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AISI DESIGN CRITERIA FOR BOLTED CONNECTIONS

By Wei-Wen Yu¹

INTRODUCTION

In the United States and some other countries, the bolted connections used for cold-formed steel structures are designed in accordance with Section 4.5 of the AISI Specification (2). These design provisions were originally developed on the basis of the Cornell Tests (16,17) and updated in 1980 to reflect the results of additional research (4, 8, 9, 12, 18) and to provide a better coordination with the specifications of the Research Council on Structural Connections and the American Institute of Steel Construction (1, 14).

The purpose of this paper is to summarize the changes of the design criteria and to document the research data used for the revision of Section 4.5 of the AISI Specification. Several design items are outlined in this paper for future consideration.

BASIS FOR THE REVISION OF THE DESIGN CRITERIA

Section 4.5 of the AISI Specification is used to prevent the following four types of failure, which may occur in bolted connections:

- Type I - Longitudinal shear failure of the sheet along two parallel lines (Fig. 1a)
- Type II - Bearing failure or piling up of material in front of the bolt (Fig. 1b)
- Type III - Tearing failure of the sheet in the net section (Fig. 1c)
- Type IV - Shearing failure of the bolt (Fig. 1d)

In the 1980 AISI Specification, three new subsections were added for scope, materials, and bolt installation. In addition, changes were made for the design provisions concerning minimum spacing and edge distance, allowable tensile stress for connected parts, allowable bearing stress between the connected part and bolt, and allowable shear stresses on bolts.

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1. Scope

During the revision of the Specification, due consideration was given to the range of thicknesses of steel sheets, strip, flat bars, and plates, which are generally used for fabricating cold-formed steel structural members. Because previous studies and past practical experience have indicated that the structural behavior of bolted connections used for joining relatively thick cold-formed steel members is similar to that of connected hot-rolled shapes and built-up members, Section 4.5 is now applicable only to cold-formed steel members that are less than 3/16 in. (4.8 mm) in thickness. For materials not less than 3/16 in. (4.8 mm), the AISC design provisions (1) can be used for the design of bolted connections in cold-formed steel structures.

2. Materials

In previous editions of the AISI Specification, allowable shear stresses were given only for A307 and A325 bolts. Because the maximum thickness for cold-formed members has been increased from 1/2 in. (12.7 mm) to 1 in. (25.4 mm), other high-strength bolts, such as A354, A449, and A490 bolts, were added to the 1980 Specification for bolted connections.

In view of the fact that A325 and A490 bolts are available only for a diameter of 1/2 in. (12.7 mm) and larger, whenever smaller bolts (less than 1/2 in. (12.7 mm) in diameter) are required in a design, high-strength A449 and A354 Grade BD bolts can be used as equivalents of A325 and A490 bolts, respectively.

For other types of fasteners, which are not listed in this section, the allowable stresses should be determined by tests in accordance with the AISI Specification.

3. Bolt Installation

This new subsection was added to the 1980 specification to ensure that bolts are properly tightened according to acceptable practice followed by building constructors. Because the required pretension in bolts usually varies with the types of connected parts, fasteners, applied loads, and applications, no specific requirements are given in the 1980 specification for installation.

The method of installation and the effect of torques on the strength of bolted connections have been studied and reported in Refs. 10, 15 and 18. This background information is useful for developing future installation procedures.

4. Minimum Spacing and Edge Distance in Line of Stress

In previous editions of the AISI Specification, the minimum end distance measured in the line of stress was determined by the following two requirements:

$$\text{and } e_{\min} = 1.5d \quad (1)$$

$$e_{\min} = \frac{P}{0.60F_y t} \quad (2)$$

in which e_{\min} is the required minimum end distance measured in the line of stress, in., d is the diameter of bolts, in., P is the allowable load transmitted by one bolt, kips, F_y is the yield point of connected parts, ksi, and t is the thickness of the thinnest connected part, in. Equation (2) was used to prevent the failure in longitudinal shearing of the connected part along two parallel lines in the direction of applied force. It was derived from the following equation with a safety factor of 2.3.

$$e = \frac{P_u}{1.4 F_y t} \quad (3)$$

In the above equation, P_u is the failure load per bolt, kips (16, 17).

During recent years, additional studies have been made on the bearing strength of connections bolted with and without washers (4,5,6 8,9,12,18). The test data as shown in Figs. 2 to 7 indicate that for bolted connections having small e/d ratios, the bearing stress at failure can be predicted by Eq. (4):

$$\frac{\sigma_b}{F_u} = \frac{e}{d} \quad (4)$$

in which σ_b is the ultimate bearing stress between the bolt and connected part, ksi, and F_u is the tensile strength of the connected part, ksi. The preceding equation is based on the results of bolted connection tests involved with the following parameters:

Diameter of bolt, d : 3/16 - 1 in. (4.8 - 25.4 mm)

Thickness of connected part, t : 0.036 - 0.261 in. (0.9 - 6.6 mm)

Edge distance, e : 0.375 - 2.50 in. (9.5 - 50.8 mm)

Yield point of steel, F_y : 25.6 - 87.60 ksi (177 - 604 MPa)

Tensile strength of steel, F_u : 41.15 - 91.30 ksi (284 - 630 MPa)

e/d ratio: 0.833 - 3.37

d/t ratio: 2.61 - 20.83

F_u/F_y ratio: 1.00 - 1.63

The dimensions of the specimens and test results are given in Ref. 18.

By substituting $\sigma_b = P_u/dt$ into Eq. (4), Eq. (5) can be obtained for the required edge distance, e , i.e.,

$$e = \frac{P_u}{F_u t} \quad (5)$$

Consequently, Eqs. (4.5.4-1) and (4.5.4-2) of the 1980 AISI Specification for the minimum end distance (Fig. 1a) were derived from Eq. (5) with a safety factor of 2.0 for $F_u/F_y \geq 1.15$ and 2.22 for $F_u/F_y < 1.15$. This is because Eq. (5) is slightly conservative for connected parts having large F_u/F_y ratios as shown in Figs. 2 and 3.

It should be noted that Eq. (5) is also used for the Specifications of the Research Council on Structural Connections and the American Institute of Steel Construction (1,14). Therefore, the present AISI requirement for minimum edge distance is the same as that required by the AISC and Research Council Specifications when $F_u/F_y \geq 1.15$.

As compared with previous editions of the AISI Specification, it can be seen that the 1980 provisions permit relatively small edge distances when $F_u/F_y \geq 1.15$. However, when $F_u/F_y < 1.15$, the 1980 and 1968 Specifications require about the same amount of edge distance (18).

