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Bolted connections in cold-formed steel structures

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FIRST PROGRESS REPORT

BOLTED CONNECTIONS IN COLD-FORMED STEEL STRUCTURES

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I. INTRODUCTION

A. Purpose of Investigation

The design of bolted connections in cold-formed steel structures is based on the present AISI Specification for the Design of Cold-Formed Steel Structural Members.[1] Prior to the development of the design criteria, bolted connections were tested at University of Michigan[2] in the 1940's and then at Cornell University[3,4] in the 1950's. The present design provisions were developed primarily on the basis of the tests conducted by George Winter and his associates at Cornell University. Additional tests were recently made by Popowich[5] on multi-bolt connections and by Dhalla[6] on connections with low ductility steels. In these tests, the specimens were tightened to specified torques, and washers were placed under the head and nut of each bolt.

During recent years, bolted connections without washers have often been used in numerous instances. In some cases, the washers were used in the connections, but the bolts may not have been tightened according to the torques previously used in the Cornell tests. In order to study the effect of washers on connection strengths, Chong and Matlock[7] have conducted connection tests with and without washers. It was found that the bearing strengths of the connections were reduced considerably when the washers were eliminated. In addition, the parameters used by Chong and Matlock for evaluation of the tensile strength of bolted connections were slightly different from those used in the AISI Specification.

It is the purpose of this investigation to review the available test data first and then to study the applicability of the present design formulas to the connections that do not have washers and/or have improper torques.

Thin sheets will be used to make an additional study of the connection strength affected by the pretension of bolts and the behavior of bolted connections. In the study carried out to date, additional parameters, such as d/t and F_u/F_y ratios, have been considered for the evaluation of the connection strength.

B. Scope of Investigation

The present research project consists of an investigation of the structural behavior of bolted connections, a review of the current design criteria, and the conduct of additional tests to provide new design information if necessary. The following items have been planned for inclusion in this study: [20]

1) Analysis of available data
2) Effect of torque or pretension in bolts on bearing strength
3) Tensile strength of connections
4) Effect of d/t ratio on bearing strength, longitudinal shearing strength, and tensile strength of steel sheets
5) Difference between single shear and double shear conditions.

In order to achieve the objectives of the investigation, the planned research work includes the following three phases: [20]

1) Analysis of available data
2) Analytical and experimental investigation
3) Preparation of recommendations

Phase 1 of the investigation was initiated in February 1976. It was carried out by Randall L. Mosby, Research Assistant, and directed by Dr. Wei-Wen Yu, Professor of Civil Engineering at the University of Missouri-Rolla. Phases 2 and 3 will be conducted in future studies.

This progress report contains the results obtained from the analysis of the available data. It also includes the plans for future analytical and experimental investigations.

The research project was sponsored by American Iron and Steel Institute. The technical guidance provided by the AISI Task Group on Bolted Connections (L.W. Ife, T.J. Jones, R.B. Matlock, and D.S. Wolford, members) and the AISI Staff (A.L. Johnson and D.P. Cassidy) is gratefully acknowledged. Thanks are also due to J.H. Senne, Chairman of the Department of Civil Engineering, for his advice. Acknowledgment is also due to E.B. Gibson, past Chairman of the AISI Task Group, for his technical guidance.

II. ANALYSES OF AVAILABLE DATA

From the Cornell investigation, Winter[3,4] observed that there are four distinct types of failure modes in bolted connections:

TYPE I - Longitudinal shearing of the steel sheet along two practically parallel planes whose distance of separation equals the bolt diameter.

TYPE II - Shearing-tearing along two distinctly inclined planes accompanied by a considerable "piling-up" of the material in front of the bolt, or bearing failure.

TYPE III - Transverse tension-tearing across the sheet.

TYPE IV - Shearing of the bolt.

In order to provide the needed additional information on the strength of bolted connections, as discussed in Article I.A., these four types of failure have been reviewed in detail.

During the review and evaluation of the available data, due consideration was given to the following factors that may affect the load-carrying capacities of bolted connections:[20]

a. Torques or pretension used in installation of bolts

b. Ratios of e/d, d/s, and d/t

c. Use of washers

d. Single and double shear conditions

e. Number of rows perpendicular and/or parallel to the line of stress

f. Ductility of material or the effect of F_u/F_y

In the above listed factors, all symbols are defined as follows:

e = edge distance, in.

d = diameter of the bolt, in.

s = spacing of bolts normal to the direction of force - for a single bolt, it is the full width of connected sheet, in.

t = thickness of connected sheet, in.

F_u = ultimate tensile stress of sheet, ksi

F_y = yield point of steel, sheet, ksi

A. Ductility of Material

Ductility is the ability of a material to undergo plastic deformation without fracture. It can be measured by the permanent elongation of a tensile specimen after fracture. This property enables the steel to redistribute the stress when a certain part of the member yields locally.

Based on his study conducted at Cornell University, Dhalla[6,12,13] indicated that the structural strength of a bolted connection is one of the most critical problems for low-ductility steels. For the design of bolted connections, the present AISI[1] Specification states in Section 4.5 that if the ratio of tensile strength to yield point is less than 1.35, a stress equal to the minimum tensile strength of the material divided by 1.35 shall be used instead of F_y. This is an additional provision concerning the ductility of the steel to maintain a minimum safety factor of 2.2.

On the basis of Dhalla's findings, Liu[14] showed that the results of bearing tests involving both high-ductility and low ductility steels can be predicted by a single formula if a proper ductility factor is used. This factor can be determined as follows:

(a) $C_2=1$, for $F_u/F_y \geq 1.35$ (1)

(b) $C_2=1.43\ (F_u/F_y)-0.93 \geq 0.643$, for

$$1.05 < F_u/F_y < 1.35 . \qquad (2)$$

Table 1 contains the test results obtained by Dhalla[6]. The results involve both high-ductility and low-ductility steels, and the F_u/F_y ratios range from 1.57 to 1.04. These data are plotted in Figures 1, 2, and 3 for different tensile strength to yield point ratios. In order to show the effectiveness of the ductility factor, Dhalla's data have been replotted in Figure 4. By using C_2, as determined by Equation (1) and (2), good correlation can be found between Winter's tests on high-ductility steels and Dhalla's tests on low-ductility steels.

B. Bearing Strength

1. General

Based on the tests performed at Cornell[8,9,10,11], Winter[3,4] concluded that when the edge distance of a bolt connection is relatively large a type of failure by bearing will control the load carrying capacity of the connection. Test results indicate that when the e/d ratio equals or exceeds 3.5 the bearing stress can be conservatively determined by Eq. (3):

$$\sigma_b = 4.9\ F_y \qquad (3)$$

where σ_b = ultimate bearing stress, ksi.

The AISI[1] design equation for allowable bearing stress for thin, cold-formed steels is derived from Eq. (3) by applying a safety factor of 2.33, i.e.,

$$F_p = 2.1\ F_y \qquad (4)$$

where F_p = allowable bearing stress, ksi.

As previously discussed in Section II.A., the ductility of steel is an important parameter for the bearing strength of a bolted connection. From the study made by Liu,[14] the following modified equations can be used to determine the ultimate and allowable bearing stresses for any type of steel:

$$\sigma_b = 4.9\ C_2F_y \tag{5}$$

$$F_p = 2.1\ C_2F_y^*. \tag{6}$$

The factor C_2 can be determined by Eqs. (1) and (2), whichever is applicable.

2. Torque Used in Installation

The present design provisions governing the bearing strength of a bolted connection are based on the early tests performed at Cornell,[8,9,10,11] for which all the bolts were torqued to the specified values. The torques used for ordinary A307 bolts are given in Table 13. Table 14 is a list of the torques used for high strength A325 bolts. The additional research of Popowich[5], Dhalla[6], and Chong and Matlock[7], is also based on these torques.

In the investigation of Liu[14], the torques used for the high strength bolts were the same as those used for the A307 ordinary bolts. This was done in a hope that the high-strength bolts would behave in the same was as ordinary bolts insofar as the bearing capacity between the connected part and bolt was concerned. Even though no specific conclusion was drawn for the effect of low values on bearing strength, satisfactory results have been obtained by using the specified minimum torques.

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*Recommended in Ref. 22.

Because the effect of torques on the bearing strength of bolted connections has not been fully studied in the past, further investigation should be carried out in this area.

Recently, there have been indications that the minimum torque requirements do not guarantee the proper tension in the bolts. Consequently, the test data often show inconsistent results. In view of the fact that the method of installation of high strength bolts for thick hot-rolled shapes cannot be directly used for thin, cold-formed sections due to the differences in grip length and size of bolts, a new method of installation should be developed.

3. Effect of e/d Ratio

As mentioned in the previous section, when the e/d ratio is equal to or greater than 3.5 the strength of connection is limited by the bearing capacity determined by Eq. (5). Test results indicate that when the e/d ratio is less than 3.5 longitudinal shearing of the steel sheets will occur. This type of shearing failure is discussed in Section II.C.

The present AISI design equation for the determination of the bearing stress applies to both single and double shear connections. In order to verify the use of Eq. (5) to both types of connections, test data obtained from Cornell[8,9,10,11], Dhalla[6], Liu,[14] and Chong and Matlock[7] have been analyzed and are given in Tables 2, 3, and 4. A graph of σ_b/C_2F_y vs. e/d, which has been constructed with these data, is shown in Fig. 5.

It can be seen that when e/d is equal to 3.5, the experimental values of σ_b/C_2F_y for both single and double shear connections can be predicted by Eq.(5). For larger e/d ratios, Eq. (5) provides a better prediction of σ_b/C_2F_y for single shear connections than double shear connections. The double shear condition gives a more conservative result on bearing strength.

It should be noted that by using the ductility factor C_2, determined by Eqs. (1) and (2), Eq. (5) can be generalized for both high-and-low-ductility steels.

4. Effect of d/t Ratio

The present design equation for bearing stress has been developed for $e/d \geq 3.5$. Since the diameter of the bolt to the thickness of the material ratio, d/t, is much larger for cold-formed steel connections than hot-rolled shapes, it was believed that the d/t ratio might affect the bearing strength of the connection. In order to study the effect of the d/t ratio on the bearing strength, the test data obtained from previous work [6-11,14] were analyzed and are listed in Tables 2, 3, and 4 of Appendix B. These results of tests were obtained from specimens with e/d ratios greater than 3.5 that failed either in bearing or a combination of bearing and other type of failure.

For single shear connections, the ratio of bearing stress at failure to yield point, σ_b/C_2F_y, has been plotted versus d/t as shown in Fig. 6. From a least squares analysis, the following equation was obtained:

$$\sigma_b/C_2F_y = 4.31 + 0.071\ d/t. \qquad (7)$$

From Eq. (7) it can be seen that as the d/t ratio increases there is a slight increase in the bearing stress. However, for double shear connections, Eq. (8) shows that the bearing stress decreases slightly as the d/t ratio increases;

$$\sigma_b/C_2F_y = 5.35 - 0.03\ d/t. \quad (8)$$

Even though Eqs. (7) and (8) may be used to predict the changes in the bearing stress for the increase of d/t, the effect of d/t is considered to be relatively small. It should be noted that in the region of $9 \leq d/t \leq 15$ only a limited amount of data are available for a detailed study. It appears that further investigation might be needed for this region of d/t ratio.

For single shear connections without washers, no significant effect was noted on the bearing stress for various d/t ratios as shown in Fig. 8.

5. Effect of Washers

The present design provisions for the bearing stress of bolt connections in cold-formed steel design are based on the tests performed at Cornell on specimens with washers both under bolt head and nut. In order to study the effect of washers on bearing strength of connections, Chong and Matlock[7] conducted a study of bolted connections without washers, for which the maximum bearing stress at failure was found to be about 45% less than those with washers. Consequently, Eq. (9) was proposed in Ref. 7 for the prediction of the ultimate bearing stress of connections without washers;

$$\sigma_b = 2.7\ F_y \quad \text{for } e/d > 2.5. \quad (9)$$

It should be noted that for connections without washers a bearing type of failure will occur for small e/d ratios as compared to the connections with washers.

If one considers the effect of ductility on bearing strength of bolted connections, Eq. (9) may be modified by using the C_2 factor as shown in Eq. (10);

$$\sigma_b = 3.5\ C_2F_y \quad \text{for } e/d > 2.5. \tag{10}$$

The correlations of the tested bearing strengths and the predicted values on the basis of Eq. (10) are shown graphically in Fig. 9. Table 4 gives the mean value and standard deviation of the ratios between the computed and tested results.

By using a safety factor of 2.3, the allowable bearing stress for bolted connections without washers can be determined as follows:

$$F_p = 1.5\ C_2F_y \quad \text{for } e/d > 2.5^* \tag{11}$$

6. Tentative Recommendations

As stated earlier, Dhalla[6] has indicated that the ductility of the steel affects the strength of a bolted connection particularly for bearing capacity. It appears that the present design equation for the determination of bearing stress may be modified by using the C_2 factor as shown in Eqs. (6) and (11) for bolted connections with and without washers, respectively.

A review of the available data indicates that the effect of torque on the bearing strength of bolted connections has not been fully investigated. A study of the effect of torque or pretension in bolts may include the following conditions, which were proposed in Reference 20:

a. No torque or pretension in bolts

b. With the same pretension in bolts as specified by the Research Council on Riveted and Bolted Structural Joints (Table 15)

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*Recommended in Ref. 22.

c. With the same torque used in the previous Cornell Tests (Table 12)

The test data obtained from Case (c) above will be compared with those obtained from Cases (a) and (b).

It has been shown from the available data that the d/t ratio has little effect on the bearing strength. However, further study appears to be needed in the region of d/t ratios from 9.0 to 15.0.

Based on their investigation of bolted connections without washers, Chong and Matlock[7] concluded that the bearing strength is actually 45% less than that for connections with washers. However, if the ductility of steel is considered, the bearing strength is found to be 29% less than that with washers. It should also be noted that the test specimens used by Chong and Matlock consisted of single shear connections only. Further study should be conducted for both single and double shear connections without washers and for connections using steel sheets thinner than 0.036 in.

C. Longitudinal Shearing Strength of Steel Sheets

1. General

As discussed in the preceding section, if the edge distance in line of stress is insufficient, longitudinal shearing of the connected sheets will occur along two practically parallel planes. Based on his research work, Winter concluded that when the e/d ratio is less than about 3.5, the bearing stress to yield point ratio increases with the increasing e/d. It can conservatively be represented by the following straight line equation:

$$\sigma_b/F_y = 1.4\ e/d. \qquad (12)$$

By inserting $\sigma_b = P_u/dt$ into Eq. (12), (P_u being the failure load, per bolt), the nominal shear stress in the two failure planes can be determined by Eq. (13):

$$\tau_s = P_u/2te = 0.7\ F_y. \qquad (13)$$

By applying the ductility constant C_2 as determined by Eqs. (1) and (2), the following modified equation can be used to predict the shear strength of a bolted connection:

$$\tau_s = 0.7\ C_2F_y \quad \text{for } e/d < 3.5. \qquad (14)$$

2. Torque Used in Installation

As mentioned in Section II.B.2, in the majority of the tests performed on bolted connections, A307 and A325 bolts that have been torqued to the specified values have been used. The exact effect of torque on the bearing strength is a specific area of needed research. It has been shown by Winter that for connections with e/d ratios less than 3.5 a shearing type of failure will occur if washers are used under both head and nut. This conclusion is based on the results of tests for which the bolts were torqued to the specified values as given in Tables 13 and 14.

When bolted connections with e/d ratios less than 3.5 and bolts with torques that satisfy the specified values are used, a shear type of failure may be prevented because the friction between the connected sheets is increased and causes a larger failure load.

Because there is not sufficient data concerning the effects of torque on the shearing strength of steel sheets of a bolted connection, further tests are needed in this area.

3. Effect of e/d Ratio

As pointed out in Section II.C.1, Eqs. (12) and (14) are valid only when e/d does not exceed 3.5. Within this range, the structural strength of the bolted connection is governed by a longitudinal shearing type of failure.

In the AISI Specification, Equations (12) and (14) are presently used for both single and double shear connections. In order to determine the possible differences between these two types of connections, the test data obtained from previous investigations[6-11,14] have been analyzed and are given in Tables 5, 6, and 7. These data deal with the specimens that have failed in longitudinal shearing of the sheets with e/d ratios less than 3.5.

Figures 10 and 11 show the correlation between the test data and the predicted values for single and double shear connections, respectively. Because the ductility factor, C_2, is used in the ratio of bearing stress to yield point, both high- and low-ductility steels can be combined in the same graph.

It can be seen from Figs. 10 and 11 that most of the test data for both single and double shear connections is on the conservative side of that predicted by Eq. (12). There is no major difference for the two types of connections.

4. Effect of d/t Ratio

As mentioned in Article II.B.3, there is a question concerning the effect of the d/t ratio on the bearing strength of a bolted connection. From the studies made on bearing strength, it has been found that for connections with e/d ratios larger than 3.5, the effect of d/t is negligible. However, further investigation may be needed for connections with d/t ratios from 9 to 15.

In order to study the effect of d/t on connections with e/d ratios less than 3.5, the available data[6-11,14] have been analyzed and are given in Tables 5, 6, and 7. In Figs. 12 through 15, the tested data have been plotted separately according to the single or double shear type of connections and to the actual value of the e/d ratios.

