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COMPARATIVE STUDY OF LOAD AND RESISTANCE FACTOR DESIGN VERSUS ALLOWABLE STRESS DESIGN

by

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INTRODUCTION

The 1980 Edition of the American Iron and Steel Institute (AISI) Specification for the Design of Cold-Formed Steel Structural Members (Ref. 1) provides design formulas for determining allowable stresses or allowable loads for structural members and connections. In allowable stress design, the actual stresses are computed from service loads that include dead, live, snow, wind, and/or earthquake loads. The allowable stresses or allowable loads are based on appropriate factors of safety recommended by AISI for different types of structural members.

Recently, the proposed load and resistance factor design (LRFD) criteria for hot-rolled steel members and connections (Ref. 2) have been developed using probabilistic and statistical techniques to account for the uncertainties in design, fabrication, material properties, and applied loads. For cold-formed steel structural members, the load and resistance factor design method has been studied under a joint research project entitled "Load and Resistance Factor Design of Cold-Formed Steel" conducted at the University of Missouri-Rolla and Washington University (Refs. 3-10). Subsequently, the tentative recommendation on the LRFD criteria were recommended in Ref. 9. In this method, load factors are applied to the external load and resistance factors are applied to the internal resistance capacities of the structure.

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The primary purpose of this investigation was to study and compare the proposed tentative recommendations on the load and resistance factor design criteria for cold-formed steel (Ref. 9) with the existing allowable stress design (ASD) criteria which are included in the 1980 Edition of the AISI Specification for the Design of Cold-Formed Steel Structural Members (Ref. 1).

LOAD AND RESISTANCE FACTOR DESIGN

The proposed recommendations on the load and resistance factor design criteria for cold-formed steel (Ref. 9) are based on the first-order principles of probabilistic theory. The general format for the LRFD criteria is as follows:

$$\phi R_n \geq \sum_{k=1}^{j} \gamma_k Q_{kn} \qquad (1)$$

where ϕ = resistance factor

R_n = nominal resistance

γ_k = load factor

Q_{kn} = nominal load effect

On the left side of Eq. (1), the resistance factor, ϕ, is a nondimensional factor less than or equal to 1.0 that accounts for the uncertainties in calculating the nominal resistance. The nominal resistance of the structure is the predicted ultimate resistance or load determined from design formulas using specified mechanical properties of material and section properties.

On the right side of the equation, factor γ is a nondimensional load factor used to reflect the possibility of overloads and uncertainties in computing the load effects. Each load factor applies to a nominal load effect Q_n and the subscript k corresponds to different types of loads. Only dead and live load effects were used to develop the LRFD criteria for cold-formed steel and to compare these two design methods.

COMPARISON

The design equation for the LRFD crtieria based on dead and live loads is as follows:

$$\phi R_n \geq 1.2D_n + 1.6L_n \qquad (2)$$

where D_n = nominal dead load

L_n = nominal live load

For the purpose of comparison, the unfactored load combination ($D_n + L_n$) or allowable load can be computed from the nominal resistance R_n, the resistance factor ϕ, and a given D_n/L_n ratio as follows:

$$\phi R_n \geq (1.2\,D_n/L_n + 1.6)L_n$$

$$\phi R_n \geq (1.2\,D_n/L_n + 1.6)[(D_n+L_n)/(D_n/L_n+1)]$$

Therefore,

$$D_n + L_n \geq \frac{R_n}{(1.2D_n/L_n + 1.6)/[\phi(D_n/L_n + 1)]} \qquad (3)$$

From Eq. (3), the factor of safety against the nominal resistance used in the LRFD criteria is as follows:

$$(\text{F.S.})_{\text{LRFD}} = \frac{1.2D_n/L_n + 1.6}{\phi(D_n/L_n + 1)} \qquad (4)$$

The allowable load for ASD is based on a factor of safety of the nominal resistance as shown in Eq. (5).

$$D_n + L_n \leq \frac{R_n}{(\text{F.S.})_{\text{ASD}}} \qquad (5)$$

Therefore, based on Eqs. (3) and (5), the allowable load ratio is as follows:

$$\frac{(P_a)_{\text{LRFD}}}{(P_a)_{\text{ASD}}} = \phi\,(\text{F.S.})_{\text{ASD}}\,\frac{D_n/L_n + 1}{1.2D_n/L_n + 1.6} \qquad (6)$$

Equation (6) was used in this study to compare the AISI Specification (Ref. 1) for allowable stress design and the proposed recommendations on the LRFD criteria (Ref. 9). This equation would only be applicable to structural members with one type of load. It does not apply to the combined bending and shear, combined bending and web crippling, and beam-column criteria where design formulas are interaction equations. Tables 1 and 2 list the ASD safety factors, the LRFD resistance factors, and the allowable load ratios for D/L = 1/3 for structural members and connections, respectively. Figure 1 shows a graph of the allowable load ratio versus dead-to-live ratio for tension members and flexural members. Curves for other structural members or connections listed in Tables 1 or 2 would be similar except that they would be shifted up or down depending on the design factors listed. As shown in the figure and tables, the LRFD criteria is slightly conservative for dead-to-live load ratios less than 1/3.

COMBINED LOADS

When a structural members has to be designed for a combination of loads or load effects, an interaction equation is used in both the AISI Specification (Ref. 1) and the Tentative Recommendations for LRFD (Ref. 9). Due to the complexity of the design equations for combined loads, specific examples were chosen for comparison.

For combined bending and shear design of webs, different examples were investigated varying the thickness, yield strength, and depth of the beams. The load case chosen was a uniformly loaded three span continuous beam. The allowable load ratio versus dead-to-live load ratio curves were all within 2% of the curve shown in Figure 1.