In addition to the changes discussed above, several new requirements have been added to the 1980 AISI criteria concerning (a) the minimum distance between the centers of holes as required for the installation of bolts, (b) the required distance between the edges of two adjacent holes, and (c) the minimum distance between the edge of a hole and the end of a member. Most of these requirements are based on the general practices applied in cold-formed steel construction.

5. Bearing Stress in Bolted Connections

When the edge distance is sufficiently large (i.e. for large e/d ratios), the bearing capacity between the connected part and fastener may govern the strength of bolted connections. Recent studies indicate that the bearing strength of bolted connections depends on the tensile strength of the connected part, the thickness of the connected part, the types of joints (lap joint or butt joint), the F_u/F_y ratio of the connected part, the use of washers, the "catenary action" of steel sheets, and rotation of fasteners. Tables 1 and 2 list several formulas for determining the ultimate bearing stress, σ_b , on the basis of various conditions. These equations were developed from the test data with the following variables (18):

- Diameter of bolt, d : 3/16 - 1 in. (4.8 - 25.4 mm)
- Thickness of connected part, t : 0.024 - 0.260 in. (0.6 - 6.6 mm)
- Edge distance, e : 0.50 - 4.50 in. (12.7 - 114 mm)
- Yield point of steel, F_y : 28.1 - 82.6 ksi (194 - 570 MPa)
- Tensile strength of steel, F_u : 41.83 - 82.6 ksi (288 - 570 MPa)

e/d ratio: 1.02 - 6.62
 d/t ratio: 3.42 - 13.50
 F_u/F_y ratio: 1.00 - 1.63

The correlations between the test results and the equations for σ_b are shown in Figs. 2 to 8.

The allowable bearing stresses, F_b , specified in Tables 4.5.6 (A) and 4.5.6 (B) of the 1980 Specification^P were derived from the ultimate bearing stresses, σ_b , by using factors of safety ranging from 2.20 to 2.33. The actual factor of safety used for each case is also indicated in Tables 1 and 2.

It should be noted that the 1980 AISI provisions are limited only to certain thicknesses of materials because of a lack of test results for very thin sheets. For the thicknesses of materials not covered in Tables 4.5.6 (A) and 4.5.6 (B), the allowable bearing stress must be determined by the test data and a factor of safety of 2.22. A limited number of test data on very thin materials can be found in Ref. 8.

6. Tension Stress on Net Section

In the 1980 provisions, the design formula used for computing the allowable tension stress, F_t , on the net section of connected parts was changed as follows:

1. The provisions are applicable only to the thinnest connected part, which is less than 3/16 in. (4.8 mm) thick. For thick materials, the allowable tension stress is determined by using the AISC Specification (1).
2. The allowable tension stress for the net section of a connected member is determined by the tensile strength of the connected part (F_u) instead of the yield point of steel (F_y).
3. Different y formulas are used for bolted connections with and without washers.
4. The allowable tension stress for the net section of a connected member is based on the type of joint, either a single shear lap joint or a double shear butt joint.

For connections in which washers are placed under both the heads and nuts of the bolts, the equations for computing the allowable tension stress [Eqs. (4.5.5-1) and (4.5.5-2)], were derived from the following formula for the ultimate tensile stress, σ_{net} , with the proper factors of safety.

$$\sigma_{net} = (1.0 - 0.9r + 3rd/s) F_u \leq F_u \quad (6)$$

In Eq. (6), σ_{net} is the ultimate tensile stress on the net section, ksi, s is the spacing of bolts perpendicular to the line of stress, in., and r is a ratio of the force transmitted by the bolt or bolts at the section considered, divided by the tension force in the member at that section. The factors of safety used for deriving Eq. (4.5.5-1) of the

AISI Specification for double shear connections and Eq. (4.5.5-2) for single shear connections are 2.0 and 2.22, respectively.

The correlations between Eq. (6) and the test data are shown graphically in Figs. 9 to 11. The test specimens were involved with the following parameters (18):

Diameter of bolt, d : 1/4 - 1-1/8 in. (6.4 - 28.6 mm)
 Thickness of steel sheet, t : 0.0335 - 0.191 in. (0.9 - 4.9 mm)
 Width of steel sheet, s : 0.872 - 4.230 in. (22 - 107 mm)
 Yield point of steel, F_y : 26.00 - 99.40 ksi (179 - 685 MPa)
 Tensile strength of steel, F_u : 41.15 - 99.80 ksi (284 - 688 MPa)
 d/s ratio: 0.063 - 0.50
 d/t ratio: 3.40 - 21.13

When washers are not used and when only one washer is used in bolted connections, the ultimate tensile stress on the net section, σ_{net} , can be determined by using Eq. (7):

$$\sigma_{net} = (1.0 - r + 2.5r d/s) F_u \leq F_u \quad (7)$$

Equation (4.5.5-3) of the 1980 Specification was derived from the above formula by using a safety factor of 2.22. Figure 12 shows the correlation between Eq. (7) and the test data presented in Ref. 4.

7. Shear Stress on Bolts

In order to achieve a better coordination with the Specifications of the Research Council on Structural Connections and the American Institute of Steel Construction (1, 14), the allowable shear stresses for A325 bolts were increased by 36% in the 1980 design provisions. This increase is also justified by tests because the revised allowable stresses provide factors of safety ranging from 2.25 to 2.52 against shear failure of bolts (19). In addition, design values for A449, A490, and A354 Grade BD bolts were added for use of high strength bolts. The 1980 Specification permits the same allowable shear stresses for A307, A325, and A490 bolts as those specified in Refs. 1 and 14 for bearing-type connections.

It should be noted that in the 1980 Specification, small allowable shear stresses are used for A449 and A354 Grade BD bolts with threads in the shear planes as compared with those used for A325 and A490 bolts. This is based on the fact that the ratios of root-area/gross-area (A_k/A_D) for the 1/4 in. (6.4 mm) and 3/8 in. (9.5 mm) diameter bolts are smaller than those of the 1/2 in. (12.7 mm) diameter and larger bolts. For details, see Table 3. The reduced allowable shear stress for A449 and A354 Grade BD bolts are derived from the A_k/A_D ratios as follows:

For A449 bolts smaller than 1/2 in. (12.7 mm) in diameter,

$$F_v = 21 \text{ (for A325 bolts)} \left[\frac{\text{Avg. } A_K/A_D \text{ for } 1/4 \text{ in. and } 3/8 \text{ in. bolts}}{\text{Avg. } A_K/A_D \text{ for } 1/2 \text{ in. and } 1 \text{ in. bolts}} \right]$$

$$= 21 \frac{0.585}{0.670} = 18.33 \text{ ksi;}$$

$$\text{use } F_v = 18 \text{ ksi (124 MPa)}$$

For A354 Grade BD bolts smaller than 1/2 in. in diameter,

$$F_v = 28 \text{ (for A490 bolts)} \times \frac{0.585}{0.671} = 24.45 \text{ ksi;}$$

$$\text{use } F_v = 24 \text{ ksi (165 MPa)}$$

FUTURE REVISION OF THE SPECIFICATION

Even though numerous changes were made in the 1980 Edition of the AISI Specification for the design of bolted connections, consideration should be given to the following items and others when the Specification is revised in the future.