For the single shear connections with e/d equal to 1.5, it can be seen from Fig. 12 that the actual bearing stress at the failure load resulting from the shearing strength of the steel sheets is not affected by the d/t ratios. But, for the double shear connections with the same e/d ratio of 1.5, there is a slight increase in the bearing stress for an increase in the d/t ratio as shown in Fig. 13. The effect of d/t can be described by the following equation:

$$\sigma_b/C_2F_y = 2.47 + 0.024\ d/t. \qquad (15)$$

When the e/d ratio is increased to 2.5, it can be seen from Fig. 14 that the d/t ratio does not affect the bearing stress in single shear connections. However, for the double shear connections with the same e/d ratio, test data show a slight decrease in the bearing stress for increasing d/t. See Fig. 15. The following equation can be used to determine the effect of d/t ratio on bearing stress, σ_b:

$$\frac{\sigma_b}{C_2F_y} = 4.22 - 0.04\ d/t. \qquad (16)$$

5. Effect of Washers

The present equation used for the determination of the shearing strength of steel sheets of a bolted connection is based on the test specimens that have had washers placed under both the heads and nuts of the bolts. From Chong and Matlock's[7] study on bolted connections without washers, it has been found that the shear stress in steel sheets at failure is less than that for connections with washers. Consequently, for bolted connections with e/d ratios less than 2.5, the bearing stress can be determined as follows:

$$\frac{\sigma_b}{F_y} = 1.08\ (e/d). \tag{17}$$

Because $\sigma_b = P_u/dt$, then at failure the shear stress in the two parallel planes of the steel sheets is

$$\tau_s = \frac{P_u}{2te} = 0.54\ F_y. \tag{18}$$

The above equation indicates a 23% reduction in shear strength when washers are not used.

Considering the actual ductility of steel, Eq. (17) may be modified by using a factor C_2 as follows:

$$\frac{\sigma_b}{C_2 F_y} = 1.4\ (e/d). \tag{19}$$

The comparisons of the test results and the predicted values are shown in Fig. 16 . Based on Eq. (19) and a factor of safety of 2.3, the following design equation can be used for the determination of the minimum edge distance in lieu of stress when $e/d \leq 2.5$:

$$e_{min} = P/(0.6\ C_2 F_y t)^* \tag{20}$$

6. Tentative Recommendations

As a result of the difference in ductility of various types of steels, the AISI requirement for the minimum spacing and edge distance of a bolted connection can be modified by using the ductility factor, C_2, as discussed in Sections II.A and II.C.(5). Therefore, the clear distance between bolts and the distance from the center of any bolt to the end of the connection member toward which the pressure of the bolt is directed shall not be less than 1 1/2 d nor less than e_{min} determined by Eq. (20).

Because most of the previous studies on the longitudinal shear strength of bolted connections have been performed on specimens that have been torqued to the same specified values, it appears that additional tests in which various amounts of torques are used should be conducted on bolted connections. In addition, connections with bolts pre-tensioned to the values specified by the Research Council on Riveted and Bolted Structural Joints (Table 15) should be investigated.

Further study is needed for bolted connections without washers to conform to Eq. (19).

D. Tensile Strength

1. General

In the design of hot-rolled steel shapes, it is a general practice to assume that the average stress on the net section of a tension member can reach the yield point of steel. This assumption is based on the fact that the effect of stress concentrations at bolt holes is rendered insignificant by plastic stress redistribution. From the results of the Cornell investigation, Winter[3,4] concluded that for test specimens failed by tearing in the net section the complete disregard of stress concentrations is not warranted for bolted connections in cold-formed steel construction. He pointed out that the d/s ratio has a decided influence on the failure stress. For the condition of one bolt in the line of stress, the tension stress at failure can be represented by

$$\sigma_{net} = (0.10 + 3.0\ d/s)\ F_u \leq F_u. \qquad (21)$$

The above equation indicates that when the d/s ratio exceeds 0.30 plastic redistribution eliminates completely the effect of stress concentration in the same manner as hot-rolled sections.

A recent study conducted at Cornell by Popowich[5] has shown that the sharp stress concentration can be much relieved when more than one bolt in line is used. As a result, the failure in the net section for two-bolt and three-bolt tests occurred at a much higher stress than for single bolt connections. As a general design criterion, the following formula has been developed to predict the failure stress in the net section for single and multibolt connections:

$$\sigma_{net} = [1 - 0.9\ r + 3\ r\ (d/s)]\ F_u \leq F_u \qquad (22)$$

where σ_{net} = failure stress in net section

r = force transmitted by the bolt or bolts at the section considered, divided by the force in the member at that section

From Eq. (22), it can be seen that when r is equal to 1.0 the same equation (Eq. (21)) developed by Winter can be obtained.

The present AISI[1] Specification states that "the tension stress on the net section of a bolted connection shall not exceed 0.6 F_y nor shall it exceed

$$(1.0 - 0.9\, r + 3\, rd/s)\; 0.6\, F_y \qquad (23)$$

It should be noted that Eqs. (21) to (23) apply to both single and double shear connections. Equations (21) to (23) are based on single shear tests only. It appears that additional tests may be needed for double shear, multibolt connections so that these two equations can be verified for both types of connections.

2. Effect of Ductility

The effect of the ductility of steel on the structural strength of bolted connections was discussed in Section II.A. Modified equations were given for the determination of the bearing stress and the longitudinal shear strength of steel sheets. Based on his recent study[6], Dhalla concluded that the ultimate tensile strength is not affected by the ductility of the steel.

Equations (21) and (22) are based on the specified tensile strength to yield point ratios equal to or greater than 1.35. When the ratio is less than 1.35, the present AISI Specification requires that a stress equal to the specified minimum tensile strength divided by 1.35 be used instead of F_y in the design formulas.

From the tests conducted at Cornell, Winter[15] concluded that the load at which tearing occurs correlates better with the tensile strength than with the yield point of the steel. By letting $F_y = F_u/1.35$, Eq. (23) can be written in terms of the tensile strength of the steel as follows:

$$(1.0 - 0.9\, r + 3\, rd/s)\, 0.44\, F_u. \qquad (24)$$

Equation (24) allows one to determine the allowable tensile stress on the net section of a bolted connection on the basis of the ultimate strength of the steel sheets.

3. Effect of d/s Ratio

As mentioned in Section II.D.1, the tensile strength of a bolted connection is dependent upon the d/s ratio, F_u and the number of bolts in the line of the load and can be predicted by Eq. (22). Even though some of Winter's tests with low d/s ratios showed the net stresses in excess of F_u, the ultimate tensile strength of steel sheets has been regarded as an upper limit for Eq. (22).

When a bolted connection is composed of only one bolt in the line of stress, Eq. (22) can be simplified to Eq. (21). The results of the Cornell tests for both single and double shear connections that failed by tearing across the net section are given in Tables 8 through 12. Figures 17 and 18 are plots of σ_{net}/F_u vs. d/s for single shear connections with high- and low-ductility steels, respecitvely. From Fig. 19, which is a combination of Figs. 17 and 18, it can be seen that Eq. (21) gives a good prediction of the tensile strength of single shear connections composed of high- and low-ductility steels. It can be concluded that the ductility has little effect on the tensile strength of a single shear connection.

Figures 20 and 21 are plots of σ_{net}/F_u vs. d/s for double shear connections with high- and low-ductility steels, respectively. If Figs. 20 and 21 are combined as shown in Fig. 22, it can be seen that for double shear connections Eq. (21) gives a conservative prediction of the test results. Again it can be concluded that the ductility has little effect on the tensile strength of a bolted connection.

Figure 23 is a plot of σ_{net}/F_u vs. d/s for multibolt connections based on the data obtained by Popowich[5]. Details of the results are given in Table 12. Equation (22) is shown for r = 1, 1/2, and 1/3. It can be seen that when r = 1/2 and 1/3, Eq. (22) gives a conservative prediction of the test results. As mentioned earlier, the data shown in Fig. 22 are for single shear connections only. Additional tests may be needed for double shear connections that are governed by tensile strength.

4. Effect of d/t Ratio

The present AISI equation for determining the tensile strength of a bolted connection is dependent upon the dimensional parameters d and s. An investigation, similar to studies of bearing and shear strengths made in Sections II.B.3 and II.C.3, was made on the effect of the d/t ratio on the tensile strength.

Test data obtained from the Cornell tests have been studied and are presented in Tables 8 through 12. In order to determine the effect of the d/t ratio on the tensile strength, the nondimensional ratios of $(\sigma_{net})_{cal}/(\sigma_n)_{test}$ are plotted against d/t in Figs. 24 to 26 for the same d/s ratios. These data are separated according to single and double shear connections that have multibolt conditions. From these figures, it can be seen that the d/t ratio has no significant effect on the tensile strength of bolted connections. It appears that a further study of the combination of d/t greater than 10.0 and d/s less than 0.15 is desirable.

5. Effect of Washers

The present equation for the tensile strength of a bolted connection is based on tests in which washers were used under both the heads and nuts Chong and Matlock , who studied the bolted connections without washers, developed the following equation for the tensile strength in net section:

$$\sigma_{net} = [0.6 - 0.66\ r + 2.92\ (d/s)]\ F_u \leq F_u . \qquad (25)$$

The above equation indicates that the tensile strength of the net section depends on the parameters "r" and "d/s". However, Eq. (22) developed by Winter for bolted connections with washers depends on the parameters r and rd/s. For this reason, further study will be made in this project to determine the appropriate parameters to be used in the prediction of tensile strength.

6. Tentative Recommendations

The preceding discussion indicates that Eq. (22) may be used for the determination of the tensile strength of a bolted connection. This equation uses the tensile strength of the steel rather than the yield point.

As a result of the different parameters involved in Eqs. (22) and (25) for connections with and without washers, respectively, further research will be conducted in this area.

E. Shearing Strength of Bolts

The shearing strength of bolts depends on the mechanical properties of the bolt, the number of shear planes, joint length, pretension in bolts, surface condition between connected parts, hole clearance, and the type of loading condition. Numerous double and single shear tests have been conducted at Cornell University to study the type of failure in which shearing of the bolt for light gage steel bolted connections occurs. On the basis of an investigation of the shear strength of connections for which ordinary bolts were used, Winter concluded that the maximum shear capacity of bolt correlates better with the tensile strength than with the yield point of the bolt material. The shear stress at failure on the root area can be determined by the following equation for single shear connections:

$$\tau_b = 0.72 F_{u_b}. \tag{26}$$

For double shear connections, the shear stress is

$$\tau_b = 0.62 F_{u_b} \tag{27}$$

where F_{u_b} is the ultimate tensile strength of the bolt. The higher shear stress for the single shear tests is believed to be due to two reasons: (1) Because of the bending and warping of the sheet, the bolt develops an oblique position, which results in a decrease of the shear stress on the normal section, with a simultaneous occurrence of tension. Because steel is stronger in tension than in shear, there is an increase in bolt resistance. (2) Although the failures of double shear tests occur in two parallel shear planes, the planes are so close to each other that some mutual weakening is conceivable for light gage steel.

Because shear failures of bolts are more sudden than those for sheets, Winter has suggested the following conservative equation for both single and double shear connections:

$$\tau_b = 0.60 F_{u_b}. \tag{28}$$

Additional tests were also conducted at Cornell on light gage steel connections with high-strength bolts. From this study, Winter[4] concluded that the equations developed from the corrections with ordinary bolts also apply to connections for which high-strength bolts are used. By using high strength bolts, the required number of bolts can be reduced, and the slip at design loads can be eliminated.

In the AISI Specification, the allowable shear stress on the gross sectional area of the bolt cannot exceed the following values:

1) For ASTM A307 bolts,

$$F_v = 10 \text{ ksi.} \tag{29}$$

2) For ASTM A325 bolts,

when threading is excluded from shear planes,

$$F_v = 22 \text{ ski*;} \tag{30}$$

and when threading is not excluded from shear planes,

$$F_v = 15 \text{ ksi*} \tag{31}$$

where F_v = the allowable shear stress.

These values are the same as the AISC Specification. It should be noted that the allowable shear stresses included in the AISI Specification are for the bearing-type connections only. No provisions are included for the design of friction-type connections.

In their recent study, Chong and Matlock[7] concluded that for bolted connections without washers the allowable shear stress on the gross cross-sectional area of bolts is the same as that for the connections using washers.

F. Other Specifications

The specifications being used in Canada and several European countries for the design of bolted connections have been briefly reviewed. The following is a comparison of some of the design criteria:

1. Minimum Edge Distance in Line of Stress

Concerning the minimum edge distance for a bolted connection, the Canadian Standard[16] specifies that

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*Higher allowable shear stresses on bolts have been proposed by subcommittee 3 of the AISI Advisory Group on Specification[22]

$$e \geq 1.5 \, d \tag{32}$$

and

$$e \geq \frac{P}{F^* t} \tag{33}$$

where F^* is the design stress based on working stress design. In addition, the limit states design may be used. The above two equations are practically identical with the AISI design provisions except that in Eq. (33) the design stress F^* shall be equal to the basic design stress F or $(F_u/r.35\ F_y)$ F, whichever is smaller.

The British[17] and French[19] specifications allow the same requirements for the edge distance for cold-formed steel as those used for hot-rolled bolted connections.

The edge distance of bolted connections in thin-walled steel structures is also one of the requirements in the Swedish recommendations.[18]

Based on the edge conditions, it requires that for unstiffened edges, the edge distance, e, is

$$1.5\ d \leq e \leq 2.5\ d.$$

For a stiffened edge, the edge distance should not exceed five times the nominal diameter of the bolt.

The above discussion indicates that in the Swedish recommendations, the minimum requirement for the end distance is similar to the AISI Specification with additional limitations.

2. Allowable Bearing Stress

With regard to the design criteria for the bearing strength of a bolted connection, the Canadian Standard is similar to the AISI Specification. The allowable bearing stress permitted by the British Standard is 0.8 F_y, which is considerably smaller than that permitted by AISI. In the French recommendation, the allowable bearing stress is determined as four times the allowable tensile strength of the steel sheets. The allowable bearing stress, permitted by the Swedish recommendations, depends on the bolted joint class, bolt quality, number of shear planes, stress grade of steel sheets, and loading conditions. For typical load cases, the allowable bearing stress varies from 0.55 F_y to 0.72 F_y.

3. Allowable Tension in Net Section

A similar allowable tension stress is being used in Canada and Sweden as that specified by the current AISI design specification. In Great Britain and France, the same allowable tension stress is used for cold-formed steel members and hot-rolled shapes.

4. Allowable Shear Stress on Bolts

The Canadian Standard permits the same allowable shear stress for A307 bolts as the AISI Specification and slightly higher values for high strength bolts. In Great Britian and France, the same allowable shear stresses are used for thin-walled, cold-formed steel members and hot-rolled shapes.

III. SUMMARY AND CONCLUSIONS

In the United States and some other countries, the design of bolted connections in cold-formed steel structures is based on the AISI Specification for the Design of Cold-Formed Steel Structural Members. The first phase of this investigation has been conducted for the purposes of reviewing the available test data on bolted connections and studying the needed additional design criteria for the 1968 Edition of the AISI Specification concerning minimum edge distance, allowable tension on net section, allowable bearing stress in bolted connections, and allowable shear stress on bolts.

Based on the analysis of available test data, it was found that the spread between the ultimate tensile strength and yield point of the steel sheets (i.e., F_u/F_y ratio) affects considerably the bearing strength of bolted connections and the shear strength of steel sheets particularly when $F_u/F_y < 1.35$. The tests made at Cornell have shown that the decrease of F_u/F_y ratio results in a reduction of bearing strength of the connection. However, the tensile strength of the connection is not affected significantly by the F_u/F_y ratio. In order to consider the effect of F_u/F_y ratio, the present AISI design formulas for the allowable bearing stress and the minimum edge distance can be modified simply by using an equivalent yield point "C_2F_y" to replace F_y in the 1968 Edition of the Specification.

A study of the difference between single shear and double shear conditions indicates that the double shear condition can provide a slightly higher bearing strength than the single shear condition. For the sake of simplicity, no modification of the present design criteria appears to be necessary.

The effect of the d/t ratio on the strengths of bolted connections was also investigated. It was found that in general the d/t ratio has little or no effect on the bearing strength of bolted connections, the longitudinal shear strength of steel sheets, and the tensile strength of net section.

The test data published by Chong and Matlock on bolted connections without washers show that the washers play an important role in the bearing and tensile strengths of connections. These data were reviewed and analyzed in the text. Design formulas are also proposed in this report.

The second phase of the project will include analytical and experimental investigations concerning the effect of torque on bearing strength, tensile strength of net section, bearing strength of thin sheets, effect of d/t, and effect of washers. Details of the planned work are discussed in Article IV of the report.

IV. FUTURE STUDY

On the basis of the research proposal submitted to American Iron and Steel Institute in 1975[20] and the analysis of available test data on bolted connections conducted in this investigation, the following future studies are planned to be carried out in the second phase of this investigation.

1. Effect of ~~Torque~~ Preload on Bearing Strength of Bolted Connections

In the study of the effect of ~~torque~~ preload on bearing strength, the following parameters will be considered:

A. ~~Torque or~~ initial tension in bolts

1) No ~~torque~~ snug tight

2) Same torque as used in the Cornell tests (See Tables 13 and 14)

3) Same initial bolt tension as specified by the Research Council on Riveted and Bolted Structural Joints (See Table 15)

B. Thickness of steel sheets

$t = 0.024$, 0.06, and 0.105 in.

C. Diameter and material of bolts

$d = 1/4$ to 3/4 in.

Use A307 bolts and high strength bolts (A325 bolts) as appropriate.

D. Ratio of e/d

$e/d = 1.5$, 2.5, 3.5, and 4.5

E. Washers

Tests will be conducted with and without washers

F. Ratio of F_u/F_y

$F_u/F_y = 1.1$ to 1.80

This means that any steel sheets or strip having an F_u/F_y ratio within the above range can be used for the tests.

G. Number of rows perpendicular and parallel to the line of stress

Use one-bolt condition ($r = 1.0$)

H. Use single shear condition only. It is assumed that the effect of torque is approximately the same for single and double shear conditions.