For combined bending and web crippling design, the same procedure was used but only a simple beam with a concentrated load at midspan was investigated. Figures 2 through 5 show typical allowable load ratio curves for specific examples. Unlike combined bending and shear, bending and web crippling results in a wide range of allowable load ratios for a given dead-to-live load ratio. Figures 3 and 5 show a decrease in allowable load ratio with increasing span length for this example.

For comparison of doubly-symmetric beam-columns, only bending about the y-axis was considered. A typical design example was a beam-column with equal moments applied to each end so that the member was bent in single curvature. Since the end moments are independent of the axial load, the ratio of the unfactored applied moment to the ultimate moment capacity based on section strength, M_T/M_{us}, was considered to be a parameter. The solution of the interaction equations for flexural failure at midlength which includes the effects of secondary moments required a computer program to calculate allowable axial loads for various lengths, end moment ratios, and dead-to-live load ratios. The interaction design equations based on failure at braced points in the beam-column yielded similar results as the equations based on failure at midspan which would be the governing equations for this example.

Figures 6 through 9 illustrate the results of typical doubly-symmetric beam-columns. Figures 6, 8, and 9 show similar shaped curves as shown in previous examples except that the slope of the curves increase with increasing end moment ratios. The relationship between allowable load ratio and slenderness ratio is shown in Figure 7. As shown in the figure, allowable load ratio increases with increasing slenderness ratio of the beam-column.

The dashed line curves shown in Figure 8 represent the beam-column subject to joint translation or transverse loading between its supports where C_m = 0.85. As shown in the figure, the effect of the coefficient, C_m, on the allowable load ratio is related to the end moment ratio. In Figure 9, the dashed line curves represent the beam-column fabricated with a steel possessing a higher yield point. The influence of the yield point on the allowable load ratio versus dead-to-live load ratio curves for various end moment ratios is similar but opposite to that of the effect of the coefficient, C_m, shown in Figure 8. These effects are negligible for small end moment ratios.

For singly-symmetric beam-columns, the direction of the moment or location of the eccentric axial load can be important so eccentricity was used as a parameter instead of end moment ratio and the allowable eccentric axial loads were solved for with a similar computer program. Since the moment is now directly proportional to the axial load, the eccentricity or end moment did not affect the slope of the allowable load ratio curves as shown in Figure 10. Figure 11 shows the allowable load ratio versus eccentricity for two different yield point materials. Figures 10 and 11 both show an increase in allowable load ratio with a decrease in eccentricity. Higher yield point materials will also result in a slight increase in allowable load ratio.

The relationship between allowable load ratio and slenderness ratio at a given dead-to-live load ratio is illustrated in Figure 12 for two different yield point materials. The figure shows an increase in allowable load ratio as the slenderness ratio increases.

CONCLUSIONS

This investigation compares the AISI Specification which is based on allowable stress design with the proposed recommendations on the load and resistance factor design for cold-formed steel structures. It was found that the dead-to-live load ratio had a significant effect on the degree of conservatism of the LRFD criteria. In general, the allowable load ratio, $(P_a)_{LRFD}/(P_a)_{ASD}$, increases as the dead-to-live load ratio increases. Because cold-formed steel members are usually thin, the dead-to-live load ratios of such light weight members are expected to be lower than the ratios used for other building materials. In view of this and the fact that the load factor used for live load is larger than the load factor for dead load, the LRFD criteria were found to be conservative in most cases.

ACKNOWLEDGMENTS

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APPENDIX I - REFERENCES

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APPENDIX II - NOTATION

C_m = bending coefficient used in beam-columns

c = distance from the centroidal axis to the fiber with maximum compression stress, negative when the fiber is on the shear center side of the centroid

D_n = nominal dead load

D/L = dead-to-live load ratio

e = eccentricity of the axial load with respect to the centroidal axis, negative when on the shear center side of the centroid

$(F.S.)_{ASD}$ = factor of safety against failure based on allowable stress design

$(F.S.)_{LRFD}$ = factor of safety against failure based on load and resistance factor design

F_y = yield point

K = effective length factor

L = member length

L_n = nominal live load

M_T = total unfactored applied moment

M_{us} = beam strength as determined from section strength

N = actual length of bearing

$(P_a)_{ASD}$ = allowable unfactored load based on allowable stress design

$(P_a)_{LRFD}$ = allowable unfactored load based on load and resistance factor design

Q_{kn} = nominal load effect

R_n = nominal resistance

r_y = radius of gyration of cross-section about centroidal principal axis

x = distance from shear center to web face

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

γ_k = load factor

ϕ = resistance factor

TABLE 1

FACTORS FOR DESIGN OF COLD-FORMED STEEL STRUCTURAL MEMBERS

Member	Failure Mode	$(F.S.)_{ASD}$	ϕ_{LRFD}	$(P_a)_{LRFD}/(P_a)_{ASD}$ for D/L = 1/3
Tension	Yielding	1.67	0.90	1.000
Flexural	Yielding	1.67	0.90	1.000
	Local buckling	1.67	0.90	1.000
	Lateral buckling	1.67	0.90	1.000
Flexural (Web)	Shear yielding	1.44	1.00	0.960
	Inelastic shear buckling	1.67	0.90	1.004
	Elastic shear buckling	1.71	0.90	1.027
	Local buckling under bending	1.67	0.90	1.000
	Crippling (single webs)	1.85	0.80	0.987
	Crippling (I-Sections)	2.00	0.80	1.067
Compression	Flexural buckling	1.92	0.80	1.022
	Torsion-flexural buckling	1.92	0.80	1.022
	Torsional buckling	1.92	0.80	1.022