- . Connection strength imparted by the inclination of fasteners, particularly when thin sheets are used in lap joints (3,10,15).
- . Combined longitudinal shearing along two parallel lines and tension in the traverse cross section of a steel sheet for bolt groups (11).
- . Bearing capacity of very thin sheets when washers are not used (8).
- . Bearing capacity affected by a selected deflection limit for connections (7).
- . Structural strength of fasteners against uplift and pull-over.
- . Allowable tension on bolts and allowable stress for combined shear and tension for bolts.

SUMMARY

The AISI design provisions for bolted connections were revised extensively in 1980. The major task of revising this portion of the Specification was carried out by a joint effort of the Task Group on Bolted Connections (L. W. Iffe, Chairman) of the AISI Sheet Committees, Committee 27 (A. L. Johnson, Chairman) of the Research Council on Structural Connections, and Subcommittee 3 (Wei-Wen Yu, Chairman) of the AISI Advisory Group on the Specification for the Design of Cold-Formed Steel Structural Members (K. H. Klippstein, Chairman). This paper briefly reviews the reasoning behind and justification for the revised design provisions of the 1980 AISI Specification supported by the available research data.

APPENDIX I-REFERENCES

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APPENDIX II - NOTATION

The following symbols are used in this paper:

- A_D = gross area of bolt;
 A_K = root area of bolt;
 d = diameter of bolt;
 e = end distance;
 e_{min} = required minimum edge distance;
 F_p = allowable bearing stress;
 F_t = allowable tension stress on net section;
 F_u = tensile strength of steel sheet or connected part;
 F_v = allowable shear stress on bolt;
 F_y = yield point of steel sheet or connected part;
 P = allowable load transmitted by one bolt;
 P_u = failure load per bolt;
 r = ratio of the force transmitted by the bolt or bolts at the section considered, divided by the tension force in the member at that section;
 s = spacing of bolts perpendicular to the line of stress (In the case of a single bolt, s is the width of sheet.);
 t = thickness of steel sheet or connected part;
 σ_b = ultimate bearing stress at failure; and
 σ_{net} = ultimate tensile stress.

TABLE 1

Bearing Strengths and Allowable Bearing Stresses of Bolted Connections with Washers under Both Bolt Head and Nut

| Thickness of Steel Sheet (in.) | Type of Joint | F_u/F_y Ratio of Steel Sheet | Ultimate Bearing Stress, σ_b (ksi) | Allowable Bearing Stress, F_p (ksi) | Factor of Safety |
|---------------------------------|--|--------------------------------|---|---------------------------------------|------------------|
| < 3/16 but > 0.024 | Inside sheet of double shear connections | ≥ 1.15 | $3.5 F_u$ | $1.50 F_u$ | 2.33 |
| | | < 1.15 | $3.0 F_u$ | $1.35 F_u$ | 2.22 |
| | Single shear connections and inside sheets of double shear connections | ≥ 1.15 | $3.0 F_u$ | $1.35 F_u$ | 2.22 |
| | | < 1.15 | $3.0 F_u$ | $1.35 F_u$ | 2.22 |

TABLE 2

Bearing Strengths and Allowable Bearing Stresses of Bolted Connections without Washers under Both Bolt Head and Nut

| Thickness of Steel Sheet (in.) | Type of Joint | F_u/F_y Ratio of Steel Sheet | Ultimate Bearing Stress, σ_b (ksi) | Allowable Bearing Stress, F_p (ksi) | Factor of Safety |
|---------------------------------|---|--------------------------------|---|---------------------------------------|------------------|
| < 3/16 but > 0.036 | Inside sheet of double shear connections | ≥ 1.15 | $3.0 F_u$ | $1.35 F_u$ | 2.22 |
| | Single shear connections and outside sheets of double shear connections | ≥ 1.15 | $2.2 F_u$ | $1.00 F_u$ | 2.20 |

Note: 1 in. = 25.4 mm; 1 ksi = 6.9 MPa

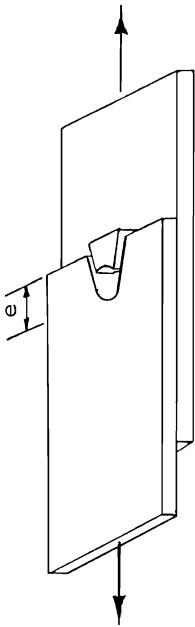
TABLE 3

Gross-Areas and Root-Areas of Structural Bolts

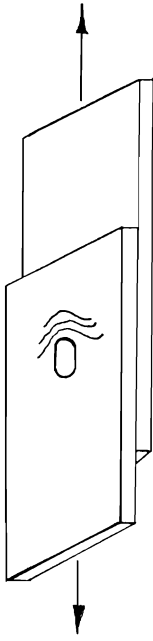
| Bolt Diameter (in.) | Gross Area A_D (in. ²) | Root Area A_K (in. ²) | $\frac{A_K}{A_D}$ |
|---------------------------|--|---|-------------------|
| 1/4 | 0.049 | 0.027 | 0.55 |
| 3/8 | 0.110 | 0.068 | 0.62 |
| 1/2 | 0.196 | 0.126 | 0.64 |
| 5/8 | 0.307 | 0.202 | 0.66 |
| 3/4 | 0.442 | 0.302 | 0.68 |
| 7/8 | 0.601 | 0.419 | 0.70 |
| 1 | 0.785 | 0.551 | 0.70 |

Note: The gross and root areas are based on the AISC Manual of Steel Construction, 8th Edition, p. 4-141.