I. The ratios of d/s and d/t are not specified for this portion of the study. They will be determined as required by the tensile strength of the connection and other practical considerations.

With regard to the pretension in bolts indicated in Item A.(c), it appears that new methods of measuring the pretension need to be developed.

The findings to be obtained from this portion of the investigation may also be used for the longitudinal shear strength of steel sheets.

2. Tensile Strength of Net Section

Because the purpose of studying tensile strength was to reevaluate the parameters to be used for determining the allowable tensile stress in bolted connection design, the following variables will be considered in the analytical and experimental investigations:

A. Torque or initial tension in bolts

Use initial tension in bolts as specified by the Research Council if new methods for measuring initial tension are available. Otherwise, the torque used for Cornell tests will be used for this portion of study.

B. Thickness of steel sheets

t = 0.024, 0.06, and 0.105 in.

C. Diameter and material of bolts

d = 1/4 to 3/4 in.

Use A307 and A325 bolts

D. Ratio of e/d

$e/d \geq 3.5$

E. Washers

Tests will be conducted with and without washers

F. Ratio of F_u/F_y

The F_u/F_y ratio of the steel used will be within the range of 1.10 to 1.80.

G. Number of rows perpendicular and parallel to the line of stress

r = 1, 1/2, and 1/3 (use one, two, and three rows parallel to the line of stress) Few tests may be conducted for multiple rows both perpendicular and parallel to the line of stress.

H. Use both single shear and double shear conditions.

I. Ratio of d/ s

d/s = 0.1, 0.2, 0.3, and 0.4

3. Other Subjects

Other future studies will be planned at a later date as necessary.

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APPENDICES

APPENDIX A

Notation

e = edge distance, from center of bolt hole.

d = diameter of the bolt

s = spacing of bolts normal to direction of force; for single bolt at section, it is full width of connected sheet

t = thickness of connected sheet

F_u = ultimate tensile stress of sheet

F_y = yield stress of material

C_2 = ductility factor

σ_b = ultimate bearing stress

F_p = allowable bearing stress

P_u = ultimate failure load

τ_s = nominal shear stress at failure

σ_{net} = tension stress at failure of bolted connection

τ_b = shear stress at failure of bolt

F_{u_b} = ultimate tensile strength of bolt

APPENDIX B

Tables

Table 1. Dimensions and Results of Bolted Connections With Washers-Both High and Low Ductility Steels [6]

Spec. No.	d (in)	t (in)	e (in)	s (in)	e/d	d/t	P_{ult} (kips)	F_y (ksi)	F_u (ksi)	σ_b (ksi)	σ_b/F_y	C_2	σ_b/C_2F_y	Failure* Type
16FAX-L14	1/2	0.062	1.25	2.5	2.5	8.06	3.20	30.1	45.9	103.20	3.43	1.000	3.43	I & II
16FAXL15			1.75		3.5		5.10			164.50	5.47	1.000	5.47	II & III
16FAXL16			1.75				4.80			154.84	5.14	1.000	5.14	II & III
16FAXL17				5.0			4.28			138.10	4.60	1.000	4.60	II
12FAXL19		0.106	1.25	2.5	2.5	4.72	6.44	28.1	44.1	121.51	4.32	1.000	4.32	II & I
12FAXL20			1.75		3.5		8.25			155.66	5.54	1.000	5.54	II & III
12FAXL21				5.0			9.55			180.20	6.41	1.000	6.41	II
1610X-L19		0.062	1.50	2.5	3.0	8.06	6.68	78.4	81.5	215.50	2.75	0.643	4.28	II
1610X-L20			1.75	2.5	3.5		7.14			230.30	2.94	0.643	4.57	II
1610X-L21				2.0			5.04			162.60	2.07	0.643	3.22	II
1610XL30			1.40	5.0	2.8		4.86			156.77	2.00	0.643	3.11	II
1615XL23			1.50	2.5	3.0		5.92	45.4	54.7	190.97	4.21	0.793	5.31	II & III
1615XL24			1.75	2.5	3.5		5.59	45.4	54.7	180.32	3.97	0.793	5.01	II
1615XL25				2.0			4.34			140.00	3.08	0.793	3.89	II
1615XL31			1.40	5.0	2.8		4.32			139.40	3.07	0.793	3.87	II
1625X-L27			1.50	2.5	3.0		4.94	38.5	49.1	159.35	4.14	0.894	4.63	II & III
1625X-L28			1.75		3.5		5.17			166.77	4.33	0.894	4.84	II & III
1625X-L29				2.0			4.20			135.50	3.52	0.894	3.94	II
1625X-L32			1.40	5.0	2.8		4.62			149.00	3.87	0.894	4.33	II
1210X-L23		0.106	1.50	2.5	3.0	4.72	11.74	70.1	72.8	221.51	3.16	0.643	4.91	II
1210X-L24			1.75		3.5		11.62			219.25	3.13	0.643	4.87	II
1210X-L25				2.0			11.86			223.77	3.20	0.643	4.98	II & III
1210X-L36			1.40	5.0	2.8		10.88			205.30	2.93	0.643	4.56	II
1215X-L27			1.50	2.5	3.0		11.03	65.2	69.3	208.11	3.20	0.643	4.98	II
1215X-L28			1.75	2.5	3.5		11.32			213.60	3.28	0.643	5.10	II
1215XL29				2.0			10.74			202.60	3.11	0.643	4.84	III & II
1215XL35			1.40	5.0	2.8		10.26			193.58	2.97	0.643	4.62	II
1225XL31			1.50	2.5	3.0		8.76	36.6	50.0	165.30	4.52	1.000	4.52	II & III
1225XL-32			1.75		3.5		8.81			166.23	4.54	1.000	4.54	II & III
1225XL33				2.0			7.92			149.43	4.08	1.000	4.08	II & III
1225XL34			1.40	5.0	2.8		8.84			166.79	4.56	1.000	4.56	II

*The types of failure are defined as follows:

I--Longitudinal shearing of the steel sheets
II--Bearing failure between steel sheet and bolt
III--Transverse tension tearing failure
IV--Shearing of the bolt

Table 2. Dimensions and Results of Bolted Connections with Washers-Bearing Strength Study (Single Shear)

Spec. No.	d (in)	t (in)	e (in)	s (in)	e/d	d/t	Fy (ksi)	Fu (ksi)	$(\sigma_b)_{test}$ (ksi)	C_2	σ_b/C_2Fy	$(\sigma_b)^*_{cal}$	$\frac{(\sigma_b)_{cal}}{(\sigma_b)_{test}}$	Failure Type	Reference
20A41SS	1/4	0.036	1.125	4.0	4.5	6.94	32.11	41.83	208.29	0.933	6.96	146.8	0.704	II	9
14A43SS	1/2	0.08	2.25			6.25	29.81	43.40	177.5	1.0	5.95	146.1	0.823	II	9
10E36SS	1.0	0.143	3.5		3.5	6.98	59.47	76.84	172.25	0.918	3.16	267.5	1.55	II	10
12Y-L7	1/2	0.106	1.75	4.0	3.5	4.72	72.4	72.8	239.0	0.643	5.13	228.14	0.952	II & I	6
12Y-L8	3/8		1.5	2.53	4.0	3.54			245.0		5.26		0.932	II	
12Y-L9	1/2		1.75	3.41	3.5	4.72			267.0		5.74		0.855	II	
12Y-L11	3/8		1.49	2.0	4.0	3.54			216.0		4.63		1.05	II & I	
12Y-L12	1/2		1.75	2.66	3.5	4.72			211.0		4.53		1.09	II & III	
12Y-L15	3/8		1.5	1.52	4.0	3.54			194.0		4.17		1.17	II & III	
12Y-L16	1/2		1.75	2.04	3.5	4.72			211.0		4.53		1.08	II	
12Y-L18	3/4		2.65	3.04	3.53	7.08			153.0		3.28		1.49	II	
7Y-L6	3/4	0.183	3.75	3.75	5.0	4.10	83.1	83.8	307.0		5.74	262.0	0.855	II & III	
20ZT12	3/16	0.038	0.66	2.08	3.5	4.93	99.4	99.8	260.0		4.07	313.2	1.20	II	
16FAX-L16	1/2	0.062	1.75	2.5	3.5	8.06	30.1	45.9	152.2	1.0	5.06	147.5	0.969	II & III	
SS2	7/8	0.116	3.06	8.0		7.54	35.49	49.44	158.57		4.47	173.9	1.1	II	14
SS2-1	7/8		3.06						121.92		3.44		1.43	II	
SS3	7/8		4.4		5.0				149.29		4.21		1.16	II	
SS5	1.0		3.5		3.5	8.62			133.84		3.77		1.3	II	
SS5-1	1.0		3.5		3.5	8.7			117.61		3.31		1.48	II	
SS6	1.0		3.5		5.0	8.62			132.25		3.73		1.31	II	
SS8	7/8	0.181	3.06		3.5	4.83	38.1	62.08	208.37		5.47	186.7	0.896	II	
SS8-1	7/8	0.181	3.06	8.0	3.5	4.83	38.1	62.08	156.59	1.0	4.11	186.7	1.2	II	
SS9	7/8	0.185	4.375	8.0	5.0	4.73			202.32		5.31		0.923	II	
SS11	1.0	0.184	3.5		3.5	5.43			200.0		5.25		0.933	II	
SS11-1		0.184	3.5		3.5				164.67		4.32		1.133	II	
SS12		0.184	5.0		5.0				191.85		5.04		0.973	II	
SS14		0.261	3.5		3.5	3.83	45.07	67.54	216.86		4.81	220.8	0.843	II	
SS14-1		0.259	3.5		3.5	3.86			178.96		3.91		0.81	II	
SS15		0.255	5.0		5.0	3.92			217.65		4.83		0.986	II	

Table 2. (con't)

Spec. No.	d (in)	t (in)	e (in)	s (in)	e/d	d/t	Fy (ksi)	Fu (ksi)	$(\sigma_b)_{test}$ (ksi)	C_2	σ_b/C_2Fy	$(\sigma_b)^*_{cal}$	$\frac{(\sigma_b)_{cal}}{(\sigma_b)_{test}}$	Failure Type	Reference
--	1/2	0.037	2.0	4.0	4.0	13.5	53.5	58.9	200.0	0.644	5.81	168.86	0.844	II	7
--	1/2	0.037	2.0	4.03	4.0	13.5	53.5	58.9	197.8	0.644	5.75	168.86	0.854	II	
--	5/16	0.037	2.06	4.06	6.6	8.45	53.5	58.9	183.4	0.644	5.33	168.86	0.921	II	
--	5/16	0.037	2.04	4.06	6.53	8.45	53.5	58.9	190.4	0.644	5.53	168.86	0.887	II	
--	1/2	0.037	2.5	4.0	5.0	13.5	53.5	58.9	207.6	0.644	6.02	168.86	0.813	II	
--	1/2	0.037	2.0	4.0	4.0	13.5	53.5	58.9	214.6	0.644	6.23	168.86	0.787	II & I	
--	1/2	0.051	2.03	4.0	4.06	9.8	40.6	50.1	158.8	0.835	4.68	166.11	1.05	II & I	
--	1/2	0.051	2.03	4.0	4.06	9.8	40.6	50.1	165.9	0.835	4.91	166.11	1.0	II & I	
--**	1/2	0.061	1.94	2.03	3.88	8.2	50.5	74.1	201.7	1.0	4.0	247.45	1.23	II	

Mean = 1.04

Standard Deviation = 0.21

$*(\sigma_b)_{cal} = 4.9\ C_2Fy$

**Two bolts perpendicular to line of stress

See Table 1 for the definition of type of failure

Table 3. Dimensions and Results of Bolted Connections with Washers-Bearing Strength Study (Double Shear)

Spec. No.	d (in)	t (in)	e (in)	s (in)	e/d	d/t	Fy (ksi)	Fu (ksi)	$(\sigma_b)_{test}$ (ksi)	C_2	σ_b/C_2Fy	$(\sigma_b)^*_{cal}$ (ksi)	$\frac{(\sigma_b)_{cal}}{(\sigma_b)_{test}}$	Failure Type	Reference
20A41DS	1/4	0.036	1.125	4.0	4.5	6.94	32.11	41.85	206.32	0.934	6.89	147.0	0.713	II	9
16C403DS	1/2	0.0591	2.0		4.0	8.46	31.95	43.95	224.03	1.0	7.01	156.6	0.7	II	9
16C503DS	1/2	0.0591	2.5		5.0	8.46	31.95	43.95	243.66	1.0	7.63	156.6	0.643	II	9
14E35DS	3/4	0.0783	2.625		3.5	9.58	54.44	70.4	242.20	0.919	4.84	245.2	1.011	I & II	10
10E36DS	1.0	0.143	3.5		3.5	6.98	59.5	71.85	199.35	0.797	4.2	232.4	1.16	II	10
10E46DS	1.0	0.143	4.5		4.5	6.98	59.5	71.85	201.5	0.797	4.2	232.4	1.16	II	10
20Z-L8	3/16	0.038	.66	2.08	3.52	4.93	75.7	81.7	206.0	0.643	4.23	238.5	1.16	II & I	6
1205XL7	3/4	0.106	2.63	3.75	3.5	7.08	81.6	81.6	252.0		4.81	257.1	1.02	II & I	
1205XL8	3/4		2.63	3.0	3.5	7.08			236.0		4.49		1.08	II & III	
1205XL9	7/8		3.06	3.5		8.25			242.0		4.62		1.06	II & III	
7Y-L32	5/8	0.183	2.19	2.98		3.42	82.6	82.6	247.0		4.65	258.3	1.05	II & I	
16FAXL15	1/2	0.062	1.75	2.5		8.06	30.1	45.9	161.8	1.0	5.38	147.5	0.912	II & III	
16FAXL17	1/2			5.0					136.0		4.52		1.08	II	
12FAX-L20	1/2	0.106		2.5		4.72	28.1	44.1	159.2		5.67	137.7	0.865	II & III	
12FAX-L21	1/2	0.106		5.0		4.72			178.4		6.35		0.772	II	
DS1-1	7/8	0.116	3.06	8.0	3.5	7.54	35.49	49.44	161.58	1.0	4.55	173.9	1.08	II	14
DS1-2		0.116	3.06						148.77		4.19		1.17		
DS2-1	1.0	0.115	3.5			8.7			139.13		3.92		1.25		
DS2-2		0.116	3.5			8.62			143.10		4.03		1.22		
DS3-1	7/8	0.181	3.06			4.83	38.1	62.08	209.94		5.51	186.7	0.889		
DS3-2		0.180	3.06			4.86			196.14		5.15		0.952		
DS4-1	1.0	0.182	3.5			5.49			229.12		6.01		0.815		
DS4-2		0.181				5.52			223.76		5.87		0.834		
DS5-1		0.259				3.86	45.07	67.54	221.62		4.92	220.8	0.996		
DS5-2		0.26				3.85	45.07		222.31		4.93		0.993		

$*(\sigma_b)_{cal} = 4.9\ C_2Fy$

Mean = 0.930

Standard Deviation = 0.170

See Table 1 for definition of type of failure

Table 4. Dimensions and Results of Bolted Connections without Washers-Bearing Strength Study [7] e/d > 2.5

Gage of Steel	Connection* Type	d (in)	t (in)	e (in)	s (in)	e/d	d/t	Fy (ksi)	Fu (ksi)	$(\sigma_b)_{test}$ (ksi)	C_2	σ_b/C_2F_y	$(\sigma_b)^{**}_{cal}$ (ksi)	$(\sigma_b)^{***}_{cal}$ (ksi)	$(\sigma_b)^{**}_{cal}/(\sigma_b)_{test}$	$(\sigma_b)^{***}_{cal}/(\sigma_b)_{test}$	Failure Type
20	1	1/2	0.037	2.06	4.06	4.06	13.5	53.5	58.9	133.0	0.644	3.9	168.86	120.6	1.27	0.91	I & II
20	1	5/16	0.037	2.04	4.03	6.53	8.45			158.4		4.6			1.07	0.76	II
20	1	5/16	0.037	2.06	4.12	6.6	8.45			138.4		4.04			1.22	0.87	I & II
20	1	1/2	0.037	2.5	4.0	5.0	13.5			122.2		3.55			1.38	0.987	II
20	1	1/2	0.037	2.5	4.0	5.0	13.5			125.0		3.63			1.35	0.965	II
17	1	1/2	0.051	2.06	4.03	4.12	9.8	40.6	50.1	113.3	0.835	3.34	166.11	118.65	1.47	1.05	I & II
17	1	1/2	0.051	2.01	4.03	4.02	9.8			117.0		3.45			1.42	1.01	I & II
17	1	1/2	0.051	2.01	4.03	4.02	9.8			115.3		3.4			1.11	1.03	I & II
17	3	5/16	0.051	2.05	1.35	6.56	6.13			109.6		3.23			1.52	1.08	II
17	3	5/16	0.051	2.07	1.35	6.62	6.13			112.7		3.33			1.47	1.05	II
17	2	1/2	0.051	1.97	2.02	3.94	9.8			109.2		3.22			1.52	1.09	I & II
16	2	1/2	0.061	1.97	2.0	3.94	8.2	50.5	74.1	147.2	1.0	2.91	247.45	176.75	1.68	1.2	II
14	1	3/4	0.079	3.0	4.0	4.0	9.5	52.8	65.9	145.1	0.855	3.21	221.2	158.0	1.52	1.09	I & II
14	1	3/4	0.079	3.01	4.0	4.0	9.5			137.6		3.05			1.61	1.15	I & II
14	1	3/4	0.079	3.0	4.0	4.0	9.5			154.8		3.43			1.43	1.02	I & II
12	1	3/4	0.104	3.03	4.06	4.04	7.2	59.3	70.6	160.3	0.772	3.5	224.34	160.23	1.4	1.00	I & II
20	1	1/2	0.037	1.5	4.0	3.0	13.5	53.5	58.9	130.3	0.644	3.77	168.86	120.6	1.3	0.926	I
20	1	1/2	0.037	1.5	3.06	3.0	13.5			123.8		3.69			1.36	0.974	I
20	1	1/2	0.037	1.5	3.03	3.0	13.5			122.2		3.54			1.38	0.987	I
17	1	1/2	0.051	1.5	2.02	3.0	9.8	40.6	50.1	112.2	0.835	3.31	166.11	118.65	1.48	1.06	I
17	1	1/2	0.051	1.44	2.02	2.88	9.8			113.7		3.35	166.11	118.65	1.46	0.04	I
20	1	1/2	0.037	2.03	4.06	4.06	13.5	53.5	58.9	120.5	0.644	3.5	168.86	120.6	1.4	1.00	I
20	1	1/2	0.037	2.07	4.06	4.14	13.5			131.4		3.81			1.28	0.918	I
20	1	1/2	0.037	1.5	4.0	3.0	13.5			134.1		3.9			1.26	0.90	I
20	1	1/2	0.037	1.75	4.0	3.5	13.5			121.6		3.53			1.4	1.0	I
20	1	1/2	0.037	2.0	4.0	4.0	13.5			138.9		4.03			1.22	0.868	I