TABLE 2

FACTORS FOR DESIGN OF CONNECTIONS FOR COLD-FORMED STEEL

Type	Failure Mode	$(F.S.)_{ASD}$	ϕ_{LRFD}	$(P_a)_{LRFD}/(P_a)_{ASD}$ for D/L = 1/3
Arc Spot Weld	Shear	1.89	0.70	0.880
	Sheet tearing	2.50	0.50-0.60	0.833-1.000
Arc Seam Weld	Shear	1.89	0.70	0.880
	Sheet tearing	2.50	0.60	1.000
Fillet Weld	Weld failure	2.00	0.70	0.933
	Sheet tearing	2.50	0.60	1.000
Flare Groove Weld	Weld failure	2.00	0.70	0.933
	Sheet tearing	2.50	0.55	0.917
Resistance Weld	Shear	2.5	0.65	1.083
Min. Bolt Edge Distance	Sheet shearing	2.00	0.70	0.933
Tension on Bolted Conn.	Sheet tearing	2.00-2.22	0.60-0.65	0.867-0.962
Bearing in Bolted Conn.	Sheet piling up	2.20-2.33	0.60-0.70	0.932-1.036

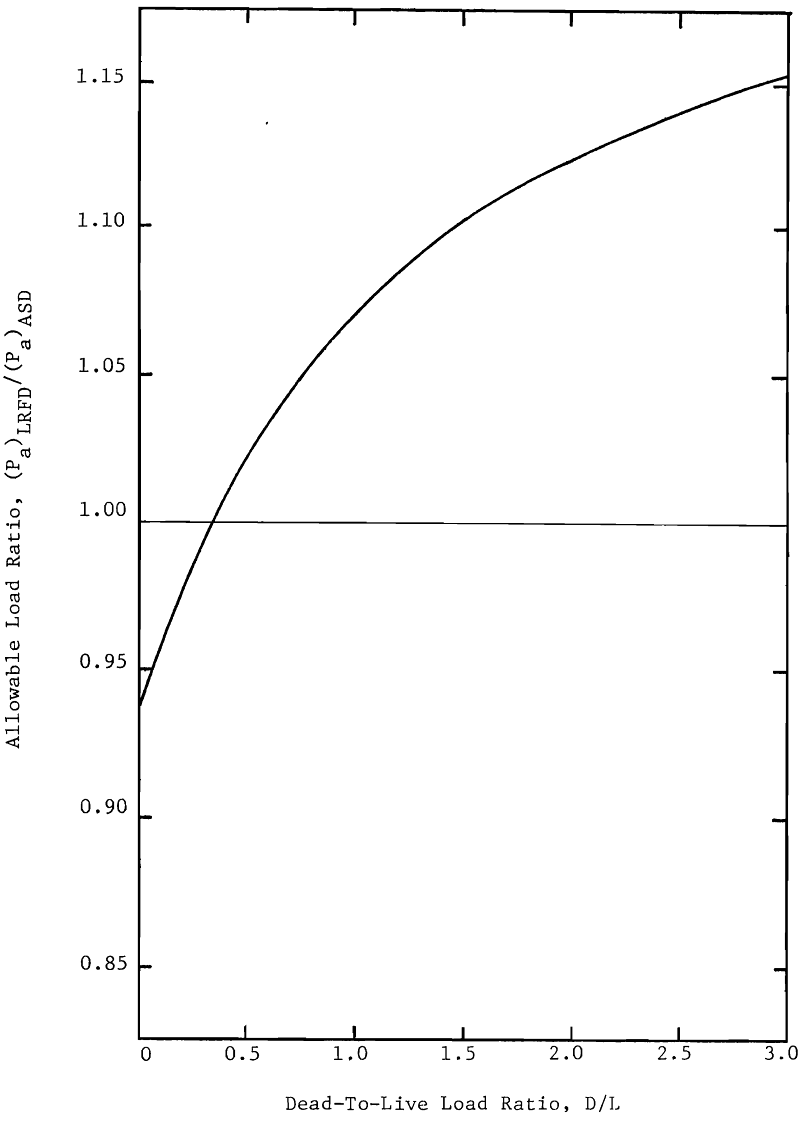

Figure 1. Allowable Load Ratio vs. D/L Ratio for Tension and Flexural Members

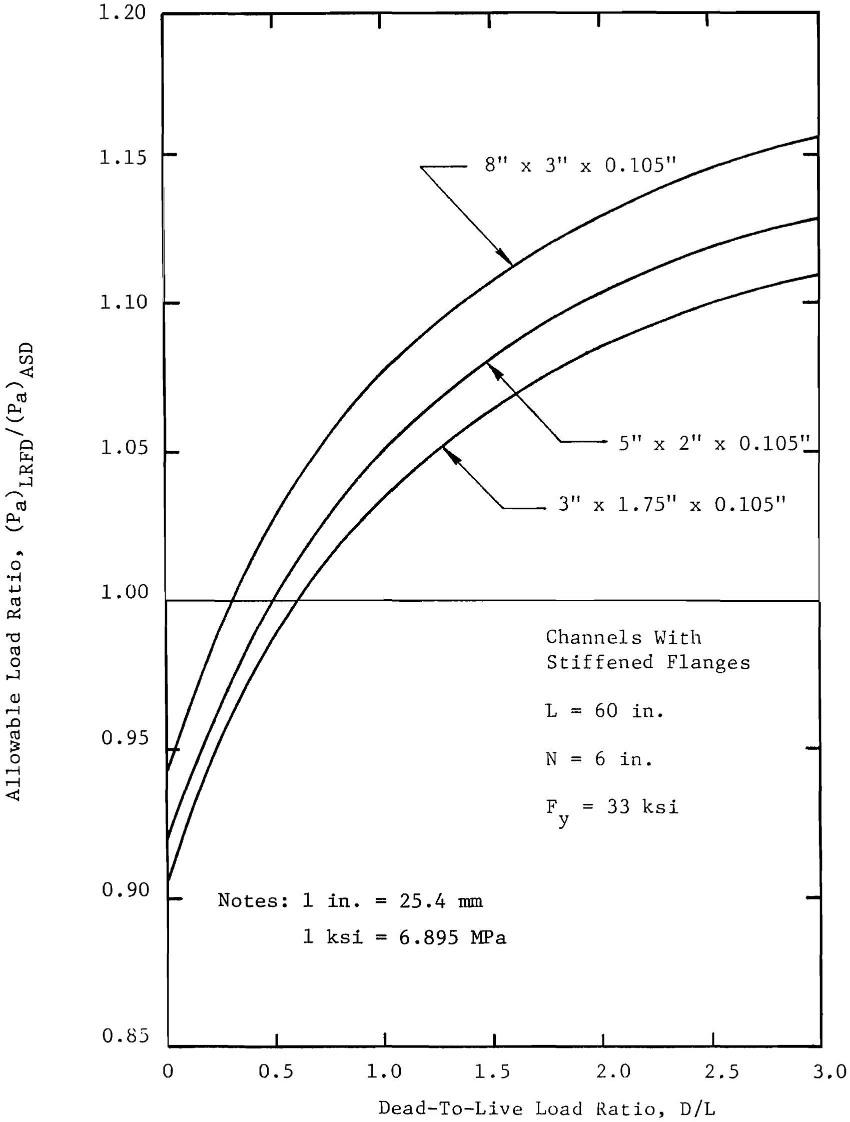

Figure 2 . Allowable Load Ratio vs. D/L Ratio for Combined Bending and Web Crippling

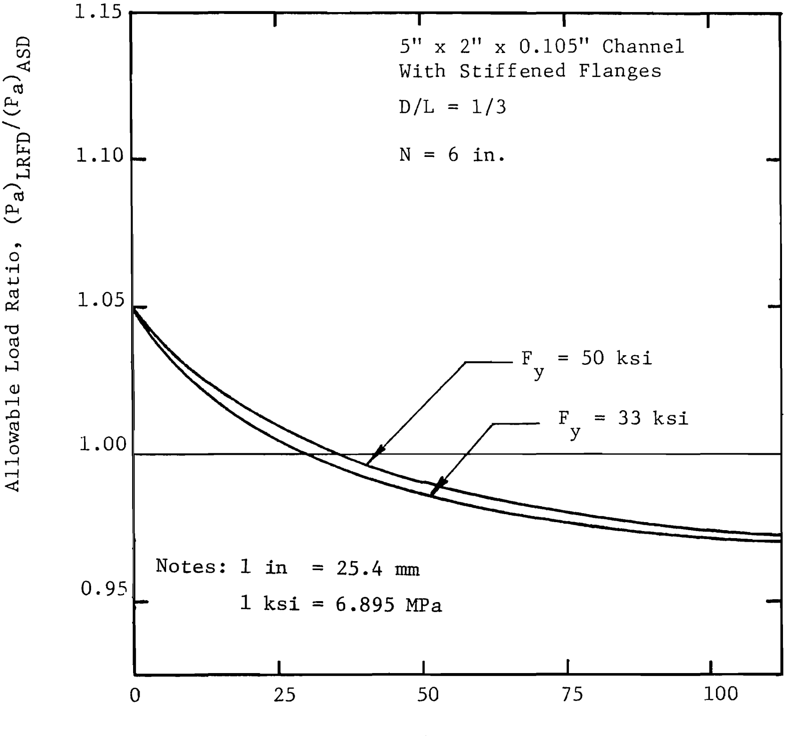

Figure 3. Allowable Load Ratio vs. Span Length for Combined Bending and Web Crippling