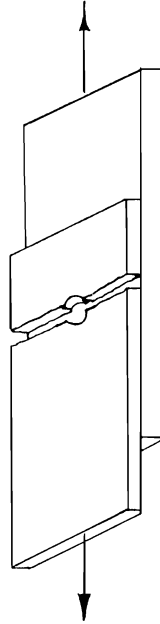
1 in. = 25.4 mm; 1 in.² = 645 mm.²



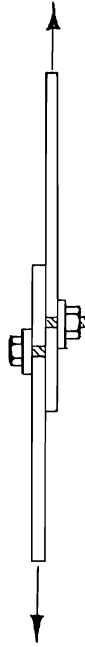
(a) Longitudinal shear failure of sheet (Type I)



(b) Bearing failure of sheet (Type II)



(c) Tensile failure of sheet (Type III)



(d) Shear failure of bolt (Type IV)

Fig. 1 Types of Failure of Bolted Connections

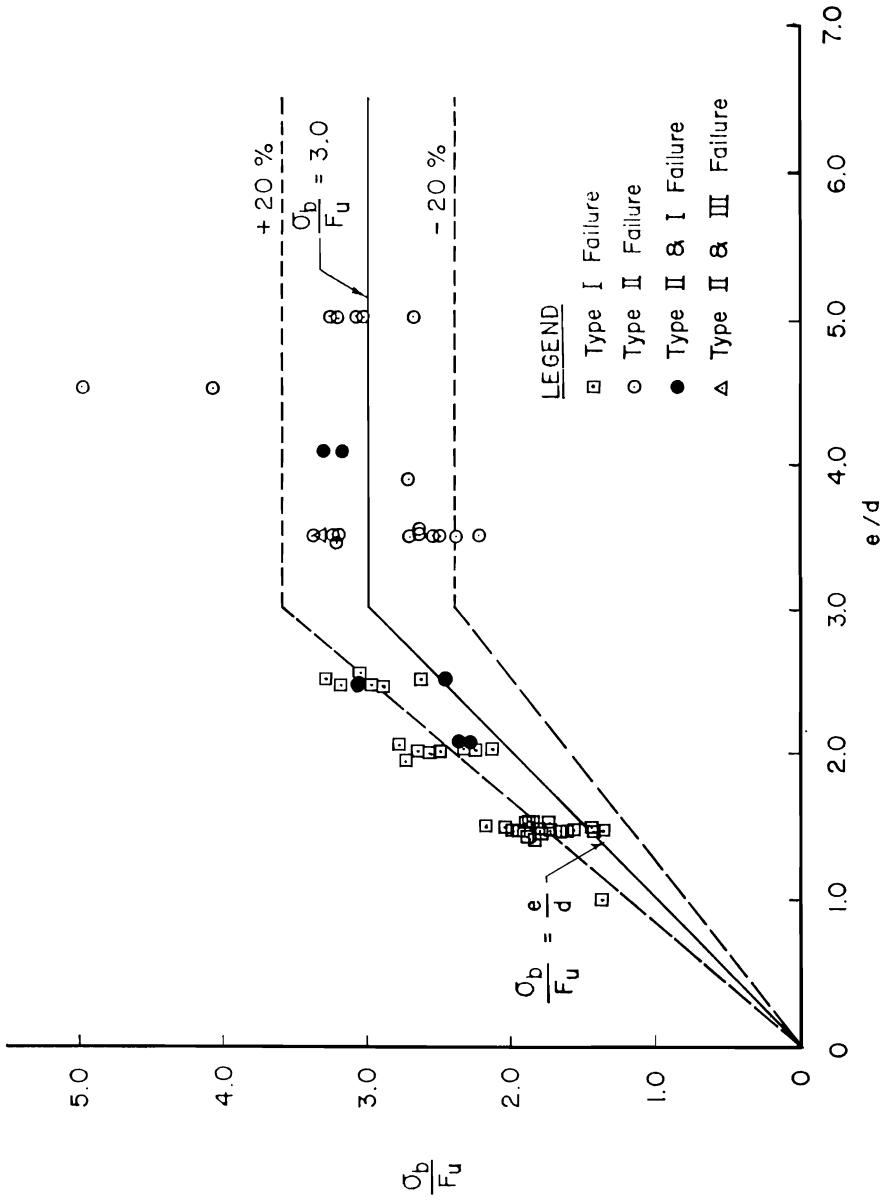


Fig. 2 Single Shear Connections with Washers, $F_u/F_y \geq 1.15$, Shear and Bearing Strength Study

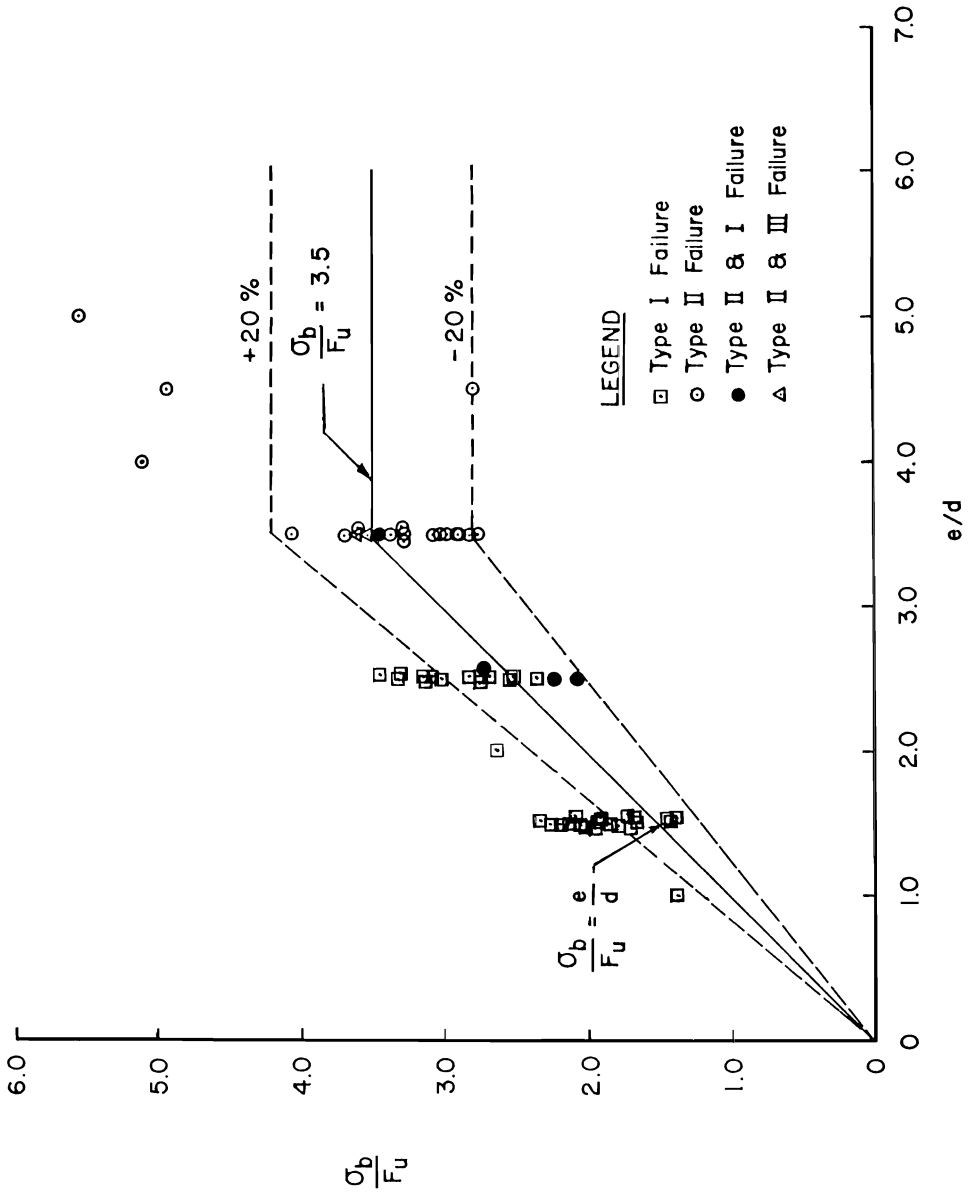


Fig. 3 Double Shear Connections with Washers, $F_u/F_y \geq 1.15$, Shear and Bearing Strength Study