All Single Shear Connections

Mean = 1.38 1.00

Standard Deviation = 0.14 0.09

*1. One bolt
2. Two bolts perpendicular to line of stress
3. Three bolts perpendicular to line of stress

$**(\sigma_b)_{cal} = 4.9\ C_2F_y$

$***(\sigma_b)_{cal} = 3.5\ C_2F_y$

See Table 1 for the definition of type of failure

Table 5. Dimensions and Results of Single Shear Bolted Connections With Washers-Shear Strength Study

Spec No	d (in)	t (in)	e (in)	s (in)	e/d	d/t	F_y (ksi)	F_u (ksi)	$(\sigma_b)_{test}$ (ksi)	C_2	σ_b/C_2F_y	$(\sigma_b)^*_{cal}$	$\frac{(\sigma_b)_{cal}}{(\sigma_b)_{test}}$	Failure Type	Reference No
20A11SS	1/4	0.0360	0.375	4.00	1.500	6.94	32.11	41.83	89.33	0.933	2.98	62.90	0.704	I	9
20A21SS	1/4		0.625		2.500				134.50	0.933	4.50	104.87	0.780	I	9
20A12SS	3/8		0.563		1.500	10.40			79.77		2.66	62.90	0.788	I	9
20A22SS	3/8		0.938		2.500	10.40			130.28		4.35	104.87	0.805	I	9
20A13SS	1/2		0.750		1.500	13.90			81.69		2.72	62.90	0.770	I	9
20A14SS	5/8		0.938		1.500	17.40			78.30		2.62	62.90	0.803	I	9
20A24SS	5/8		1.560		2.500	17.40			125.38		4.20	104.87	0.836	I & II	9
20A15SS	3/4		1.130		1.500	20.80			84.61		2.82	62.90	0.743	I	9
16C105SS	3/4	0.0591	0.750		1.000	12.70	31.95	43.81	58.89		2.00	41.73	0.709	I	9
16C205SS	3/4		1.500		2.000	12.70			109.87		3.70	83.47	0.760	I	9
14A11SS	1/4	0.0800	0.375		1.500	3.13	29.81	43.40	80.30	1.000	2.69	62.60	0.780	I	9
14A12SS	3/8		0.563		1.500	4.70			74.30		2.52	62.60	0.843	I	9
14A22SS	3/8		0.938		2.500				129.78		4.36	104.34	0.804	I	9
14A13SS	1/2		0.750		1.500	6.25			77.10		2.59	62.60	0.812	I	9
14A23SS	1/2		1.250		2.500				122.73		4.11	104.34	0.850	I	9
12A11SS	1/4	0.0931	0.375		1.500	2.70	25.60	41.15	77.99		3.05	53.76	0.689	I	9
12A12SS	3/8		0.563		1.500	4.03			80.49		3.15	53.76	0.668	I	9
12A14SS	5/8		0.938			6.71	26.65	41.40	76.53		2.87	56.60	0.731	I	9
18E12SS	3/8	0.0460	0.563			8.24	46.75	68.00	108.93		2.33	98.20	0.901	I	10
18E22SS	3/8	0.0460	0.938		2.500	8.24			197.62		4.23	163.63	0.828	I	10
18E14SS	5/8	0.0460	0.938		1.500	13.74			112.52		2.41	98.20	0.873	I	10
14E13SS	1/2	0.0780	0.750			6.40	54.44	70.40	111.30	0.920	2.23	105.20	0.945	I	10
14E23SS	1/2	0.0780	1.250		2.500	6.40			182.50		3.64	175.30	0.960	I	10
14E15SS	3/4		1.130		1.500	9.60			119.50		2.40	105.20	0.880	I	10

$*(\sigma_b)_{cal} = 1.4(e/d)C_2F_y$

See Table 1 for the definition of type of failure.

Table 5 (con't)

Spec No	d (in)	t (in)	e (in)	s (in)	e/d	d/t	F_y (ksi)	F_u (ksi)	$(\sigma_b)_{test}$ (ksi)	C_2	σ_b/C_2F_y	$(\sigma_b)_{cal}^*$	$\frac{(\sigma_b)_{cal}}{(\sigma_b)_{test}}$	Failure Type	Reference No
14E25SS	3/4	0.0780	1.880	4.00	2.500	9.60	54.44	70.40	170.90	0.920	3.41	175.30	1.030	I & II	10
10E15SS	3/4	0.1430	1.130		1.500	5.23	59.47	76.84	107.30		2.00	115.00	1.070	I	10
10E16SS	1.0		1.500		1.500	7.00			104.50		2.00	115.00	1.100	I	10
8E15SS	3/4	0.1901	1.130		1.500	3.95	56.45	76.98	107.10	1.000	1.90	118.50	1.110	I	10
12Y-L10	5/8	0.1060	2.110	4.12	3.370	5.90	72.40	72.80	204.00	0.643	4.40	219.65	1.080	I & II	6
7Y-L1	3/4	0.1830	0.620	1.50	0.833	4.10	83.10	83.80	62.00		1.17	62.30	1.000	I	6
7Y-L2	3/4		0.690	1.50	0.917	4.10			64.00		1.20	68.54	1.070	I	6
7Y-T3	3/4		0.620	1.50	0.833	4.10	86.40	91.30	58.50		1.06	64.80	1.110	I	6
7Y-L4	3/4		1.000	1.88	1.330	4.10	83.10	83.80	97.20		1.82	99.73	1.030	I	6
7Y-T4	3/4		1.000	1.88	1.330	4.10	86.40	91.30	102.00		1.84	103.70	1.020	I	6
7Y-T5	3/4	0.1830	1.750	3.00	2.330	4.10	86.40	91.30	186.00	0.643	3.34	181.45	0.976	I & II	6
SS1	7/8	0.1150	1.750	8.00	2.000	7.61	35.49	49.44	128.45	1.000	3.62	99.40	0.774	I	14
SS4	1.0	0.1160	2.000		2.000	8.62			122.51		3.45	99.40	0.811	I	14
SS7	7/8	0.1810	1.750		2.000	4.83	38.10	62.08	142.07		3.73	106.70	0.751	I	14
SS10	1.0	0.1840	2.000		2.000	5.43			137.50		3.61	106.70	0.776	I	14
SS13	1.0	0.2610	2.000		2.000	3.83	45.07	67.54	142.34		3.16	126.20	0.791	I	14
-	1/2	0.0370	1.030	4.00	2.060	13.50	53.50	58.90	159.50	0.644	4.63	99.37	0.623	I	7
-	1/2	0.0370	1.060	4.03	2.200	13.50			162.70		4.72	106.12	0.652	I	7
-	1/2	0.0370	1.000	4.00	2.000	13.50			149.73		4.35	96.47	0.644	I	7
-	1/2	0.0510	0.970	4.06	1.940	9.80	40.60	50.10	134.10	0.835	3.95	92.10	0.687	I	7
-	1/2	0.0510	1.020	4.06	2.040	9.80			136.90		4.04	96.82	0.707	I	7
-	1/2	0.0610	1.030	4.03	2.060	8.20	50.50	74.10	173.10	1.000	3.43	145.60	0.841	I & II	7
-	1/2	0.0610	1.030	4.06	2.060	8.20			167.90		3.32	145.60	0.867	I & II	7

$*(\sigma_b)_{cal} = 1.4(e/d)C_2F_y$

See Table 1 for the definition of type of failure.

Mean = 0.850

Standard Deviation = 0.140

Table 6. Dimensions and Results of Bolted Connections Without Washers Shear Strength Study [7] $e/d \leq 2.5$

Gage of Steel	Connection* Type	d (in)	t (in)	e (in)	s (in)	e/d	d/t	F_y (ksi)	F_u (ksi)	$(\sigma_b)_{test}$ (ksi)	C_2	σ_b/C_2F_y	$(\sigma_b)_{cal}$** (ksi)	$\frac{(\sigma_b)_{cal}}{(\sigma_b)_{test}}$	Failure Type
20	1	1/2	0.037	1.00	4.00	2.00	13.5	53.5	58.9	129.20	0.644	3.74	96.50	0.747	I & II
20	1	1/2	0.037	1.00	4.00	2.00	13.5	53.5	58.9	127.70	0.644	3.70	96.50	0.756	I & II
20	1	1/2	0.037	0.50	4.00	1.00	13.5	53.5	58.9	90.81	0.644	2.64	48.23	0.531	I
20	1	1/2	0.037	0.50	4.00	1.00	13.5	53.5	58.9	82.20	0.644	2.39	48.23	0.587	I
20	3	1/2	0.037	1.00	3.94	2.00	13.5	53.5	58.9	116.60	0.644	3.38	96.50	0.828	I
20	3	1/2	0.037	1.00	3.94	2.00	13.5	53.5	58.9	116.76	0.644	3.39	96.50	0.826	I
20	2	1/2	0.037	1.00	4.00	2.00	13.5	53.5	58.9	118.40	0.644	3.43	96.50	0.815	I
20	2	1/2	0.037	1.00	4.00	2.00	13.5	53.5	58.9	116.80	0.644	3.39	96.50	0.826	I
16	1	1/2	0.061	0.51	4.00	1.02	8.2	50.5	74.1	90.82	1.000	1.80	72.11	0.794	I & II
16	1	1/2	0.061	0.52	4.00	1.04	8.2	50.1	74.1	101.30	1.000	2.00	73.53	0.726	I & II
16	3	1/2	0.061	1.00	4.03	2.00	8.2	50.1	74.1	143.20	1.000	2.86	140.30	0.980	I & II
16	3	1/2	0.061	1.00	4.06	2.00	8.2	50.1	74.1	147.50	1.000	2.94	140.30	0.951	I & II

All Single Shear Connections

Mean = 0.780

* 1 One Bolt

2 Two bolts parallel to the line of stress

3 Three bolts parallel to the line of stress

Standard deviation = 0.130

**$(\sigma_b)_{cal} = 1.4(e/d)C_2F_y$

See Table 1 for the definition of type of failure.

Table 7. Dimensions and Results of Double Shear Bolted Connections with Washers-Shear Strength Study

Spec. No.	d (in)	t (in)	e (in)	s (in)	e/d	d/t	Fy (ksi)	Fu (ksi)	$(\sigma_b)_{test}$ (ksi)	C_2	σ_b/C_2F_y	$(\sigma_b)^*_{cal}$	$\frac{(\sigma_b)_{cal}}{(\sigma_b)_{test}}$	Failure Type	Reference
20A11DS	1/4	0.036	0.375	4.0	1.5	6.94	32.11	41.85	95.85	0.934	3.2	62.98	0.659	I	9
20A21DS	1/4		0.625		2.5				142.75		4.76	104.98	0.735	I	
20A12DS	3/8		0.563		1.5	10.42			93.89		3.13	62.98	0.671	I	
20A13DS	1/2		0.75			13.9			84.42		2.82	62.98	0.746	I	
20A14DS	5/8		0.938			17.36			88.09		2.93	62.98	0.715	I	
20A15DS	3/4		1.125			20.83			88.7		2.96	62.98	0.71	I	
16C103DS	1/2	0.059	0.5		1.0	8.46	31.95	43.81	58.55	1.0	1.83	44.73	0.764	I	
16C203DS	1/2		1.0		2.0	8.46			112.69		3.53	89.5	0.794	I	
14A11DS	1/4	0.08	0.375		1.5	3.13	29.81	43.4	78.37		2.63	62.6	0.799	I	
14A21DS	1/4		0.625		2.5	3.13			131.86		4.42	104.34	0.791	I	
14A12DS	3/8		0.563		1.5	4.69			83.47		2.8	62.6	0.75	I	
14A12DS	3/8		0.938		2.5	4.69			129.33		4.34	104.34	0.807	I	
14A13DS	1/2		0.75		1.5	6.25			81.91		2.75	62.6	0.764	I	
14A23DS	1/2		1.25		2.5	6.25			130.58		4.38	104.34	0.799	I	
12A11DS	1/4	0.0931	0.375		1.5	2.68	26.0	41.15	82.18		3.17	54.6	0.664	I	
12A21DS	1/4		0.625		2.5	2.68			134.81		5.19	91.0	0.675	I	
12A12DS	3/8		0.563		1.5	4.03			79.04		3.04	54.6	0.691	I	
12A22DS	3/8		0.938		2.5	4.03			134.39		5.17	91.0	0.677	I	
12A14DS	5/8		0.938		1.5	6.71			83.82		3.22	54.6	0.651	I	
12A24DS	5/8		1.563		2.5	6.71			127.73		4.92	91.0	0.712	I	
10A12DS	3/8	0.143	0.563		1.5	2.62	36.6	48.0	84.84	0.945	2.46	72.63	0.856	I	
10A22DS	3/8	0.143	0.938		2.5	2.62			133.56		3.86	121.05	0.906	I	
8B23DS	1/2	0.188	1.25		2.5	2.66	35.15	47.1	124.75	0.973	3.65	119.71	0.96	I	
8B25DS	3/4	0.188	1.88		2.5	4.0			129.16		3.78	119.71	0.927	I	
18E12DS	3/8	0.046	0.563		1.5	8.24	46.75	68.0	110.71	1.0	2.37	98.2	0.887	I	10
18E22DS	3/8		0.938		2.5	8.24			185.37		3.97	163.63	0.883	I	
18E14DS	5/8		0.938		1.5	13.74			110.91		2.37	98.2	0.885	I	
18E24DS	5/8		1.563		2.5	13.74			171.97		3.68	163.63	0.951	I	
14E13DS	1/2	0.078	0.75		1.5	6.39	54.44	70.4	122.4	0.919	2.45	105.06	0.858	I	
14E13DS	1/2		1.25		2.5	6.39			190.9		3.82	175.1	0.917	I	
14E15DS	3/4		1.125		1.5	9.58			121.35		2.43	105.06	0.866	I	
10E12DS	3/8	0.143	0.563		1.5	2.61	59.5	71.85	101.55	0.797	2.15	99.63	0.981	I	
10E13DS	1/2		0.75		1.5	3.5			107.1		2.26	99.63	0.93	I	
10E23DS	1/2		1.25		2.5	3.5			180.8		3.81	165.98	0.918	I	
10E15DS	3/4		1.13		1.5	5.23			121.45		2.57	99.63	0.82	I	

Table 7.(con't)

Spec. No.	d (in)	t (in)	e (in)	s (in)	e/d	d/t	Fy (ksi)	Fu (ksi)	$(\sigma_b)_{test}$ (ksi)	C_2	σ_b/C_2F_y	$(\sigma_b)_{cal}$	$\frac{(\sigma_b)_{cal}}{(\sigma_b)_{test}}$	Failure Type	Reference
10E26DS	1.0	0.143	2.5	4.0	2.5	7.0	59.5	71.85	167.0	0.797	2.53	165.98	0.994	I	10
8E15DS	3/4	0.19	1.125		1.5	3.95	56.45	76.98	108.95	1.0	1.93	118.55	1.09	I	
8E25DS	3/4		1.875		2.5	3.95			158.3		2.81	197.6	1.25	I & II	
7Y-L22	1/2	0.183	0.88	5.0	1.75	2.73	83.1	83.8	136.8	0.643	2.57	130.91	0.957	I	6
7Y-L23	1/2		0.75		1.5				112.3		2.1	112.2	1.0	I	6
7Y-L24	1/2		1.4		2.8				263.0		4.91	209.46	0.796	I & II	6
7Y-L25	1/2		1.5	3.33	3.0				240.0		4.5	224.4	0.935	I & II	6
20Z-L5	1/2	0.038	1.0	2.5	2.0	13.16	75.7	81.7	130.8	0.727	2.38	154.12	1.18	I & II	6
20Z-L7	3/16		0.47	2.08	2.5	4.93			192.0		3.5	192.62	1.0	I	6
1605X-L5	1/2	0.062	1.0	2.5	2.0	8.06	83.25	83.25	157.0	0.643	2.94	149.9	0.955	I	6
1605X-L6	1/2		1.4	5.0	2.8	8.06	87.6	87.6	224.0		4.0	220.81	0.986	I & II	6
1205X-L10	1/2	0.106	1.4	5.0	2.8	4.72	80.5	80.5	206.0		4.0	202.93	0.985	I & II	6
7Y-L31	1/2	0.183	1.5	2.5	3.0	2.73	82.6	82.6	222.5		4.18	223.07	1.0	I	6
16FAX-L14	1/2	0.062	1.25	2.5	2.5	8.06	30.1	45.9	101.6	1.0	3.38	105.4	1.04	I & II	6
12FAX-L19	1/2	0.106	1.25	2.5	2.5	4.72	28.1	44.1	120.2		4.28	98.4	0.818	I & II	6

*$(\sigma_b) = 1.4(e/d)\ C_2F_y$

Mean = 0.860

See Table 1 for the definition of type of failure.