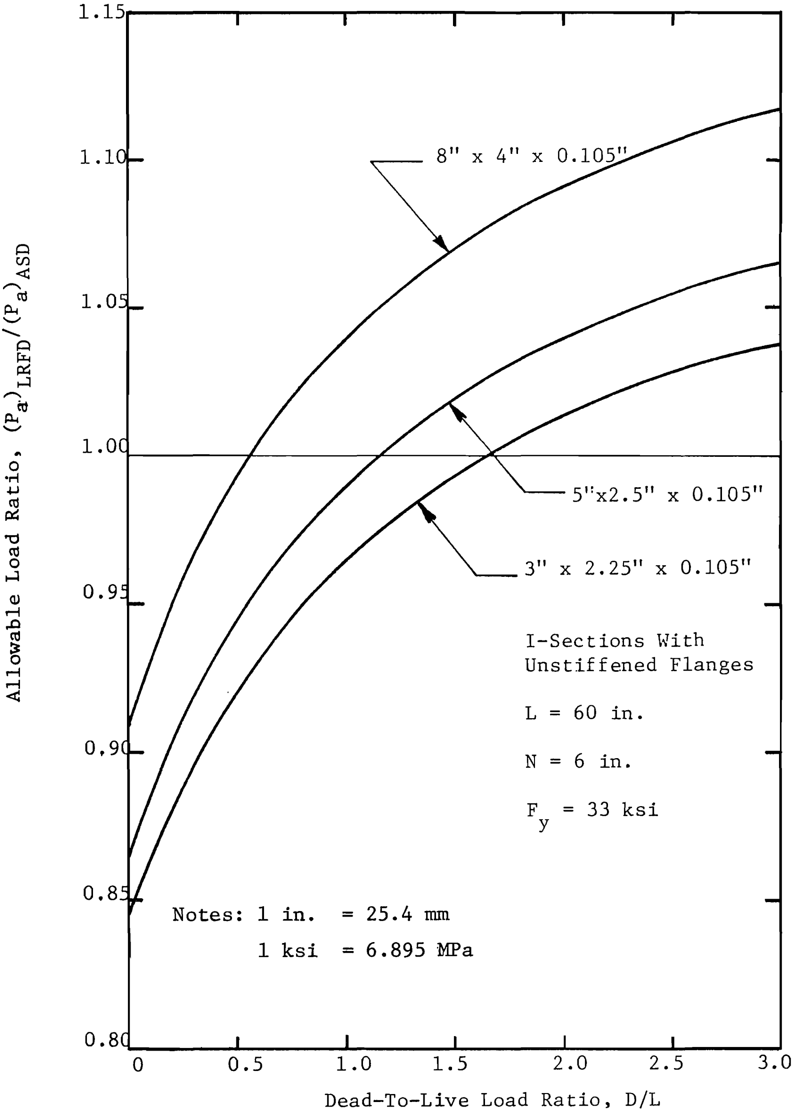

Figure 4. Allowable Load Ratio vs. D/L Ratio for Combined Bending and Web Crippling

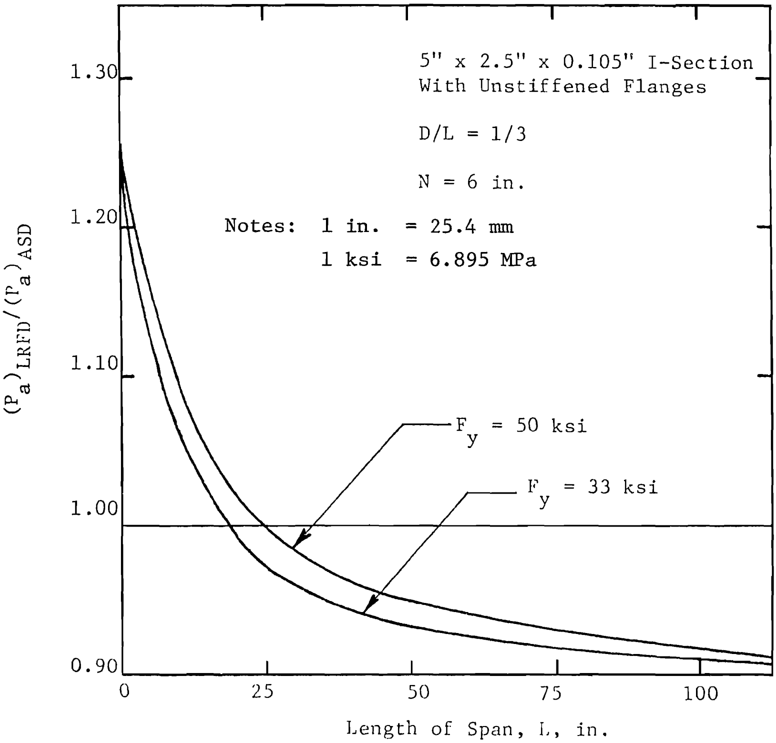

Figure 5. Allowable Load Ratio vs. Span Length for Combined Bending and Web Crippling