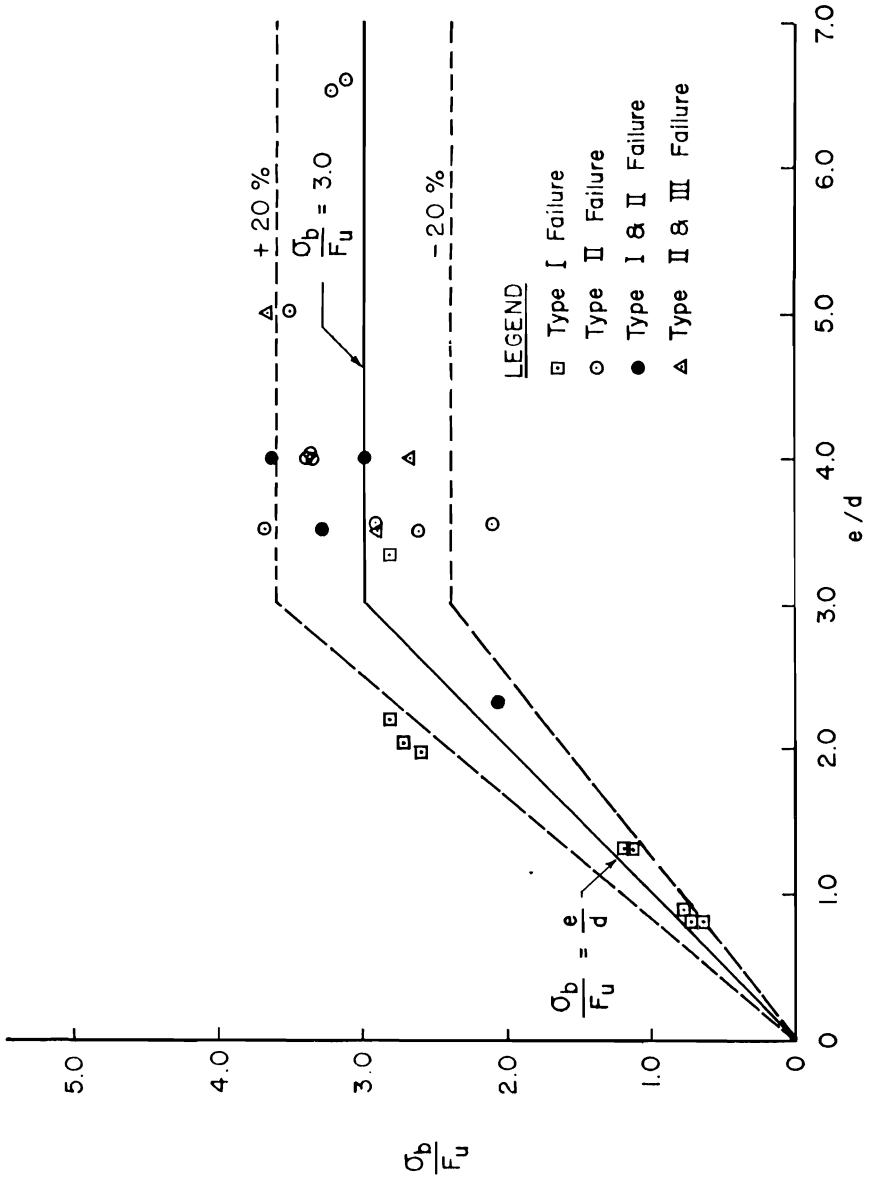


Fig. 4 Single Shear Connections with Washers, $F_u/F_y < 1.15$, Shear and Bearing Strength Study

