRINT
477 LPRINT "The compressive stress is=" F "(ksi)" ",and the corresponding
    stress in tension fiber is = " FT "(ksi)"

480 REM "Check web fully effective?"
490 IX = L3 +L4 -L1*YCG**2
495 IXX = T*IX
500 PRINT "the actual Ix is="  IXX
501 LPRINT "The actual moment of inertia, Ix, is="  IXX "(in.**4)"
502 LPRINT
510 DC1 = YCG -(R1+T/2)
520 DT1 = DWEB-DC1
530 F1 = (DC1/YCG)*F
540 F2 = (DT1/YCG)*F
545 IF YCG < D2 THEN SI = -(F2/F1) ELSE SI = F2/F1
560 KOW = 4+2*(1-SI)**3+2*(1-SI)
570 LUMDA1 = (1.052/(KOW**.5))*(DWEB/T)*((F1/(PRF*EO))**.5)
575 PRINT "dc1=" DC1 "dt1=" DT1 "si=" SI "kow=" KOW "lumda1=" LUMDA1
576 LPRINT "dc1=" DC1 "(in.)" "dt1=" DT1 "(in.)"
577 LPRINT "si=" SI "kow=" KOW "lumda1=" LUMDA1
578 LPRINT
580 RO1 = (1-.22/LUMDA1)/LUMDA1
590 IF LUMDA1 <= .673 THEN BE= DWEB ELSE BE=RO1*DWEB
```

```
610 B1 = BE/(3-SI)
620 IF SI <=-.236 THEN B2 = BE/2 ELSE B2 = BE-B1
640 BT = B1+B2
660 PRINT "web is fuly effective, and bt=" BT
661 LPRINT "Web is fuly effective, and b1+b2 =" BT "(in.)"
662 LPRINT
668 SE = IXX/YCG
671 LPRINT
672 LPRINT "The effective section modulus, Seff, =" SE "(in.**3)"
673 LPRINT
680 IF A1$ = "Y" THEN MN = SE*FY ELSE MN = SE*F
690 PRINT "the nominal moment of the hat section is=" MN
691 LPRINT "The nominal moment of the hat section is Mn = Se*F =" MN
    "(in.-kip)"
692 LPRINT
700 MA = MN/SF
710 PRINT " the allowable moment of the hat section is=" MA
711 LPRINT "The allowable moment of the hat section is=" MA "(in.-kip)"
715 RATIO = MT/MN
718 LPRINT
720 PRINT "Mtest/Mpred = " RATIO
725 LPRINT "Mtest/Mpred = " RATIO
1000 STOP
```

APPENDIX D

COMPUTER PROGRAM USED FOR THE PREDICTION OF THE FLEXURAL BUCKLING STRESS BASED ON THE TANGENT MODULUS THEORY

```
1  REM ***************************************************************
2  REM  THIS PROGRAM DETERMINES THE FLEXURAL BUCKLING STRESS OF
3  REM  STAINLESS STEEL COLUMNS BASED ON THE TANGENT MODULUS THEORY.
4  REM  SEE DESIGNATION OF SYMBOLS IN FIG. 25(b) FOR COLUMN DIMENSIONS.
5  REM ***************************************************************
12 INPUT "Specimen No."; TYPE$
13 LPRINT "Specimen No. -----  " TYPE$
14 INPUT "Is this problem need to calculate the sectional properties"; R$
15 IF R$ = "Y" THEN GOSUB 500
18 INPUT "Critical Stress="; SC
19 LPRINT "Critical Stress=" SC "(ksi)"
20 INPUT "Eo="; EO
22 LPRINT "Eo=" EO "(ksi)"
23 INPUT "Fy="; FY
24 LPRINT "Fy=" FY "(ksi)"
25 IF R$ = "Y" THEN 29
27 INPUT "KL/r="; SL
28 LPRINT "KL/r=" SL
29 FE = 3.14159**2*EO/(SL**2)
30 INPUT "n(coefficient)="; N
32 LPRINT "n(coefficient)=" N
36 PRINT
37 GOSUB 600
51 RATIO = SC/S2
52 FFN = S2
53 PRINT "Fe=" FE  "ratio=" RATIO
54 LPRINT
55 LPRINT "Fe=" FE "(ksi)    Fn=" FFN "(ksi)     Fcr/Fn=" RATIO
58 LPRINT
59 LPRINT
60 STOP

500 REM **** This subroutine determine the Moment of Inertia about x-axis
501 REM **** , Ix, and about y-axis, Iy. In addition, Radius of Gyration
502 REM **** rx and ry is included.
504 LPRINT "The cross-sectional dimensions of the I-section:
    Lip Length, D1, Stiffened Flange Length, FL, Web Length, D2,
    Bend Radius, R, and Thickness, T ="
505 INPUT D1,FL,D2,R,T,L
506 PRINT "d1=" D1 "f1=" FL "d2=" D2 "r=" R "t=" T "l=" L "    (in.)"
507 LPRINT "d1=" D1 "f1=" FL "d2=" D2 "r=" R "t=" T "l=" L "    (in.)"
508 R1=R+T/2: U=1.57*R1:
510 INPUT "Is this a I-section or Box-section"; Q$
512 IF Q$ = "B" THEN 552
513 REM **** Sectional Properties for I-sections
515 A=D2-(2*R1+T): B=FL-(R1+T/2):
```

```
520 AREA = T*(2*A+2*B+2*U+2*B+2*U)
530 IX = 2*T*(B*(B/2+R1+T/2)**2+.0833*B**3+U*(.363*R1+T/2)**2+.149*R1**3+
    B*(B/2+R1+T/2)**2+.0833*B**3+U*(.363*R1+T/2)**2+.149*R1**3)
540 XB = (2*T/AREA)*(U*.363*R1+A*(A/2+R1)+U*(A+1.637*R1)+B*(A+2*R1))
550 IY = 2*T*(.358*R1**3+A*(A/2+R1)**2+.0833*A**3+U*(A+1.637*R1)**2+
    .149*R1**3+B*(A+2*R1)**2)-AREA*XB**2
551 GOTO 560

552 REM **** Sectional Properties for Box-Sections
553 A=D2-(2*R1+T): B=FL-(2*R1+T): C=D1-(R1+T/2)
554 AREA=T*(A+2*B+2*U+2*C+2*U)*2
555 IY = 2*T*(.0417*A**3+B*(A/2+R1)**2+U*(A/2+.637*R1)**2+.149*R1**3
    +.0833*C**3+.25*C*(A+C+4*R1)**2+U*(A/2+1.363*R1)**2+.149*R1**3)*2
556 XB = (4*T/AREA)*(B*(B/2+R1)+U*(.363*R1)+U*(B+1.637*R1)+C*(B+2*R1))
557 IX = (2*T*(B*(B/2+R1)**2+.0833*B**3+.356*R1**3+C*(B+2*R1)**2
    +U*(B+1.637*R1)**2+.149*R1**3)-(AREA/2)*XB**2
    +(AREA/2)*(FL-XB-T/2)**2)*2
560 RX = (IX/AREA)**.5
570 RY = (IY/AREA)**.5
575 SLX= L/RX: SLY=L/RY
576 IF SLX >= SLY THEN SL = SLX ELSE SL = SLY
580 PRINT "Ix=" IX "Iy=" IY "rx=" RX "ry=" RY "Area=" AREA
581 LPRINT "Ix=" IX "Iy=" IY "rx=" RX "ry=" RY "Area=" AREA
583 PRINT "KL/r=" SL
584 LPRINT "KL/r=" SL
585 RETURN

600 REM  ****  This subroutine calculate the final stress level in the
601 REM  ****  section by using the Newton-Ralphson Iteration Method.
602 ESP = .0001
604 INPUT "The assumed stress level ="; S1
605 LPRINT "The assumed initial stress level =" S1 "(ksi)"
606 PRINT "No. Iterations", "Stress"
607 LPRINT
608 LPRINT "No. of", "Stress"
609 LPRINT "Iterations","(ksi)"
610 I = 0
615 I = I+1
620 FS = S1-FE*(FY/(FY+.002*N*EO*(S1/FY)**(N-1)))
630 DFS = 1+FE*.002*N*(N-1)*EO*(S1/FY)**(N-2)/(FY+.002*N*EO*(S1/FY)
    **(N-1))**2
640 IDFS = 1/DFS
645 DEL = -IDFS*FS
650 S2 = S1+DEL
652 S1 = S2
666 PRINT I, S2
668 LPRINT I, S2
669 IF I >= 100 THEN PRINT "Iteration exceeds 100 times, N.G."
670 IF ABS(DEL) > ESP THEN 615
690 RETURN
```

APPENDIX E

COMPUTER PROGRAM USED FOR THE PREDICTION OF THE TORSIONAL-FLEXURAL BUCKLING STRESS BASED ON THE TANGENT MODULUS THEORY

```
1 REM ************************************************************
2 REM  THIS PROGRAM IS TO DETERMINE THE TORSIONAL-FLEXURAL BUCKLING
3 REM  STRESS OF HAT SECTIONS. SEE DESIGNATION OF SYMBOLS IN
4 REM  FIG. 25(c) FOR DIMENSIONS.
4 REM ************************************************************
5 REM
7 PI = 3.141593
10 CLS
12 INPUT "Specimen No. ";A$
13 LPRINT "Specimen No. " A$
14 LPRINT
15 DATA 0.7795,1.0709,0.3898,0.03543,0.05433
17 DATA 41.15,29800,4.86
18 REM DATA 1.2008,1.7008,0.6024,0.063,0.07913
19 REM DATA 42.97,31780,4.72
20 REM DATA 1.6102,2.4803,0.811,0.07874,0.1299
21 REM DATA 43.73,30750,5.01
22 REM DATA 1.7559,2.5551,0.7992,0.07874,0.08268
23 REM DATA 33.3,27760,9.52
24 REM DATA 0.7677,1.0945,0.4213,0.03543,0.04173
25 REM DATA 48.11,29750,6.48
26 REM DATA 1.1850,1.9843,0.6102,0.0623,0.06142
27 REM DATA 45.84,28770,6.06
28 REM DATA 1.7244,2.5866,0.8150,0.07874,0.07795
29 REM DATA 41.68,27000,5.50
30 REM INPUT "Hat-section Web Length, D ,Stiffened Flange Length,
   H, Lip Length, C,  Thickness, t, and Bend Radius, r = ";D,H,C,T,R
31 READ D,H,C,T,R
32 LPRINT "Hat-section Web Length, D =" D "    Stiffened Flange Length,
   H=" H " Lip Length, C=" C "(in.)"
34 LPRINT "Hat-section Thickness, t =" T "    Bend Radius , r=" R"(in.)"
40 INPUT "Hat-section column length , L "; L
42 LPRINT "Hat-section Column Length, L =" L "(in.)"
43 LPRINT
45 INPUT "Tested Failure Load , Ptest = ";PT
47 LPRINT "Tested Failure Load , Ptest = " PT "(kips)"
48 LPRINT
50 REM INPUT "Materia Properties, Fy, Eo, and n =";FY,EO,N
51 READ FY,EO,N
52 GO = EO/2.6
55 LPRINT "Material Properties : Fy =" FY ",Eo=" EO" (ksi) and
   Constant n = ",N
56 LPRINT
60 RS = R ÷ T/2 : U = 1.57*RS
90 W1 = D-(2*RS+T) : H1 = H-(2*RS+T) : C1 = C-(RS+T/2)
120 A = T*(H1+2*W1+2*C1+4*U)
130 IX = 2*T*(.0417*H1**3+W1*(H1/2+RS)**2+U*(H1/2+.637*RS)**2+.149*RS**3
```

```
    +.0833*C1**3+C1/4*(H1+C1+4*RS)**2+U*(H1/2+1.363*RS)**2+.149*RS**3)
140 XB = (2*T/A)*(W1*(W1/2+RS)+U*(.363*RS)+U*(W1+1.637*RS)+C1*(W1+2*RS))
150 RX = (IX/A)**.5
160 IY = 2*T*(W1*(W1/2+RS)**2+.0833*W1**3+.356*RS**3+C1*(W1+2*RS)**2+
    U*(W1+1.637*RS)**2+.149*RS**3)-A*XB**2
162 RY = (IY/A)**.5
164 LPRINT
165 LPRINT "Ix =" IX "   Xb = " XB "   Rx = " RX "    A = " A
167 LPRINT "Iy =" IY "   Ry = " RY
172 LRX=(L+2.3622)/RX
174 SEX=PI**2*EO/LRX**2
183 J=(T**3/3)*(H1+2*W1+2*C1+4*U)
184 MB=(W1+2*RS)*T*(6*(C1+RS)*(H1+2*RS)**2+3*(W1+2*RS)*(H1+2*RS)**2+
    8*(C1+RS)**3)/(12*IX)
185 CW=((H1+2*RS)**2/4)*(IY+XB**2*A*(1-(H1+2*RS)**2*A/(4*IX)))+
    (2*(W1+2*RS)**2*T*(C1+RS)**3/3-(H1+2*RS)*(W1+2*RS)**2*(C1+RS)**2*T+
    (H1+2*RS)**2*(W1+2*RS)*T*(C1+RS)**3*XB*A/(3*IX)-
    4*(W1+2*RS)**2*T**2*(C1+RS)**6/(9*IX))
186 XO=-(XB+MB)
187 RO=(RX**2+RY**2+XO**2)**.5
188 LPRINT "J = " J "   m = " MB "   Cw = " CW "Xo =" XO "Ro = "RO
189 ST=(GO*J+PI**2*EO*CW/(.5*L)**2)/(A*RO**2)
191 LPRINT " **** Calculate the Torsional-Flexural Buckling Stress, Ftf"
193 IF RX>RY THEN RR=RY ELSE RR=RX
195 BATA=1-(XO/RO)**2
197 FE1=(SEX+ST-((SEX+ST)**2-4*BATA*SEX*ST)**.5)/(2*BATA)
198 FF = FE1
199 GOSUB 600 : FE1 = S2
200 LR = (L+2.3622)/RR
205 FE2 = PI**2*EO/LR**2
207 FF = FE2
208 LPRINT " *** Calculate the Flexural Buckling Stress
    w.r.t. minor-axis, Fn."
209 GOSUB 600: FE2 = S2
211 IF FE1 < FE2 THEN FE = FE1 ELSE FE = FE2
213 PRINT "The T-F-B Stress, Fe1 = " FE1 "   The F-B Stress, Fe2 =" FE2
215 LPRINT "The T-F-B Stress, Fe1 = " FE1 "   The F-B Stress, Fe2 =" FE2
220 IF FE > FY THEN FE = FY
222 LPRINT "The design stress, Fe = " FE
223 LPRINT
230 PN = FE*A
235 RIO = PT/PN
260 WT = W1/T : HT = H1/T : CT = C1/T
390 LPRINT USING " W/T = ####.### ";WT
400 LPRINT USING " H/T = ####.### ";HT
410 LPRINT USING " RR = ####.### ";RR
420 LPRINT USING " L/R = ####.### ";LR
430 LPRINT USING " Pn = ####.### ";PN
440 LPRINT USING " Ptest/Pn = ####.### ";RIO
460 END
```

```
600 REM  ****  This subroutine calculate the final stress level in the
601 REM  ****  section by using the Newton-Ralphson Iteration Method.
602 ESP = .0001
604 INPUT "The assumed stress level ="; S1
605 LPRINT "The assumed initial stress level =" S1 "(ksi)"
606 PRINT "No. Iterations", "Stress"
608 LPRINT "No. of", "Stress"
609 LPRINT "Iterations"
610 I = 0
615 I = I+1
620 FS = S1-FF*(FY/(FY+.002*N*EO*(S1/FY)**(N-1)))
630 DFS = 1+FF*.002*N*(N-1)*EO*(S1/FY)**(N-2)/(FY+.002*N*EO*
    (S1/FY)**(N-1))**2
640 IDFS = 1/DFS
645 DEL = -IDFS*FS
650 S2 = S1+DEL
652 S1 = S2
666 PRINT I, S2
668 LPRINT I, S2
669 IF I >= 100 THEN PRINT "Iteration exceeds 100 times, N.G."
670 IF ABS(DEL) > ESP THEN 615
680 LPRINT
690 RETURN
```

TABLE 1

Specified Yield Strengths of Stainless Steels

Type of Stress	F_y, ksi						
	Types 201, 301, 304, and 316 +						Types 409, 430 and 439 ++
	Annealed		1/16-Hard		1/4-Hard	1/2-Hard	
Longitudinal Tension	30	45#	40*	45	75	110	30
Transverse Tension	30	45#	40*	45	75	110	30
Transverse Compression	30	45#	40*	45	90	120	30
Longitudinal Compression	28	40#	36*	41	50	65	30

1 ksi = 6.895 MPa

+ Based on ASTM A666-84 (Ref. 41).
++ Based on ASTM A240-86 (Ref. 42).
# For Type 201-2 (Class 2).
* Flat bars, for Type 201 only.

TABLE 2a

Tested Mechanical Properties of 1/4-Hard and 1/2-Hard Type 301 Austenitic Stainless Steels Obtained from Reference 24

Type of Stainless Steels	Yield Strength F_y		Tensile Strength F_u		No. of Tests
	Mean (ksi)	St. Dev. (ksi)	Mean (ksi)	St. Dev. (ksi)	
Type 301, 1/4-Hard					
LT	85.9	5.92	137.9	---	17
TT	88.3	6.39	137.0	---	81
TC	100.0	5.31			17
LC	59.7	4.26			17
Type 301, 1/2-Hard					
LT	121.1	8.66	167.0	---	29
TT	113.9	8.58	168.1	---	93
TC	136.7	9.35			29
LC	82.1	9.13			29

1 ksi = 6.895 MPa

Note: St. Dev. = Standard Deviation.
LT = Longitudinal Tension; TT = Transverse Tension.
LC = Longitudinal Compression; TC = Transverse Compression.

TABLE 2b

Tested Mechanical Properties of Annealed and Strain-Flattened Types 201-2 and 304 Austenitic Stainless Steels Obtained from References 47 and 48

Type of Stainless Steels	Yield Strength F_y		Tensile Strength F_u		No. of Tests
	Mean (ksi)	St. Dev. (ksi)	Mean (ksi)	St. Dev. (ksi)	
Type 201-2					
LT	52.16	1.05	108.05	3.63	6
TT	55.56	2.68	105.83	3.10	6
TC	55.14	2.41			5
LC	42.90	0.62			6
Type 304					
LT	42.10	1.28	98.08	2.08	32
TT	42.05	1.76	94.35	2.22	35
TC	44.68	1.17			24
LC	42.88	1.27			27

1 ksi = 6.895 MPa

Note: See Note in Table 2a.

TABLE 2c

Tested Mechanical Properties of 1/4-Hard and 1/2-Hard Types 201 and 301 Austenitic Stainless Steels Obtained from Reference 49

Type of Stainless Steels	Yield Strength F_y		Tensile Strength F_u		No. of Tests
	Mean (ksi)	St. Dev. (ksi)	Mean (ksi)	St. Dev. (ksi)	
Type 201, 1/4-Hard					
LT	78.08	7.12	138.33	6.91	12
TT	85.50	4.24	130.00	1.41	2
Type 201, 1/2-Hard					
LT	139.58	8.89	172.71	7.00	118
TT	103.01	3.43	143.09	4.08	96
Type 301, 1/4-Hard					
LT	91.34	7.66	138.20	7.10	112
TT	87.06	7.24	130.44	3.36	9
Type 301, 1/2-Hard					
LT	142.95	12.81	166.73	9.17	244
TT	121.20	6.41	158.70	3.81	20
LT	116.92	10.12	169.63	6.09	487

1 ksi = 6.895 MPa

Note: See Note in Table 2a.