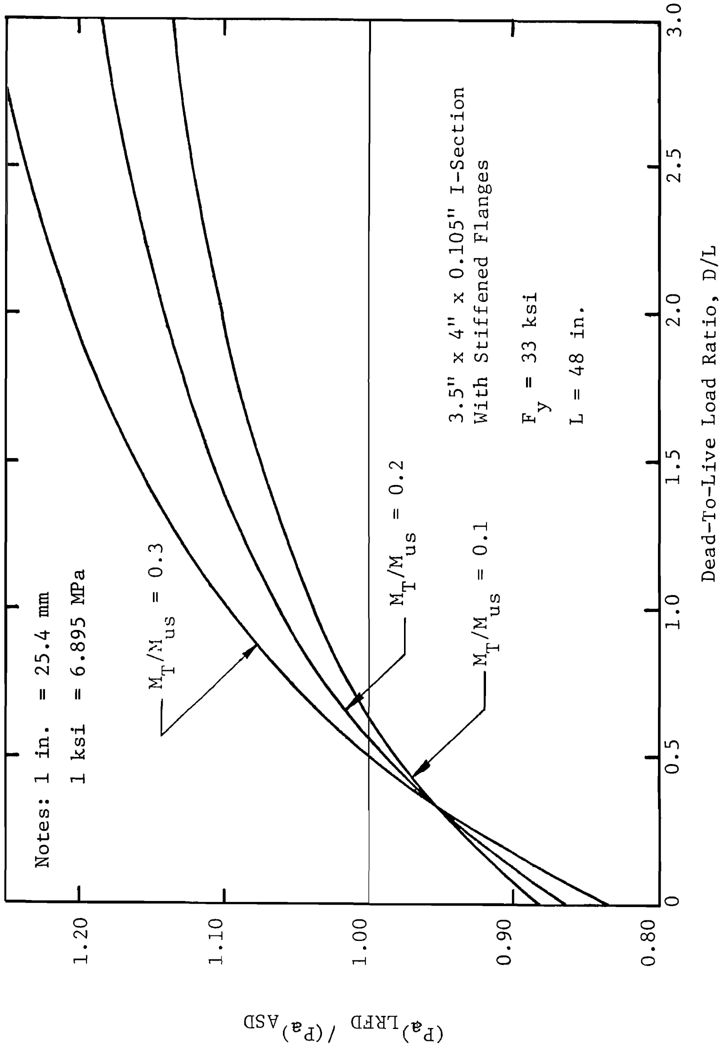

Figure 6. Allowable Load Ratio vs. D/L Ratio for Beam-Columns

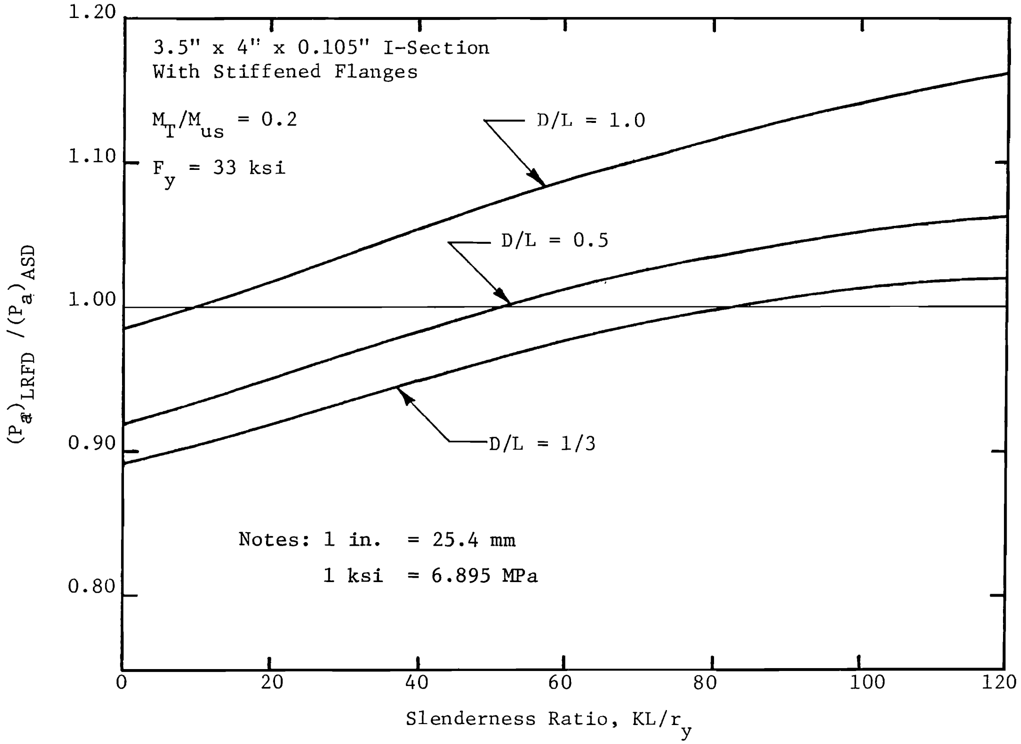

Figure 7. Allowable Load Ratio vs. Slenderness Ratio for Beam-Columns

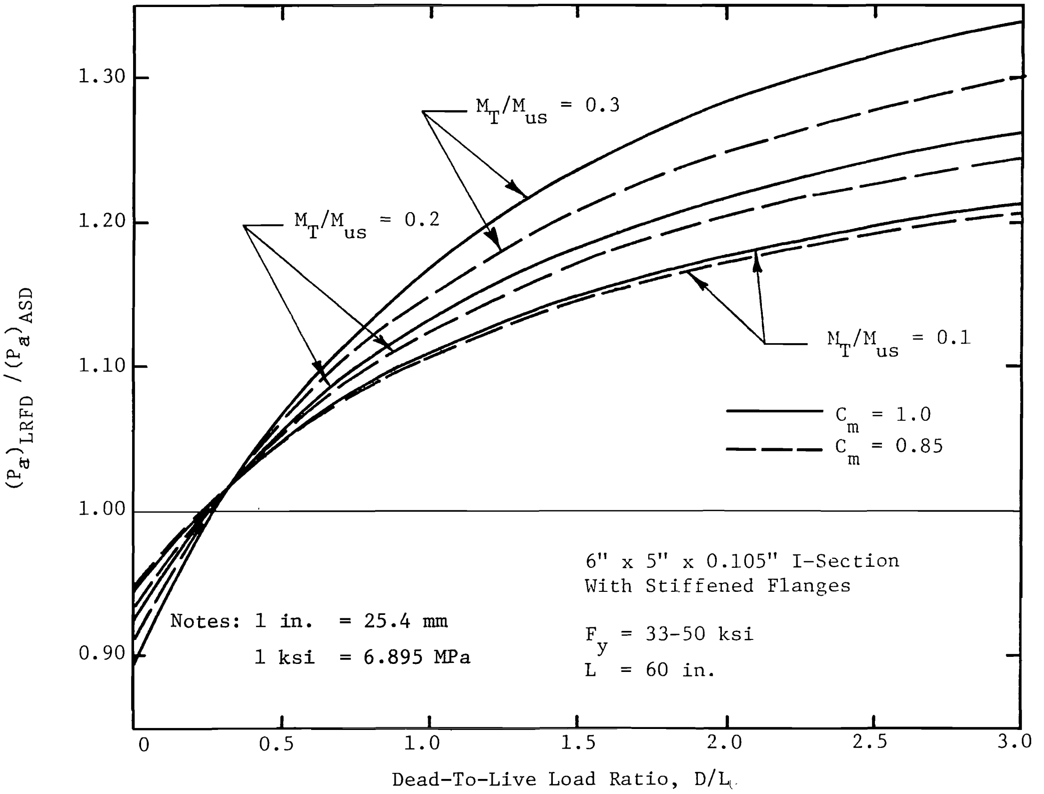