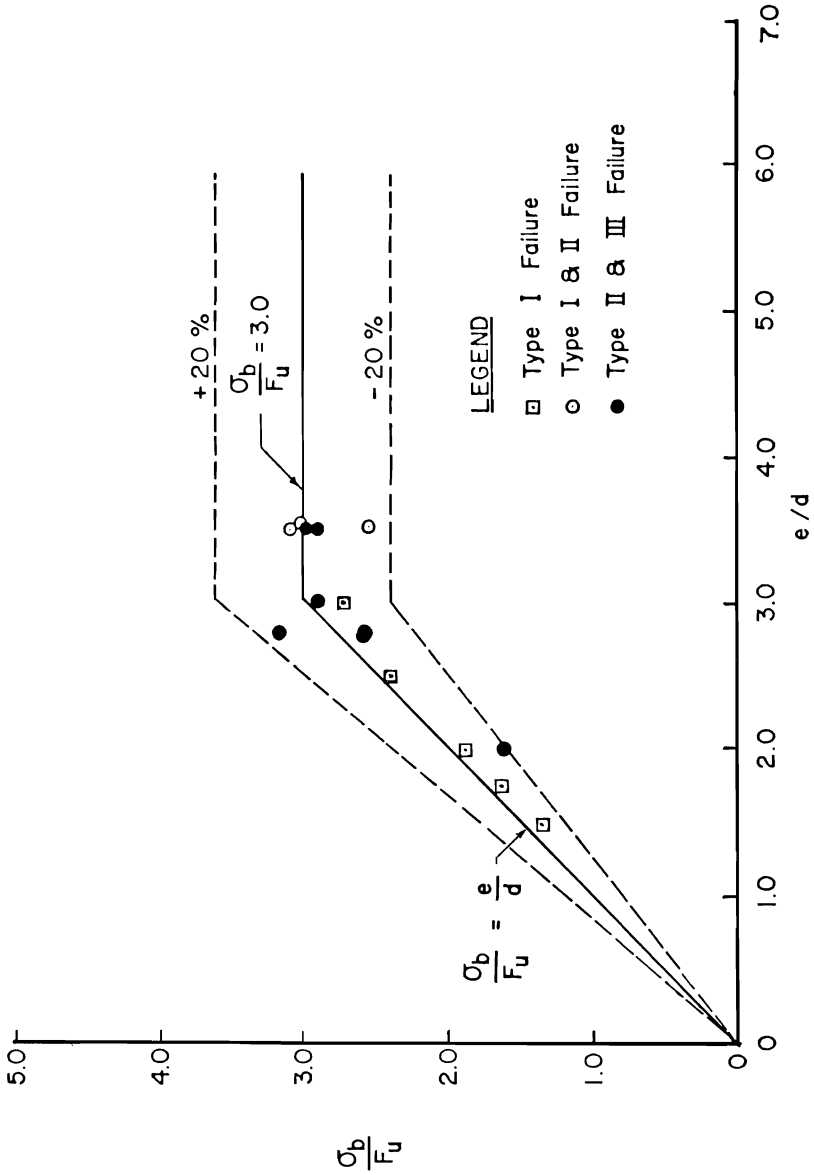


Fig. 5 Double Shear Connections with Washers, $F_u/F_y < 1.15$, Shear and Bearing Strength Study

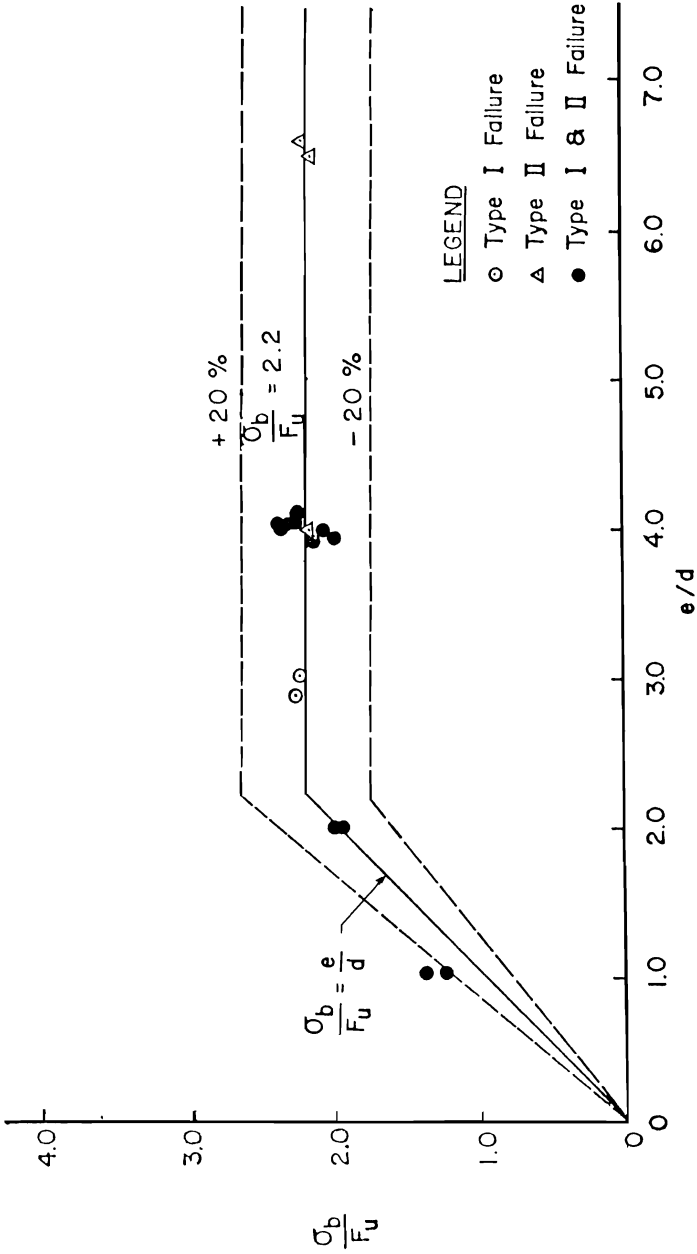


Fig. 6 Single Shear Connections without Washers, $F_u/F_y \geq 1.15$, $t \geq 0.036$ in. Shear and Bearing Strength Study

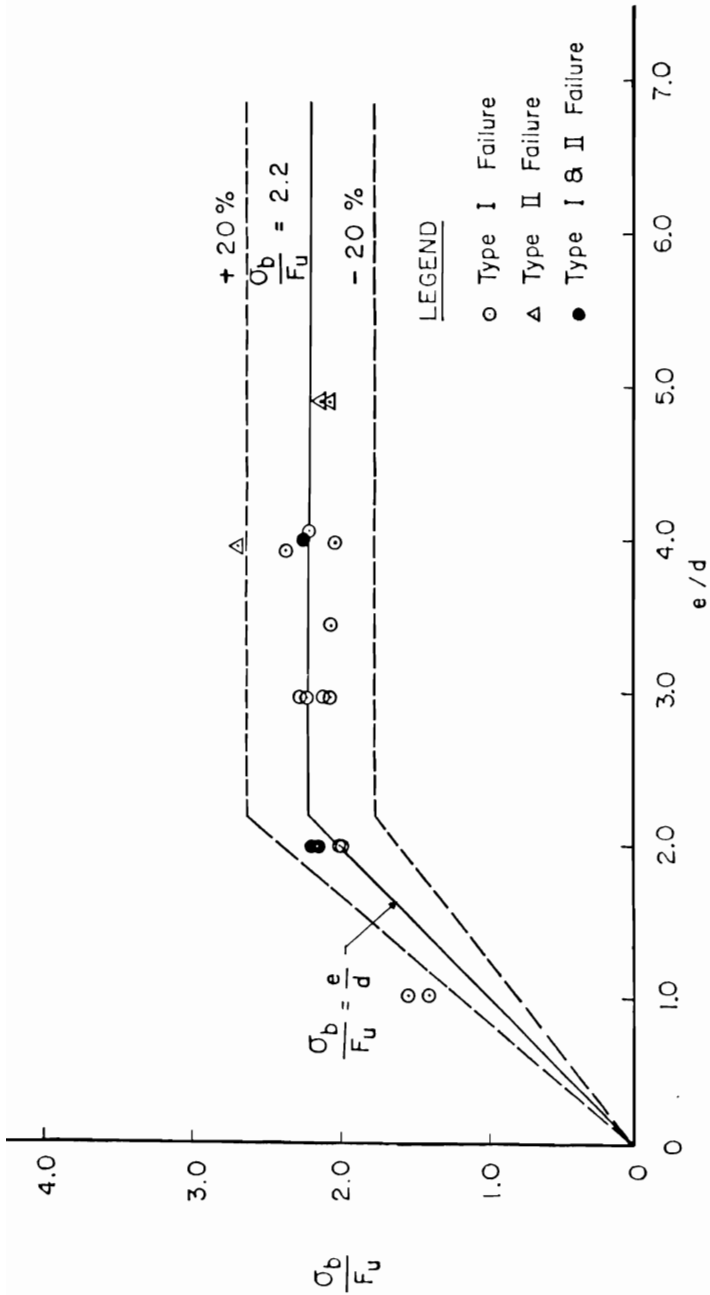


Fig. 7 Single Shear Connections without Washers, $F_u/F_y < 1.15$, $t \geq 0.036$ in. Shear and Bearing Strength Study