TABLE 3a

Statistics on Yield Strengths of 1/4-Hard and 1/2-Hard Type 301 Austenitic Stainless Steels

Type of Stainless Steels	Specified Yield Strength (ksi)	(Tested F_y)/(Specified F_y) Mean	(Tested F_y)/(Specified F_y) C.O.V.	Number of Tests Used in the Analysis	Ref. No.
Type 301, 1/4-Hard					
LT	75	1.1456	0.0689	17	24
TT	75	1.1768	0.0724	81	24
TC	90	1.1114	0.0531	17	24
LC	50	1.1948	0.0713	17	24
Total		1.1667	0.0724	132	
Type 301, 1/2-Hard					
LT	110	1.1006	0.0715	29	24
TT	110	1.0355	0.0753	93	24
TC	120	1.1391	0.0684	29	24
LC	65	1.2632	0.1112	29	24
Total		1.0994	0.1109	180	

1 ksi = 6.895 MPa; C.O.V. = Coefficient of Variation

Note: 1. See Note in Table 2a.
2. For 1/4- and 1/2-Hard Type 301 stainless steels, the specified yield strengths are based on Ref. 41 and given in Table 1.
3. Refer to Table 2a for test results of F_y.

TABLE 3b

Statistics on Yield Strengths of Annealed and Strain-Flattened Types 201-2 and 304 Austenitic Stainless Steels

Type of Stainless Steels	Specified Yield Strength (ksi)	(Tested F_y)/(Specified F_y) Mean	C.O.V.	Number of Tests Used in the Analysis	Ref. No.
Type 201-2					
LT	45	1.1591	0.0201	6	47
TT	45	1.2347	0.0483	6	47
TC	45	1.2253	0.0145	6	47
LC	40	1.0725	0.0437	5	47
Total		1.1773	0.0631	23	
Type 304					
LT	30	1.4033	0.0303	32	48
TT	30	1.4017	0.0419	35	48
TC	30	1.4293	0.0273	24	48
LC	28	1.5957	0.0284	27	48
Total		1.4521	0.0635	118	

1 ksi = 6.895 MPa; C.O.V. = Coefficient of Variation

Note:

1. See Note in Table 2a.
2. For annealed Types 201-2 and 304 stainless steels, the specified yield strengths are based on Ref. 41 and given in Table 1.
3. Refer to Table 2b for test results of F_y.

TABLE 3c

Statistics on Yield Strengths of 1/4-Hard and 1/2-Hard Types 201 and 301 Austenitic Stainless Steels

Type of Stainless Steels	Specified Yield Strength (ksi)	(Tested F_y)/(Specified F_y) Mean	(Tested F_y)/(Specified F_y) C.O.V.	Number of Tests Used in the Analysis	Ref. No.
Type 201, 1/4-Hard					
LT	75	1.0411	0.0912	12	49
TT	75	1.1400	0.0496	2	49
Total		1.0552	0.0907	14	
Type 201, 1/2-Hard					
LT	110	1.2689	0.0637	118	49
TT	110	0.9365	0.0333	96	49
Total		1.1198	0.1584	214	
Type 301, 1/4-Hard					
LT	75	1.2179	0.0839	112	49
TT	75	1.1608	0.0832	9	49
Total		1.2137	0.0845	121	
Type 301, 1/2-Hard					
LT	110	1.2995	0.0896	244	49
TT	110	1.1018	0.0529	20	49
LT	110	1.0629	0.0866	487	49
Total		1.1408	0.1304	751	

1 ksi = 6.895 MPa; C.O.V. = Coefficient of Variation

Note:
1. See Note in Table 2a.
2. For 1/4-Hard and 1/2-Hard Types 201 and 301 stainless steels, the specified yield strengths are based on Ref. 41 and given in Table 1.
3. Refer to Table 2c for test results of F_y.

TABLE 4a

Statistics on Tensile Strengths and Elongations of 1/4-Hard and 1/2-Hard Type 301 Austenitic Stainless Steels

Type of Stainless Steels	Specified Values		(Tested Values)/(Specified Values)				Number of Tests Used in the Analysis	Ref. No.
	F_u	Elong	F_u		Elong			
	(ksi)	(%)	Mean	C.O.V.	Mean	C.O.V.		
Type 301, 1/4-Hard								
LT	125	25	1.103	---	1.576	---	17	24
TT	125	25	1.096	---	1.432	---	81	24
Total			1.097	---	1.457	---	98	
Type 301, 1/2-Hard								
LT	150	18	1.113	---	1.467	---	29	24
TT	150	18	1.121	---	1.322	---	93	24
Total			1.119	---	1.356	---	122	

1 ksi = 6.895 MPa; Elong = Elongation; C.O.V. = Coefficient of Variation

Note:

1. See Note in Table 2a.
2. For 1/4- and 1/2-Hard Type 301 stainless steels, the specified tensile strengths and elongations are based on Ref. 41.
3. Refer to Table 2a for test results of F_u.

TABLE 4b

Statistics on Tensile Strengths and Elongations of Annealed and Strain-Flattened Types 201-2 and 304 Austenitic Stainless Steels

Type of Stainless Steels	Specified Values		(Tested Values)/ (Specified Values)				Number of Tests Used in the Analysis	Ref. No.
	F_u (ksi)	Elong (%)	F_u Mean	F_u C.O.V.	Elong Mean	Elong C.O.V.		
Type 201-2								
LT	95	40	1.137	0.034	1.395	0.014	6	47
TT	95	40	1.114	0.029	1.438	0.044	6	47
Total			1.126	0.032	1.417	0.035	12	
Type 304								
LT	75	40	1.308	0.021	1.465	0.039	32	48
TT	75	40	1.258	0.024	1.498	0.052	35	48
Total			1.282	0.030	1.482	0.047	67	

1 ksi = 6.895 MPa; Elong = Elongation; C.O.V. = Coefficient of Variation

Note:

1. See Note in Table 2a.
2. For Annealed Types 201-2 and 304 stainless steels, the specified tensile strengths and elongations are based on Ref. 41.
3. Refer to Table 2b for test results of F_u.

TABLE 4c

Statistics on Tensile Strengths and Elongations of 1/4-Hard and 1/2-Hard Types 201 and 301 Austenitic Stainless Steels

Type of Stainless Steels	Specified Values		(Tested Values)/ (Specified Values)				Number of Tests Used in the Analysis	Ref. No.
	F_u	Elong	F_u		Elong			
	(ksi)	(%)	Mean	C.O.V.	Mean	C.O.V.		
Type 201, 1/4-Hard								
LT	125	25	1.107	0.050	2.103	0.048	12	49
TT	125	25	1.040	0.011	1.580	0.054	2	49
Total			1.097	0.051	2.028	0.105	14	
Type 201, 1/2-Hard								
LT	150	15	1.151	0.041	1.561	0.152	118	49
TT	150	15	0.954	0.029	1.709	0.148	96	49
Total			1.063	0.099	1.627	0.157	214	
Type 301, 1/4-Hard								
LT	125	25	1.106	0.051	1.670	0.132	112	49
TT	125	25	1.044	0.026	1.427	0.061	9	49
Total			1.101	0.052	1.652	0.135	121	
Type 301, 1/2-Hard								
LT	150	15	1.112	0.055	1.721	0.205	244	49
TT	150	15	1.058	0.024	1.633	0.209	20	49
LT	150	15	1.131	0.036	2.143	0.110	487	49
Total			1.123	0.045	1.992	0.175	751	

1 ksi = 6.895 MPa; Elong = Elongation; C.O.V. = Coefficient of Variation

Note:

1. See Note in Table 2a.
2. For 1/4- and 1/2-Hard Types 201 and 301 stainless steels, the specified tensile strengths and elongations are based on Ref. 41.
3. Refer to Table 2c for test results of F_u.

TABLE 5

Tested Mechanical Properties of Types 409, 430, and 439 Ferritic Stainless Steels

Type of Stainless Steels	Yield Strength F_y		Tensile Strength F_u		No. of Tests	Ref. No.
	Mean (ksi)	St. Dev. (ksi)	Mean (ksi)	St. Dev. (ksi)		
Type 409						
LT	34.2	2.50	58.6	1.93	15	32
TT	39.7	3.33	64.3	2.70	4977	32,33,43
TC	36.8	3.05			12	32
LC	34.9	2.06			14	32
Types 430 and 439						
LT	45.8	1.74	74.7	0.82	26	32
TT	52.2	3.92	78.4	4.23	4209	32,33,44,45
TC	52.3	1.99			27	32
LC	45.6	2.92			29	32

1 ksi = 6.895 MPa

Note: See Note in Table 2a.

TABLE 6

Statistics on Yield Strengths of Types 409, 430, and 439 Ferritic Stainless Steels

Type of Stainless Steels	Specified Yield Strength (ksi)	(Tested F_y)/(Specified F_y) Mean	(Tested F_y)/(Specified F_y) C.O.V.	Number of Tests Used in the Analysis	Ref. No.
Type 409					
LT	30	1.1406	0.0727	15	32
TT	35 +	1.1340	0.0844	4977	32,33,43
TC	35 +	1.0510	0.0829	12	32
LC	30	1.1615	0.0589	14	32
Total		1.1339	0.0844	5018	
Types 430 & 439					
LT	40 +	1.1459	0.0382	26	32
TT	45 +	1.1613	0.0752	4209	32,33,44,45
TC	45 +	1.1631	0.0375	27	32
LC	40 +	1.1414	0.0642	29	32
All		1.1611	0.0748	4291	

1 ksi = 6.895 MPa; C.O.V. = Coefficient of Variation
+ Adjusted values.

Note: 1. See Note in Table 2a.
2. For Types 409, 430, and 439 stainless steels, the ASTM specified yield strength is 30 ksi as given in Table 1.
3. Refer to Table 5 for test results of F_y.

TABLE 7

Statistics on Tensile Strengths and Elongations of Types 409, 430, and 439 Ferritic Stainless Steels

Type of Stainless Steels	Specified Values		(Tested Values)/(Specified Values)				Numbers of Tests Used in the Analysis	Ref. No.
	F_u	Elong	F_u		Elong			
	(ksi)	(%)	Mean	C.O.V.	Mean	C.O.V.		
Type 409								
LT	55	22	1.066	0.033	1.730	0.085	15	32
TT	55	22	1.169	0.042	1.532	0.084	4977	32,33, 43
Total			1.169	0.042	1.533	0.084	4992	
Types 430 & 439								
LT	65	22	1.149	0.011	1.293	0.111	26	32
TT	65	22	1.206	0.054	1.198	0.115	4209	32,33, 44,45
Total			1.206	0.054	1.199	0.115	4235	

1 ksi = 6.895 MPa; Elong = Elongation; C.O.V. = Coefficient of Variation

Note: 1. See Note in Table 2a.
2. For Types 409, 430, and 439 stainless steels, the specified tensile strengths and elongations are based on Ref. 42.
3. Refer to Table 5 for test results of F_u.

TABLE 8

Statistics on Thicknesses of Austenitic and Ferritic Stainless Steels

Type	Nominal Thickness (mm)	(Measured Thickness)/ (Nominal Thickness)		No. of Samples	Ref. No
		Mean	C.O.V.		
201-2	0.5	1.0771	0.01985	7	47
201-2	1.2	1.0109	0.01075	16	47
304	0.9	0.9704	0.00693	30	48
304	1.6	0.9957	0.01060	52	48
304	2.0	0.9758	0.00526	36	48
409	1.2	0.9833	0.00329	20	32
409	2.0	0.9986	0.00809	40	32
430	0.9	0.9648	0.00822	18	32
430	1.2	0.9707	0.00584	39	32
430	1.6	0.9539	0.00824	16	32
430	2.0	0.9614	0.00526	35	32
All	0.5-2.0	0.9821	0.02320	309	

1 mm = 0.03937 in.

TABLE 9

Summary of Statistics on Yield Strengths of Austenitic and Ferritic Stainless Steels

Type of Stainless Steels	(Tested F_y)/(Specified F_y)		Number of Tests Used in the Analysis	Soure Reference
	Mean	C.O.V.		
301, 1/4-Hard	1.167	0.072	132	24
301, 1/2-Hard	1.099	0.111	180	24
201-2, Annealed	1.177	0.063	23	47
304, Annealed	1.452	0.064	118	48
201, 1/4-Hard	1.055	0.091	14	49
201, 1/2-Hard	1.120	0.158	214	49
301, 1/4-Hard	1.214	0.085	121	49
301, 1/2-Hard	1.141	0.131	751	49
409	1.134	0.084	5018	32,33,43
430 & 439	1.161	0.075	4291	32,33,44,45
Total	1.149	0.092	10862	

Note: Refer to statistical results in Tables 3 and 6.

TABLE 10

Summary of Statistics on Tensile Strengths and Elongations of Austentic and Ferritic Stainless Steels

Type of Stainless Steels	(Tested F_u)/(Spec. F_u)		(Tested Elong.)/(Spec. Elong.)		No. of Tests Used in Analysis	Source Reference
	Mean	C.O.V.	Mean	C.O.V.		
301, 1/4-Hard	1.097	---	1.457	---	98	24
301, 1/2-Hard	1.119	---	1.356	---	122	24
201-2, Annealed	1.126	0.032	1.417	0.035	12	47
304, Annealed	1.282	0.030	1.482	0.047	67	48
201, 1/4-Hard	1.097	0.051	2.028	0.105	14	49
201, 1/2-Hard	1.063	0.099	1.627	0.157	214	49
301, 1/4-Hard	1.101	0.052	1.652	0.135	121	49
301, 1/2-Hard	1.123	0.045	1.992	0.175	751	49
409	1.169	0.042	1.533	0.084	4992	32,33,43
430 & 439	1.206	0.054	1.199	0.115	4235	32,33,44,45
Total	1.178	0.056	1.434	0.195	10406	

Spec. = Specified.

Note: Refer to statistical results in Tables 4 and 7.

TABLE 11

Dimensions of Beam Test Specimens

Specimen No.	B (in.)	D (in.)	F (in.)	d (in.)	R (in.)	t (in.)	L (in.)
F-1b	4.74	1.53	1.00	0.30	0.0625	0.0305	36
F-2	2.77	1.52	0.76	0.30	0.0625	0.0305	36
F-3	2.36	1.02	0.78	---	0.0625	0.0420	36
F-4	2.01	1.04	0.88	---	0.0625	0.0494	36
F-5	1.46	1.00	0.60	---	0.0625	0.0608	36
F-6a	3.8352	1.5073	1.0137	0.3016	0.0625	0.0296	36
F-6b	3.8320	1.5077	1.0162	0.3046	0.0625	0.0297	36
F-7	4.7554	1.5066	1.0128	0.3017	0.0625	0.0296	36
F-8a	4.7544	1.5318	0.9939	0.3036	0.0625	0.0298	54
F-8b	4.7860	1.5051	1.0030	0.3034	0.0625	0.0298	54
AS304F-2	2.3968	1.5081	1.7525	0.3070	0.0625	0.0309	44
AS304F-3	3.6940	1.5005	0.8777	0.3004	0.0625	0.0315	44
AS304F-4	4.9188	1.5054	1.0033	0.3009	0.0625	0.0315	44
H301F-1	1.9238	0.9892	0.9055	---	0.1250	0.0624	44
H301F-2	2.7424	0.9934	0.8165	0.3716	0.1250	0.0624	44
H301F-3	2.5834	1.4919	0.8008	0.2958	0.0938	0.0328	44
H301F-4	5.1844	1.4914	1.0061	0.2941	0.0938	0.0328	44

1 in. = 25.40 mm

Note: 1. Measured dimensions are obtained from Refs. 23 and 24.
2. All specimens used for beam tests are hat sections. See designation of symbols in Fig. 4.
3. Specimens with Series F and AS304F are made using annealed and strained flattened Type 304 stainless steels, while specimens with Series H301F are made using 1/2-Hard Type 301 stainless steels.

TABLE 12

Comparison of Tested and Predicted Ultimate Moments of Cold-Formed Stainless Steel Beams Having Stiffened Compression Elements

Specimen No.	w/t	F_{yc} (ksi)	F_{yt} (ksi)	M_{test} (in.-k)	M_{pred} (in.-k)	$\frac{M_{test}}{M_{pred}}$	Ref. No.
F-1b	149.31	34.5	38	3.843	3.393	1.133	23
F-2	84.72	34.5	38	3.510	3.124	1.124	23
F-3	51.21	34.5	38	3.474	2.731	1.272	23
F-4	36.16	34.5	38	4.590	3.496(4.032)	1.313(1.138)	23
F-5	19.96	34.5	38	4.050	2.866(3.568)	1.413(1.135)	23
F-6a	123.34	34.5	38	3.915	3.144	1.245	23
F-6b	122.81	34.5	38	3.888	3.162	1.230	23
F-7	154.43	34.5	38	3.942	3.184	1.238	23
F-8a	153.35	34.5	38	4.010	3.280	1.223	23
F-8b	154.41	34.5	38	3.861	3.209	1.203	23
AS304F-2	71.52	34.1	41.1	3.562	3.064	1.163	24
AS304F-3	113.02	34.1	41.1	3.844	3.334	1.153	24
AS304F-4	150.18	34.1	41.1	4.185	3.467	1.207	24
H301F-1	24.82	100.5	125.8	11.470	10.235	1.121	24
H301F-2	37.94	100.5	125.8	11.143	10.800	1.032	24
H301F-3	71.04	89.9	128.3	9.152	6.956	1.316	24
H301F-4	150.34	89.9	128.3	9.400	7.369	1.276	24

Number of Specimens	N = 17
Mean	P_m = 1.199(1.189)
Coefficient of Variation	V_P = 0.064(0.0608)

1 ksi = 6.895 MPa; 1 in.-k = 0.113 kN-m.

Note: 1. For cross-sectional dimensions of specimens, see Table 11.

2. F_{yc} and F_{yt} are yield strengths in longitudinal compression and tension, respectively.

3. The value in the parenthesis is determined on the basis of Inelastic Reserve Capacity approach as discussed in Section 4.2(2).

TABLE 13

Computed Safety Index β for Section Bending Strength of Cold-Formed Carbon Steel Beams[16]

Case	No. of Tests	M_m	V_M	F_m	V_F	P_m	V_P	β
Stiffened Compression Flanges (φ = 0.95)								
FF. FW.	8	1.10	0.10	1.0	0.05	1.10543	0.03928	2.76
PF. FW.	30	1.10	0.10	1.0	0.05	1.11400	0.08889	2.65
PF. PW.	5	1.10	0.10	1.0	0.05	1.08162	0.09157	2.53
Unstiffened Compression Flanges (φ = 0.90)								
FF. FW.	3	1.10	0.10	1.0	0.05	1.43330	0.04337	4.05
PF. FW.	40	1.10	0.10	1.0	0.05	1.12384	0.13923	2.67
PF. PW.	10	1.10	0.10	1.0	0.05	1.03162	0.05538	2.66

Note: FF. = Fully effective flanges
PF. = Partially effective flanges
FW. = Fully effective webs
PW. = Partially effective webs

TABLE 14

Dimensions of Stub Column Test Specimens

Specimen No.	D (in.)	B (in.)	t (in.)	F (in.)	R (in.)	A ($in.^2$)	L (in.)
