A Summary of Changes and Derivation of LRFD Bolt Design Provisions

CHARLES J. CARTER, RAYMOND H. R. TIDE, and JOSEPH A. YURA

INTRODUCTION

Technical changes made in the 1994 RCSC *LRFD Specification for Structural Joints Using ASTM A325 or A490 Bolts* include such areas as shear-tension interaction for high-strength bolts in bearing connections and clear-distance-based bolt bearing strength. In this paper, corresponding changes are proposed for the AISC *LRFD Specification for Structural Steel Buildings* and the supporting background information is summarized. Additionally, a change is proposed for the service-load slip resistance reduction factor for shear-tension interaction in slip-critical connections in both documents. Finally, a change made in 1993 AISC LRFD Specification Section J8.1 covering bearing strength of pins is documented.

SHEAR-TENSION INTERACTION IN BEARING CONNECTIONS

The design strength of bolts subjected to combined shear and tension has historically been determined on the basis of either elliptical interaction curves, as specified by RCSC, or straight-line approximations of these curves, as specified by AISC. While an elliptical solution is numerically more accurate, an approximate method using three straight lines offers reasonable design simplicity as well as near maximum design efficiency through the full range of shear-tension interaction.

In its 1988 Specification, RCSC limited f_t the tensile stress due to factored loads according to the following general expression:

$$f_t \leq \phi\sqrt{F_{nt}^2 - \left(\frac{F_{nt}}{F_{nv}}\right)^2 f_v^2} \qquad (1)$$

where

ϕ = 0.75 = resistance factor for shear-tension interaction

F_{nt} and F_{nv} = nominal tensile and shear strengths (ksi), respectively

f_v = actual shear stress due to factored loads (ksi)

AISC based the three-straight line approximation equations in the 1993 LRFD Specification Table J3.3 upon this elliptical solution.

As illustrated in Figure 1, it was determined that three straight lines will reasonably represent the ellipse when the ratio of the length of the vertical segment V to the length of the horizontal segment H is equal to the ratio of $(R_n)_t$ to $(R_n)_v$, which is also the slope of the middle segment. This ratio is tabulated for various combinations of fastener grade and thread condition in Table 1. It can be seen that threaded fasteners generally can be assigned to two categories: threads included in the shear plane with a ratio of 1.9 (this includes A307 bolts) and threads excluded from the shear plane with a ratio of 1.5. For rivets, a ratio of 1.8 is used.

Given the above, the y-intercept of the straight line is the only independent variable and a value approximately equal to 1.3 times $\phi(R_n)_t$ results in a sloping line that best approximates the elliptical function regardless of whether threads are included or excluded from the shear plane. For this assigned

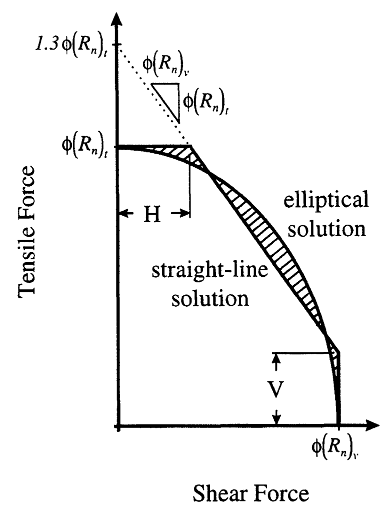

Fig. 1. Bolt shear-tension interaction: elliptical solution and three-straight-line approximation.

Charles J. Carter is director of manuals, American Institute of Steel Construction, Inc., Chicago, IL.

Raymond H. R. Tide is senior consultant, Wiss, Janney, Elstner Associates, Inc., Northbrook, IL.

Joseph A. Yura is Warren S. Bellowes Centennial Professor of Civil Engineering, University of Texas, Austin, TX.

y-intercept value, V and H are approximately equal to 0.3 times $(R_n)_t$ and 0.3 times $(R_n)_v$, respectively.

The accuracy of the assumed values of slope and y-intercept was checked by computing the area (shaded in Figure 1) between the curve for the elliptical solution and the straight lines for the approximate solution. Slightly larger y-intercept values result in a better balance of area outside the elliptical solution as compared to the area inside the elliptical solution. However, at the corners where the horizontal and vertical lines intersect with the sloping lines, the difference in design strength (straight-line solution minus elliptical solution) increases as the y-intercept value is increased. Because this increase in design strength is increasingly unconservative, this criterion governs the above y-intercept selection and no attempt is made to balance areas about the straight-line segment.