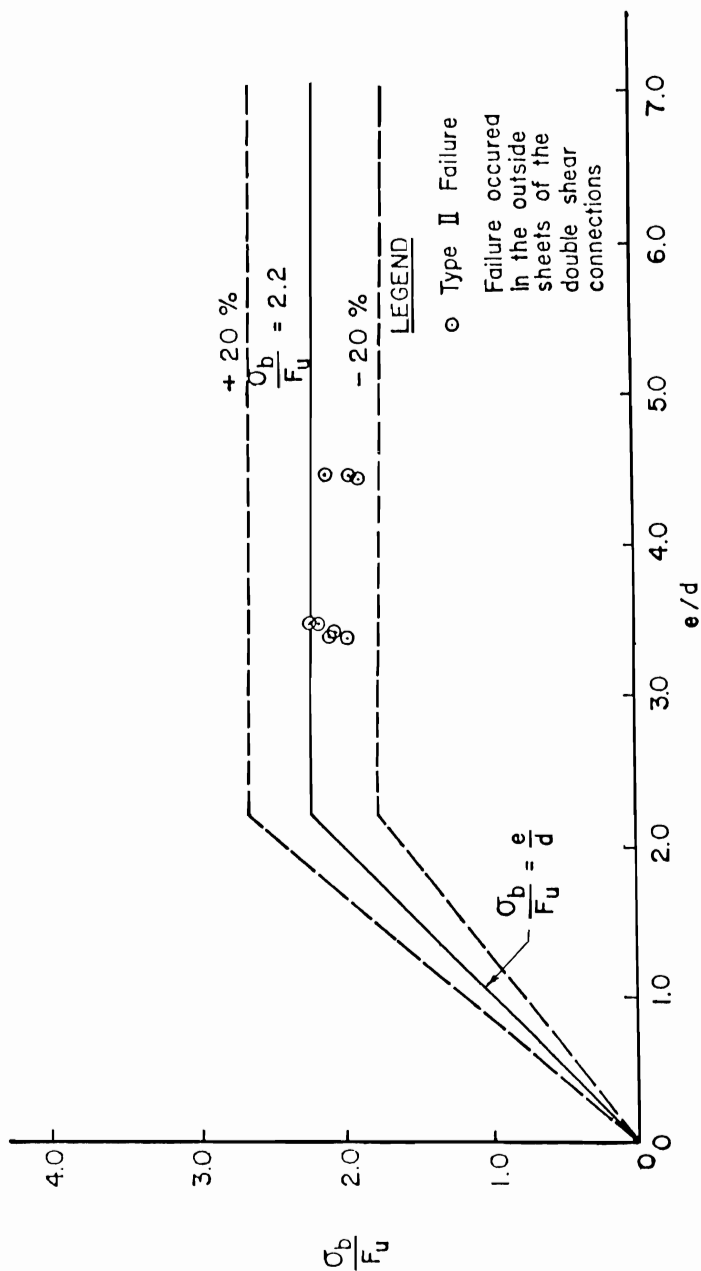


Fig. 8 Double Shear Connections without Washers, $F_u/F_y > 1.15$, $t \geq 0.036$ in. Bearing Strength Study

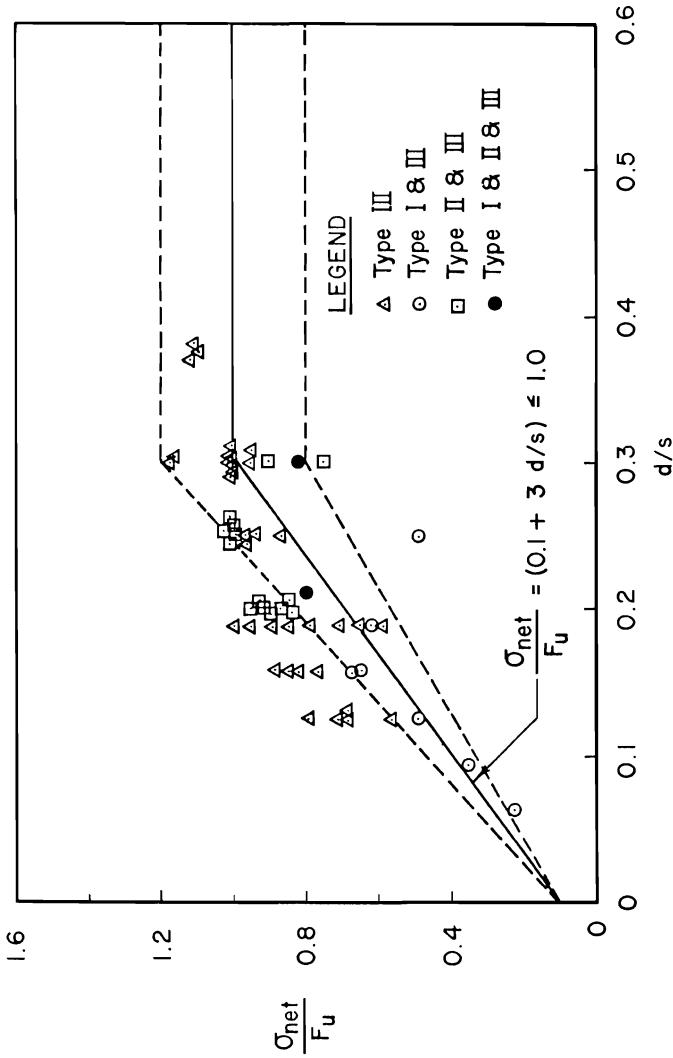


Fig. 9 Effect of d/s on Tensile Strength of Bolted Connections with Washers (Double Shear, One Bolt)