UFC-1	1.9550	0.6500	0.0360	---	0.0469	0.2252	3.988
UFC-2	1.9945	0.8078	0.0362	---	0.0469	0.2521	7.967
UFC-3	2.0163	0.9794	0.0362	---	0.0469	0.2785	14.89
UFC-4	2.0082	1.1728	0.0364	---	0.0469	0.3076	14.98
UFC-5	2.9858	1.3542	0.0360	---	0.0469	0.4008	19.96
UFC-6	2.9598	1.5508	0.0360	---	0.0469	0.4272	19.92
UFC-7	2.9750	1.7275	0.0361	---	0.0469	0.4550	19.88
UFC-8	2.9798	1.9048	0.0360	---	0.0469	0.4796	19.95
H301UE-1	1.5784	0.5158	0.0325	---	0.1250	0.1576	3.555
H301UE-2	1.6019	0.7325	0.0326	---	0.1230	0.1878	5.939
H301UE-3	1.5995	1.1165	0.0324	---	0.1250	0.2363	9.91
H301UE-4	1.5682	1.7519	0.0324	---	0.1250	0.3166	11.63
H301SC-2	0.9926	2.8407	0.0619	0.679	0.1250	0.7018	12.0
H301SC-4	0.8427	5.2894	0.0324	0.387	0.1090	0.4797	15.0

1 in. = 25.40 mm; 1 $in.^2$ = 645.16 mm^2

Note: 1. Measured dimensions are obtained from Refs. 23 and 24.
2. For designation of symbols, see Fig. 7.
3. Series UFC are made using annealed and skin passed Type 304 stainless steels, and Series H301UE and H301SC are made using 1/2-Hard Type 301 stainless steels.

TABLE 15

Comparison of Tested and Predicted Failure Loads of Cold-Formed Stainless Steel Stub Columns

Specimen No.	w/t	F_{yc} (ksi)	A_e (in.)	P_{test} (kips)	P_{pred} (kips)	$\frac{P_{test}}{P_{pred}}$	Ref. No.
UFC-1	15.75	34.5	0.197	8.962	6.804	1.317	23
UFC-2	20.02	34.5	0.206	8.512	7.106	1.198	23
UFC-3	24.76	34.5	0.211	8.475	7.267	1.166	23
UFC-4	29.93	34.5	0.216	8.738	7.442	1.174	23
UFC-5	35.31	34.5	0.227	9.925	7.786	1.275	23
UFC-6	40.78	34.5	0.226	10.012	7.836	1.278	23
UFC-7	45.55	34.5	0.230	10.075	7.920	1.272	23
UFC-8	50.61	34.5	0.229	10.575	7.914	1.336	23
H301UE-1	11.02	89.9	0.123	15.80	11.078	1.426	24
H301UE-2	17.63	89.9	0.128	14.55	11.514	1.264	24
H301UE-3	29.60	89.9	0.130	15.00	11.681	1.284	24
H301UE-4	49.21	89.9	0.131	15.80	11.805	1.339	24
H301SC-2	39.85	100.5	0.590	72.70	59.250	1.227	24
H301SC-4	154.51	89.9	0.221	23.05	19.889	1.159	24

Number of Specimens	N = 14
Mean	P_m = 1.265
Coefficient of Variation	V_P = 0.060

1 ksi = 6.895 MPa; 1 kip = 4.448 kN.

Note: 1. For cross-sectional dimensions of specimens, see Table 14.
2. F_{yc} is the yield strength in longitudinal compression, and A_e is the effective area.
3. $P_{pred} = F_{yc}A_e$.

TABLE 16

Dimensions and Sectional Properties of Column Specimens

Specimen No.	D (in.)	B (in.)	R (in.)	t (in.)	A ($in.^2$)	I_y ($in.^4$)	r_y (in.)
UPC-1	1.955	0.650	0.0469	0.0360	0.2311	0.0132	0.239
UPC-2	1.992	0.808	0.0469	0.0360	0.2565	0.0253	0.314
UPC-3	2.011	0.980	0.0469	0.0360	0.2827	0.0452	0.400
UPC-4	2.007	1.174	0.0469	0.0360	0.3103	0.0777	0.500
UPC-5	2.998	1.352	0.0469	0.0356	0.4028	0.1173	0.540
UPC-6	2.962	1.544	0.0469	0.0360	0.4323	0.1765	0.639
UPC-7	2.974	1.725	0.0469	0.0360	0.4593	0.2464	0.732
UPC-8	2.970	1.904	0.0469	0.0358	0.4821	0.3293	0.827
PC-5 to PC-16	1.958	0.620	0.0625	0.0609	0.365	0.0202	0.235
PC-103 to PC-106	2.022	0.790	0.0625	0.0603	0.373	0.0337	0.306
304-1 to 304-6	1.575	0.591	0.0394	0.0346	0.1826	0.0095	0.228

1 in. = 25.4 mm

Note: 1. Measured dimensions are obtained from Refs. 23 and 38.
2. All specimens are I-sections except for specimens PC-103 through PC-106, which are box-sections. See designation of symbols in Fig. 9.
3. All specimens are made using annealed and skin passed Type 304 austenitic stainless steels.

TABLE 17

Comparison of Tested and Predicted Failure Loads of Cold-Formed Stainless Steel Columns Based on Flexural Buckling

Specimen No.	l/r	F_{yc} (ksi)	F_c (ksi)	A_e (in.)	P_{test} (kips)	P_{pred} (kips)	$\frac{P_{test}}{P_{pred}}$
UPC-1	32.32	34.5	34.50	0.197	8.030	6.804	1.180
UPC-2	55.77	34.5	25.34	0.225	7.135	5.692	1.254
UPC-3	44.07	34.5	29.12	0.221	8.225	6.428	1.280
UPC-4	35.42	34.5	32.90	0.215	7.928	7.080	1.120
UPC-5	42.11	34.5	29.89	0.234	8.700	6.993	1.244
UPC-6	35.56	34.5	32.83	0.232	9.150	7.603	1.204
UPC-7	31.02	34.5	34.50	0.228	9.400	7.880	1.193
UPC-8	27.49	34.5	34.50	0.227	9.962	7.832	1.272
PC-7	28.03	34.5	34.50	0.365	17.355	12.586	1.379
PC-8	36.84	34.5	32.20	0.365	15.597	11.747	1.328
PC-9	45.64	34.5	28.54	0.365	13.486	10.412	1.295
PC-10	54.44	34.5	25.72	0.365	12.139	9.383	1.294
PC-14	59.68	34.5	24.30	0.365	10.793	8.865	1.217
PC-12	70.69	34.5	21.75	0.365	9.628	7.935	1.213
PC-13	79.88	34.5	19.96	0.365	8.620	7.282	1.184
PC-15	99.96	34.5	16.72	0.365	6.574	6.100	1.078
PC-16	130.03	34.5	12.91	0.365	4.950	4.710	1.051
PC-5	158.19	34.5	10.08	0.365	3.516	3.677	0.956
PC-6	177.03	34.5	8.51	0.365	2.963	3.105	0.954
PC-103	37.25	34.5	32.00	0.373	16.805	11.947	1.407
PC-104	55.66	34.5	25.37	0.373	13.086	9.472	1.382
PC-105	72.37	34.5	21.41	0.373	10.516	7.994	1.316
PC-106	81.62	34.5	19.65	0.373	10.202	7.336	1.391
304-1	21.75	42.9	42.90	0.163	6.902	7.003	0.986
304-2	37.86	42.9	38.21	0.169	7.149	6.450	1.108
304-3	53.97	42.9	32.04	0.177	5.261	5.672	0.927
304-4	70.08	42.9	27.56	0.183	5.980	5.032	1.188
304-5	86.19	42.9	23.88	0.183	4.879	4.361	1.119
304-6	102.30	42.9	20.63	0.183	4.159	3.768	1.104

Number of Specimens	$N = 29$
Mean	$P_m = 1.194$
Coefficient of Variation	$V_P = 0.114$

1 ksi = 6.895 MPa; 1 kip = 4.448 kN.

Note: 1. For cross-sectional dimensions of specimens, see Table 16.
2. Test data are obtained from Refs. 23 and 38.

TABLE 18

Dimensions and Sectional Properties of Hat Sections Used for Torsional-Flexural Buckling of Columns

Specimen Series	D (in.)	B (in.)	C (in.)	R (in.)	t (in.)	A (in.^{2})
304-0.9	0.7795	1.0709	0.3898	0.05433	0.03464	0.1115
304-1.6	1.2008	1.7008	0.6024	0.07913	0.06339	0.3016
304-2.0	1.6102	2.4803	0.8110	0.12990	0.07717	0.5139
409-2.0	1.7559	2.5551	0.7992	0.08268	0.07598	0.5643
430-0.9	0.7677	1.0945	0.4213	0.04173	0.03346	0.1033
430-1.6	1.1850	1.9843	0.6102	0.06142	0.06063	0.3046
430-2.0	1.7244	2.5866	0.8150	0.07795	0.07520	0.5238

1 in. = 25.4 mm

Note: 1. Measured dimensions are obtained from Ref. 50.
2. See designation of symbols in Fig. 11a.
3. The specimen designation is given as follows:

304 - 0.9 - x
- x — Test No.
- 0.9 — Nominal thickness (mm)
- 304 — Type of stainless steel

TABLE 19

Comparison of Tested and Predicted Failure Loads of Cold-Formed Stainless Steel Columns Based on Torsional-Flexural Buckling

Specimen No.	l/r_y	F_{yc} (ksi)	P_{test} (kips)	P_{pred} (kips)	$\frac{P_{test}}{P_{pred}}$
304-0.9-1	27.08	41.15	4.924	4.584	1.074
304-0.9-2	46.42	41.15	3.889	3.424	1.136
304-0.9-3	59.32	41.15	3.732	2.933	1.272
304-0.9-4	110.90	41.15	1.799	1.748	1.029
304-1.6-1	17.69	42.97	15.535	13.170	1.180
304-1.6-2	30.32	42.97	12.185	12.305	0.990
304-1.6-3	42.95	42.97	12.028	10.134	1.187
304-1.6-4	55.58	42.97	10.701	8.706	1.229
304-1.6-5	80.84	42.97	8.071	6.785	1.189
304-1.6-6	131.37	42.97	4.204	4.487	0.937
304-1.6-7	156.63	42.97	3.575	3.691	0.968
304-2.0-1	13.13	43.73	23.449	23.127	1.014
304-2.0-2	22.50	43.73	23.394	23.127	1.012
304-2.0-3	31.88	43.73	20.953	20.915	1.002
304-2.0-4	41.25	43.73	20.683	18.311	1.130
304-2.0-5	60.00	43.73	16.457	14.827	1.110
304-2.0-6	78.76	43.73	13.174	12.378	1.064
304-2.0-7	116.26	43.73	8.768	8.845	0.991
409-2.0-1	12.07	33.30	22.077	18.722	1.179
409-2.0-2	20.69	33.30	20.773	18.503	1.123
409-2.0-3	29.31	33.30	19.694	16.915	1.164
409-2.0-4	37.93	33.30	17.716	15.796	1.122
409-2.0-5	55.17	33.30	16.457	14.146	1.163
409-2.0-6	72.41	33.30	14.906	12.779	1.166
409-2.0-7	89.65	33.30	11.533	11.393	1.012
430-0.9-1	24.53	48.11	5.755	5.503	1.046
430-0.9-2	46.61	48.11	4.766	4.235	1.126
430-0.9-3	59.55	48.11	4.631	3.724	1.243
430-0.9-4	85.45	48.11	3.507	2.878	1.219
430-0.9-5	111.34	48.11	2.091	2.126	0.984
430-0.9-6	163.13	48.11	1.439	1.245	1.156
430-0.9-7	201.97	48.11	0.944	0.823	1.147

TABLE 19 (Continued)

Comparison of Tested and Predicted Failure Loads of Cold-Formed Stainless Steel Columns Based on Torsional-Flexural Buckling

Specimen No.	l/r_y	F_{yc} (ksi)	P_{test} (kips)	P_{pred} (kips)	$\frac{P_{test}}{P_{pred}}$
430-1.6-1	16.03	45.84	15.692	14.754	1.064
430-1.6-2	30.47	45.84	15.288	13.962	1.095
430-1.6-3	43.16	45.84	14.546	11.969	1.215
430-1.6-4	55.86	45.84	12.815	10.571	1.212
430-1.6-5	81.25	45.84	9.420	8.472	1.112
430-1.6-6	106.64	45.84	7.442	6.746	1.103
430-1.6-7	132.03	45.84	6.183	5.070	1.220
430-2.0-1	11.04	41.68	25.022	23.461	1.067
430-2.0-2	20.98	41.68	26.079	23.461	1.112
430-2.0-3	29.73	41.68	23.404	21.615	1.083
430-2.0-4	38.47	41.68	20.998	19.139	1.097
430-2.0-5	55.96	41.68	17.379	15.731	1.105
430-2.0-6	73.44	41.68	15.018	13.219	1.136
Number of Specimens					N = 45
Mean					P_m = 1.111
Coefficient of Variation					V_p = 0.074

1 ksi = 6.895 MPa; 1 kip = 4.448 kN.

Note: 1. For cross-sectional dimensions of specimens, see Table 18.
2. Test data are obtained from Ref. 50.
3. See Note (3) in Table 18 for specimen designation.

TABLE 20

Computed Safety Index β for Cold-Formed Carbon Steel Columns[16]

Case	No. of Tests	M_m	V_M	F_m	V_F	P_m	V_P	β
1	5	1.10	0.10	1.0	0.05	1.14610	0.10452	3.13
2	24	1.10	0.10	1.0	0.05	1.05053	0.07971	2.89
3	15	1.10	0.10	1.0	0.05	1.05523	0.07488	2.93
4	3	1.10	0.10	1.0	0.05	1.10550	0.07601	3.11
5	28	1.10	0.10	1.0	0.05	1.04750	0.11072	2.76
6	25	1.10	0.10	1.0	0.05	1.22391	0.21814	2.72
7	9	1.00	0.06	1.0	0.05	0.96330	0.04424	2.39
8	41	1.10	0.10	1.0	0.05	1.19620	0.09608	3.34
9	18	1.10	0.10	1.0	0.05	1.02900	0.08131	2.81
10	12	1.10	0.11	1.0	0.05	1.06180	0.11062	2.77
11	8	1.00	0.06	1.0	0.05	1.15290	0.10544	2.92
12	30	1.10	0.10	1.0	0.05	1.07960	0.15061	2.68
13	14	1.10	0.10	1.0	0.05	1.07930	0.08042	3.00
14	32	1.10	0.10	1.0	0.05	1.08050	0.10772	2.89

Note: Case 1 = Stub columns having unstiffened compression flanges with fully effective widths

Case 2 = Stub columns having unstiffened compression flanges with partially effective widths

Case 3 = Thin plates with partially effective widths

Case 4 = Stub columns having stiffened compression flanges with fully effective flanges and webs

Case 5 = Stub columns having stiffened compression flanges with partially effective flanges and fully effective webs

Case 6 = Stub columns having stiffened compression flanges with partially effective flanges and partially effective webs
Case 7 = Long columns having unstiffened compression flanges subjected to elastic flexural buckling
Case 8 = Long columns having unstiffened compression flanges subjected to inelastic flexural buckling
Case 9 = Long columns having stiffened compression flanges subjected to inelastic flexural buckling
Case 10 = Long columns subjected to inelastic flexural buckling (including cold-work)
Case 11 = Long columns subjected to elastic torsional-flexural buckling
Case 12 = Long columns subjected to inelastic torsional-flexural buckling
Case 13 = Stub columns with circular perforations
Case 14 = Long columns with circular perforations

TABLE 21

Comparison of Tested and Predicted Ultimate Strengths of Groove Welds in As-Welded Condition

Specimen No.	t (in.)	F_y (ksi)	F_{ua} (ksi)	F_{xx} (ksi)	F_{ult} (ksi)	$\frac{F_{ult}}{F_{ua}}$
Q16B-1	0.060	91.4	106.4	105.0	131.5	1.236
Q16B-2	0.061	91.4	106.4	105.0	131.0	1.231
Q22B-1	0.031	90.7	116.9	105.0	140.0	1.198
Q22B-2	0.031	90.7	116.9	105.0	137.0	1.172
H16B-1	0.062	115.7	112.1	105.0	132.0	1.178
H16B-2	0.063	115.7	112.1	105.0	133.5	1.191
H21B-1	0.030	122.8	139.9	105.0	157.0	1.122
H21B-2	0.031	122.8	139.9	105.0	175.0	1.251
H25B-1	0.020	134.3	119.7	105.0	124.0	1.036
H25B-2	0.020	134.3	119.7	105.0	127.0	1.061

Number of Specimens	N = 10
Mean	P_m = 1.168
Coefficient of Variation	V_P = 0.063

1 in. = 25.4 mm; 1 ksi = 6.895 MPa

Note: 1. Test data are obtained from Ref. 26. For test specimens, see Fig. 13.
2. Specimen designations with capital letter Q and H are made of 1/4- and 1/2- Hard Type 301 stainless steels, respectively.
3. All specimens were welded by using the Tungsten Inert Gas process with ER-308 filler metal.
4. For as-welded condition, weld reinforcement not removed but base metal thickness used to calculate stresses.

TABLE 22

Comparison of Tested and Predicted Ultimate Strengths of Butt-Joint Weldments - TIG Process

Specimen No.	t (in.)	F_y (ksi)	F_{ua} (ksi)	F_{xx} (ksi)	F_{ult} (ksi)	$\frac{F_{ult}}{F_{ua}}$
TIG-1	0.019	83.0	131.9	88.9	141.0	1.069
TIG-2	0.019	83.0	131.9	88.9	122.0	0.925
TIG-3	0.019	83.0	131.9	88.9	135.0	1.024
TIG-4	0.050	95.5	103.8	88.9	119.0	1.147
TIG-5	0.050	95.5	103.8	88.9	124.0	1.195
TIG-6	0.050	95.5	103.8	88.9	124.0	1.195
TIG-7	0.093	93.0	100.0	88.9	111.0	1.110
TIG-8	0.093	93.0	100.0	88.9	114.0	1.114
TIG-9	0.093	93.0	100.0	88.9	112.0	1.112
TIG-10	0.187	94.0	111.9	88.9	109.0	0.975
TIG-11	0.187	94.0	111.9	88.9	111.0	0.993
TIG-12	0.187	94.0	111.9	88.9	113.0	1.010

Number of Specimens	N = 12
Mean	P_m = 1.072
Coefficient of Variation	V_P = 0.082

1 in. = 25.4 mm; 1 ksi = 6.895 MPa

Note: 1. Test data were obtained from Ref. 46. The welded length of test specimens is taken as one inch.

2. All specimens are made of 1/4-Hard Type 301 stainless steels. The weld reinforcement not removed, but base metal thickness used to calculate stresses.

3. The test specimens are welded by using Tungsten Inert Gas process with ER-308 filler metal.

TABLE 23

Comparison of Tested and Predicted Ultimate Strengths of Butt-Joint Weldments - MIG Process

Specimen No.	t (in.)	F_y (ksi)	F_{ua} (ksi)	F_{xx} (ksi)	F_{ult} (ksi)	$\frac{F_{ult}}{F_{ua}}$
MIG-1	0.019	83.0	131.9	88.9	150.0	1.138
MIG-2	0.019	83.0	131.9	88.9	146.0	1.108
MIG-3	0.019	83.0	131.9	88.9	153.0	1.160
MIG-4	0.050	95.5	103.8	88.9	110.0	1.060
MIG-5	0.050	95.5	103.8	88.9	113.0	1.089
MIG-6	0.050	95.5	103.8	88.9	115.0	1.108
MIG-7	0.093	93.0	100.0	88.9	122.0	1.220
MIG-8	0.093	93.0	100.0	88.9	123.0	1.230
MIG-9	0.093	93.0	100.0	88.9	120.0	1.200
MIG-10	0.187	94.0	111.9	88.9	106.0	0.948
MIG-11	0.187	94.0	111.9	88.9	106.0	0.948
MIG-12	0.187	94.0	111.9	88.9	110.0	0.984

Number of Specimens	$N = 12$
Mean	$P_m = 1.099$
Coefficient of Variation	$V_p = 0.090$

1 in. = 25.4 mm; 1 ksi = 6.895 MPa

Note: 1. See Notes (1) and (2) in Table 22.