Accordingly, the straight-line approximation equations based upon the 1988 RCSC Specification elliptical solutions are as listed in Table 2. The corresponding general equation for nominal strength (ksi) is:

$$(F_n)_t = 1.3F_{nt} - \frac{F_{nt}}{F_{nv}} f_v \le F_{nt} \qquad (2)$$

For comparison, corresponding elliptical solutions determined from equation 1 are also listed.

As illustrated in Figure 2, the formulation chosen by RCSC in its 1988 Specification results in an acceptable design solution when the tension is more dominant than the shear (curve A). However, as the tension approaches zero, the design shear strength by curve A would unconservatively approach the nominal shear strength of the bolt. In such a case,

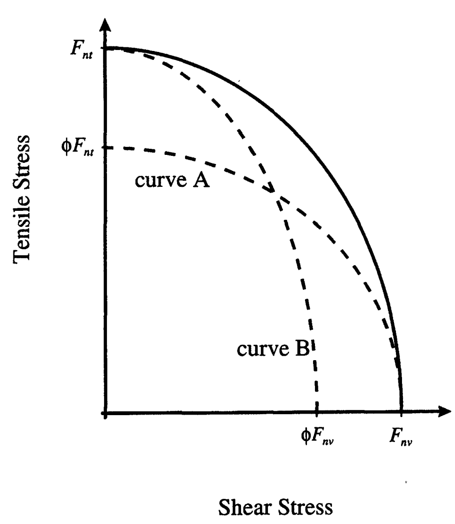

Fig. 2. Bolt shear-tension interaction per 1988 RCSC LRFD Specification.

Table 1.

Fastener		Thread Condition	F_{nt}	F_{nv}	F_{nt}/F_{nv}
A325		N	90	48	1.9
		X	90	60	1.5
A490		N	113	60	1.9
		X	113	75	1.5
AISC Specification Section A3		N	$0.75F_u$	$0.40F_u$	1.9
		X	$0.75F_u$	$0.50F_u$	1.5
A307		—	45	24	1.9
A502	gr. 1	—	45	25	1.8
	gr. 2	—	60	33	1.8

it would be more appropriate to calculate the design strength based upon curve B as:

$$f_v \le \phi\sqrt{F_{nv}^2 - \left(\frac{F_{nv}}{F_{nt}}\right)^2 f_t^2} \qquad (3)$$

In most practical cases, however, it would be difficult to define whether shear or tension were dominant and the two-equation solution above would become cumbersome.

To rectify this situation, in its 1994 LRFD Specification, RCSC has adopted a subtle philosophical change, replacing the overall resistance factor for shear-tension interaction with individual resistance factors on shear and tensile strengths. Accordingly, Equation 1 is revised as

$$f_t \le \sqrt{(\phi F_{nt})^2 - \left(\frac{\phi F_{nt}}{\phi F_{nv}}\right)^2 f_v^2} = \phi\sqrt{F_{nt}^2 - \left(\phi\frac{F_{nt}}{F_{nv}}\right)^2 f_v^2} \qquad (4)$$

where

ϕ = 0.75 for shear and tension and all other terms are as defined previously.

Multiplying through by bolt area to convert stresses to loads and resistances, RCSC Specification Equation LRFD 4.2 is obtained by rearranging terms:

$$\left[\frac{P_u}{(\phi R_n)_t}\right]^2 + \left[\frac{V_u}{(\phi R_n)_v}\right]^2 \le 1.0 \qquad (5)$$

where

P_u and V_u = required tensile and shear strengths, respectively

$(\phi R_n)_t$ and $(\phi R_n)_v$ = design tensile and shear strengths, respectively