Standard Deiviation = 0.140

Table 8. Dimensions and Results of Bolted Connections with Washers-Tensile Strength Study (Single Shear)

Spec. No.	d (in)	t (in)	s (in)	e/d	d/s	d/t	Fy (ksi)	Fu (ksi)	$(\sigma_{net})_{test}$ (ksi)	$\frac{(\sigma_{net})_{test}}{Fu}$	$(\sigma_{net})^*_{cal}$ (ksi)	$\frac{(\sigma_{net})_{cal}}{(\sigma_{net})_{test}}$	Failure Type	Reference
20A41SS1	1/4	0.0346	4.0	4.5	0.0625	7.23	32.11	41.85	15.5	0.370	12.03	0.776	III	9
20A41SS2	1/4	0.0349	"	"	"	7.16			14.87	0.355	12.03	0.809	III	9
20A22SS1	3/8	0.0354		2.5	0.094	10.6			13.5	0.323	16.0	1.185	I & III	9
20A32SS1	3/8	0.0335		3.5	0.094	11.2			14.74	0.352	16.0	1.085	I & III	9
20A32SS2	3/8	0.0342		3.5	0.094	10.96			19.94	0.476	16.0	0.802	III	9
20A42SS1	3/8	0.0349		4.5	0.094	10.74			14.35	0.343	16.0	1.115	I & III	9
20A42SS3	3/8	0.036		4.5	0.094	10.42			13.1	0.313	16.0	1.221	III	9
20A23SS1	1/2	0.0352		2.5	0.125	14.2			17.15	0.41	19.9	1.16	I & III	9
20A43SS1	1/2	0.0352		4.5	0.125	14.2			17.19	0.411	19.9	1.157	I & III	9
20A43SS3	1/2	0.0361		4.5	0.125	13.9			20.55	0.491	19.9	0.968	III	9
20A34SS	5/8	0.0359		3.5	0.156	17.4			24.64	0.59	23.77	0.965	III	9
20A44SS	5/8	0.0353		4.5	0.156	17.7			21.9	0.523	23.77	1.09	III	9
20A25SS1	3/4	0.0357		2.5	0.188	21.0			25.3	0.605	27.8	1.1	III	9
20A35SS1	3/4	0.0357		3.5	0.188	21.0			25.13	0.60	27.8	1.1	III	9
16C305SS	3/4	0.0591		3.0	0.188	12.7	32.0	44.0	31.28	0.711	29.22	0.934	III	9
16C505SS	3/4	0.0591		5.0	0.188	12.7			30.32	0.690	29.22	0.964	III	9
14A23SS1	1/2	0.0832		2.5	0.125	6.0	29.8	43.4	17.97	0.414	20.62	1.15	I & III	9
14B25SS1	3/4	0.0798		2.5	0.188	9.4			25.12	0.579	28.82	1.15	III	9
14B35SS1	3/4	0.0771		3.5	0.188	9.73			23.79	0.548	28.82	1.21	III	9
14B45SS	3/4	0.0814		4.5	0.188	9.21			26.21	0.604	28.82	1.1	III	9
14B26SS1	1.0	0.0768		2.5	0.25	13.0			33.33	0.768	36.89	1.11	III	9
14B36SS1	3/4	0.0741		3.5	0.188	10.12			33.31	0.767	28.82	0.865	III	9
14B46SS1	3/4	0.0789		4.5	0.188	9.51			35.9	0.827	28.82	0.803	III	9
12A34SS1	5/8	0.0922		3.5	0.156	6.78	26.0	41.15	37.2	0.904	23.4	0.629	III	9
12A44SS1	5/8	0.0922		4.5	0.156	6.78			24.3	0.591	23.4	0.963	III	9
8B45SS1	3/4	0.1867		4.5	0.188	4.02	32.0	46.0	29.07	0.632	30.54	1.05	I & III	9
8B26SS1	1.0	0.1893		2.5	0.25	5.28			43.7	0.95	39.1	0.895	III	9
8B46SS1	1.0	0.1884		4.5	0.25	5.31			46.98	1.02	39.1	0.832	III	9
18E42SS1	3/8	0.0451		4.5	0.094	8.31	46.75	68.0	20.85	0.307	26.0	1.25	III & I	10
18E24SS1	5/8	0.0441		2.5	0.156	14.2			29.78	0.438	38.62	1.3	I & III	10
18E34SS	5/8	0.0444		3.5	0.156	14.08			37.8	0.556	38.62	1.02	III	10
18E44SS1	5/8	0.0448		4.5	0.156	13.95			35.04	0.515	38.62	1.1	III	10
14E35SS1	3/4	0.0789		3.5	0.188	9.51	54.44	70.4	47.95	0.681	46.75	0.975	III	10
14E45SS1	3/4	0.0781		4.5	0.188	9.6			55.45	0.788	46.75	0.843	III	10
10E26SS1	1.0	0.1455		2.5	0.25	6.87	59.5	71.85	55.25	0.77	61.1	1.11	III	10
14G25SS	3/4	0.0766	2.0	2.5	0.375	9.8	29.8	43.4	49.4	1.14	43.4	0.879	III	10
14G35SS	3/4	0.0753		3.5	0.375	9.96			47.0	1.08	43.4	0.923	III	10
14G45SS	3/4	0.0795		4.5	0.375	9.43			46.5	1.07	43.4	0.933	III	10

Mean = 1.010

Standard Deviation = 0.150

$*(\sigma_{net})_{cal} = (.1 + 3\ d/s)\ Fu$

See Table 1 for the definition of type of failure.

Table 9. Dimensions and Results of Single Shear Connections With Washers-Tensile Strength Study[6]

Spec No	d (in)	t (in)	s (in)	e/d	d/s	d/t	F_y (ksi)	F_u (ksi)	$(\sigma_{net})_{test}$ (ksi)	$\frac{(\sigma_{net})_{test}}{F_u}$	$(\sigma_{net})^*_{cal}$ (ksi)	$\frac{(\sigma_{net})_{cal}}{(\sigma_{net})_{test}}$	Failure Type
12Y-L12	1/2	0.104	2.660	3.500	0.188	4.81	72.40	72.80	50.96	0.700	48.34	0.949	II & III
12Y-L13	5/8	↓	3.330	3.480		6.01			36.00	0.495	48.34	1.340	I & II & III
12Y-L14	3/4	↓	3.930	3.460	0.191	7.21			70.64	0.970	49.00	0.694	II & III
12Y-L15	3/8	↓	1.520	3.990	0.247	3.61			66.12	0.910	61.22	0.926	I & II & III
12Y-L17	5/8	↓	2.548	3.400	0.245	6.01			54.70	0.751	60.80	1.110	I & II & III
12Y-L18	3/4	↓	3.040	3.530	0.247	7.21			52.22	0.717	61.22	1.170	II & III
12Y-L19	7/8	↓	3.530	3.430	0.248	8.41			52.55	0.722	61.44	1.170	III
7Y-T3	3/4	0.183	1.500	0.833	0.500	4.10	86.40	91.30	84.74	0.928	91.30	1.080	III
7Y-L5		↓	3.750	2.500	0.200		83.10	83.90	52.00	0.620	58.73	1.130	I & II & III
7Y-L6		↓	3.750	5.000			83.10	83.10	79.00	0.951	58.73	0.743	II & III
12Y-L27	3/8	0.105	0.872	5.330	0.430	3.57	87.00	88.10	85.00	0.965	88.10	1.040	III
12Y-L28	5/8	0.105	1.500	4.000	0.420	5.95	87.00	88.10	88.70	1.010	88.10	0.993	III
7Y-T30	3/4	0.183	1.870	3.330	0.400	4.10	87.00	91.00	96.60	1.060	91.00	0.942	III
7Y-L20		↓	1.500	1.500	0.500		83.10	83.80	84.60	1.010	83.80	0.991	III
7Y-L21		↓	2.500	3.200	0.300				83.10	0.992	83.80	1.010	III
20Z-L1	1/2	0.039	1.500	3.500	0.330	12.82	75.50	81.70	85.30	1.040	81.70	0.960	III
20Z-L2		↓		2.000					74.90	0.917	81.70	1.090	I & II & III
20Z-L3	3/4	↓	2.500	2.000	0.300	19.23			63.80	0.781	81.70	1.280	I & II & III
20Z-T10	1/2	↓	1.500	3.500	0.330	12.82	94.40	99.80	70.80	0.710	99.80	1.400	III
20Z-T11		↓	2.500	3.000	0.200				40.23	0.403	70.00	1.740	II & III
1605X-L1	3/4	0.065	2.500	3.000	0.300	11.54	83.25	83.25	81.30	0.977	83.25	1.020	III
16FAX-L16	1/2	0.060		3.500	0.200	8.33	30.10	45.90	41.30	0.900	32.13	0.778	II & III

$*(\sigma_{net})_{cal} = (.1 + 3d/s)F_u$

Mean = 1.070

See Table 1 for the definition of type of failure.

Standard Deviation = 0.230

Table 10. Dimensions and Results of Bolted Connections with Washers-Tensile Strength Study (Double Shear)

Spec. No.	d (in)	t (in)	s (in)	e/d	d/s	d/t	Fy (ksi)	Fu (ksi)	$(\sigma_{net})_{test}$ (ksi)	$\frac{(\sigma_{net})_{test}}{Fu}$	$(\sigma_{net})^{*}_{cal}$ (ksi)	$\frac{(\sigma_{net})_{cal}}{(\sigma_{net})_{test}}$	Failure Type	Reference
20A21DS2	1/4	0.0347	4.0	2.5	0.063	7.2	32.11	41.85	9.66	0.231	12.1	1.25	I & III	9
20A22DS	3/8	0.0344	.		0.094	10.9			14.84	0.355	16.0	1.08	I & III	9
20A23DS1	1/2	0.0354			0.125	14.12			20.8	0.497	19.9	0.957	I & III	9
20A33DS1	1/2	0.0360		3.5		13.9			23.6	0.564		0.843	III	9
20A43DS	1/2	0.0356		4.5		14.04			29.0	0.693		0.686	III	9
20A34DS	5/8	0.0354		3.5	0.156	17.66			35.81	0.856	23.77	0.664	III	9
20A44DS1	5/8	0.036		4.5		17.36			34.56	0.826		0.688	III	9
20A25DS	3/4	0.0355		2.5	0.188	21.13			29.86	0.714	27.8	0.931	III	9
20A35DS1	3/4	0.0357		3.5		21.01			35.68	0.853	27.8	0.779	III	9
16C403DS1	1/2	0.0591		4.0	0.125	8.46	32.0	44.0	31.33	0.712	20.9	0.667	III	9
16C503DS1	1/2			5.0					34.98	0.795		0.597	III	9
14A43DS1	1/2	0.077		4.5		6.49	29.8	43.4	29.77	0.686	20.62	0.693	III	9
14B25DS1	3/4	0.0797		2.5	0.188	9.41			28.38	0.654	28.62	1.02	III	9
14B35DS1	3/4	0.077		3.5		9.74			34.27	0.79		0.841	III	9
14B26DS1	1.0	0.076		2.5	0.25	13.23			37.6	0.866	36.9	0.981	III	9
14B36DS1	1.0	0.0734		3.5	0.25	13.62			42.39	0.977		0.870	III	9
12A34DS1	5/8	0.0922		3.5	0.156	6.78	26.0	41.15	31.83	0.774	23.37	0.734	III	9
12A44DS1	5/8			4.5					36.87	0.896		0.634	III	9
8B35DS1	3/4	0.197		3.5	0.188	3.81	32.0	46.0	41.4	0.90	30.54	0.743	III	9
8B45DS1	3/4	0.1808		4.5		4.15			46.5	1.01		0.657	III	9
8B45DS1	1.0	0.191		2.5	0.25	5.24			43.35	0.942	39.1	0.902	III	9
18E34DS1	5/8	0.0451		3.5	0.156	13.86	46.75	68.0	43.98	0.647	38.62	0.878	I & III	9
18E44DS1	5/8	0.0453		4.5	0.156	13.8			45.84	0.674		0.842	I & III	10
14E25DS1	3/4	0.0781		2.5	0.188	9.6	54.44	70.4	42.1	0.598	46.75	1.11	III	10
14E45DS1	3/4	0.0781		4.5		9.54			67.4	0.957		0.694	III	10
10E25DS1	3/4	0.1351		2.5		5.55	59.5	71.85	44.85	0.624	47.71	1.06	I & III	10
10E16DS1	1.0	0.1421		1.5	0.25	7.04			35.4	0.493	61.1	1.73	I & III	10
10E46DS1	1.0	0.1411		4.5		7.09			69.4	0.966		0.88	III	10
14G25DS1	3/4	0.0768	2.0	2.5	0.375	9.77	29.8	43.4	47.8	1.1	43.4	0.908	III	10
14G35DS	3/4	0.0760		3.5	0.375	9.87			48.3	1.11	43.4	0.90	III	10
14G45DS	3/4	0.0755		4.5	0.375	9.93			49.7	1.15	43.4	0.87	III	10

$*(\sigma_{net})_{cal} = (.1 + 3d/s)F_u$

Mean = 0.870

Standard Deviation = 0.220

See Table 1 for the definition of type of failure

Table 11. Dimensions and Results of Double Shear Bolted Connections With Washers-Tensile Strength Study[6]

Spec No	d (in)	t (in)	s (in)	e/d	d/s	d/t	F_y (ksi)	F_u (ksi)	$(\sigma_{net})_{test}$ (ksi)	$\frac{(\sigma_{net})_{test}}{F_u}$	$(\sigma_{net})^*_{cal}$ (ksi)	$\frac{(\sigma_{net})_{cal}}{(\sigma_{net})_{test}}$	Failure Type
20Z-L9	3/4	0.039	2.5	3.0	0.30	19.23	75.50	81.70	74.00	0.906	81.70	1.100	II & III
20ZT13							99.40	99.80	74.45	0.746	99.80	1.340	II & III
1605X-L2		0.065				11.54	83.25	83.25	85.70	1.030	83.25	0.971	III
1605XL3				2.0					68.72	0.825		1.210	I & II & III
1205X-L8		0.105	3.0	3.5	0.25	7.14	81.60	81.60	81.85	1.000	69.36	0.847	II & III
1205X-L9	7/8		3.5	3.5		8.33			83.25	1.020	69.36	0.833	II & III
1205X-L11	3/4		2.5	3.0	0.30	7.14	80.50	80.50	77.30	0.960	80.50	1.040	III
7Y-L32	5/8	0.183	3.0	3.5	0.21	3.42	82.60	82.60	66.20	0.801	60.30	0.911	I & II & III
16FAX-L12	3/4	0.060	2.5	3.0	0.30	12.50	30.10	45.90	46.00	1.000	45.90	0.998	III
16FAX-L13			2.5	3.5					46.20	1.010		0.994	III
16FAXL15	1/2		2.5		0.20	8.33			43.87	0.956	32.13	0.732	II & III
1610XL18	3/4			3.0	0.30	12.50	78.40	81.50	84.32	1.030	81.50	0.967	III
12FAXL18	3/4	0.107		3.0	0.30	7.01	28.10	44.10	45.10	1.020	44.10	0.987	III
12FAXL20	1/2			3.5	0.20	4.67			41.10	0.932	30.87	0.751	II & III
1615XL22	3/4	0.600		3.0	0.30	12.50	45.40	54.70	61.80	1.180	54.70	0.885	III
1615XL23	1/2				0.20	8.33			50.90	0.931	38.30	0.752	II & III
1625XL26	3/4				0.30	12.50	38.50	49.10	57.17	1.160	49.10	0.859	III
1625XL27	1/2				0.20	8.33			42.50	0.866	34.37	0.808	II & III
1625XL28	1/2			3.5	0.20				44.50	0.906		0.772	II & III
1210XL32	3/4	0.107		3.0	0.30	7.01	70.10	72.80	77.70	1.070	72.80	0.937	III
1210XL25	1/2		2.0	3.5	0.25	4.67			77.10	1.060	61.88	0.803	II & III
1215XL26	3/4		2.5	3.0	0.30	7.01	65.20	69.30	66.00	0.952	69.30	1.050	III
1215XL29	1/2		2.0	3.5	0.25	4.67			69.83	1.010	58.91	0.844	II & III
1225X-L30	3/4		2.5	3.0	0.30	7.01	36.60	50.00	53.61	1.070	50.00	0.933	III
1225XL31	1/2				0.20	4.67			42.40	0.848	35.00	0.825	II & III
1225XL32				3.5					42.50	0.850		0.823	II & III
1225XL33			2.0		0.25				51.50	1.030	42.50	0.825	II & III

$^*(\sigma_{net})_{cal} = (.1 + 3d/s)F_u$

Mean = 0.920

See Table 1 for the definition of type of failure.