2. All specimens are welded by using Metal Inert Gas process with pulsed type of ER308 filler metal.

TABLE 24

Comparison of Tested and Predicted Ultimate Strengths of Butt-Joint Weldments - Coated Electrode Welding Process

Specimen No.	t (in.)	F_y (ksi)	F_{ua} (ksi)	F_{xx} (ksi)	F_{ult} (ksi)	$\frac{F_{ult}}{F_{ua}}$
CE-1	0.050	95.5	103.8	88.9	109.0	1.050
CE-2	0.050	95.5	103.8	88.9	127.0	1.224
CE-3	0.050	95.5	103.8	88.9	125.0	1.205
CE-4	0.093	93.0	100.0	88.9	120.0	1.200
CE-5	0.093	93.0	100.0	88.9	113.0	1.130
CE-6	0.093	93.0	100.0	88.9	121.0	1.210
CE-7	0.187	94.0	111.9	88.9	109.0	0.975
CE-8	0.187	94.0	111.9	88.9	112.5	1.006
CE-9	0.187	94.0	111.9	88.9	123.0	1.100
Number of Specimens						N = 9
Mean						P_m = 1.122
Coefficient of Variation						V_P = 0.085

1 in. = 25.4 mm; 1 ksi = 6.895 MPa

Note: 1. See Notes (1) and (2) in Table 22.

2. All specimens are welded by using Coated Electrode Wleding process with E-308 filler metal.

TABLE 25

Comparison of Tested and Predicted Failure Loads of Longitudinal Fillet Welds

Specimen No.	t (in.)	L (in.)	F_{ua} (ksi)	F_{xx} (ksi)	P_{test} (kips)	P_{n1} (kips)	P_{n2} (kips)	$\frac{P_{test}}{P_{n1}}$	$\frac{P_{test}}{P_{n2}}$
Q16FL-1	0.059	1.12	106.4	105	3.34	3.72	3.68	0.898	0.908
Q16FL-2	0.059	2.07	106.4	105	5.59	5.59	6.80	1.000	1.011
Q16FL-3	0.059	2.54	106.4	105	8.20	6.86	8.34	1.196	0.983
Q22FL-1	0.031	0.83	116.9	105	1.93	1.38	1.43	1.399	1.350
Q22FL-2	0.031	1.51	116.9	105	2.72	2.35	2.60	1.157	1.046
H16FL-1	0.062	1.02	112.1	105	3.98	3.91	3.52	1.017	1.131
H16FL-2	0.062	1.98	112.1	105	6.50	5.92	6.83	1.093	0.952
H16FL-3	0.062	2.52	112.1	105	8.20	7.53	8.69	1.089	0.944
H21FL-1	0.033	0.81	139.9	105	1.75	1.79	1.49	0.977	1.174
H21FL-2	0.033	1.50	139.9	105	2.98	2.98	2.75	1.000	1.084
Number of Specimens								N = 10	
Mean								P_m = 1.083	1.058
Coefficient of Variation								V_P = 0.131	0.126

1 in. = 25.4 mm; 1 ksi = 6.895 MPa; 1 kip = 4.448 kN.

Note: 1. For test specimens, see Fig. 15a.
2. See Note (2) in Table 21.
3. Test data are obtained from Ref. 26.

TABLE 26

Comparison of Tested and Predicted Failure Loads of Transverse Fillet Welds

Specimen No.	t (in.)	L (in.)	F_{ua} (ksi)	F_{xx} (ksi)	P_{test} (kips)	P_{n1} (kips)	P_{n2} (kips)	$\frac{P_{test}}{P_{n1}}$	$\frac{P_{test}}{P_{n2}}$
Q16FT-1	0.059	1.70	106.4	105	8.82	8.00	7.45	1.102	1.184
Q16FT-2	0.059	2.26	106.4	105	11.64	10.64	9.89	1.094	1.177
Q16FT-3	0.059	3.13	106.4	105	14.30	14.74	13.71	0.970	1.043
Q22FT-1	0.031	1.63	116.9	105	5.20	4.43	3.75	1.174	1.387
Q22FT-2	0.031	2.61	116.9	105	7.70	7.09	6.01	1.085	1.281
H16FT-1	0.062	1.22	112.1	105	6.40	6.36	5.62	1.006	1.139
H16FT-2	0.062	2.12	112.1	105	11.16	11.05	9.76	1.010	1.143
H16FT-3	0.062	3.06	112.1	105	16.10	15.95	14.08	1.009	1.143
H21FT-1	0.033	1.65	139.9	105	5.52	5.71	4.04	0.966	1.366
H21FT-2	0.033	2.52	139.9	105	7.46	8.73	6.17	0.855	1.209
Number of Specimens								N = 10	
Mean								P_m = 1.027	1.207
Coefficient of Variation								V_p = 0.088	0.089

1 in. = 25.4 mm; 1 ksi = 6.895 MPa; 1 kip = 4.448 kN.