Table 2.				
Fastener		Thread Condition	Nominal Strength, $(F_n)_t$ (ksi)	
			Elliptical Solution	Straight-line Approximation
A325		N	$\sqrt{90^2 - 3.52 f_v^2}$	$117 - 1.9 f_v \leq 90$
		X	$\sqrt{90^2 - 2.25 f_v^2}$	$117 - 1.5 f_v \leq 90$
A490		N	$\sqrt{113^2 - 3.54 f_v^2}$	$147 - 1.9 f_v \leq 113$
		X	$\sqrt{113^2 - 2.27 f_v^2}$	$147 - 1.5 f_v \leq 113$
AISC Specification Section A3		N	$\sqrt{(0.75 F_u)^2 - 3.52 f_v^2}$	$0.98 F_u - 1.9 f_v \leq 0.75 F_u$
		X	$\sqrt{(0.75 F_u)^2 - 2.25 f_v^2}$	$0.98 F_u - 1.5 f_v \leq 0.75 F_u$
A307		—	$\sqrt{45^2 - 3.52 f_v^2}$	$59 - 1.9 f_v \leq 45$
A502	gr. 1	—	$\sqrt{45^2 - 3.24 f_v^2}$	$59 - 1.8 f_v \leq 45$
	gr. 2	—	$\sqrt{60^2 - 3.31 f_v^2}$	$78 - 1.8 f_v \leq 60$

This formulation eliminates the aformentioned anomoly and provides a single simple equation. Of significance, this elliptical formulation provides excellent agreement with the combined tension/shear test data (Kulak et al., 1987). In addition, it also defines the elliptical shear-tension interaction equation for bolts from which the straight-line approximation must be determined.

The foregoing three-straight line approximation requires some minor adjustment for this new case. In terms of design strength, the appropriate y-intercept value would be 1.3 times $(\phi R_n)_t$ and the slope of the line would be equal to the ratio of $(\phi R_n)_t$ to $(\phi R_n)_v$., as illustrated in Figure 3. Converted to stresses, the resulting general equation is:

$$\phi(F_n)_t = 1.3\phi F_{nt} - \frac{\phi F_{nt}}{\phi F_{nv}} f_v \leq \phi F_{nt} \qquad (6)$$

Dividing through by ϕ, the nominal stress is obtained in equation 7:

$$(F_n)_t = 1.3 F_{nt} - \frac{F_{nt}}{\phi F_{nv}} f_v \leq F_{nt} \qquad (7)$$

For the purpose of comparison, design strengths for one ASTM A325N bolt from Equations 1, 2, 3, 4, and 6 are plotted in Figure 4.

Revised straight-line approximation equations based upon the 1994 RCSC Specification elliptical solutions are as listed in Table 3. For comparison, corresponding elliptical solutions determined from equation 4 are also listed. It is recommended that these revised straight-line approximation equations be adopted in the AISC LRFD Specification.

CLEAR-DISTANCE-BASED BOLT BEARING PROVISIONS

The traditional approach to calculation of bearing strength at bolt holes in both the AISC and RCSC Specifications has been based upon edge distances and spacings measured to fastener centerlines. Adjustment constants C_1 and C_2 account for differing hole type (oversized, slotted) and a table of minimum edge distances precludes location of a hole too close to an edge.

As illustrated in Figure 5, the current bearing strength provisions, shown as a function of edge distance to the center of the hole are discontinuous at the juncture between tearout-controlled bearing strength and hole-elongation-controlled

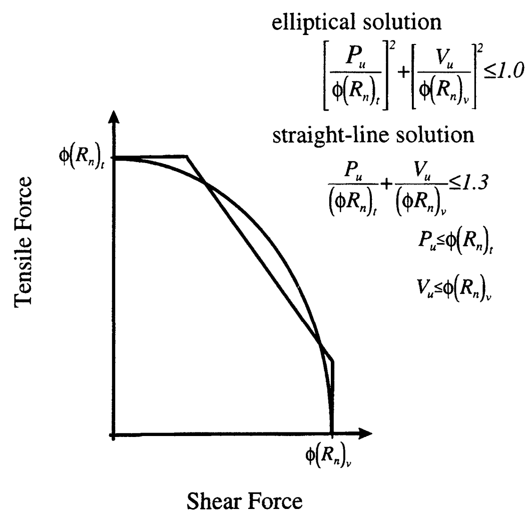

Fig. 3. Bolt shear-tension interaction per 1994 RCSC LRFD Specification with proposed straight-line approximation.