Standard Deviation = 0.140

Table 12. Dimensions and Results of Multi-Bolted Connections With Washers-Tensile Strength Study [5]

Spec No	No of Bolts	d (in)	t (in)	s (in)	e/d	d/s	d/t	F_y (ksi)	F_u (ksi)	$(\sigma_{net})_{test}$ (ksi)	$\frac{(\sigma_{net})_{test}}{F_u}$	$(\sigma_{net})^*_{cal}$ (ksi)	$\frac{(\sigma_{net})_{cal}}{(\sigma_{net})_{test}}$	Failure Type
4F16A	1	3/4	0.060	4.01	4.00	0.1875	12.50	31.00	44.40	23.40	0.527	29.42	1.260	II & III
8F351	1	1 1/8	0.185	4.00	2.67	0.2810	6.08	55.70	77.40	68.70	0.887	73.00	1.060	II & III
14F451	1	1/2	0.078		6.00	0.1250	6.41	62.50	76.20	28.40	0.373	36.20	1.270	II & III
16A15	1	1/2	0.060				8.33	31.60	45.00	20.00	0.445	21.40	1.070	III
3C16A	2				3.50			31.00	44.40	37.60	0.847	32.75	0.871	II & III
4C16A	2	3/4	0.058	4.01	2.33	0.1875	12.93			40.00	0.903	36.91	0.923	II & III
8F352	2	1 1/8	0.185	4.00	2.67	0.2810	6.08	55.70	77.40	80.40	1.040	75.20	0.935	II & III
10F452	2	3/4	0.144		3.33	0.1875	5.21	62.80	80.70	74.60	0.926	67.10	0.900	III
14F452	2	1/2	0.078		5.00	0.1250	6.41	62.50	76.20	64.00	0.841	56.20	0.878	II & III
316A1	3		0.060		3.50		8.33	31.60	45.00	37.80	0.840	37.13	0.982	III
316A2	3									42.00	0.933		0.884	III
116A3	3	3/4			2.33	0.1875	12.50			43.50	0.968	39.94	0.918	III
216A3	3									43.00	0.956		0.929	III
16051A	3	1/2			4.00	0.1250	8.33	84.90	84.90	85.00	1.000	70.04	0.824	III
16052A	3	3/4			2.33	0.1875	12.50			100.00	1.180	75.35	0.754	III
16101A	3	1/2			4.00	0.1250	8.33	75.60	79.30	81.00	1.020	65.42	0.808	III
16102A	3	3/4			2.33	0.1875	12.50			86.40	1.090	70.40	0.815	III
7085S	3	5/8	0.184	3.22	5.00	0.1940	3.40	85.00	85.00	86.40	1.020	76.00	0.880	III
7091S	3	5/8	0.182	3.30		0.1940		86.25	86.25	84.80	0.983	76.76	0.905	III
7092S	3		0.183	4.23	6.80	0.1480				84.75	0.983	73.14	0.863	III
7093S	3		0.185							83.60	0.970		0.875	III

$*(\sigma_{net})_{cal} = (1 - .9r + 3rd/s)F_u$

See Table 1 for the definition of type of failure.

Mean = 0.930

Stanard Deviation = 0.130

Table 13. Torques Used in Installation of A307 Bolts (Cornell Tests) [3]

Bolt Diam. in.	Torque ft. lb.
1/4	5
3/8	14
1/2	40
5/8	50
3/4	110
1	250

Table 14. Torques Used in Installation of High Strength Bolts (Cornell Tests) [4]

Bolt Diam. in.	Torque ft. lb
1/4	11.0
3/8	37.5
1/2	95.0
5/8	190.0
3/4	335.0
1.0	750.0

Table 15. Bolt Tension Specified by the Research Council on Riveted and Bolted Structural Joints [21]

Bolt Diam, in.	Minimum Bolt Tension, kips	
	A325 Bolts	A490 Bolts
1/2	12	15
5/8	19	24
3/4	28	35
7/8	39	49
1	51	64
1 1/8	56	80
1 1/4	71	102
1 3/8	85	121
1 1/2	103	148

APPENDIC C

Figures

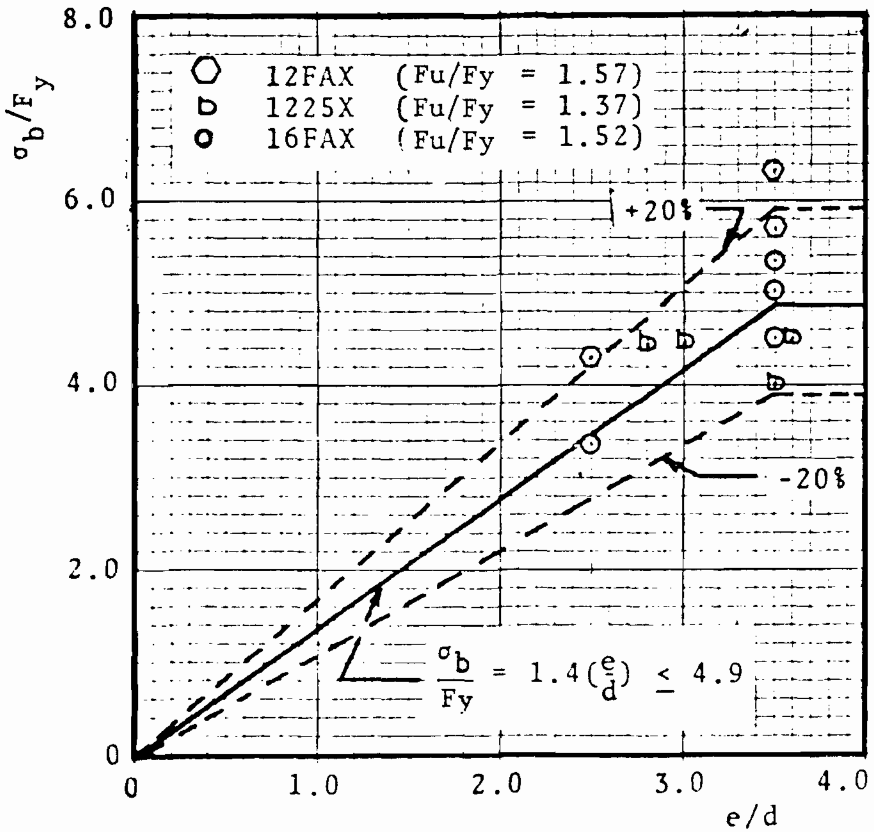

Fig. 1 Effect of Ductility (Fu/Fy ≥ 1.35) [6]

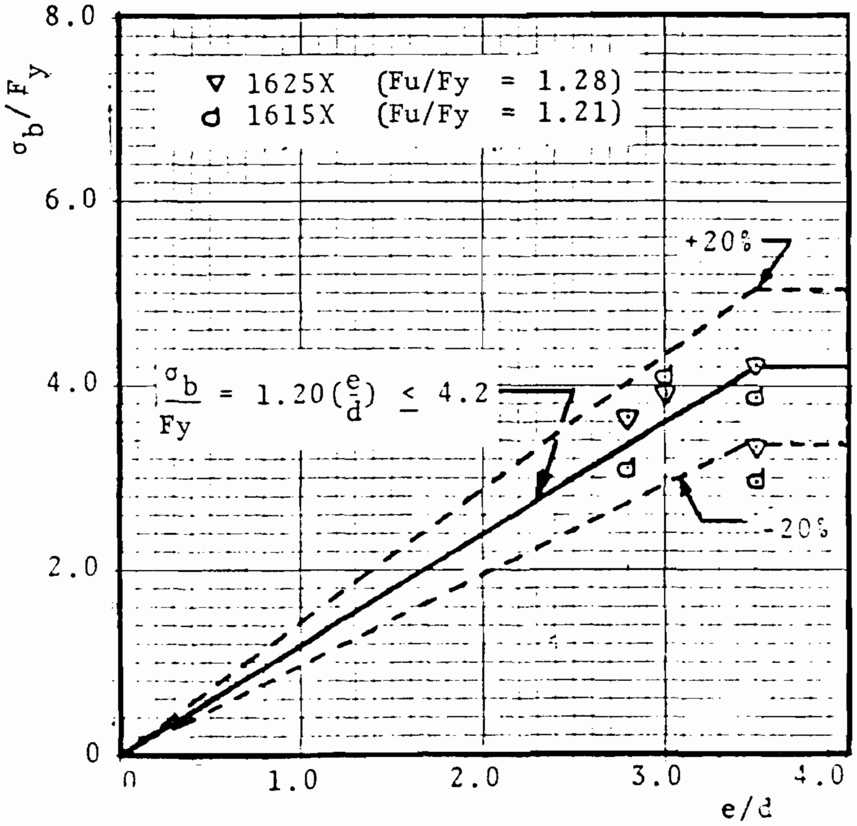

Fig. 2 Effect of Ductility (Fu/Fy ≃ 1.25) [6]

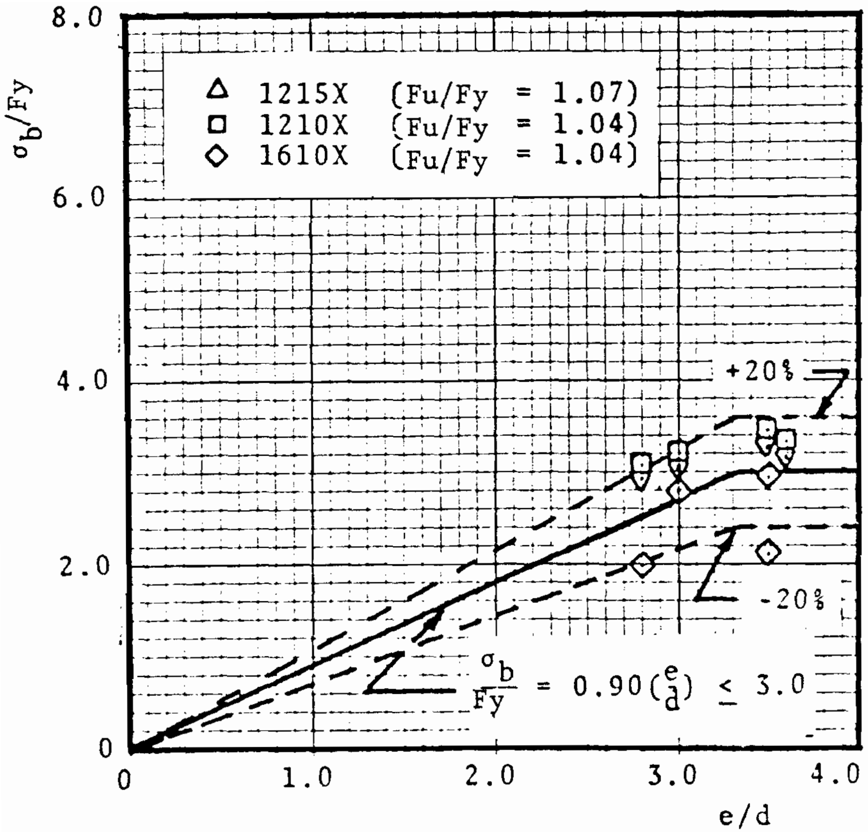

Fig. 3 Effect of Ductility ($F_u/F_y \leq 1.1$) [6]

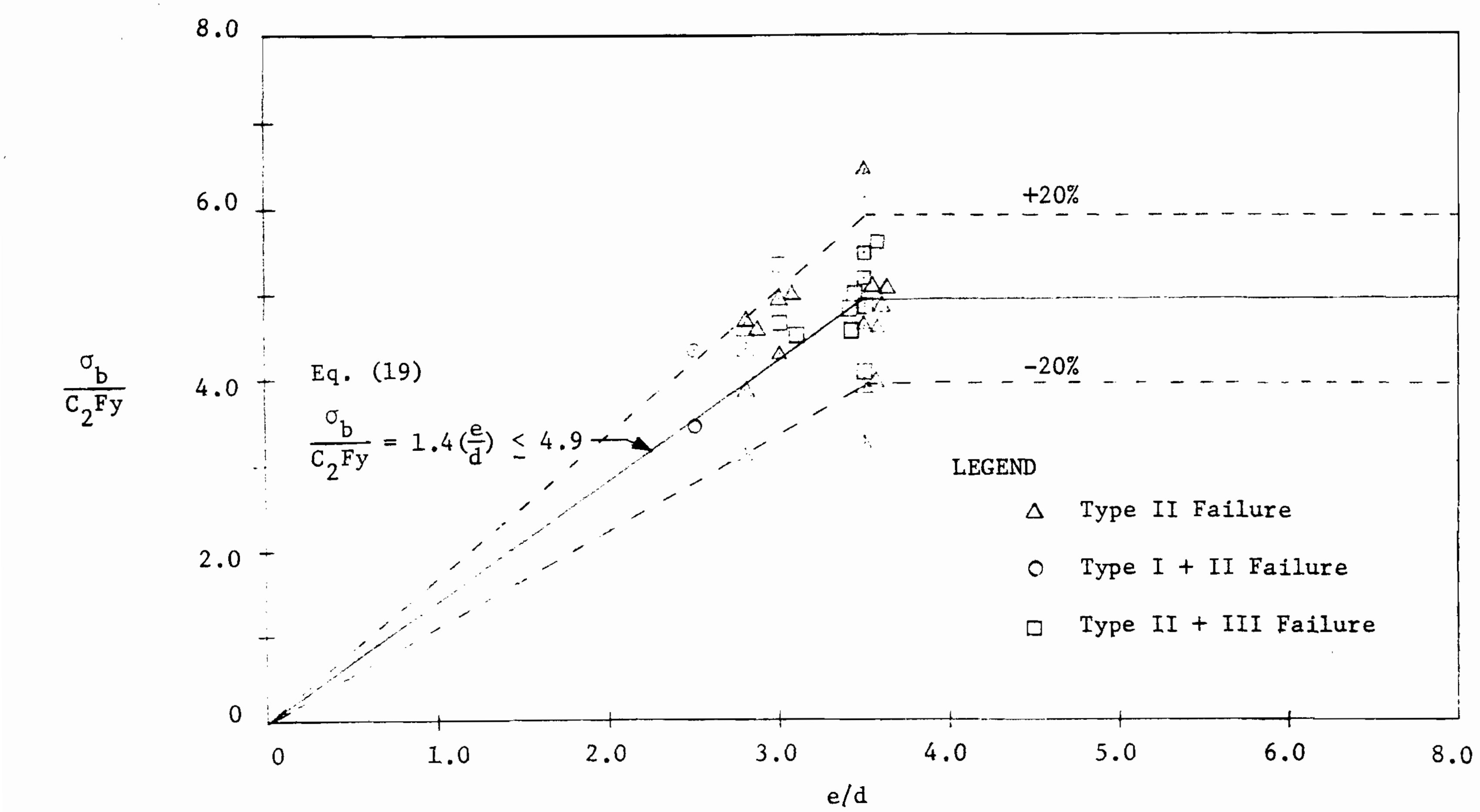

Fig. 4 Effect of C_2 Factor (Combination of the Test Data Shown in Figs. 1, 2 and 3) [6]

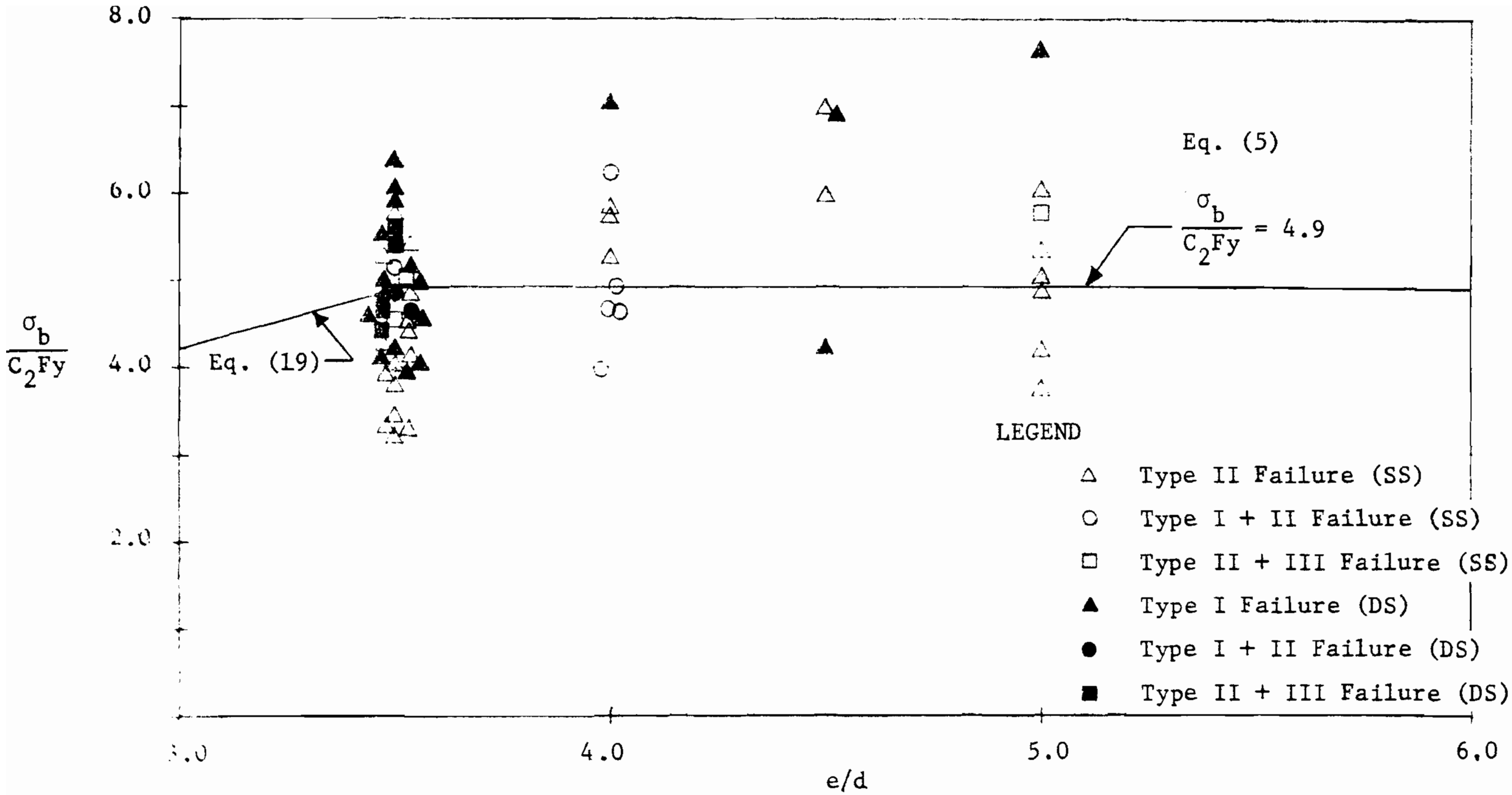

Fig. 5 Effect of Single and Double Shear Connections on Bearing Strength [9,10]