Note: 1. For test specimens, see Fig. 15b.
2. See Note (2) in Table 21.
3. Test data are obtained from Ref. 26.

TABLE 27

Computed Safety Index β for Plate Failure of Cold-Formed Carbon Steel Welded Connections[16]

Case	M_m	V_M	F_m	V_F	P_m	V_P	Φ	β
Arc Spot Welds								
1	1.10	0.08	1.00	0.15	1.10	0.17	0.60	3.52
2	1.10	0.08	1.00	0.15	0.98	0.18	0.50	3.64
Fillet Welds								
3	1.10	0.08	1.00	0.15	1.01	0.08	0.60	3.65
4	1.10	0.08	1.00	0.15	0.89	0.09	0.55	3.59
5	1.10	0.08	1.00	0.15	1.05	0.11	0.60	3.72

Note: Case 1 = For $d_a/t \leq 0.815\sqrt{(E/F_u)}$
Case 2 = For $d_a/t > 1.397\sqrt{(E/F_u)}$
Case 3 = Longitudinal Loading, $L/t < 25$
Case 4 = Longitudinal Loading, $L/t \geq 25$
Case 5 = Transverse Loading

TABLE 28

Comparison of Tested and Predicted Failure Loads of Bolted Connections for Shear Strength Study

Specimen No.	t (in.)	d (in.)	e (in.)	e/d	F_u (ksi)	P_{test} (kips)	P_{pred} (kips)	$\frac{P_{test}}{P_{pred}}$
1	0.0620	0.375	0.551	1.47	166.6	5.82	5.69	1.0226
2	0.0624	0.375	0.559	1.49	166.6	5.78	5.81	0.9948
8	0.0322	0.250	0.371	1.48	193.8	2.51	2.32	1.0819
9	0.0326	0.250	0.367	1.47	193.8	2.60	2.32	1.1207
Number of Specimens								$N = 4$
Mean								$P_m = 1.0550$
Coefficient of Variation								$V_P = 0.0539$

1 in. = 25.4 mm; 1 ksi = 6.895 MPa; 1 kip = 4.448 kN.

Note: 1. Test data are obtained from Ref. 26.
2. All specimens were made using 1/2-Hard Type 301 stainless steels. For test specimens, see Fig. 20.
3. Single shear connection is used for these test specimens.

TABLE 29

Comparison of Tested and Predicted Failure Loads of Bolted Connections for Bearing Strength Study

Specimen No.	t (in.)	d (in.)	Connection Type	e/d	F_u (ksi)	P_{test} (kips)	P_{pred} (kips)	$\frac{P_{test}}{P_{pred}}$
4	0.0622	0.50	DS	3.48	166.6	13.40	14.25	0.9405
6 *	0.0620	0.75	SS	3.50	166.6	16.30	15.49	1.0520
20	0.0622	0.75	DS	3.51	166.6	22.90	21.37	1.0715
21	0.0624	0.75	DS	4.49	166.6	24.25	21.44	1.1310
11	0.0324	0.375	SS	2.46	193.8	4.95	4.71	1.0510
13	0.0325	0.5	SS	2.49	193.8	6.34	6.30	1.0060
14	0.0325	0.5	SS	2.48	193.8	5.82	6.30	0.9238
17 *	0.0322	0.75	SS	2.46	193.8	9.00	9.36	0.9615
16	0.0325	0.50	SS	3.48	193.8	6.10	6.30	0.9685
10	0.0325	0.25	DS	4.47	193.8	4.10	4.33	0.9468
12	0.0320	0.375	DS	4.48	193.8	6.38	6.40	0.9976
19 *	0.0324	0.75	SS	4.49	193.8	11.26	9.42	1.1955
23	0.0209	0.25	DS	4.52	165.4	2.35	2.38	0.9888

Number of Specimens $N = 13$
Mean $P_m = 1.0180$
Coefficient of Variation $V_p = 0.0784$

1 in. = 25.4 mm; 1 ksi = 6.895 MPa; 1 kip = 4.448 kN.
* Combined bearing, shearing and tearing failure.
(SS = Single Shear; DS = Double Shear)

Note: See Notes (1) and (2) in Table 28.

TABLE 30

Comparison of Tested and Predicted Ultimate Tensile Strengths of Bolted Connections

Specimen No.	t (in.)	d/s	Connection Type	No. of Bolts	F_u (ksi)	P_{test} (kips)	P_{pred} (kips)	P_{test}/P_{pred}
5	0.0624	0.187	SS	1	166.6	15.40	15.88	0.9700
7	0.0619	0.187	SS	1	166.6	15.20	15.71	0.9675
18	0.0326	0.375	SS	2	193.8	16.60	14.85	1.1175
15	0.0327	0.250	SS	2	193.8	12.50	11.91	1.0492