Table 3.				
Fastener		Thread Condition	Nominal Strength, $(F_n)_t$ (ksi)	
			Elliptical Solution	Straightline Approximation
A325		N	$\sqrt{90^2 - 6.25f_v^2}$	$117 - 2.5f_v \leq 90$
		X	$\sqrt{90^2 - 4.00f_v^2}$	$117 - 2.0f_v \leq 90$
A490		N	$\sqrt{113^2 - 6.31f_v^2}$	$147 - 2.5f_v \leq 113$
		X	$\sqrt{113^2 - 4.04f_v^2}$	$147 - 2.0f_v \leq 113$
AISC Specification Section A3		N	$\sqrt{(0.75F_u)^2 - 6.25f_v^2}$	$0.98F_u - 2.5f_v \leq 0.75F_u$
		X	$\sqrt{(0.75F_u)^2 - 4.00f_v^2}$	$0.98F_u - 2.0f_v \leq 0.75F_u$
A307		—	$\sqrt{45^2 - 6.25f_v^2}$	$59 - 2.5f_v \leq 45$
A502	gr. 1	—	$\sqrt{45^2 - 5.76f_v^2}$	$59 - 2.4f_v \leq 45$
	gr. 2	—	$\sqrt{60^2 - 5.86f_v^2}$	$78 - 2.4f_v \leq 60$

bearing strength. Research by Kim and Yura (1996) and Lewis and Zwerneman (1996) indicated that, while current AISC and RCSC Specification provisions for hole-elongation-controlled bearing strength calculation are correct, tearout-controlled cases are not adequately addressed. Additionally, it was desired to simplify and generalize bearing strength provisions by reformulating them based upon clear distances, thereby eliminating the need for adjustment factors and minimum edge distance requirements. Therefore, revised provisions for bearing strength at bolt holes were proposed to RCSC and adopted in the 1994 RCSC Specification as follows:

> The design bearing strength of the connected material for a bolt in a connection with standard, oversized, and short-slotted holes independent of the direction of loading, or a long-slotted hole with the slot parallel to the direction of the bearing force is ϕR_n where:
>
> (1) when deformation at the bolt hole at service load is a design consideration;

$$R_n = 1.2L_c t F_u \leq 2.4dtF_u \qquad \text{(LRFD 4.3)}$$

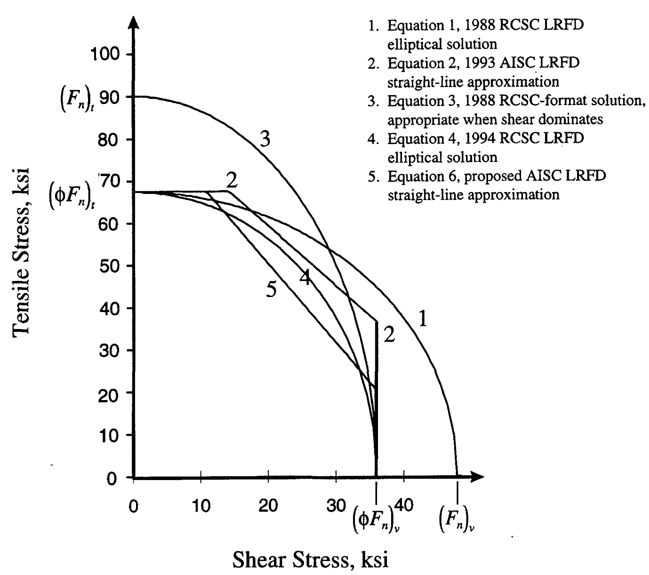

Fig. 4. Comparison of RCSC, AISC, and proposed design strength solutions for ASTM A325 N bolt.

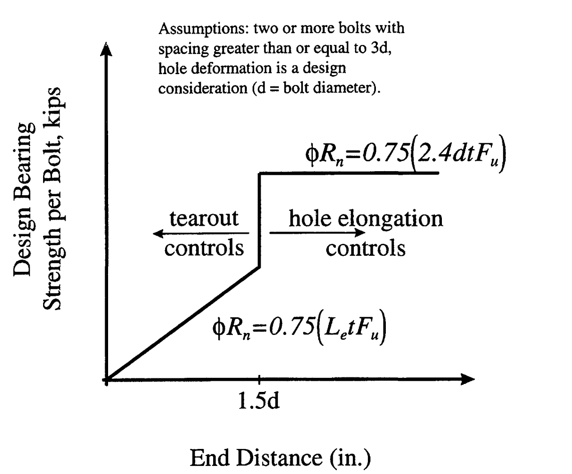

Fig. 5. Bolt bearing strength per 1993 AISC LRFD Specification.