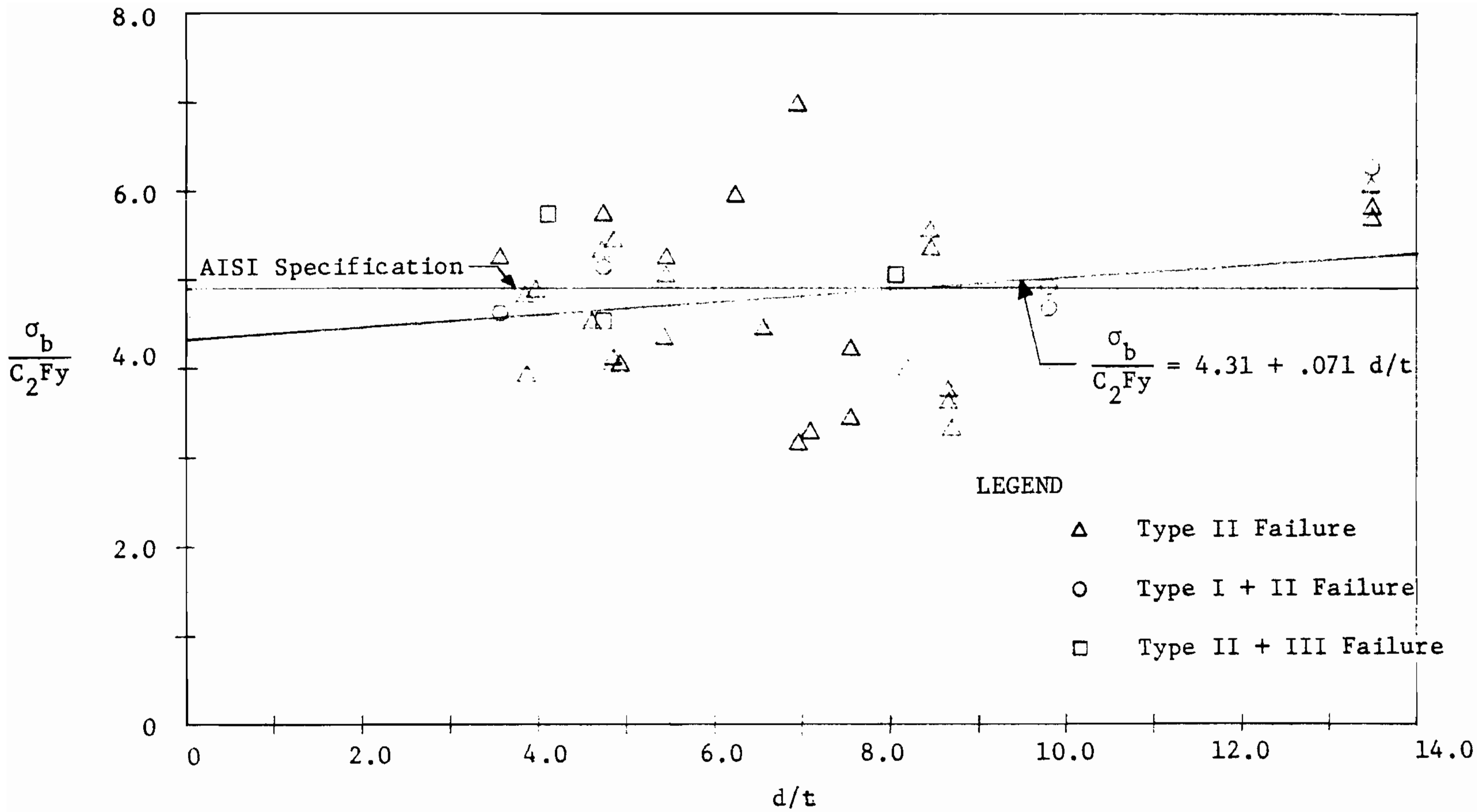

Fig. 6 Effect of d/t Ratio on Bearing Strength (Single Shear) [6,7,9,10,14]

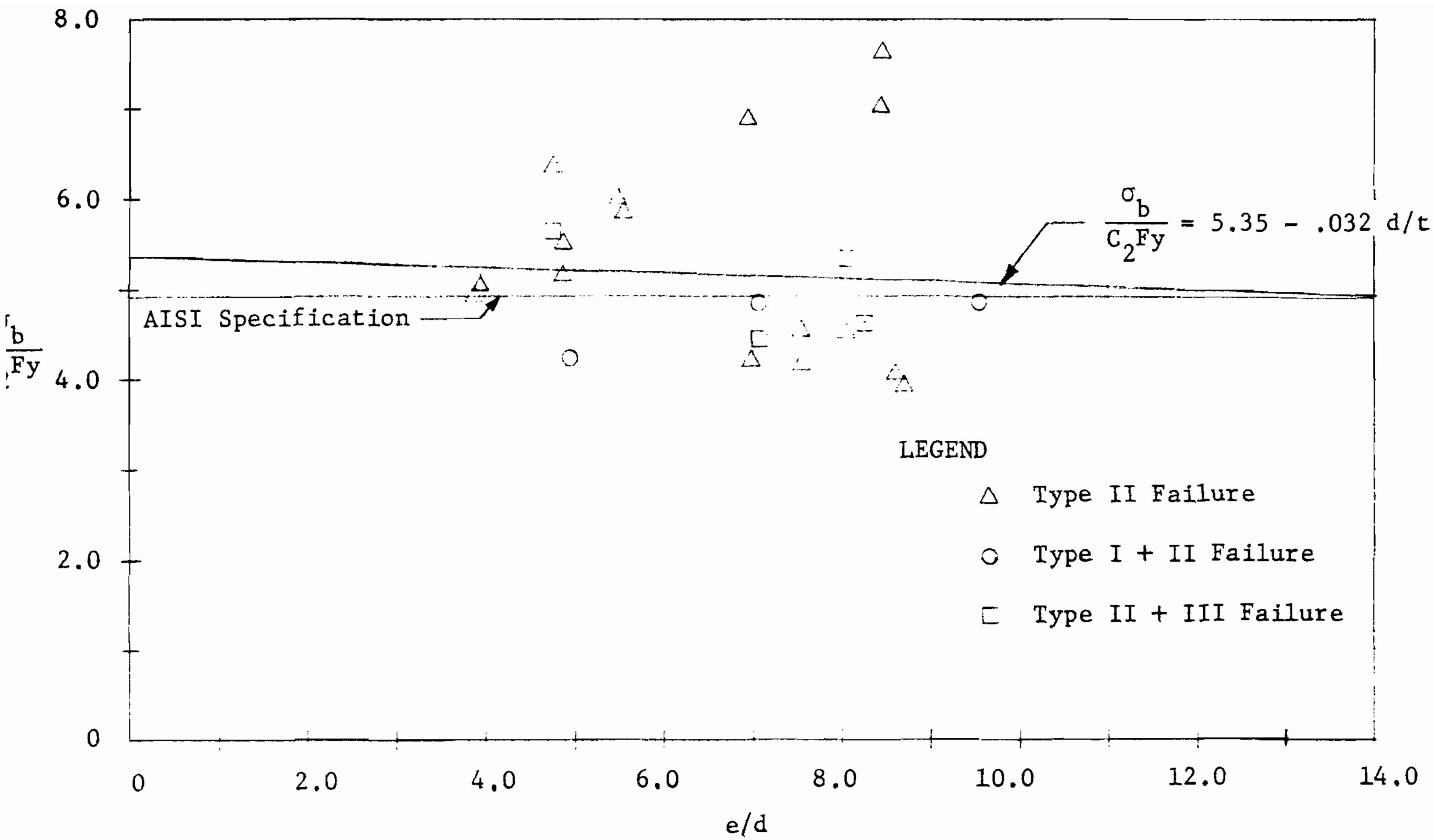

Fig. 7 Effect of d/t Ratio on Bearing Strength (Double Shear) [6,9,10,14]

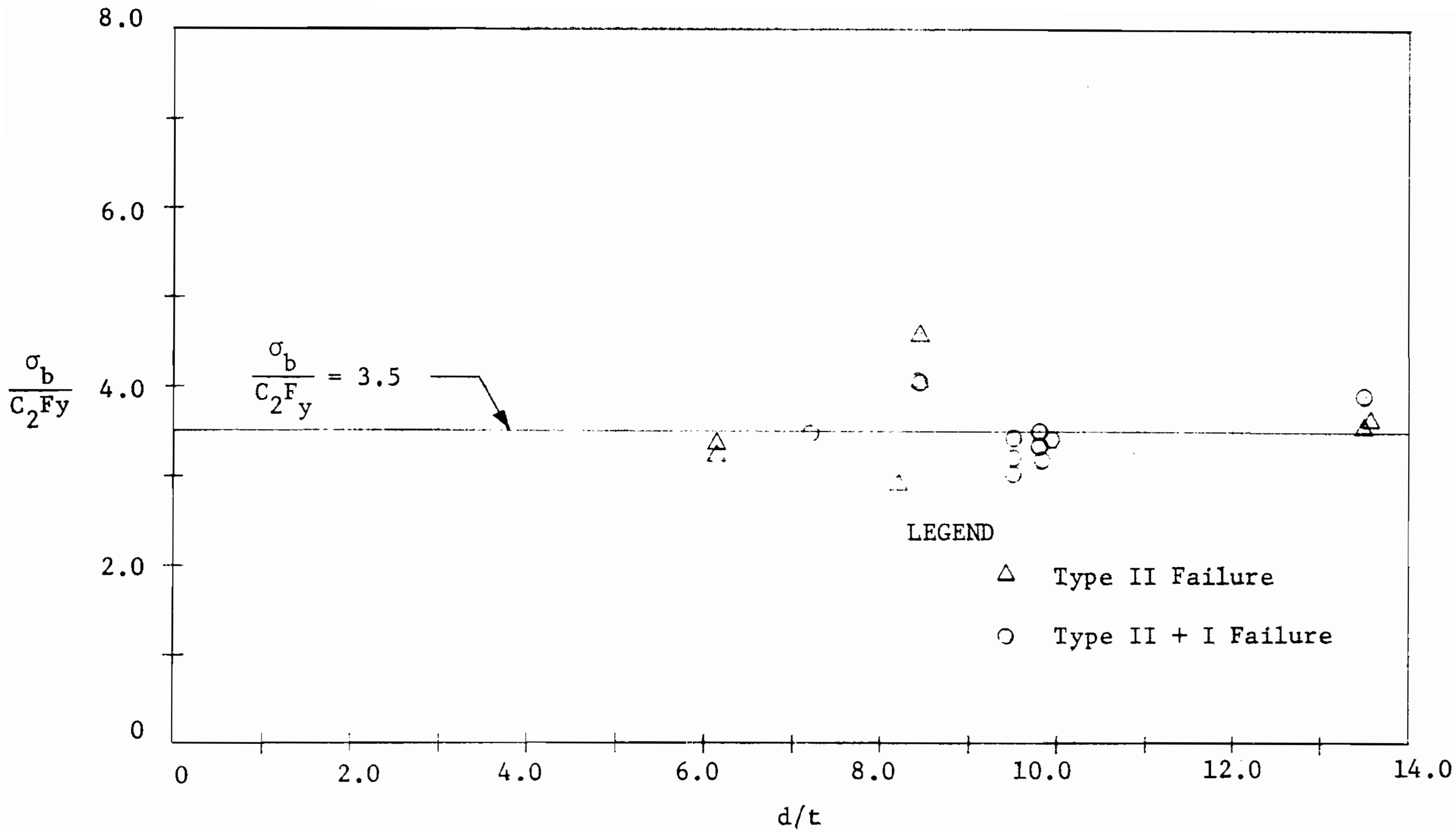

Fig. 8. Effect of d/t Ratio on Bearing Strength of Connections without Washers (Single Shear)[7]

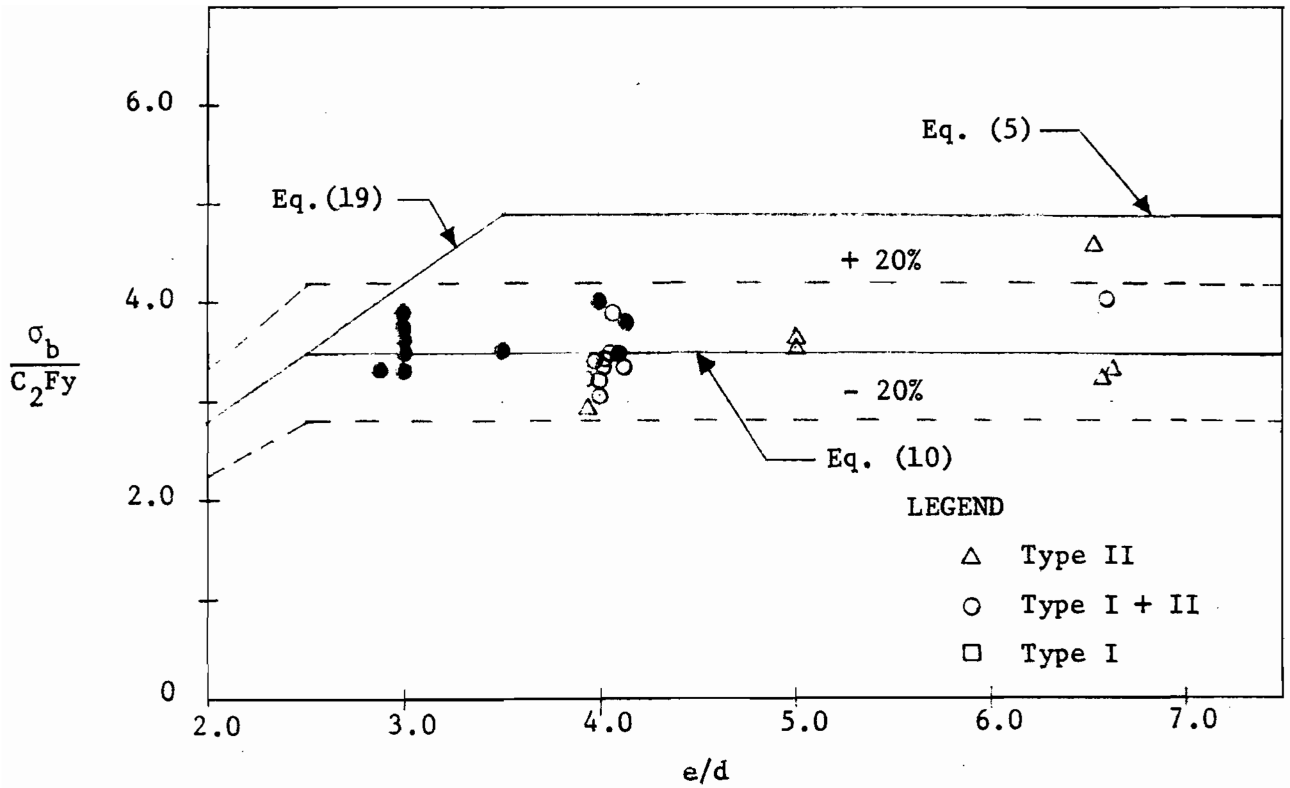

Fig. 9. Effect of e/d on Bearing Strength of Bolted Connections without Washers[7]

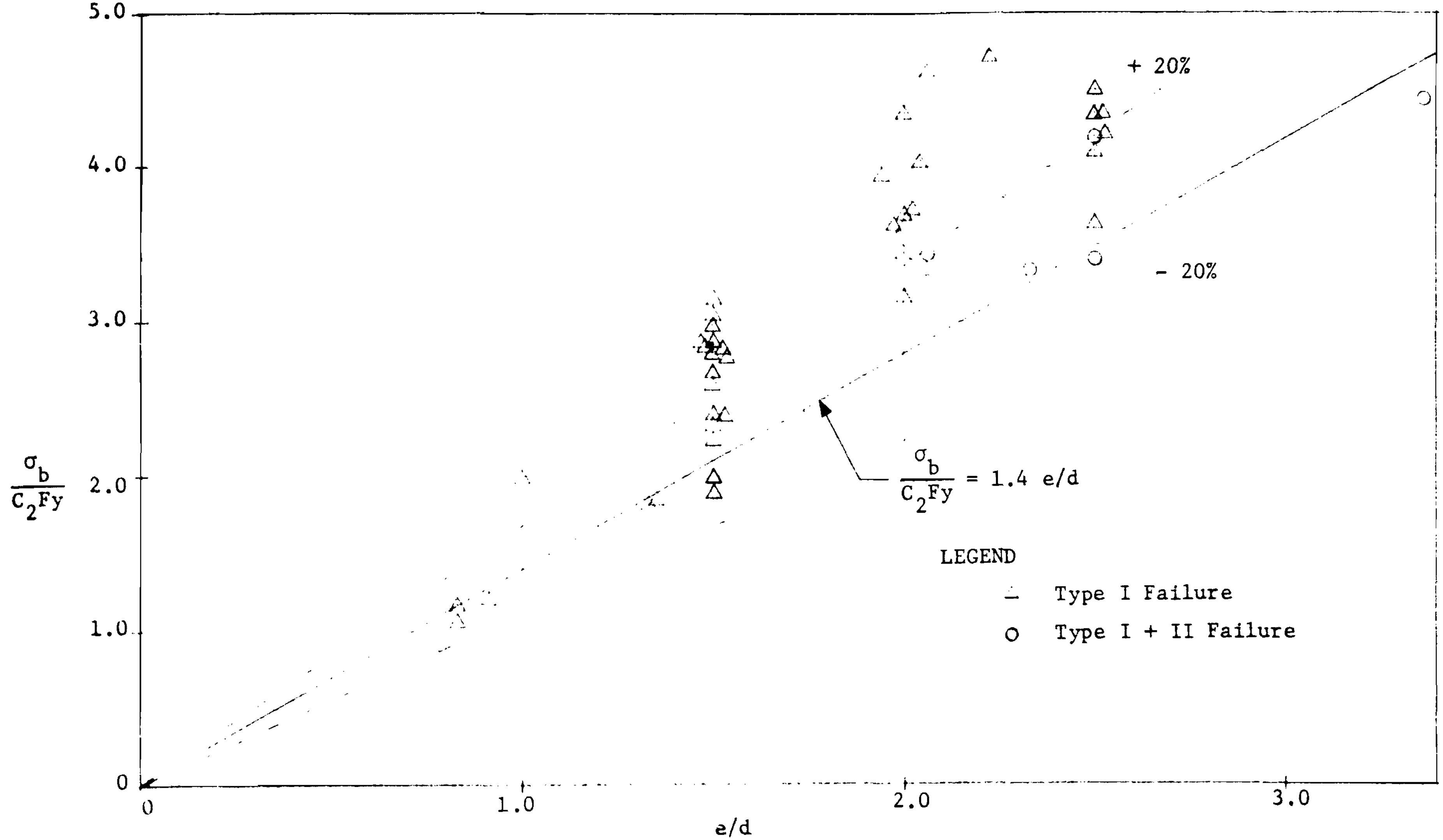

Fig. 10 Effect of e/d on Longitudinal Shear Strength of Steel Sheets (Single Shear) [6,7,9,10,14]