22	0.0327	0.187	DS	1	193.8	16.02	13.64	1.1741
24	0.0210	0.250	DS	2	165.4	10.62	8.83	1.2027
25	0.0210	0.375	DS	2	165.4	12.97	10.59	1.2247

Number of Specimens	N = 7
Mean	P_m = 1.1009
Coefficient of Variation	V_P = 0.0975

1 in. = 25.4 mm; 1 ksi = 6.895 MPa; 1 kip = 4.448 kN.
(SS = Single Shear; DS = Double Shear)

Note: See Notes (1) and (2) in Table 28.

TABLE 31

Computed Safety Index β for Cold-Formed Carbon Steel Bolted Connections[16]

Case	M_m	V_M	F_m	V_F	P_m	V_P	Φ	β
Minimum Spacing and Edge Distance								
1	1.10	0.08	1.00	0.05	1.13	0.12	0.70	3.75
2	1.10	0.08	1.00	0.05	1.18	0.14	0.70	3.84
3	1.10	0.08	1.00	0.05	0.84	0.05	0.60	3.61
4	1.10	0.08	1.00	0.05	0.94	0.09	0.60	3.90
5	1.10	0.08	1.00	0.05	1.06	0.11	0.70	3.62
6	1.10	0.08	1.00	0.05	1.14	0.19	0.60	3.87
Tension Stress on Net Section								
7	1.10	0.08	1.00	0.05	1.14	0.20	0.65	3.53
8	1.10	0.08	1.00	0.05	0.95	0.21	0.55	3.41
9	1.10	0.08	1.00	0.05	1.04	0.14	0.65	3.63
Bearing Stress on Bolted Connections								
10	1.10	0.08	1.00	0.05	1.08	0.23	0.55	3.65
11	1.10	0.08	1.00	0.05	0.97	0.07	0.65	3.80
12	1.10	0.08	1.00	0.05	1.02	0.20	0.60	3.43
13	1.10	0.08	1.00	0.05	1.05	0.13	0.60	4.06
14	1.10	0.08	1.00	0.05	1.01	0.04	0.70	3.71
15	1.10	0.08	1.00	0.05	0.93	0.05	0.65	3.70

Note: Case 1 = Single shear, with washers, $F_u/F_y \geq 1.15$
Case 2 = Double shear, with washers, $F_u/F_y \geq 1.15$
Case 3 = Single shear, with washers, $F_u/F_y < 1.15$
Case 4 = Double shear, with washers, $F_u/F_y < 1.15$
Case 5 = Single shear, without washers, $F_u/F_y \geq 1.15$
Case 6 = Single shear, without washers, $F_u/F_y < 1.15$
Case 7 = $t < 3/16$ in., double shear, with washers
Case 8 = $t < 3/16$ in., single shear, with washers
Case 9 = $t < 3/16$ in., single shear, without washers
Case 10 = $0.024 \leq t < 3/16$ in., double shear, with washers, $F_u/F_y \geq 1.15$
Case 11 = $0.024 \leq t < 3/16$ in., double shear, with washers, $F_u/F_y < 1.15$
Case 12 = $0.024 \leq t < 3/16$ in., single shear, with washers, $F_u/F_y \geq 1.15$
Case 13 = $0.024 \leq t < 3/16$ in., single shear, with washers, $F_u/F_y < 1.15$
Case 14 = $0.036 \leq t < 3/16$ in., single shear, without washers, $F_u/F_y \geq 1.15$
Case 15 = $0.036 \leq t < 3/16$ in., double shear, without washers, $F_u/F_y \geq 1.15$

TABLE 32

Available Test Data Used for the Calibrations of Proposed LRFD Provisions

	Subject	Number of Tests	Reference No.
1.	Bending strength of beams based on the initiation of yielding or inelastic reserve capacity	10 7	23 24
2.	Compression strength of stub columns	8 6	23 24
3.	Concentrically loaded compression members based on flexural buckling	23 6	23 38
4.	Concentrically loaded compression members based on torsional-flexural buckling	45	50
5.	Groove welds with as-welded conditions	10 33	26 46
6.	Logitudinal Fillet Welds	10	26
7.	Transverse Fillet Welds	10	26
8.	Shear Failure of Bolted Connections	4	26
9.	Bearing Failure of Bolted Connections	13	26
10.	Tension Failure of Bolted Connections	7	26

TABLE 33

Computed Safety Indices, β, for Cold-Formed Stainless Steel Structural Members and Connections Using $D_n/L_n = 0.2$