(2) when deformation at the bolt hole at service load is not a design consideration;

$$R_n = 1.5L_c tF_u \leq 3.0dtF_u \qquad \text{(LRFD 4.4)}$$

"The design bearing strength of the connected material for a bolt in a connection with long-slotted holes with the slot perpendicular to the direction of force is ϕR_n where:

$$R_n = 1.0L_c tF_u \leq 2.0dtF_u \qquad \text{(LRFD 4.5)}$$

In the foregoing:

R_n = nominal bearing strength of the connected material, kips
F_u = specified minimum tensile strength of the connected material, ksi
L_c = clear distance, in the direction of the force, between the edge of the hole and the edge of the adjacent hole or edge of the material, in.
d = nominal diameter of the bolt, in.
t = thickness of the connected material, in.
ϕ = resistance factor, 0.75

For connections, the bearing resistance shall be taken as the sum of the bearing resistances of the individual bolts."

As illustrated in Figure 6 (RCSC Specification Commentary Figure C4) for case (1) above, the tearout-controlled bearing strength is calculated as the block shear rupture resistance of the material upon which the loaded bolt bears, conservatively neglecting any contribution of the material beyond the closest edge of the bolt hole.

It is proposed that the above approach be incorporated into the AISC LRFD Specification for consistency.

SHEAR-TENSION INTERACTION IN SLIP-CRITICAL CONNECTIONS

The traditional approach to the design of slip-critical connections subjected to combined shear and tension has been to multiply the shear-only slip resistance by a reduction factor to account for the unclamping effect of the tensile force. In service-load design, this factor has historically been taken as

$$\left(1 - \frac{T}{T_b}\right) \qquad (8)$$

where

T = service-load tension per bolt
T_b = minimum fastener tension as specified in Table J3.1 of the 1993 AISC LRFD Specification.

The 1993 LRFD Specification also includes provisions for checking slip resistance at the factored-load level. The corresponding reduction factor is

$$\left(1 - \frac{T_u}{1.13T_b N_b}\right) \qquad (9)$$

where

T_u = factored-load tension (on the joint)
T_b was defined previously
N_b = number of bolts carrying the factored-load tension T_u

The factor 1.13 in the denominator accounts for the expected installed tension, which averages 13 percent above the minimum specified bolt tension T_b for bolts installed with the calibrated wrench method (Kulak, et al., 1987).

While factored-load provisions and service-load provisions result in similar connections when used for shear-only and tension-only designs, there exists an anomaly for the case of connections designed for combined shear and tension when the above reduction factors are applied. Specifically, fewer bolts are required with the service-load provisions than with the factored-load provisions.

The factored-load reduction factor for shear in the presence of tension is correct. That is, when the externally applied tension per bolt T_u / N_b equals the expected clamping force per bolt $1.13T_b$, all preload in the bolts has been removed and the slip resistance is theoretically zero. Furthermore, the service-load provisions should ideally result in the same reliability as the factored-load provisions. With the possible range of live-to-dead-load ratios, this suggests that there is a range of values for the nominal safety factor in service-load design that is implied by the load factors in factored-load design. Note that the nominal safety factor should not be less than that implied for the shear-only condition itself.

Consider the ⅞-in. diameter A325-SC (Class A) bolt in a standard hole subjected to a load at angle θ as shown in Figure

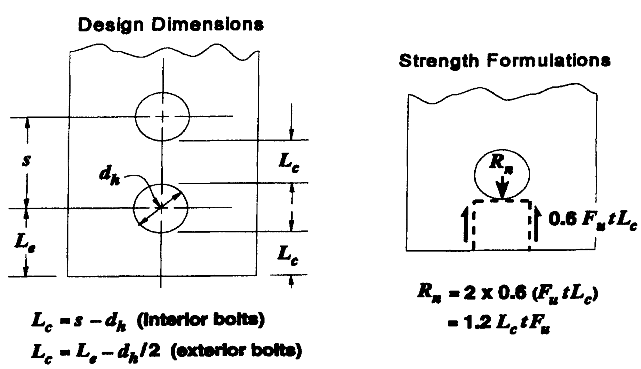

Fig. 6. Bolt bearing strength per 1994 AISC LRFD Specification.