Figure 8. Allowable Load Ratio vs. D/L Ratio for Beam-Columns

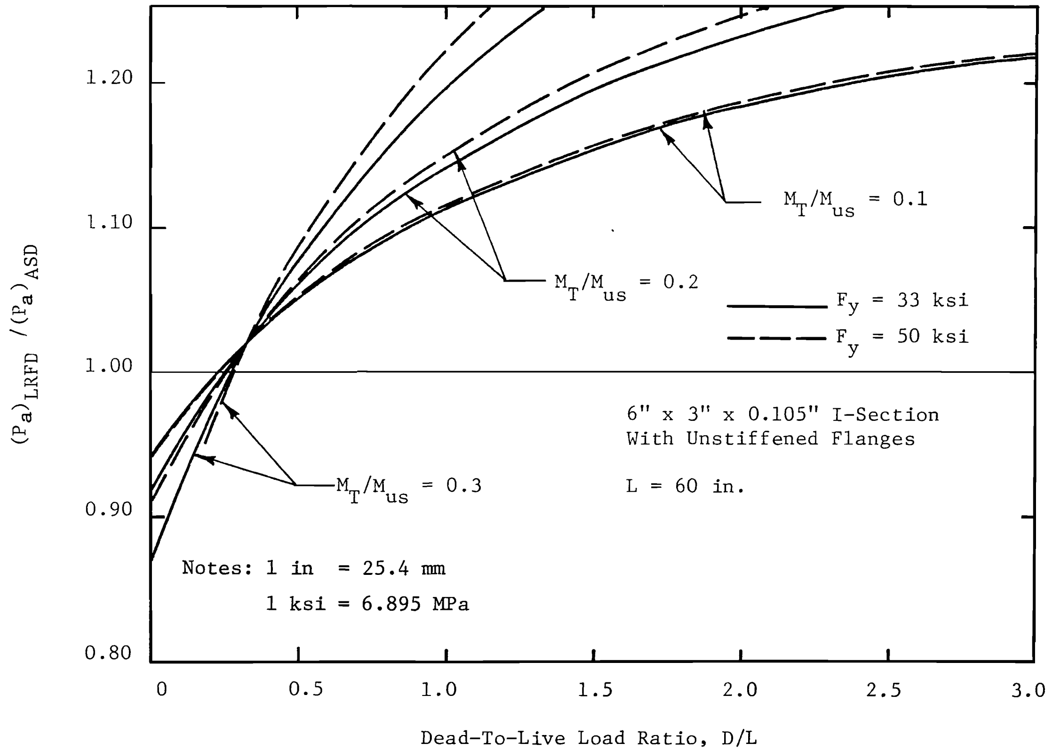

Figure 9. Allowable Load Ratio vs. D/L Ratio for Beam-Columns

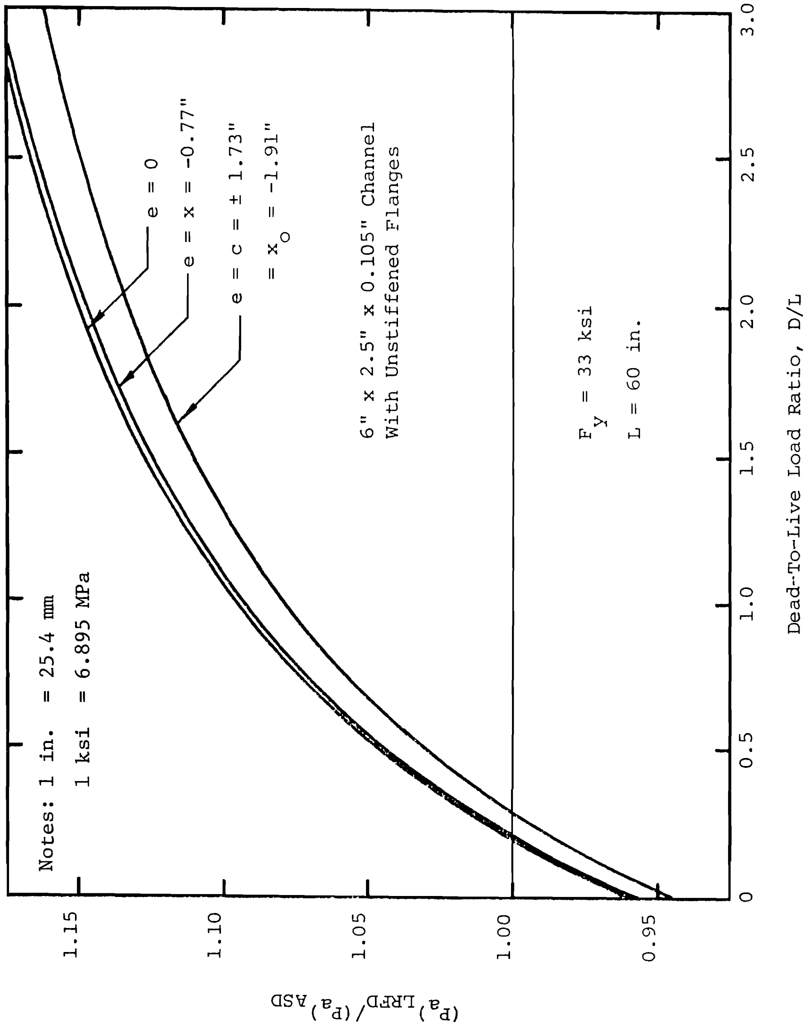

Figure 10. Allowable Load Ratio vs. D/L Ratio for Beam-Columns