Case	No. of Tests	φ	M_m	V_M	F_m	V_F	P_m	V_P	β
1	17	0.95	1.10	0.10	1.0	0.05	1.189	0.061	3.04
2	14	0.95	1.10	0.10	1.0	0.05	1.265	0.006	3.40
3	29	0.85	1.10	0.10	1.0	0.05	1.194	0.114	3.26
4	45	0.85	1.10	0.10	1.0	0.05	1.111	0.074	3.17
5	43	0.60	1.10	0.05	1.0	0.15	1.113	0.084	4.13
6	10	0.55	1.10	0.05	1.0	0.15	1.083	0.131	4.09
7	10	0.55	1.10	0.05	1.0	0.15	1.058	0.126	4.04
8	10	0.55	1.10	0.05	1.0	0.15	1.027	0.088	4.14
9	10	0.65	1.10	0.05	1.0	0.15	1.207	0.089	4.11
10	4	0.70	1.10	0.05	1.0	0.05	1.055	0.054	4.10
11	13	0.65	1.10	0.05	1.0	0.05	1.018	0.078	4.14
12	7	0.70	1.10	0.05	1.0	0.05	1.101	0.098	4.04

Note:

Case 1 = Bending strengths of beams
Case 2 = Concentrically loaded compression members based on the stub column tests
Case 3 = Concentrically loaded compression members based on the flexural buckling of columns
Case 4 = Concentrically loaded compression members based on the torsional-flexural buckling of columns
Case 5 = Groove Welds with as-welded conditions
Case 6 = Plate Failure of Longitudinal Fillet Welds
Case 7 = Weld Failure of Longitudinal Fillet Welds
Case 8 = Plate Failure of Transverse Fillet Welds
Case 9 = Weld Failure of Transverse Fillet Welds
Case 10 = Shear failure of bolted connections
Case 11 = Bearing failure of bolted connections
Case 12 = Tension failure of bolted connections

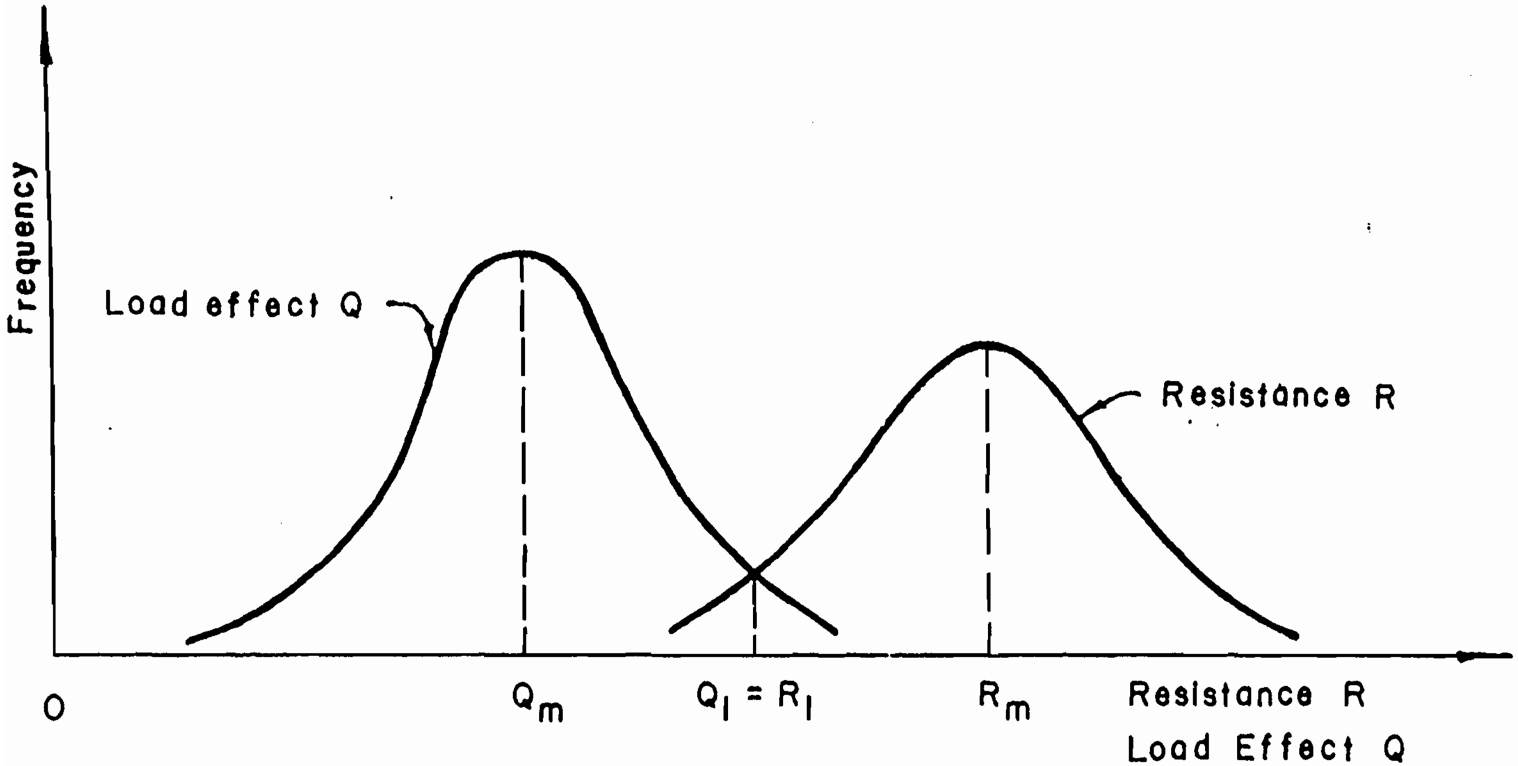


Fig. 1 Frequency Distributions of Resistance and Load Effect[15]

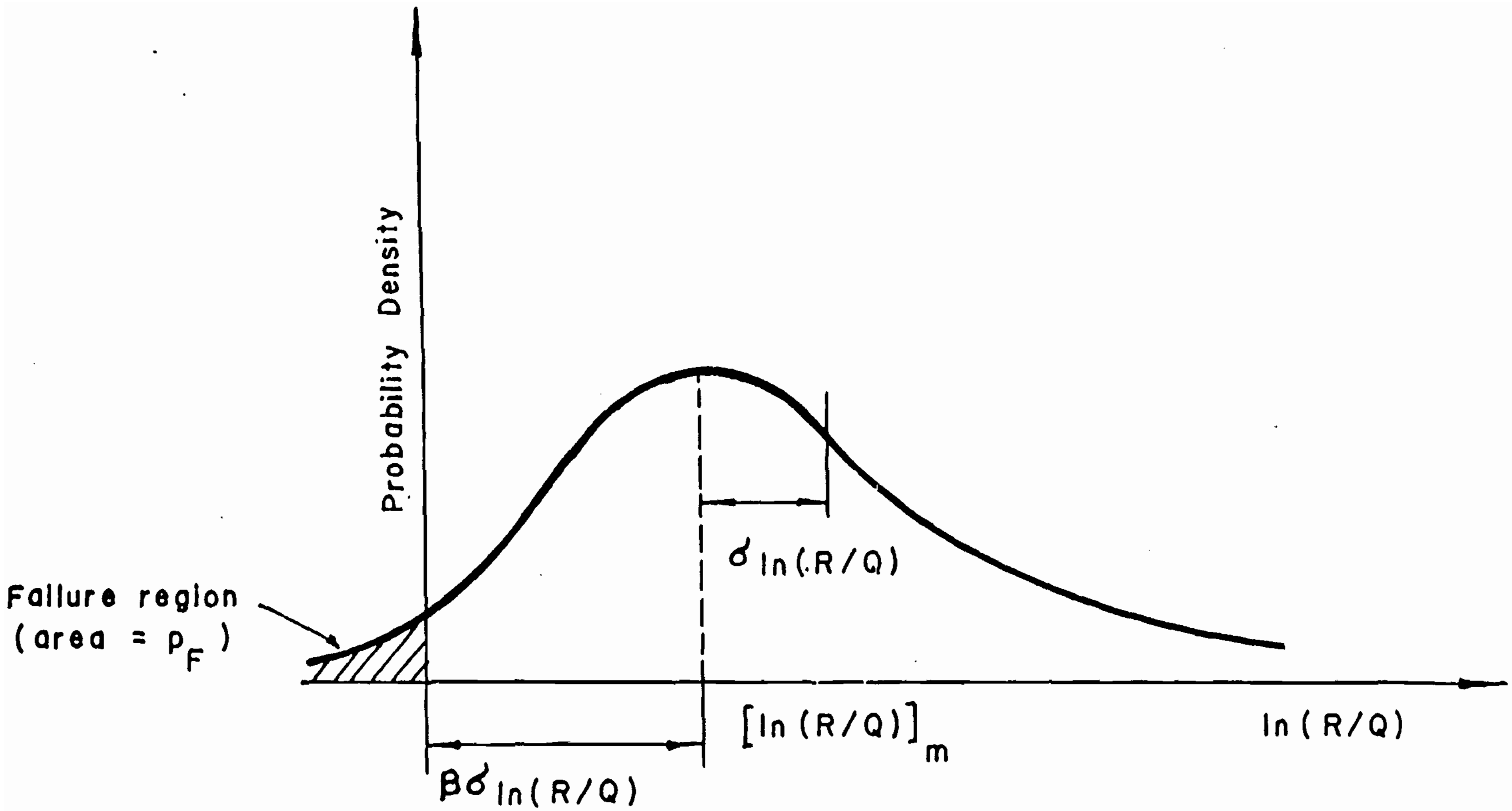
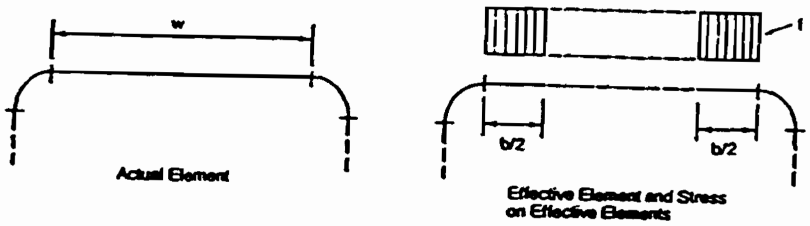
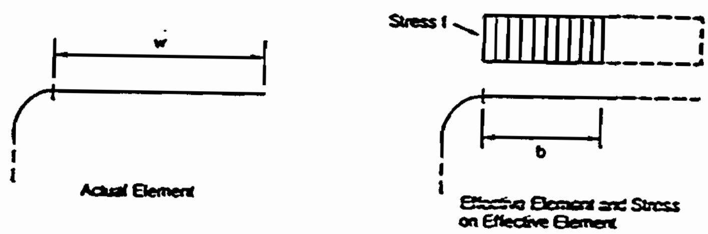


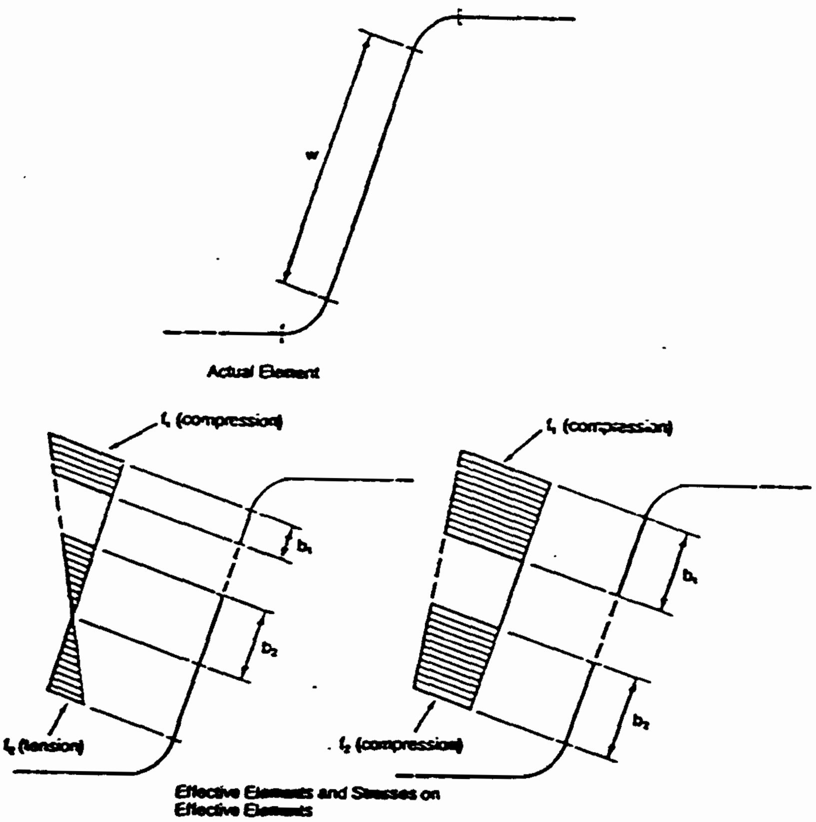
Fig. 2 Probability Distribution of ln(R/Q)[15]



a. Stiffened Elements with Uniform Compression

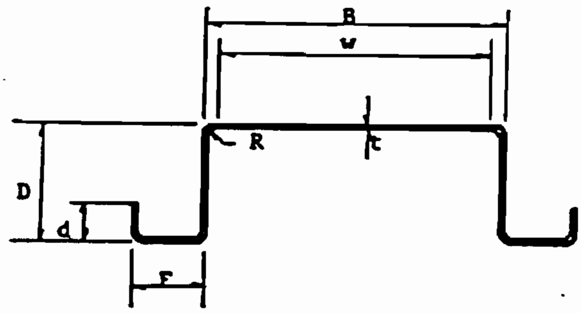


b. Unstiffened Elements with Uniform Compression

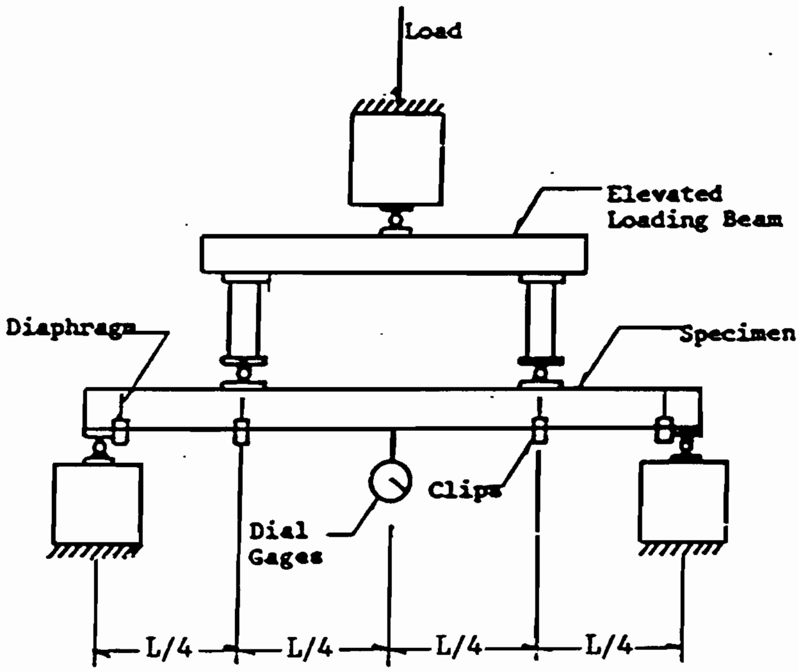


c. Stiffened Elements with Stress Gradient and Webs

Fig. 3 Effective Widths of Stiffened and Unstiffened Elements



a. Cross-Section of Beam Specimens



b. Test Setup

Fig. 4 Beam Specimens and Test Setup [25]

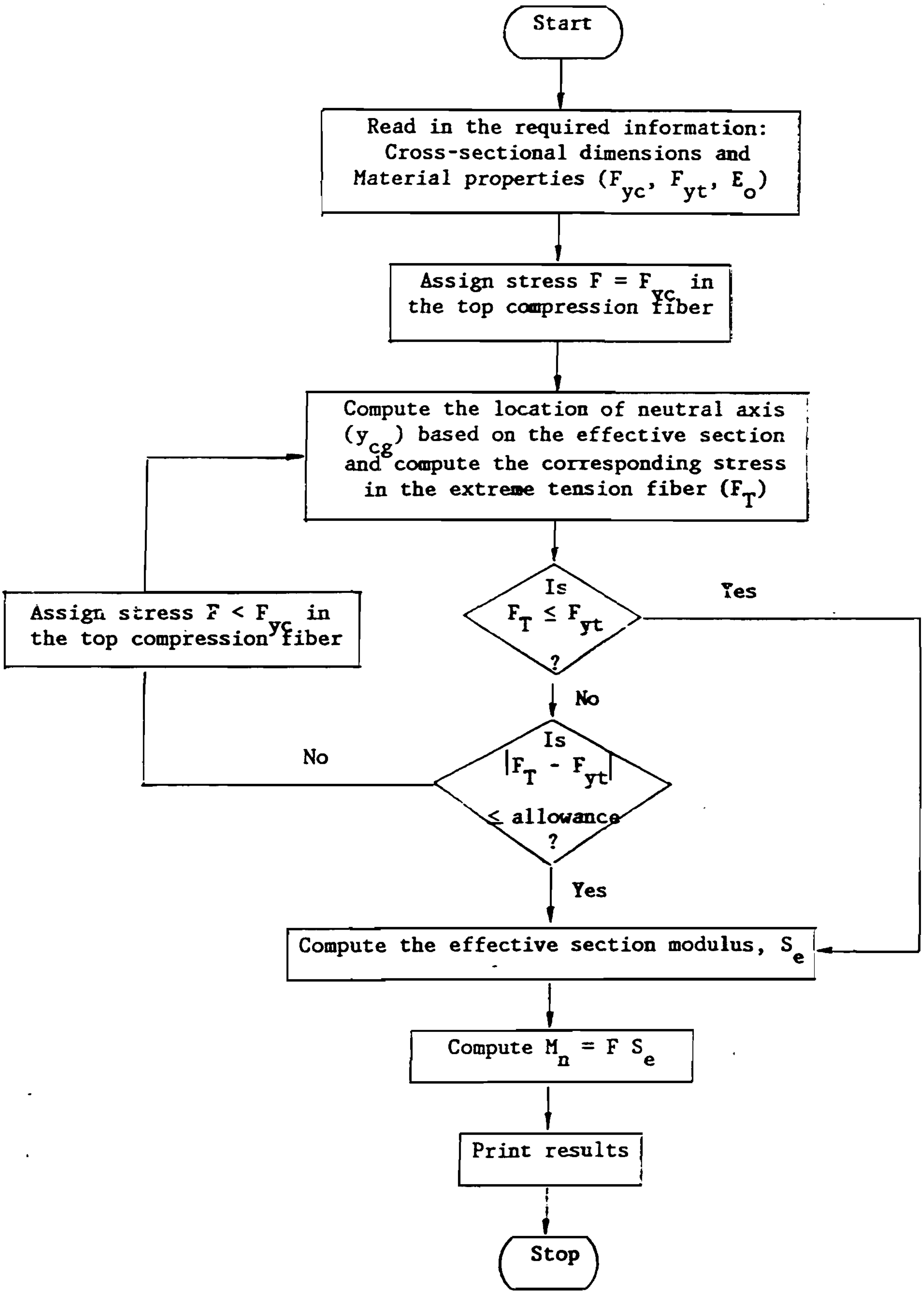
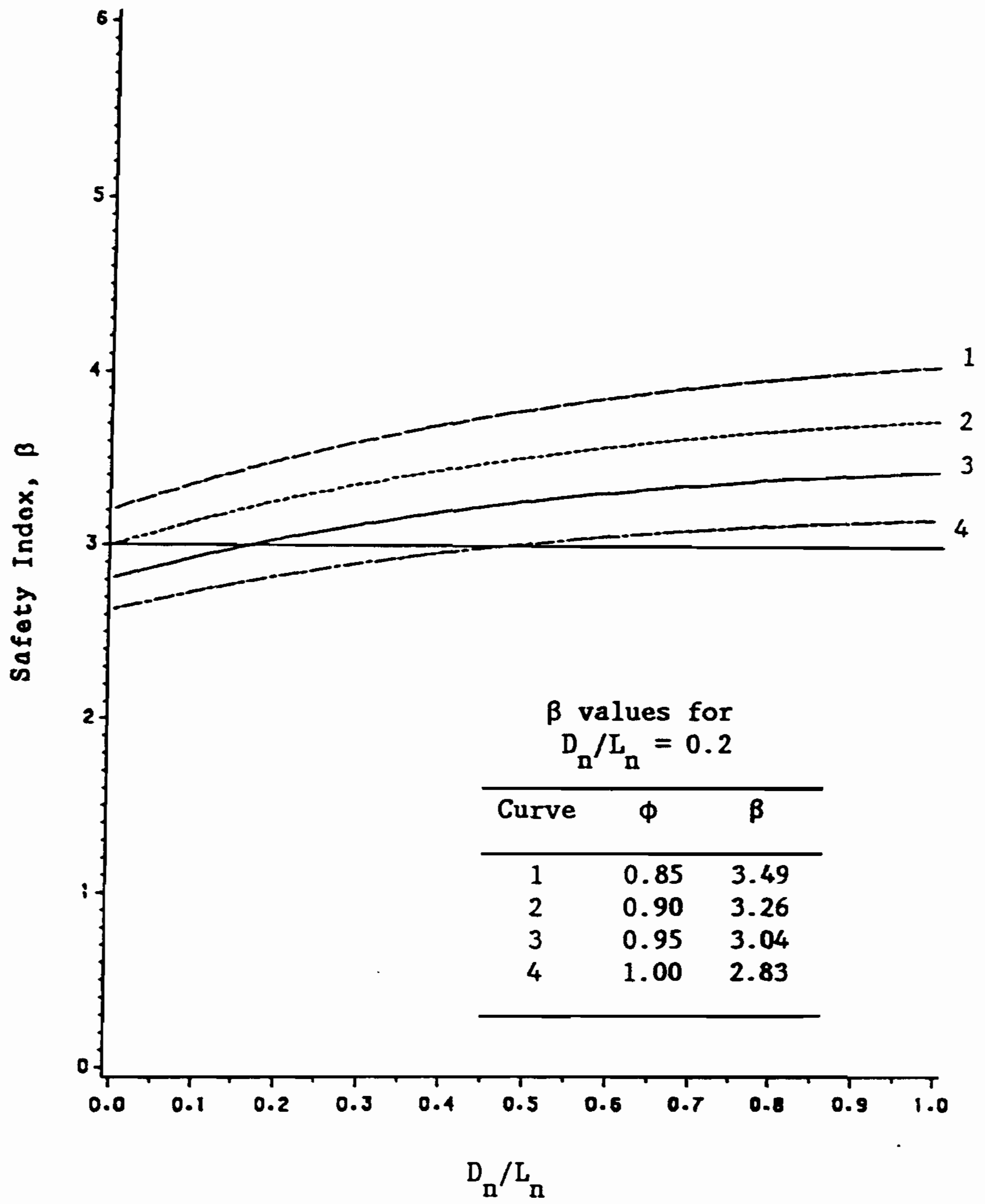
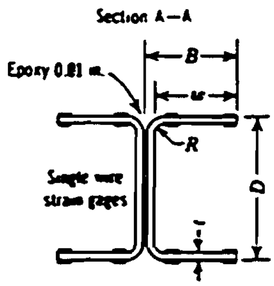


Fig. 5 Flow Chart for Determining Nominal Moment Based on Initiation of Yielding

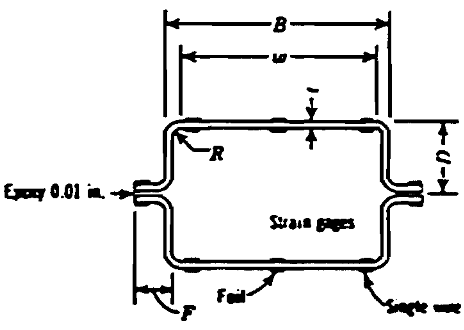


Curve	φ	β
1	0.85	3.49
2	0.90	3.26
3	0.95	3.04
4	1.00	2.83

Fig. 6 Safety Indices, β, for Different Resistance Factors, φ, and D_n/L_n Ratios for Stainless Steel Beams

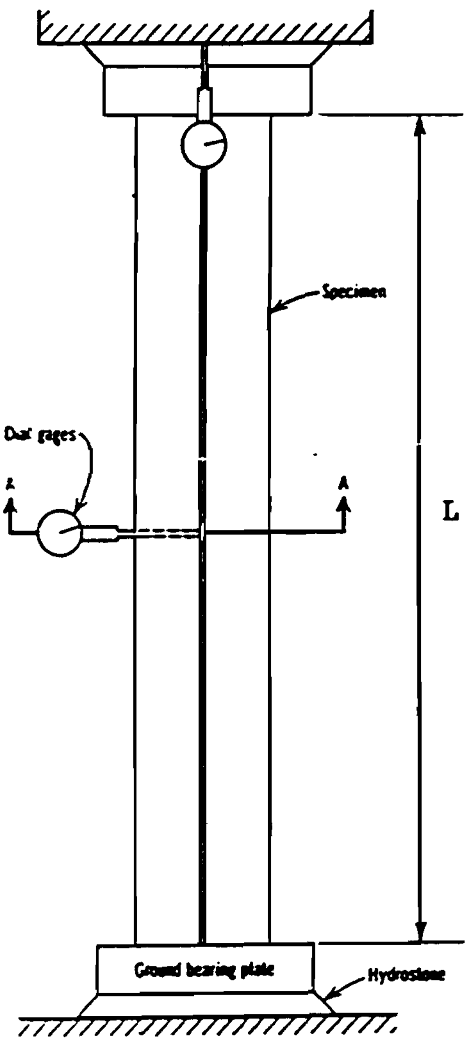


Series UFC and H301UE



Series H301SC

a. Cross-Sections of Stub Column Specimens



b. Test Setup

Fig. 7 Specimens and Test Setup Used for Stub Column Tests

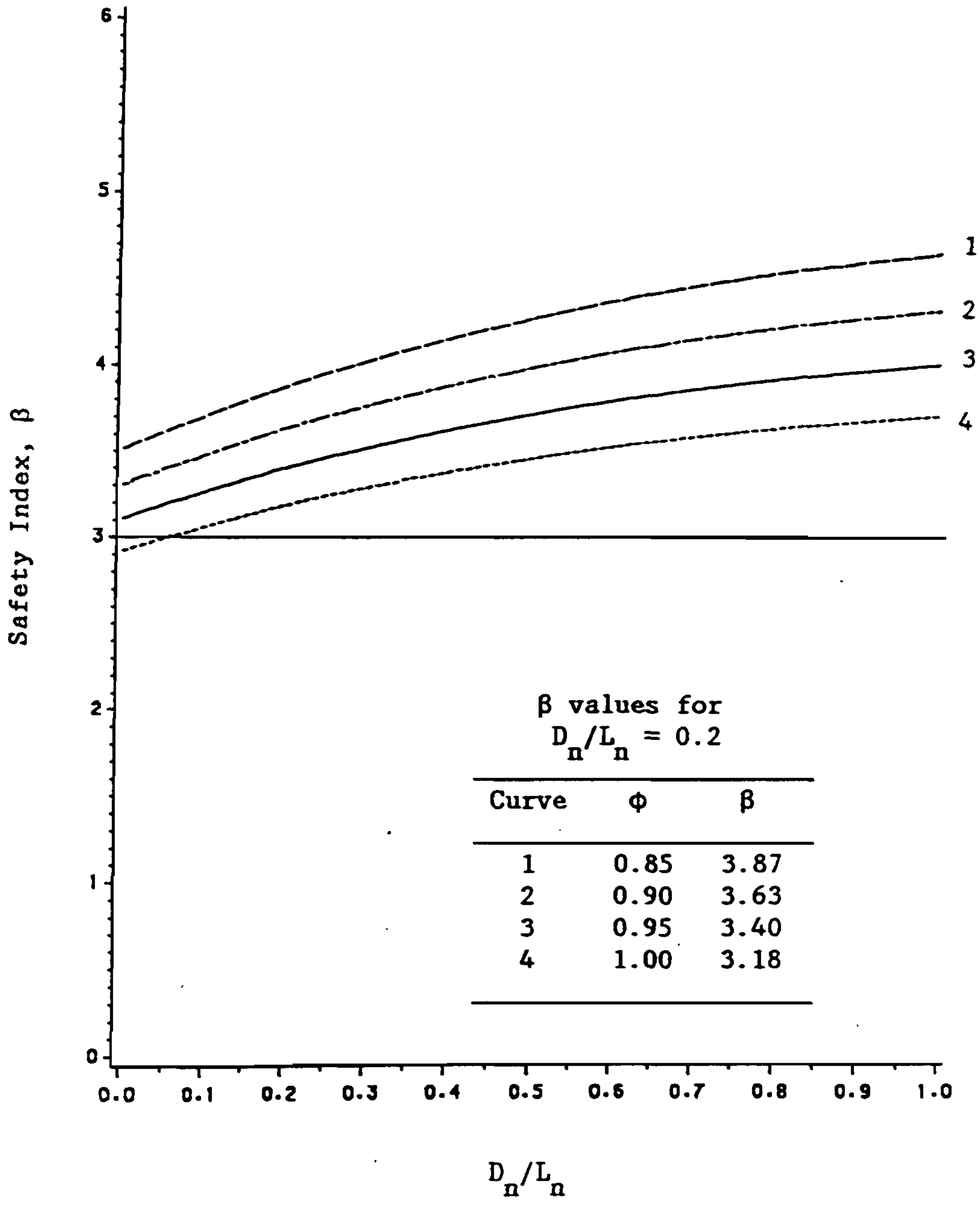
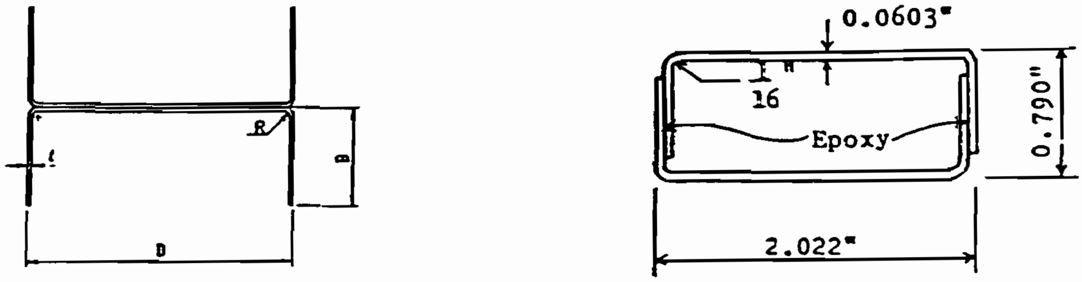
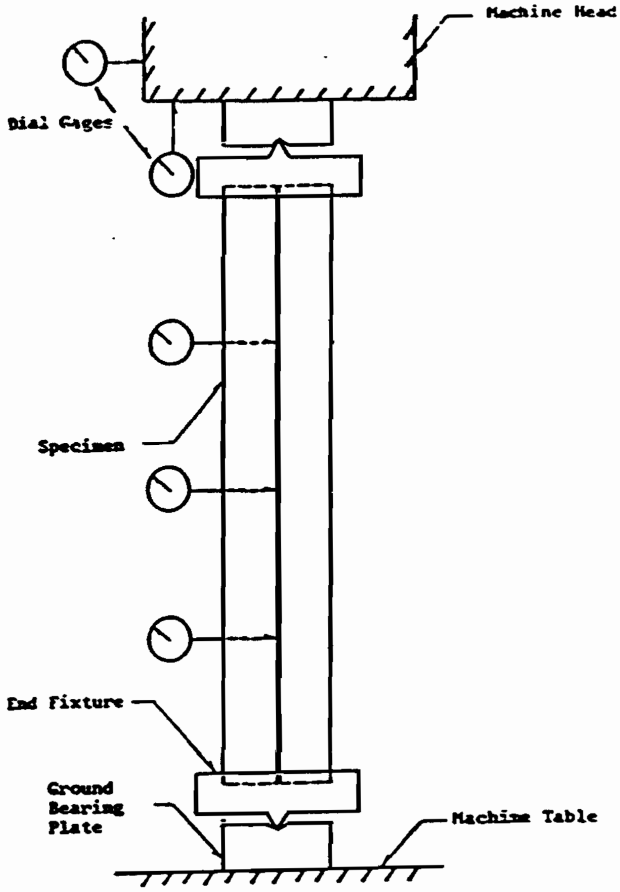


Fig. 8 Safety Indices, β, for Different Resistance Factors, φ, and D_n/L_n Ratios for Stainless Steel Stub Columns



a. I-Section and Box Section



b. Test Setup