7. For the case of shear-only loading ($\theta = 0°$), the slip resistance at factored loads from LRFD Specification Appendix J3.8b is:

$$\phi R_n = 1.13\mu T_b = 1.13 \times 0.33 \times 39 = 14.5 \text{ kips} \qquad (10)$$

The slip resistance at service loads from LRFD Specification Section J3.8a is:

$$\phi F_v A_b = 1.0 \times 17 \times 0.6013 = 10.2 \text{ kips} \qquad (11)$$

Thus, the implied factor of safety is 14.5 / 10.2 or 1.42. For the case of tension-only loading ($\theta = 90°$), the design strength from LRFD Specification Section J3.6 is:

$$\phi R_n = 0.75 \times 90 \times 0.6013 = 40.6 \text{ kips} \qquad (12)$$

and the service-load capacity from ASD Specification Section J3.4 is:

$$R_a = 44 \times 0.6013 = 26.5 \text{ kips} \qquad (13)$$

Thus, the implied factor of safety is 40.6 / 26.5 or 1.53. As a minimum then, the service-load factor of safety for the case of combined shear and tension ($0° < \theta < 90°$) must not be less than the lesser of these, which is 1.42.

Another way to establish a minimum service-load factor of safety is to determine the effective total load factor from the LRFD load factors for gravity load ($1.2D + 1.6L$). Considering standard holes and slip-critical connections ($\phi = 1.0$), if the live-load-to-dead-load ratio L / D is 1.0, the effective load factor on the total service load is ½(1.2) + ½(1.6) = 1.4. Similarly, if L / D is 3.0, the effective load factor is ¼(1.2) + ¾(1.6) = 1.5. The minimum service-load factor of safety of 1.42 determined previously fits within these rough limits.

At the factored-load level, the shear that would cause slip of the slip-critical bolt in Figure 7 subjected to combined shear and tension is V_{slip} where:

$$V_{slip} = 14.5\left(1 - \frac{T_u}{1.13T_b}\right) \qquad (14)$$

For the case when $\theta = 45°$, $V_{slip} = T_u$, and equation 14 can be rewritten as:

$$V_{slip}\left(\frac{1}{14.5} + \frac{1}{1.13 \times 39}\right) = 1 \qquad (15)$$

from which V_{slip} = 10.9 kips.

To provide for an equivalent design using both factored-load and service-load provisions, the value of Q in the equation 16 must be determined such that the ratio $V_{slip} / V_{all} = 1.42$, the minimum service-load factor of safety determined previously.

$$V_{all} = 10.2\left(1 - \frac{T}{QT_b}\right) \qquad (16)$$

Again for the case when $\theta = 45°$, $V_{all} = T$, and equation 16 can be rewritten as:

$$V_{all}\left(\frac{1}{10.2} + \frac{1}{Q \times 39}\right) = 1 \qquad (17)$$

Rearranging equations 15 and 17 to solve for V_{slip} and V_{all} and setting the ratio $V_{slip} / V_{all} = 1.42$, the value of Q is determined to be 0.798. For simplicity, it is suggested that Q be taken as 0.8.

Table 4.				
Load angle, θ	T_u / V_{slip} or T / V_{all}	V_{slip}, kips	V_{all}, kips	V_{slip} / V_{all}
15°	0.268	13.3	9.38	1.42
30°	0.577	12.2	8.58	1.42
45°	1.00	10.9	7.69	1.42
60°	1.73	9.24	6.52	1.42
75°	3.73	6.51	4.60	1.42