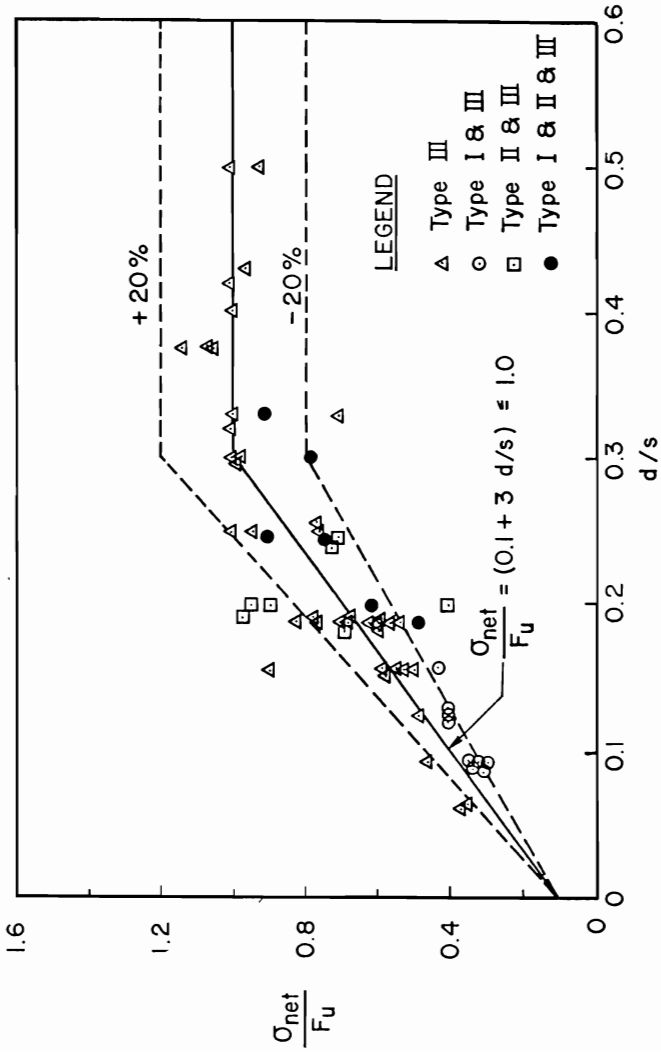


Fig. 10 Effect of d/s on Tensile Strength of Bolted Connections with Washers (Single Shear, One Bolt)

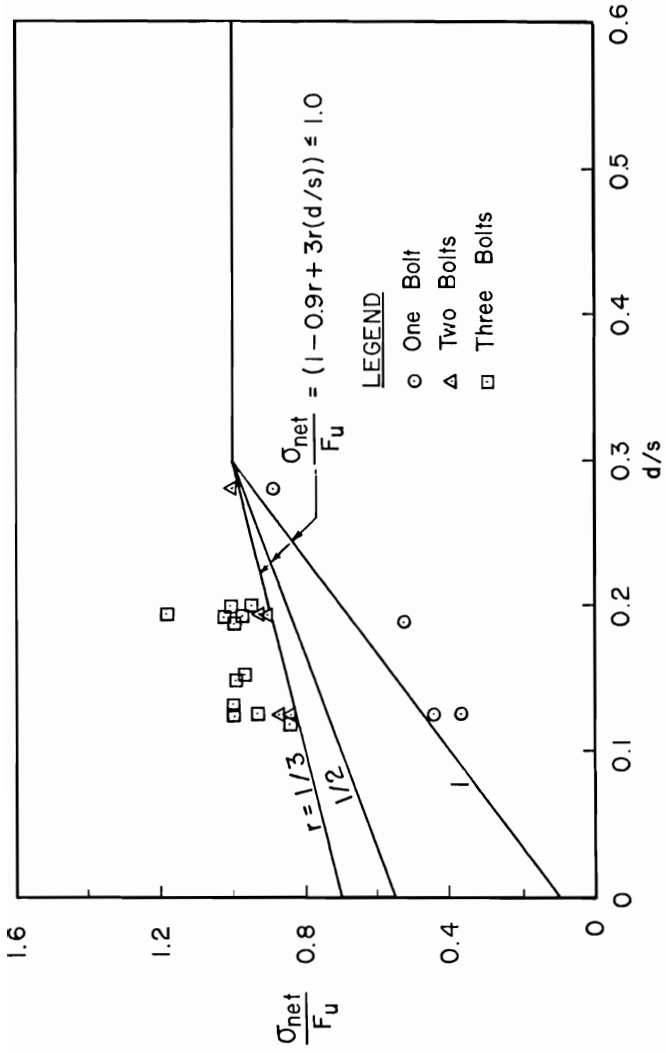


Fig. 11 Effect of d/s on Tensile Strength of Bolted Connection with Washers (Single Shear, Multi-Bolt)¹³

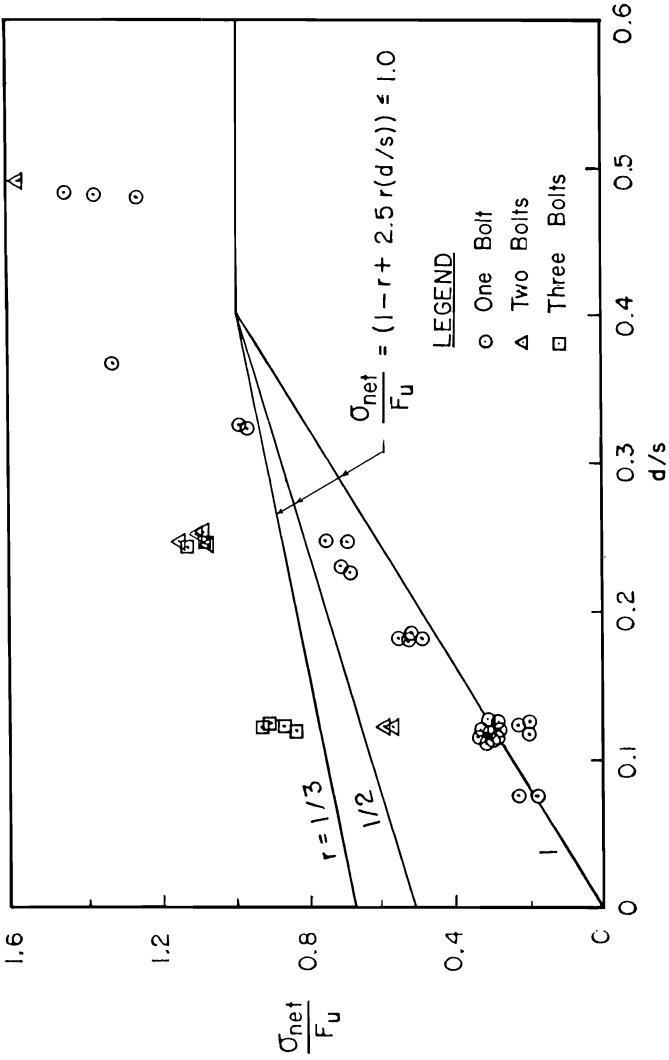


Fig. 12 Effect of d/s on Tensile Strength of Bolted Connections, Without Washers (Single Shear, Multi-Bolt)⁴