Fig. 9 Specimens and Test Setup Used for Flexural Column Buckling Tests

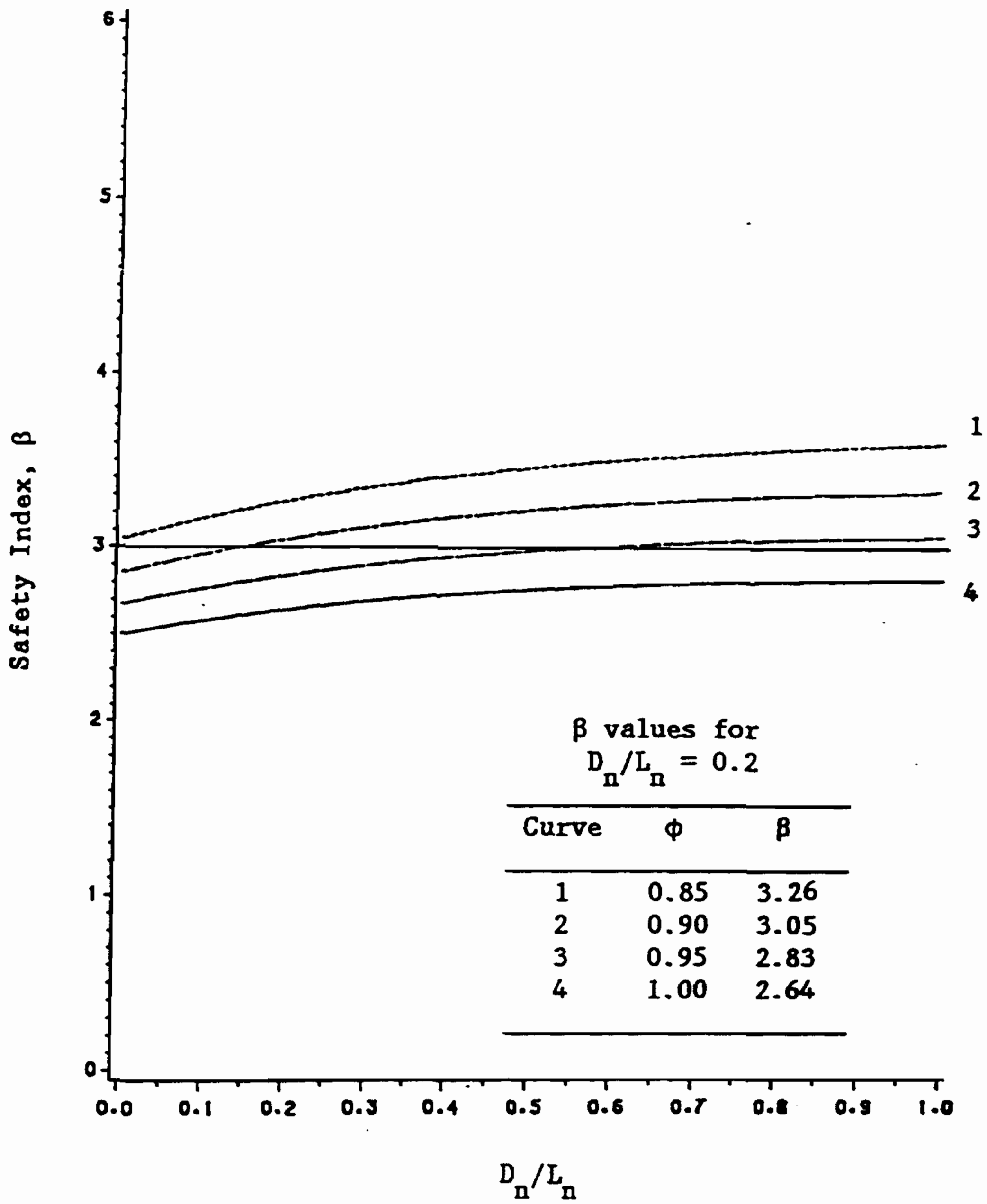
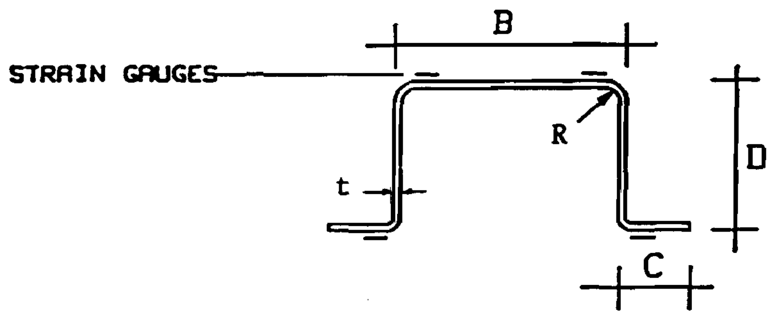
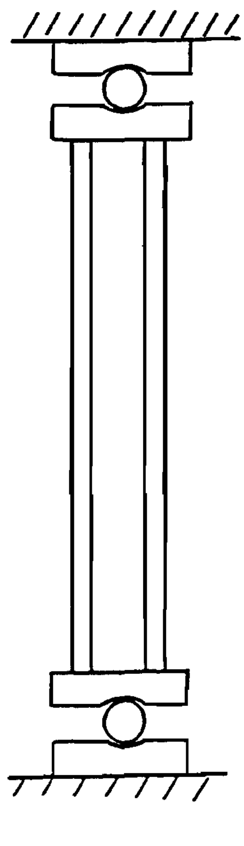


Fig. 10 Safety Indices, β, for Different Resistance Factors, φ, and D_n/L_n Ratios for Stainless Steel Columns Subjected to Flexural Buckling



a. Hat Section



b. Test Setup

Fig. 11 Hat Section and Test Setup Used in Reference 50

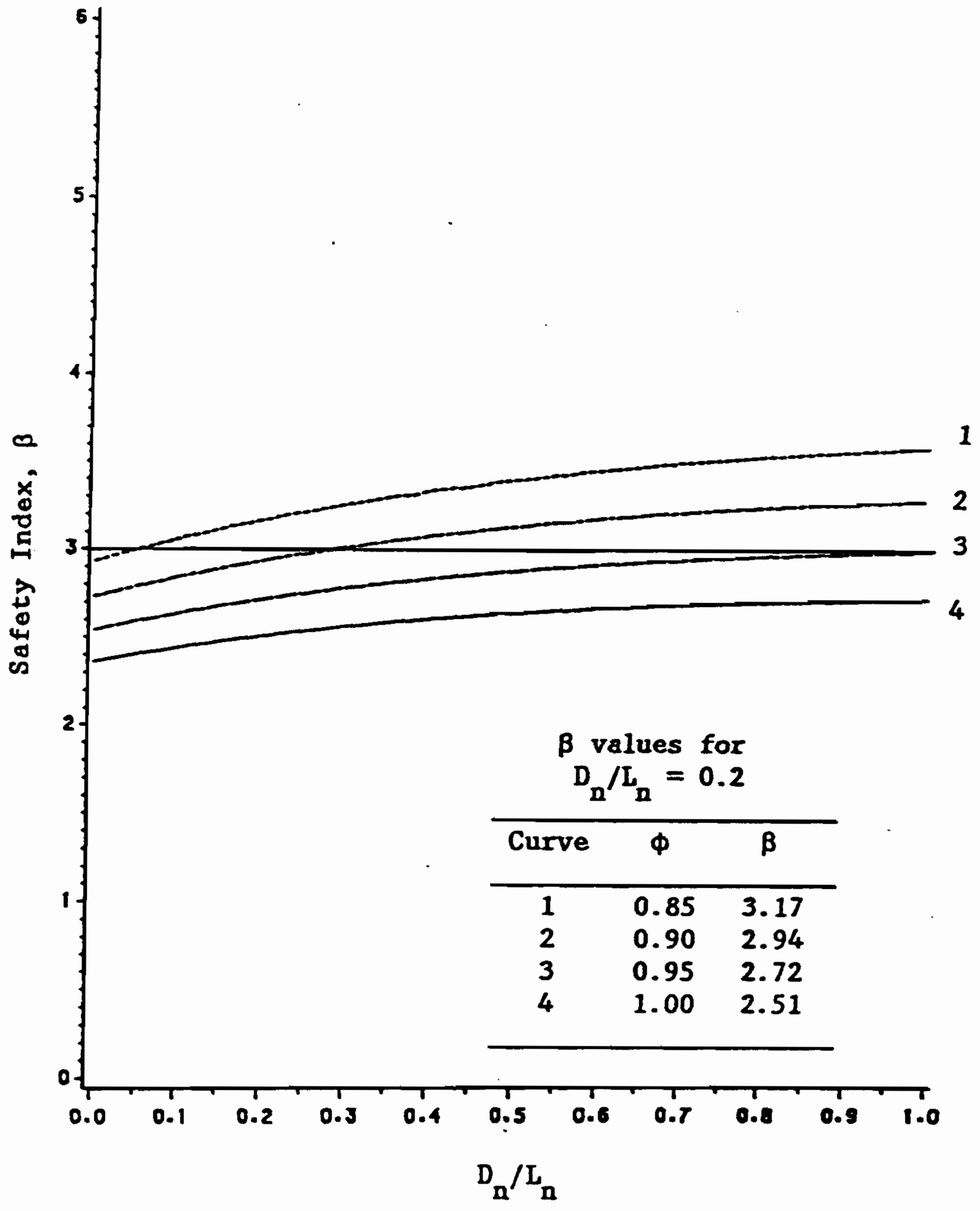
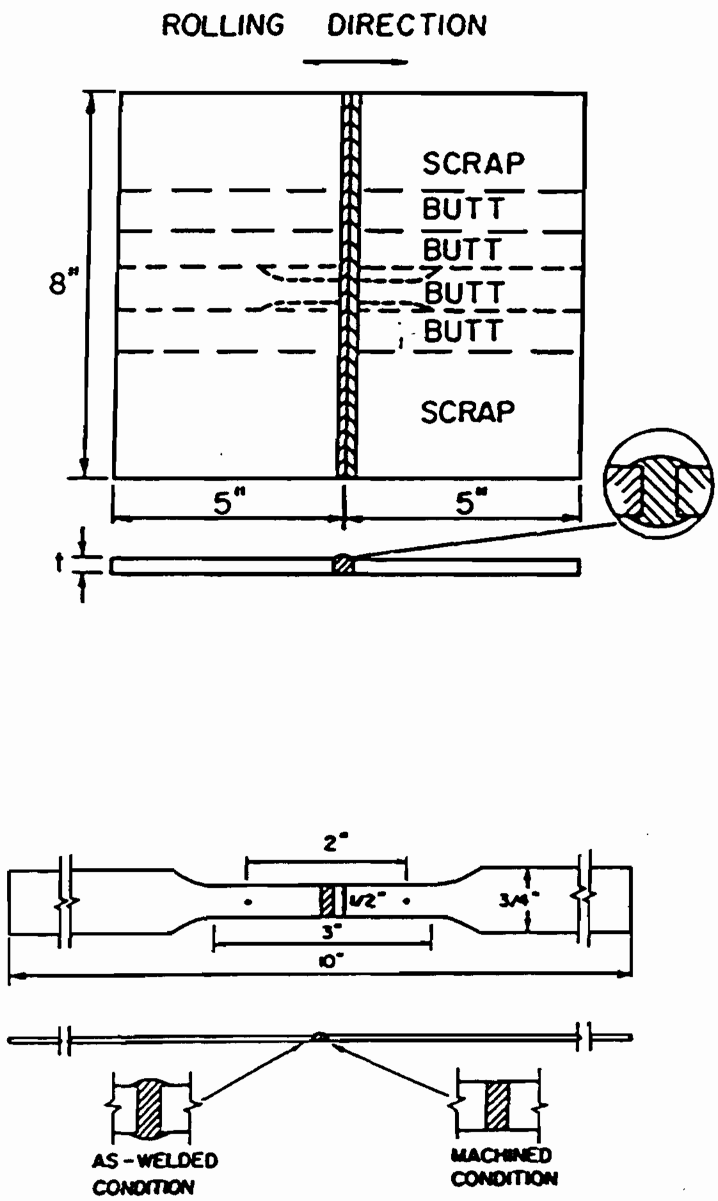


Fig. 12 Safety Indices, β, for Different Resistance Factors, φ, and D_n/L_n Ratios for Stainless Steel Columns Subjected to Torsional-Flexural Buckling



27

Fig. 13 Typical Groove Welded Specimens

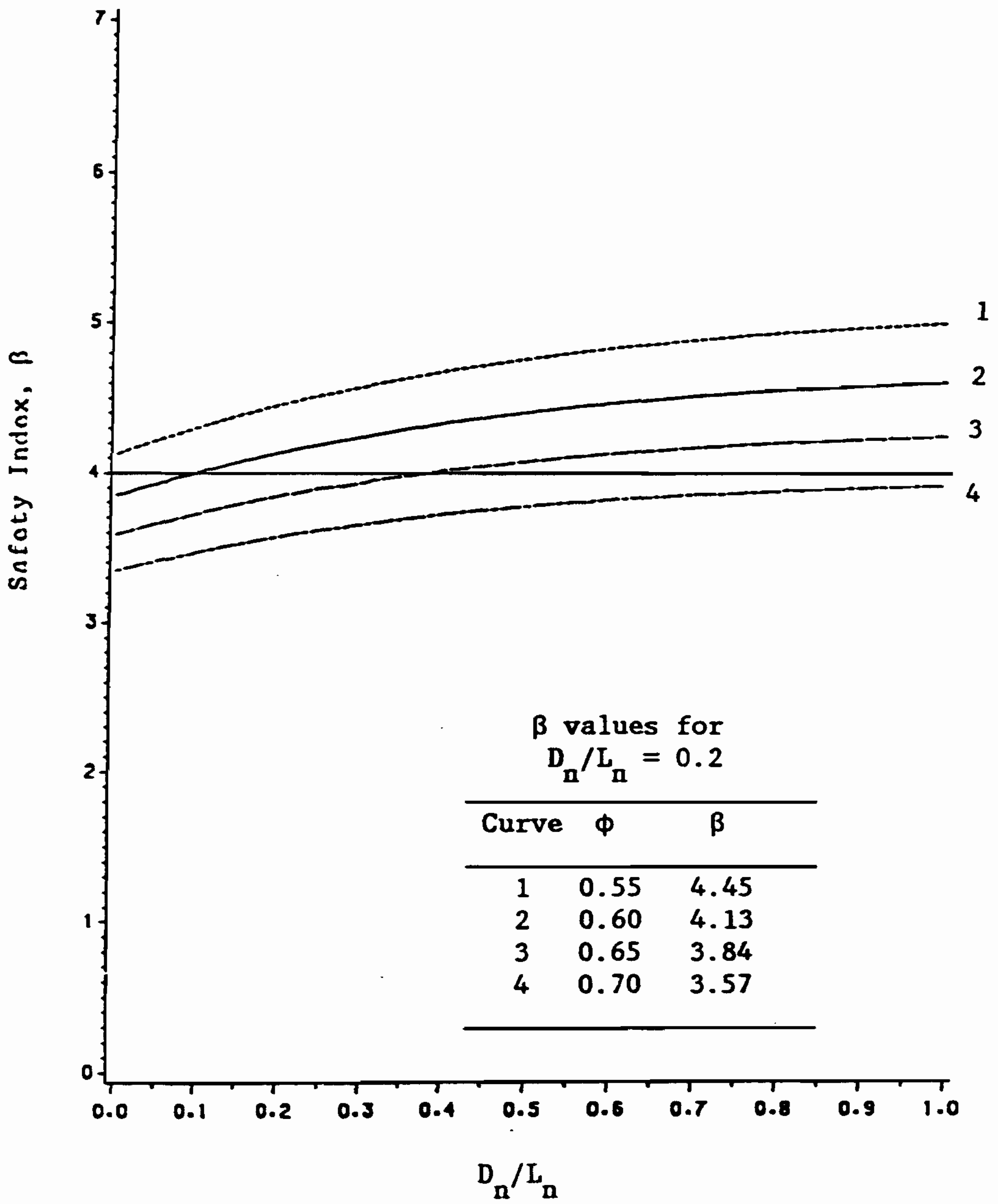
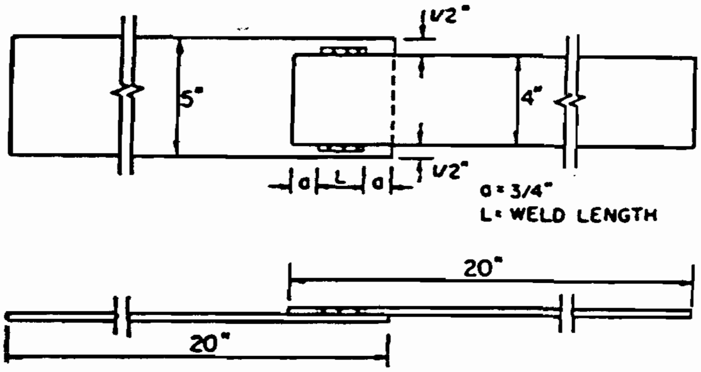
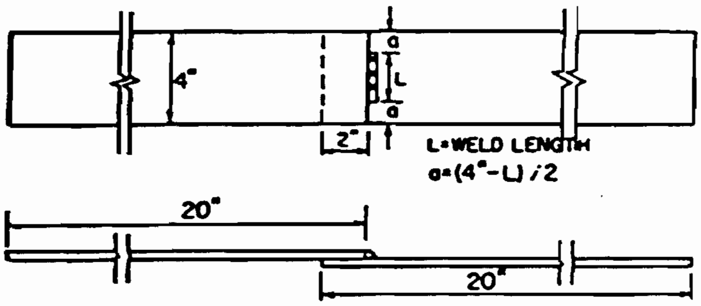


Fig. 14 Safety Indices, β, for Different Resistance Factors, φ, and D_n/L_n Ratios for Groove Welds



a. Longitudinal Fillet Welds



b. Transverse Fillet Welds

Fig. 15 Connections Using Fillet Welds

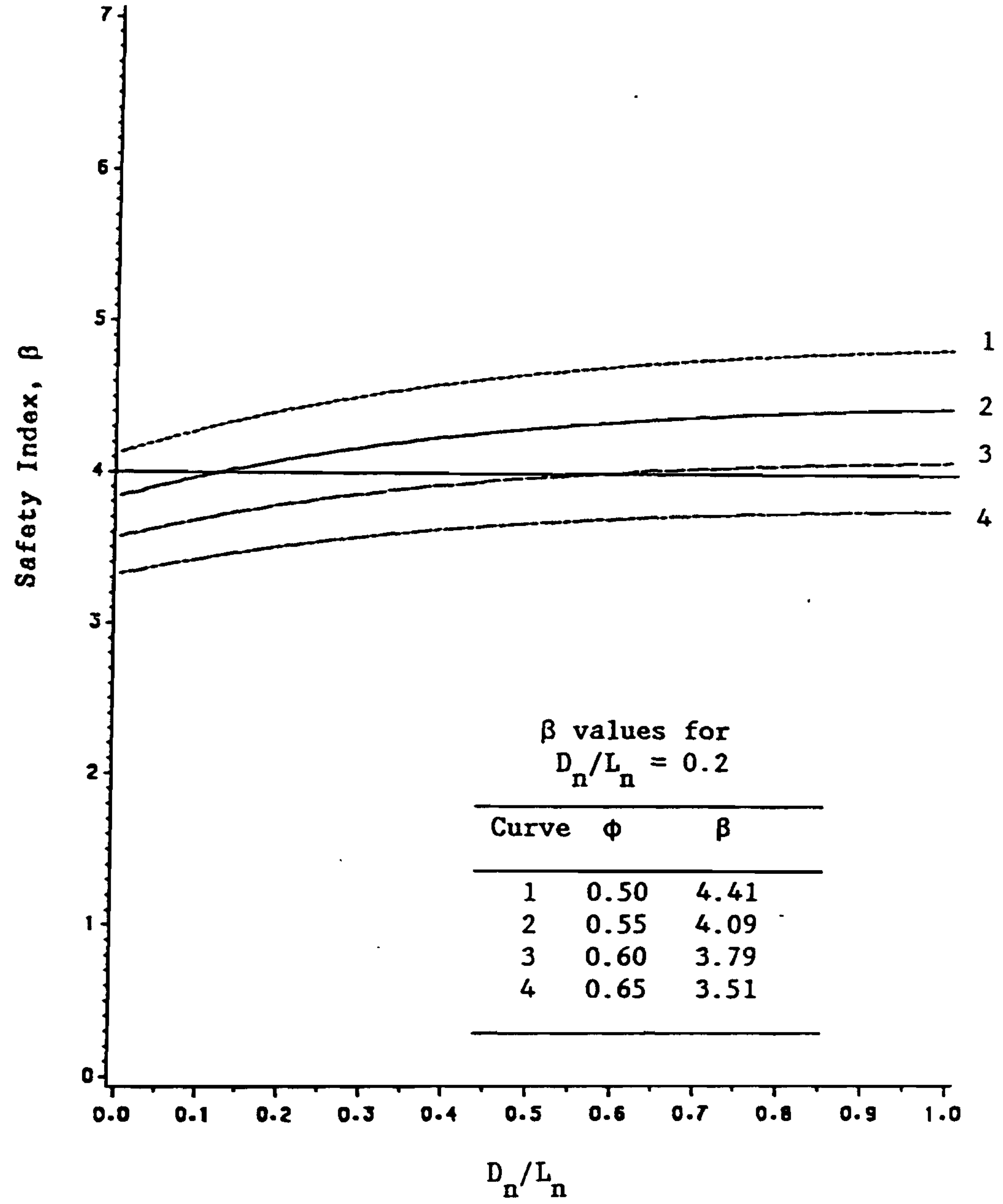
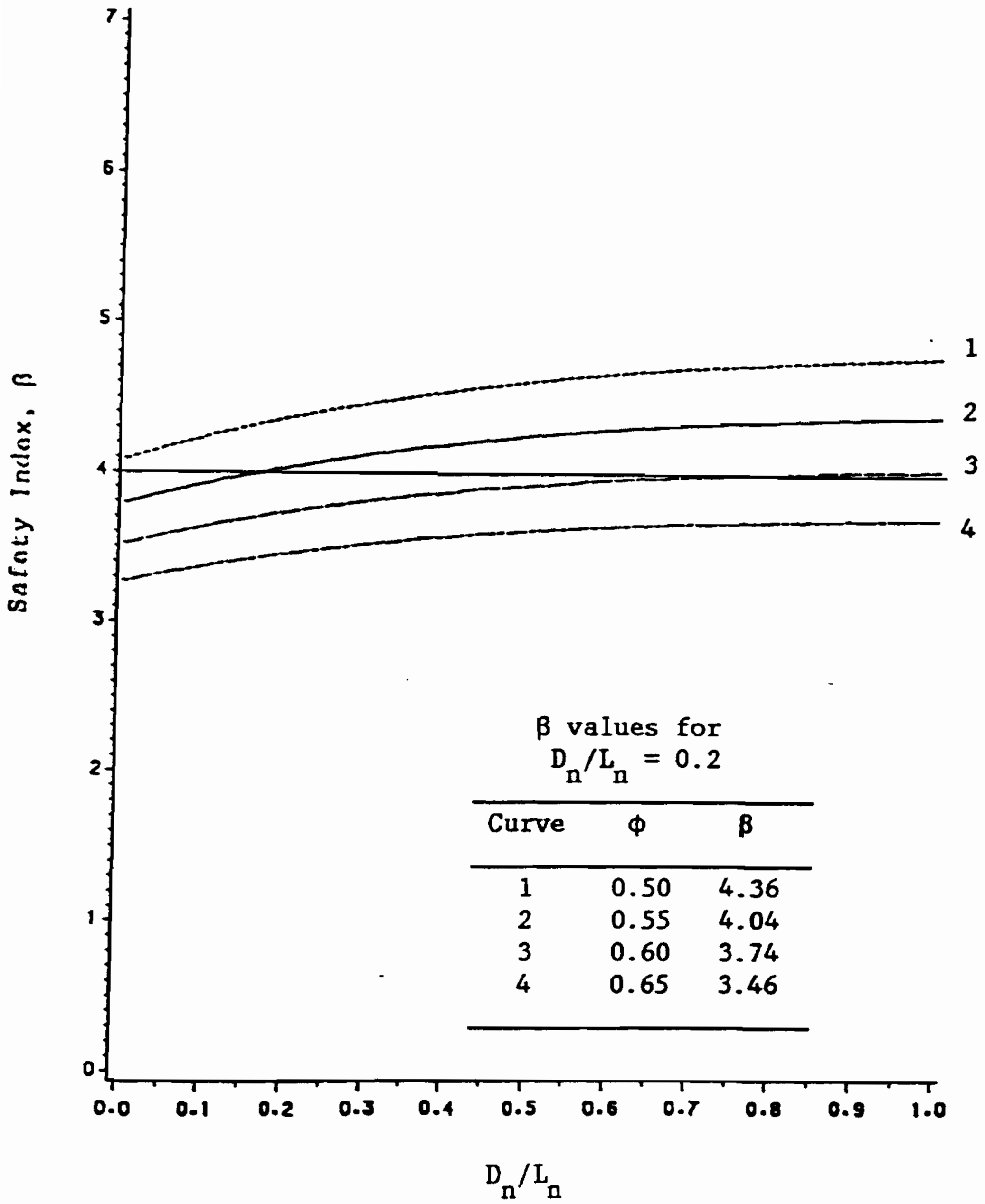


Fig. 16 Safety Indices, β, for Different Resistance Factors, Φ, and

D_n/L_n Ratios for Plate Failure of Longitudinal Fillet Welds



Curve	φ	β
1	0.50	4.36
2	0.55	4.04
3	0.60	3.74
4	0.65	3.46

Fig. 17 Safety Indices, β, for Different Resistance Factors, φ, and D_n/L_n Ratios for Weld Failure of Longitudinal Fillet Welds

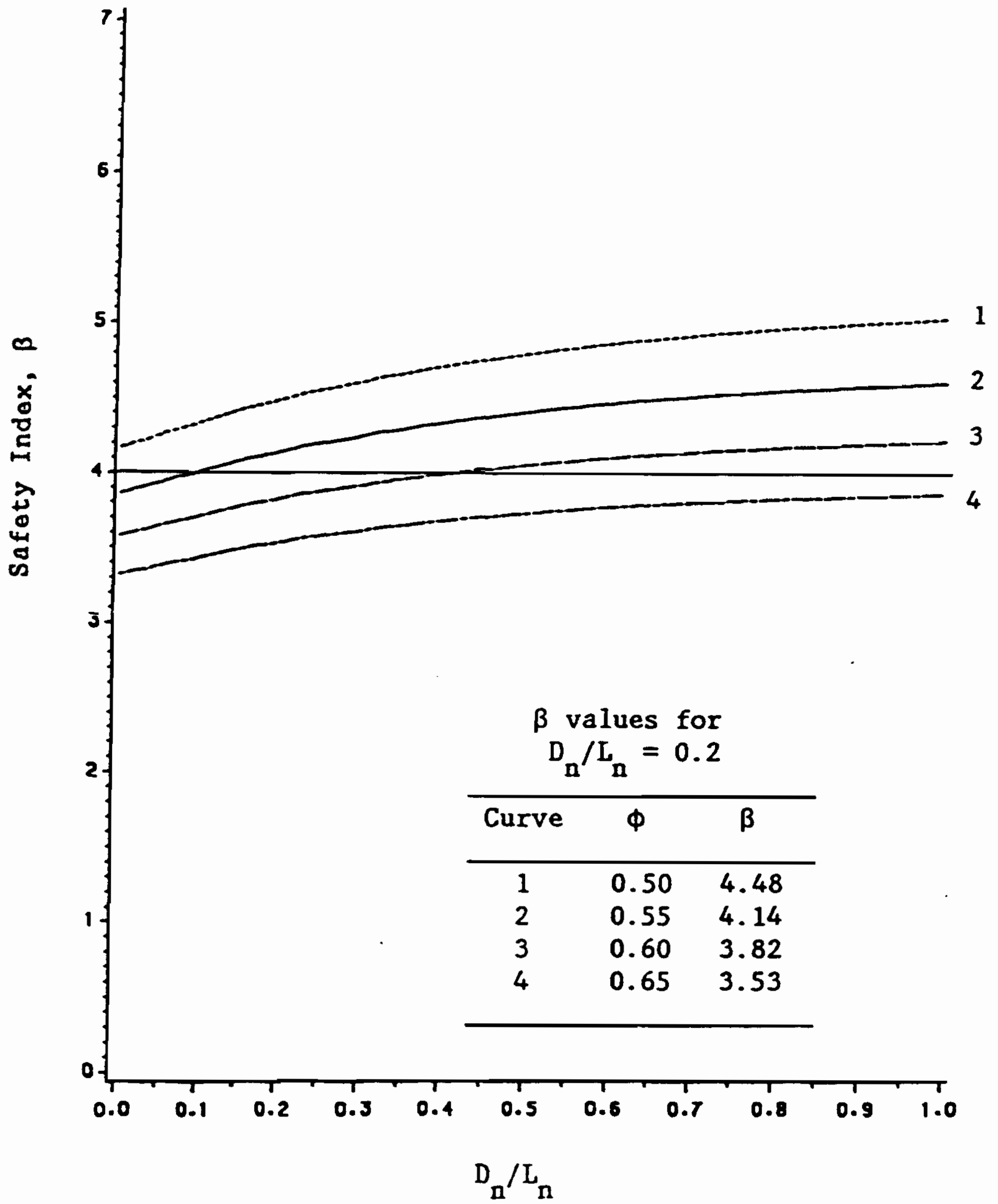


Fig. 18 Safety Indices, β, for Different Resistance Factors, Φ, and

D_n/L_n Ratios for Plate Failure of Transverse Fillet Welds

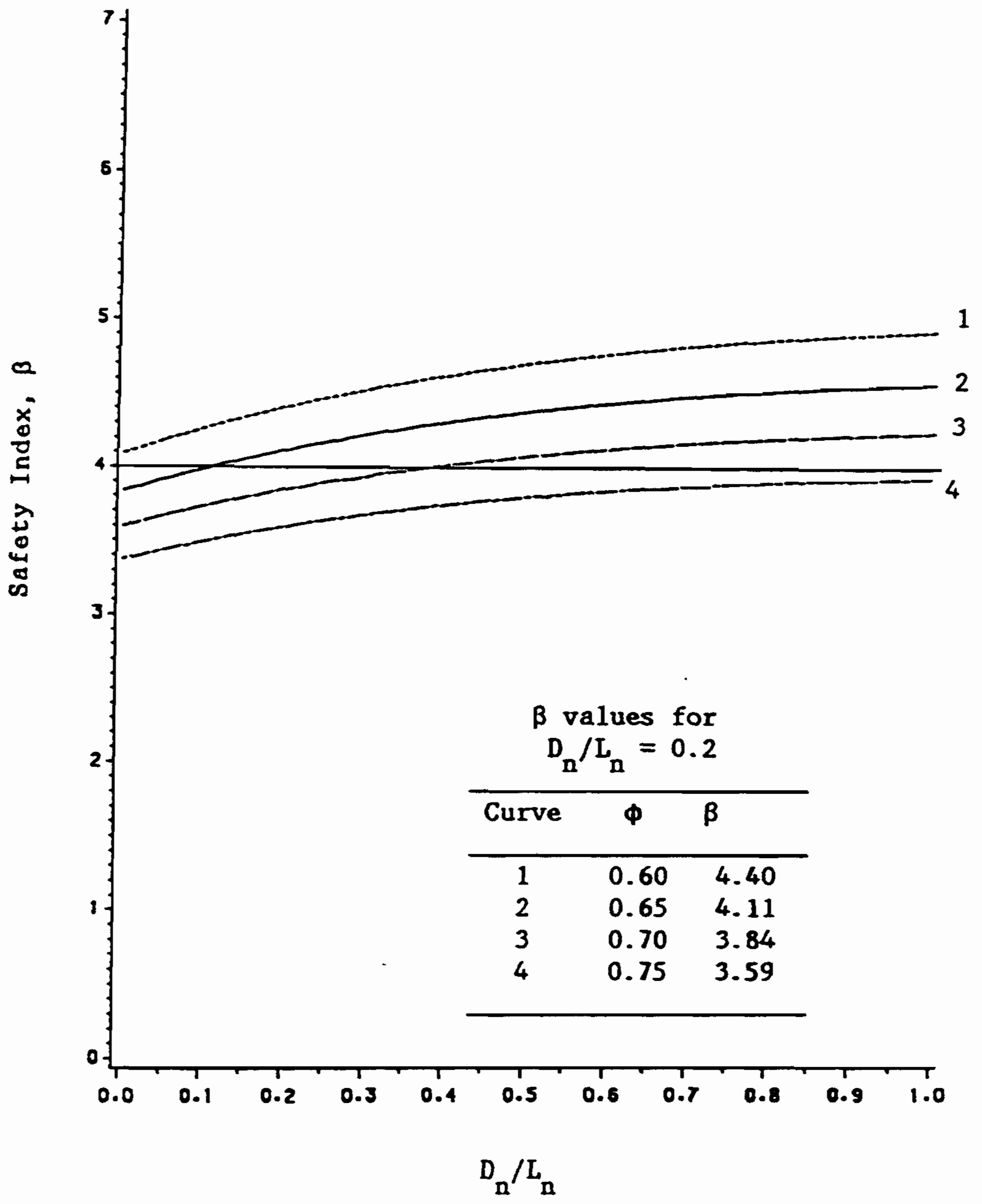
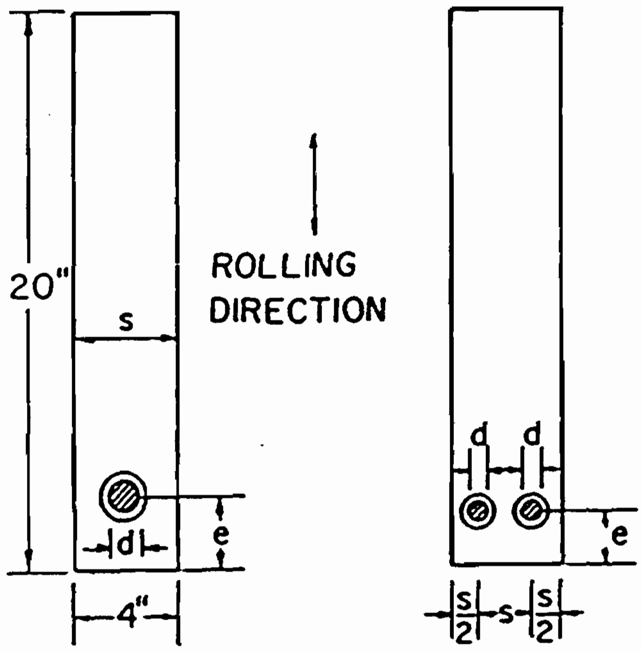
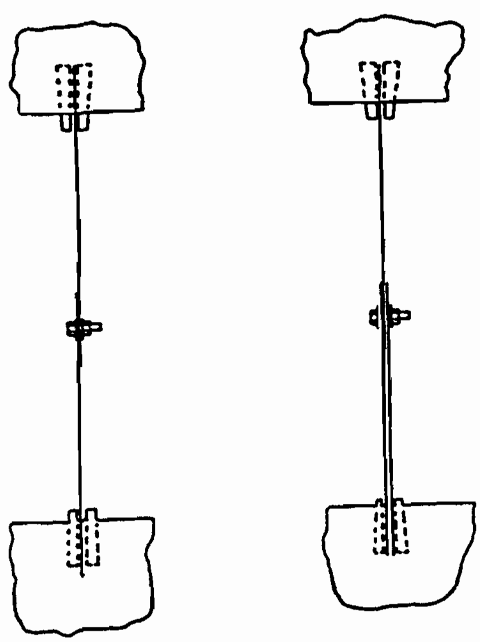


Fig. 19 Safety Indices, β, for Different Resistance Factors, φ, and D_n/L_n Ratios for Weld Failure of Transverse Fillet Welds



a. Typical Test Blanks with One or Two Bolts



Single Shear (SS)   Double Shear (DS)

b. Types of Connections

27

Fig. 20 Test Specimens Used for Bolted Connections

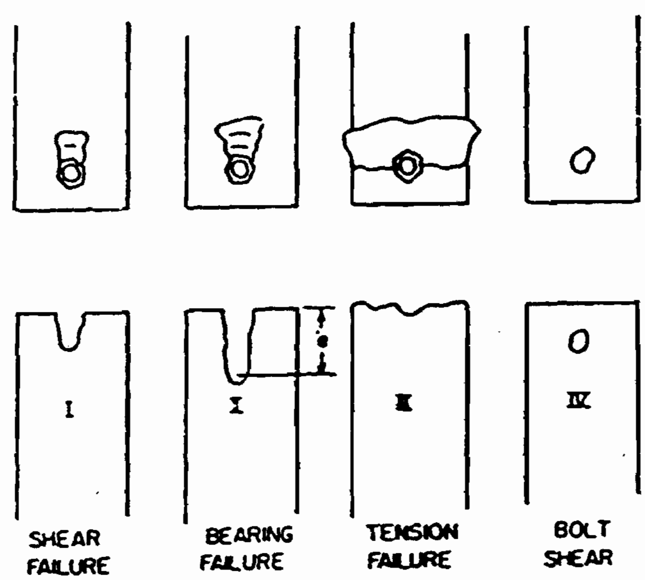
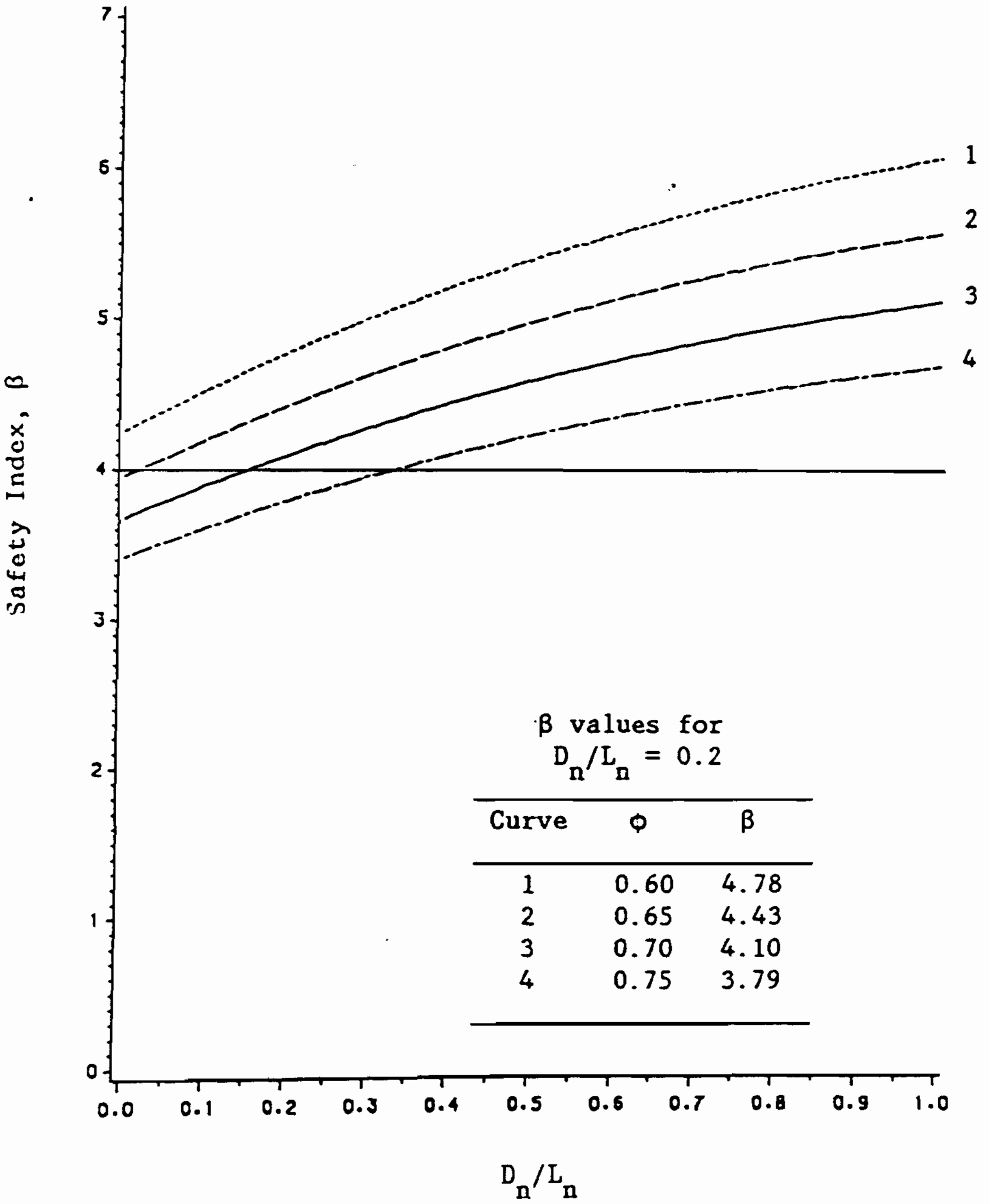


Fig. 21 Types of Failure Modes for Bolted Connections [27]



Curve	φ	β
1	0.60	4.78
2	0.65	4.43
3	0.70	4.10
4	0.75	3.79

Fig. 22 Safety Indices, β, for Different Resistance Factors, φ, and D_n/L_n Ratios for Shear Strength Study of Bolted Connections

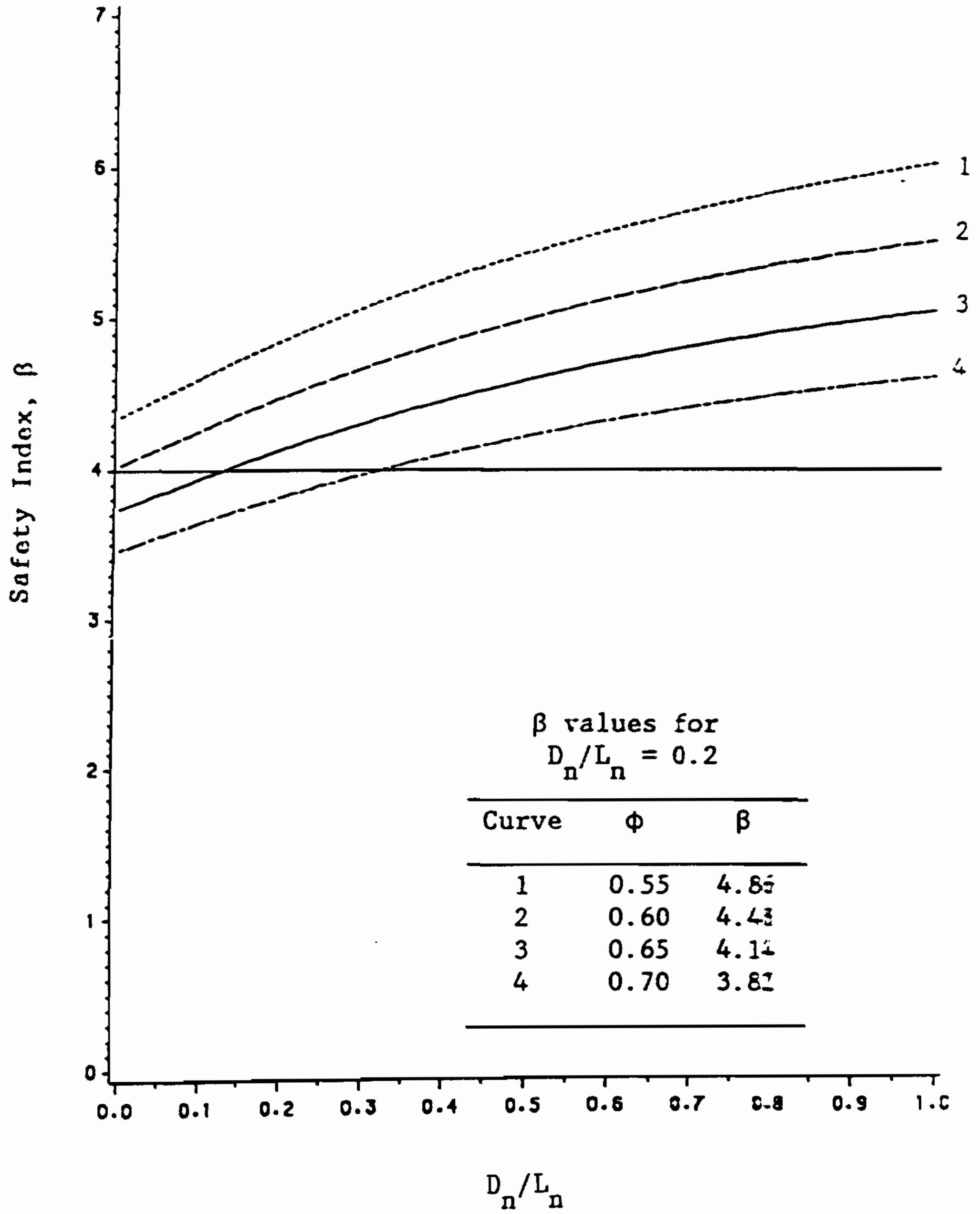


Fig. 23 Safety Indices, β, for Different Resistance Factors, Φ, and D_n/L_n Ratios for Bearing Strength Study of Bolted Connections

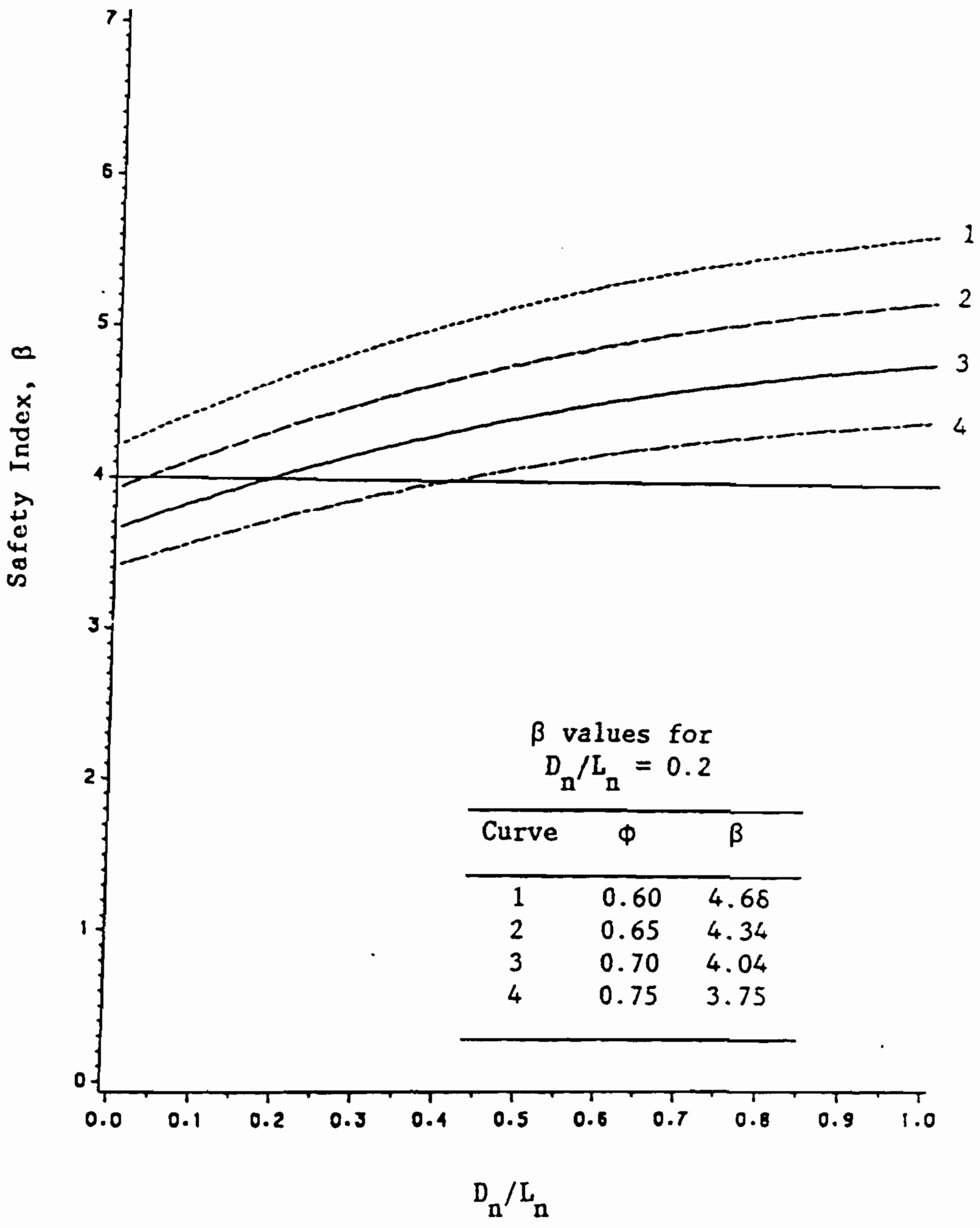
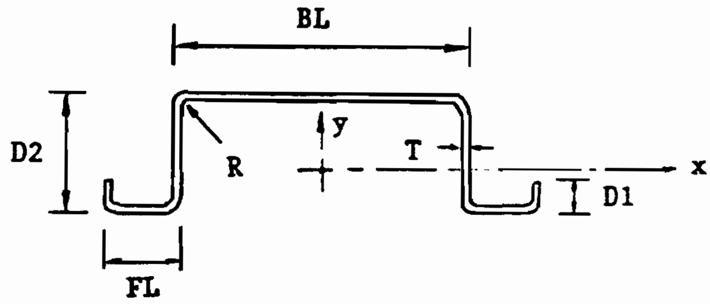
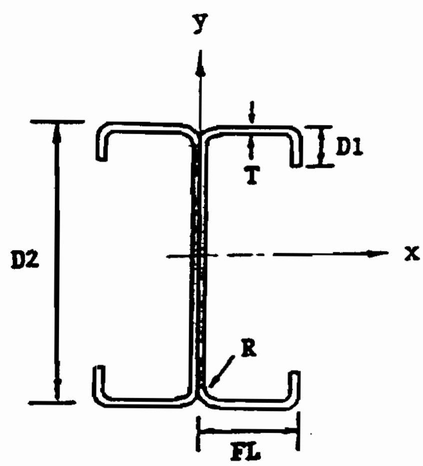


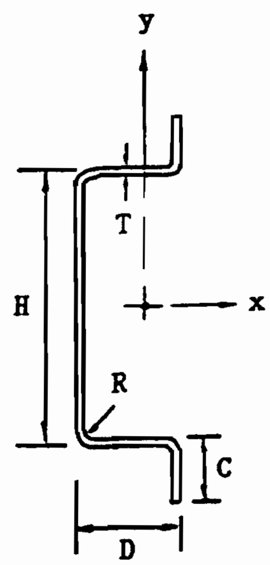
Fig. 24 Safety Indices, β, for Different Resistance Factors, ϕ, and D_n/L_n Ratios for Tensile Strength Study of Bolted Connections



a. **Hat Section with Lips**



b. **I-Section with Lips**



c. **Hat Section without Lips**

Fig. 25 Cross-Sectional Dimensions Used as Input Variables in Computer Programs