As verified in Table 4, this value of Q consistently provides for the minimum service-load factor of safety of 1.42 at other selected load angles. It is proposed that the service-load reduction factor for tension in the presence of shear in LRFD Specification Section J3.9a be changed to

$$\left(1 - \frac{T}{0.8T_b N_b}\right) \qquad (18)$$

where

T = service-load tension

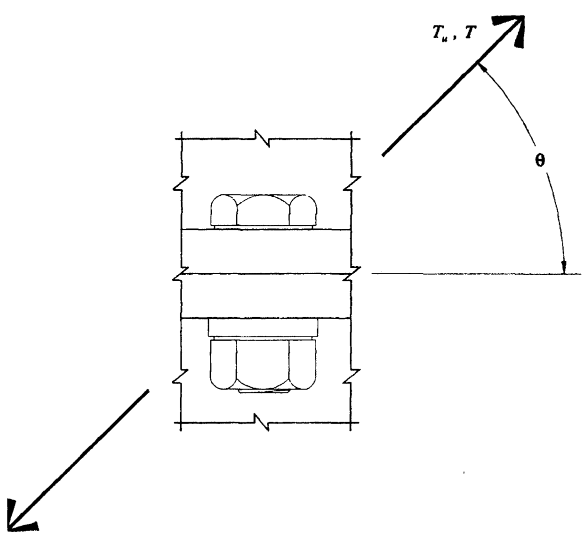

Fig. 7. Bolt subjected to combined shear and tension.

T_b = minimum fastener tension as specified in Table J3.1 of the AISC LRFD Specification

N_b = number of bolts carrying the service-load tension T

Because this same equation appears in the 1994 RCSC LRFD Specification, a similar change in Section 5(b) is recommended.

BEARING STRENGTH OF PINS

Section J8.1 of the 1986 AISC LRFD Specification provided the nominal bearing strength of milled or finished surfaces in contact with pins as:

$$R_n = 2.0F_y A_{pb} \tag{19}$$

where

F_y = specified minimum yield stress, ksi

A_{pb} = projected bearing area, in.^{2}

The corresponding Commentary indicates that this formula was "transformed from allowable stress to LRFD format by multiplying by [the factor of safety]" to determine the design strength.

As with almost all connection-related limit states, the implied ASD factor of safety is 2.0. From the 1989 ASD Specification, the allowable bearing force is:

$$R_a = 0.9F_y A_{pb} \tag{20}$$

and all variables are as defined previously. However, with an ASD factor of safety of 2, the corresponding nominal bearing strength is:

$$R_n = 2R_a = 1.8F_y A_{pb} \tag{21}$$

Thus, given the Commentary statement above, the lower nominal strength given in equation 21 has been adopted in the 1993 AISC LRFD Specification. As illustrated in Figure 8, this equation gives the most appropriate representation of bearing strength and is generally equivalent to that provided in ASD at a live to dead load ratio of approximately 3. The corresponding resistance factor remains unchanged at ϕ = 0.75. Furthermore, the bearing strength is still less than the limiting bearing strength of $2.4F_u$ that is considered suitable for high-strength bolts (LRFD 4.3) as discussed earlier in this paper.

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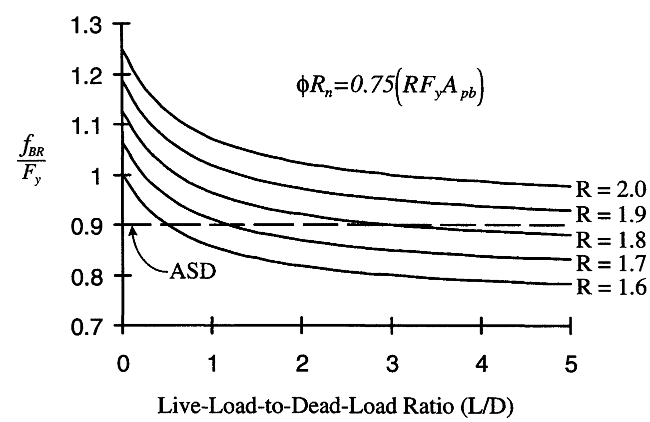

Fig. 8. Comparison of pin bearing strength in LRFD and ASD.

DISCUSSIONS

A Summary of Changes and Derivation of LRFD Bolt Design Provisions

Paper by CHARLES J. CARTER, RAYMOND H. R. TIDE, and JOSEPH A. YURA
(3rd Quarter, 1997)

Discussion by Joseph Biren, P.E.

In the subject paper, the authors present two alternative methods for the determination of strength when a bolt is subjected to combined shear and tension: the elliptical interaction approach that has historically been used by the Research Council on Structural Connections (RCSC) and the three-straight-line approach that has historically been used by AISC. The RCSC elliptical solution (Equation 5 in the subject paper) represents a simple formulation that provides for a straight-forward calculation. As such it is not clear why a three-straight-line approximation is needed. Additionally, Equation 5 is a transparent presentation of the assumed interaction concept and constraints and, as such, would greatly assist practicing engineers. Perhaps AISC should simply adopt the RCSC elliptical solution directly.