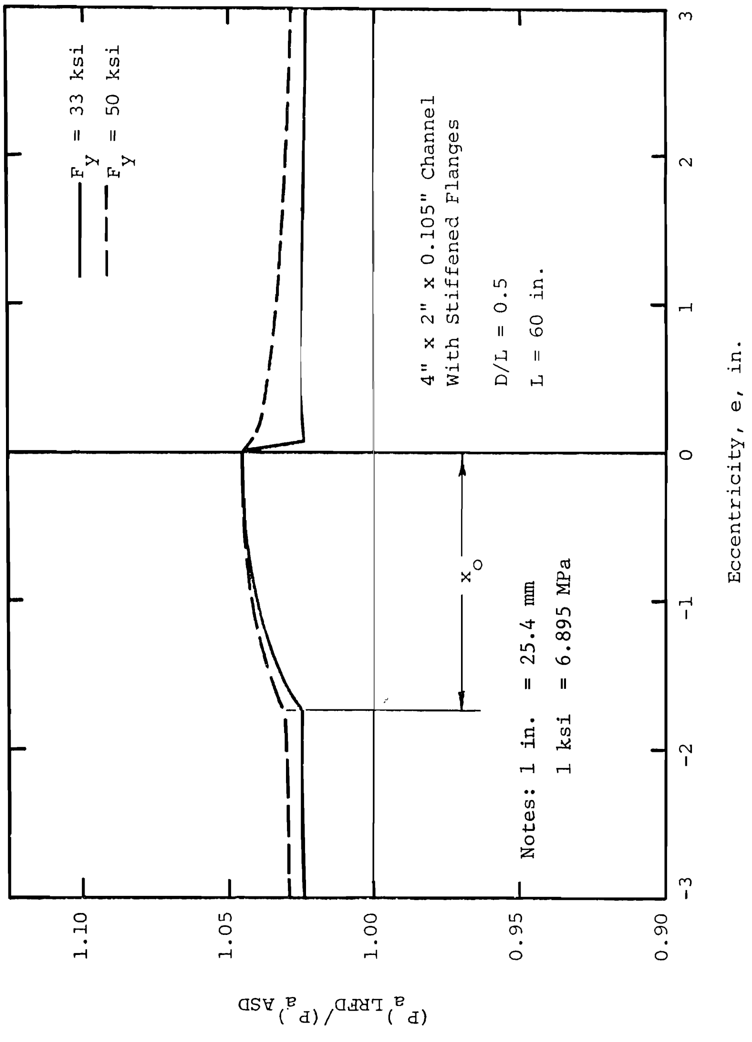

Figure 11. Allowable Load Ratio vs. Eccentricity for Beam-Columns

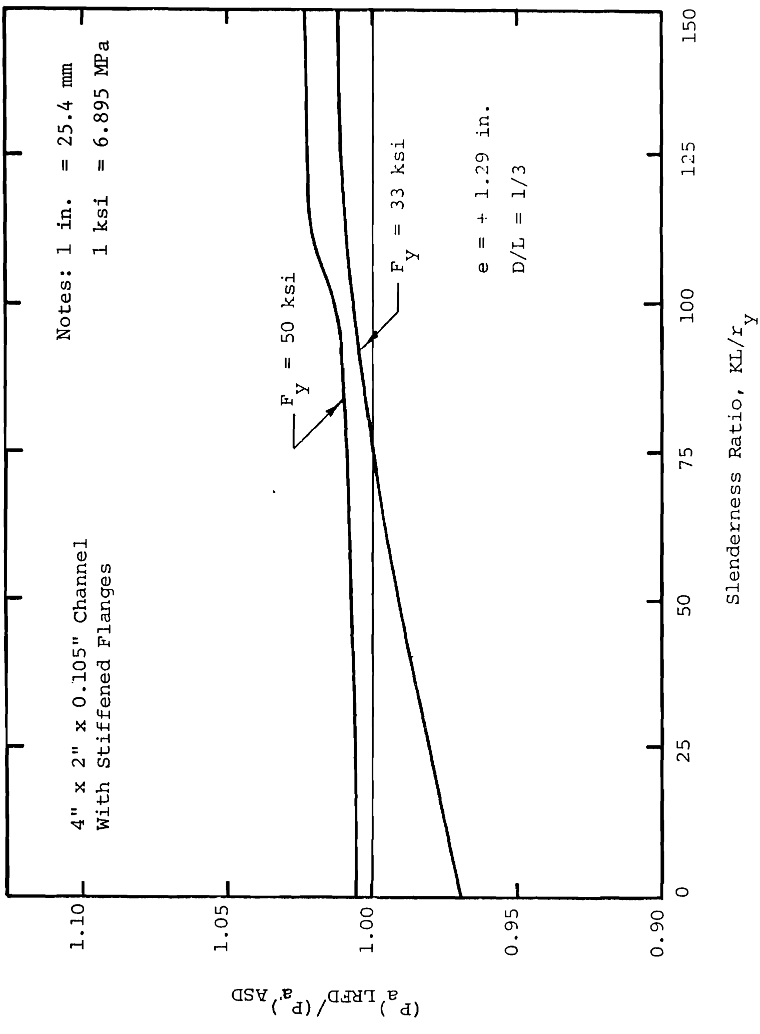

Figure 12. Allowable Load Ratio vs. Slenderness Ratio for Beam-Columns