Also, there is a typesetting error in Equation 4 in the term to the right of the equals sign. The proper form is as follows:

$$f_t \leq \sqrt{(\phi F_{nt})^2 - \left(\frac{\phi F_{nt}{}^2}{\phi F_{nv}}\right) f_v^2} = \phi \sqrt{F_{nt}^2 - \left(\frac{F_{nt}}{\phi F_{nv}}\right)^2 f_v^2}$$

Discussion by Pierre Dumonteil, P.E.

It is certain that the errors discovered by the authors in the existing bolt design strength formulae must be corrected. However, the writer, for one, does not agree with the point of view that (1) stresses, as in Table 3, are more convenient and, therefore, should be specified rather than bolt strengths, as in equation 5 or on Figure 3, and (2) a straight-line approximation is more practical than the RCSC elliptical solution.

The writer's disagreement is based on the following reasons:

(a) It is easier to look up the basic bolt design strengths for tension and shear given in the appropriate tables of the AISC *Manual of Steel Construction, Volume II—Connections* than it is to calculate stresses.

(b) The elliptical solution amounts to nothing more than calculating the side of a right-angled triangle (which is truly what it is), and its simple form is easy to remember.

(c) It provides excellent agreement with the test data.

(d) In limit states design philosophy, member and component strengths or resistances are to be preferred unless the use of stresses cannot be avoided. This is not the case here.

Statements (a) and (b) are best verified with a spreadsheet: compare the instructions required to follow the stress approach step by step, with the bolt load method using Equation 5 in the subject paper.

The writer strongly recommends that the elliptical solution should be adopted in the exact form of Equation 5, without modification.

Joseph Biren, P.E., is principal of the structural engineering firm of Joseph Biren located in Westfield, NJ.

Pierre Dumonteil, P.E., is structural engineer, Krupps Robins, Greenwood Village, CO.

ERRATA

Practical Application of Energy Methods to Structural Stability Problems

Paper by SHANKAR NAIR
(4th Quarter, 1997)

Page 133, right column, 5th and 4th lines from bottom:
From first principles:

$$(L-a)^2 = L^2 - d^2$$

Expand to:

$$L^2 - 2aL + a^2 = L^2 - d^2$$

Discussion of A Summary of Changes and Derivation of LRFD Bolt Design Provisions

Paper by CHARLES J. CARTER, RAYMOND H. R. TIDE, and JOSEPH A. YURA
(3rd Quarter, 1997)

Discussion by JOSEPH BIREN
(1st Quarter, 1998)

Page 39, right column, last line of discussion:

$$f_t \le \sqrt{(\phi F_{nt})^2 - \left(\frac{\phi F_{nt}}{\phi F_{nv}}\right)^2 f_v^2} = \phi\sqrt{F_{nt}^2 - \left(\frac{F_{nt}}{\phi F_{nv}}\right)^2 f_v^2}$$

CLOSURE

A Summary of Changes and Derivation of LRFD Bolt Design Provisions

Paper by CHARLES J. CARTER, RAYMOND H. R. TIDE, and JOSEPH A. YURA
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Closure by Charles J. Carter, P.E.

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The RCSC elliptical solution is simple, straightforward and has the advantage of being load and strength based. However, it can be an ill-conditioned solution when one load component is dominant over the other. That is, at the extremes (high shear in combination with low tension or vice versa), a small change in one component results in a comparatively large change in the corresponding component. The three-straight-line approximation eliminates this anomaly, yet maintains excellent agreement with the test data. Furthermore, at small levels of tension, the three-straight-line approximation results in no calculated reduction in the shear strength. Similarly, at small levels of shear, there is no calculated reduction in the tensile strength. In the end, because both alternatives are permitted, implementation can be based upon individual preference.

The authors also thank Mr. Biren for correcting the typesetting error in the right-most term of Equation 4 of the subject paper. The correct form is as given in Mr. Biren's discussion.

Charles J. Carter, P.E., is director of manuals, American Institute of Steel Construction, Inc., Chicago, IL.