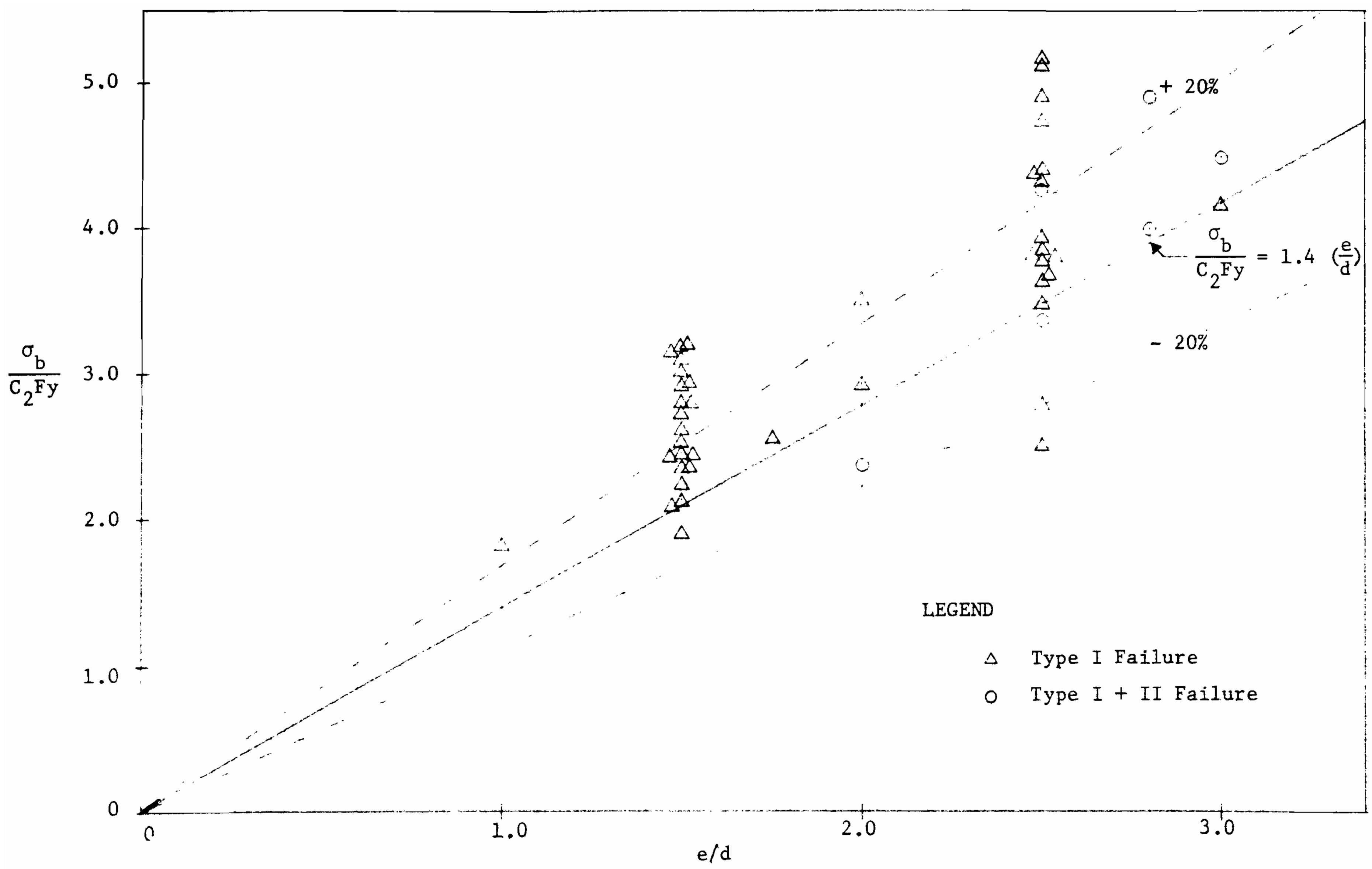

Fig. 11 Effect of e/d on Longitudinal Shear Strength of Steel Sheets (Double Shear) [6,9,10]

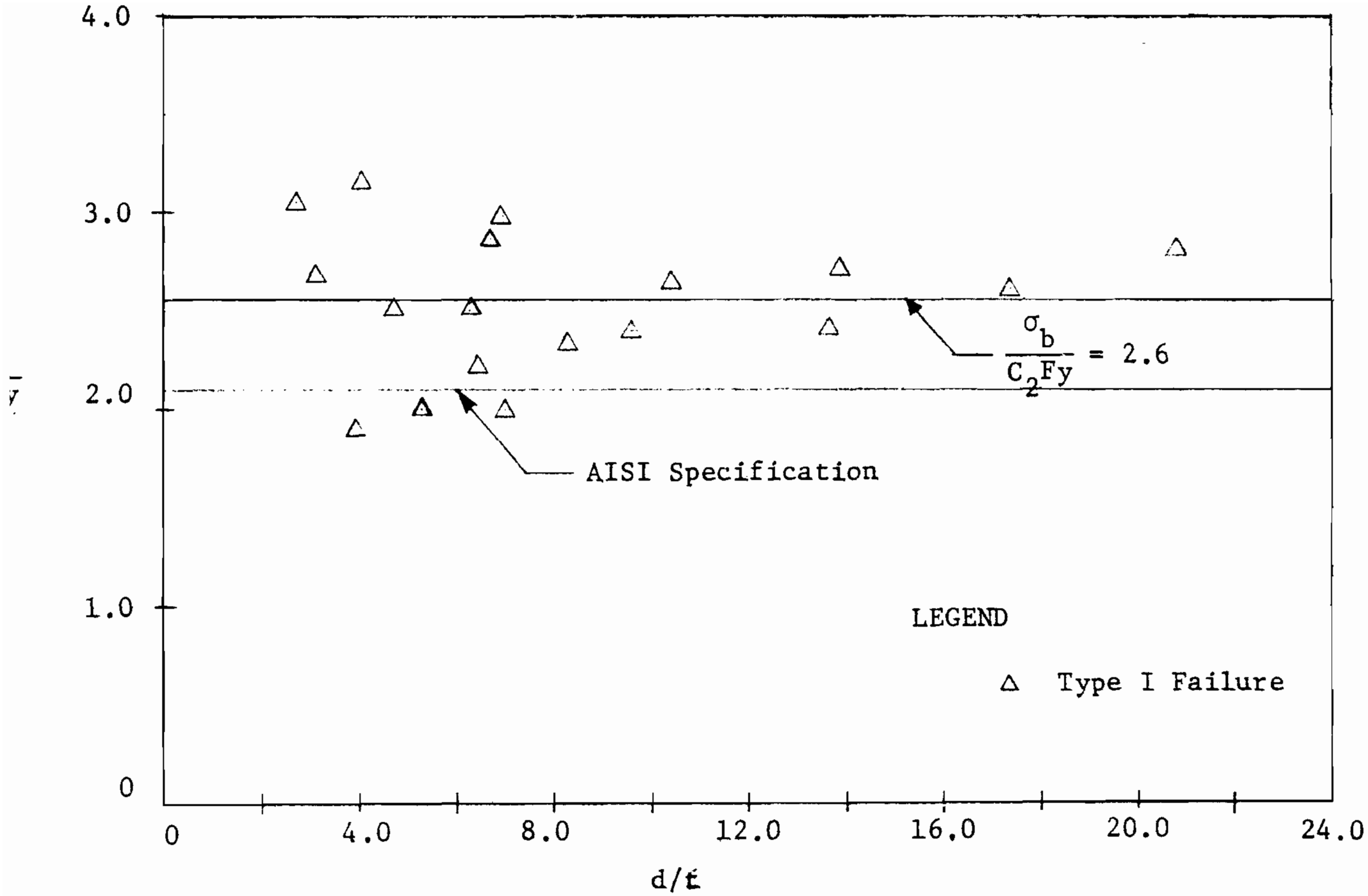

Fig. 12 Effect of d/t on Longitudinal Shear Strength of Steel Sheets (Single Shear, e/d = 1.5)[9,10]

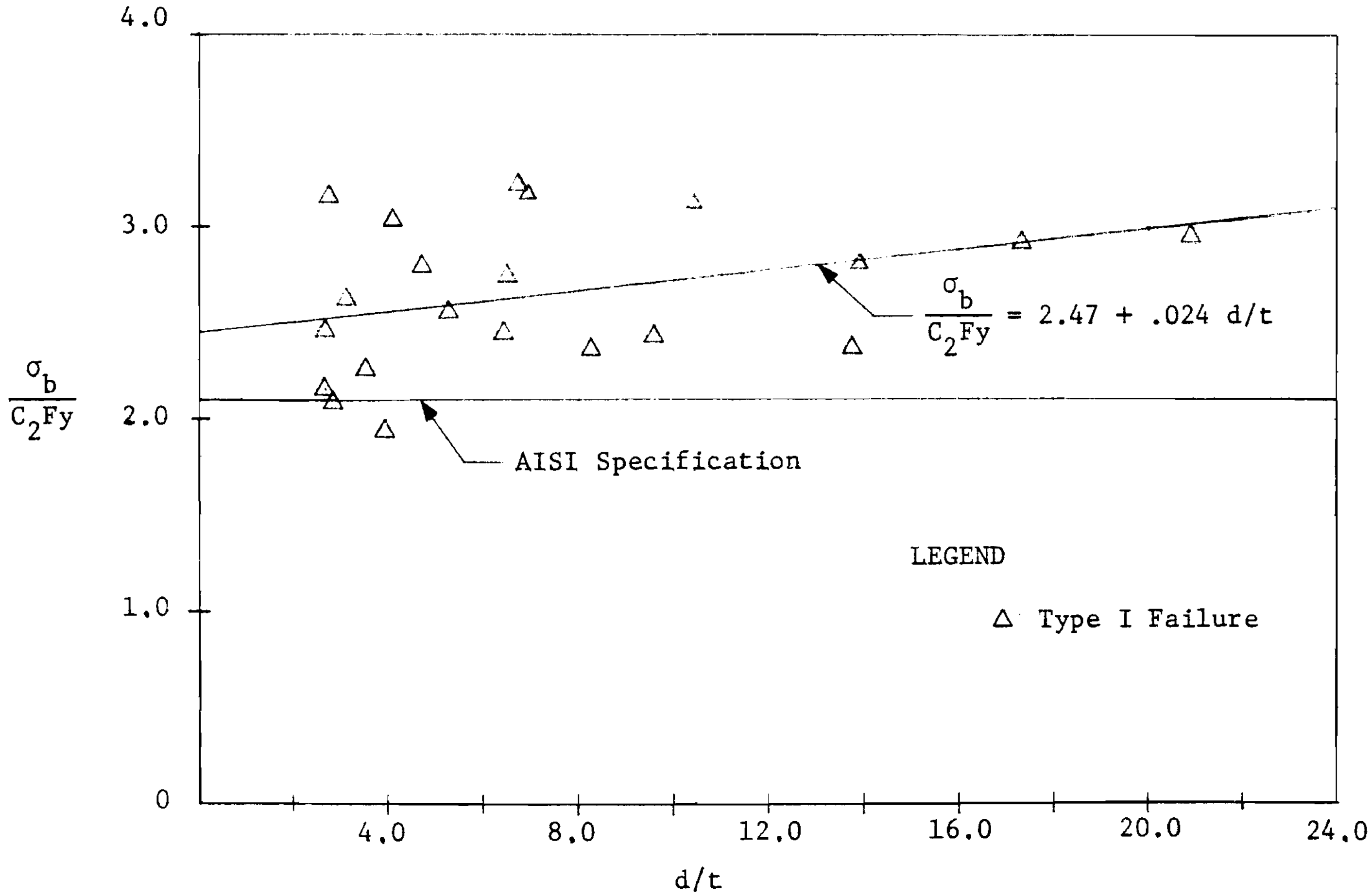

Fig. 13. Effect of d/t on Longitudinal Shear Strength of Steel Sheets (Double Shear, e/d = 1.5) [9,10]

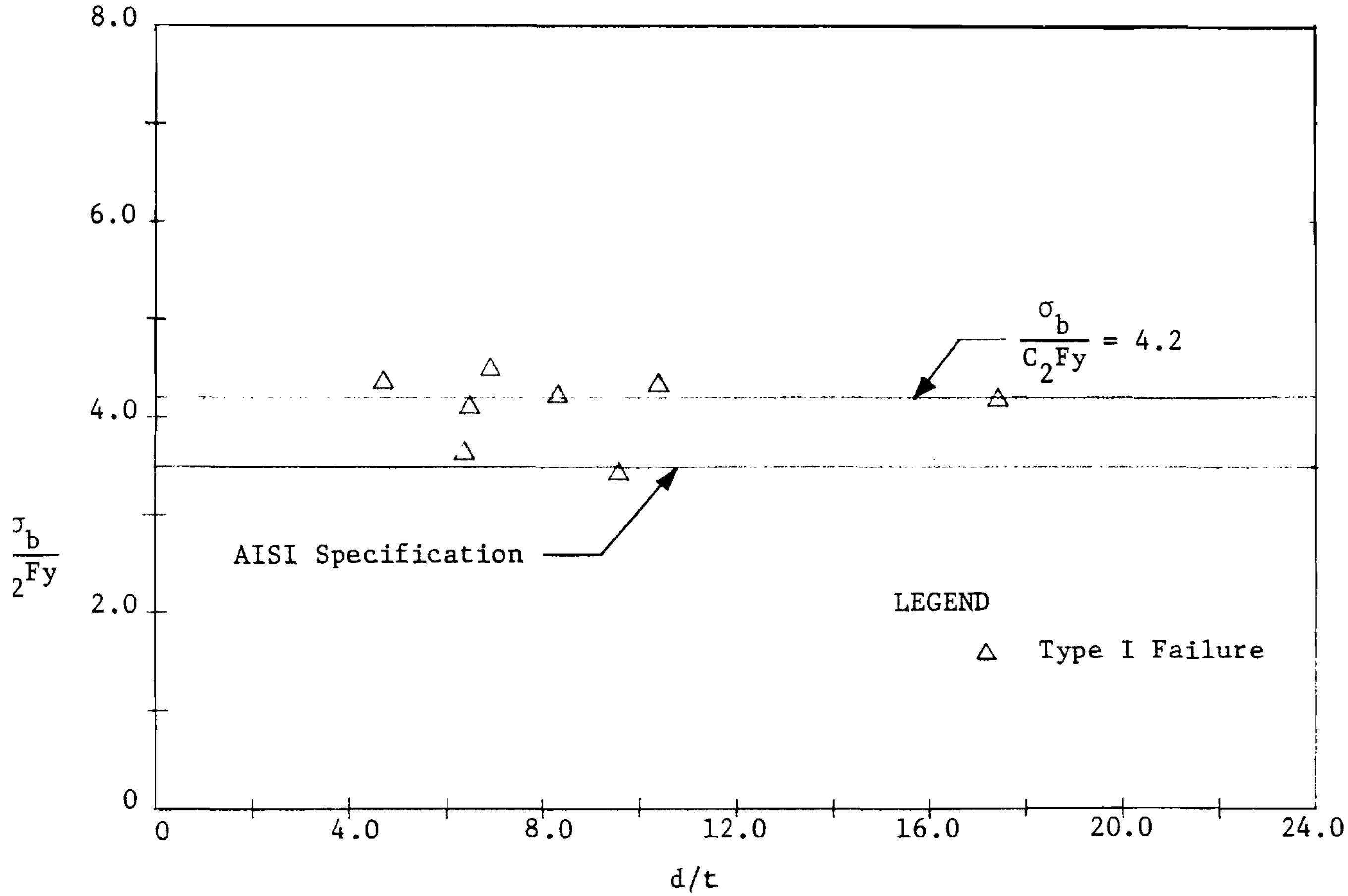

Fig. 14 Effect of d/t on Longitudinal Shear Strength of Steel Sheets (Single Shear, e/d = 2.5) [9,10]

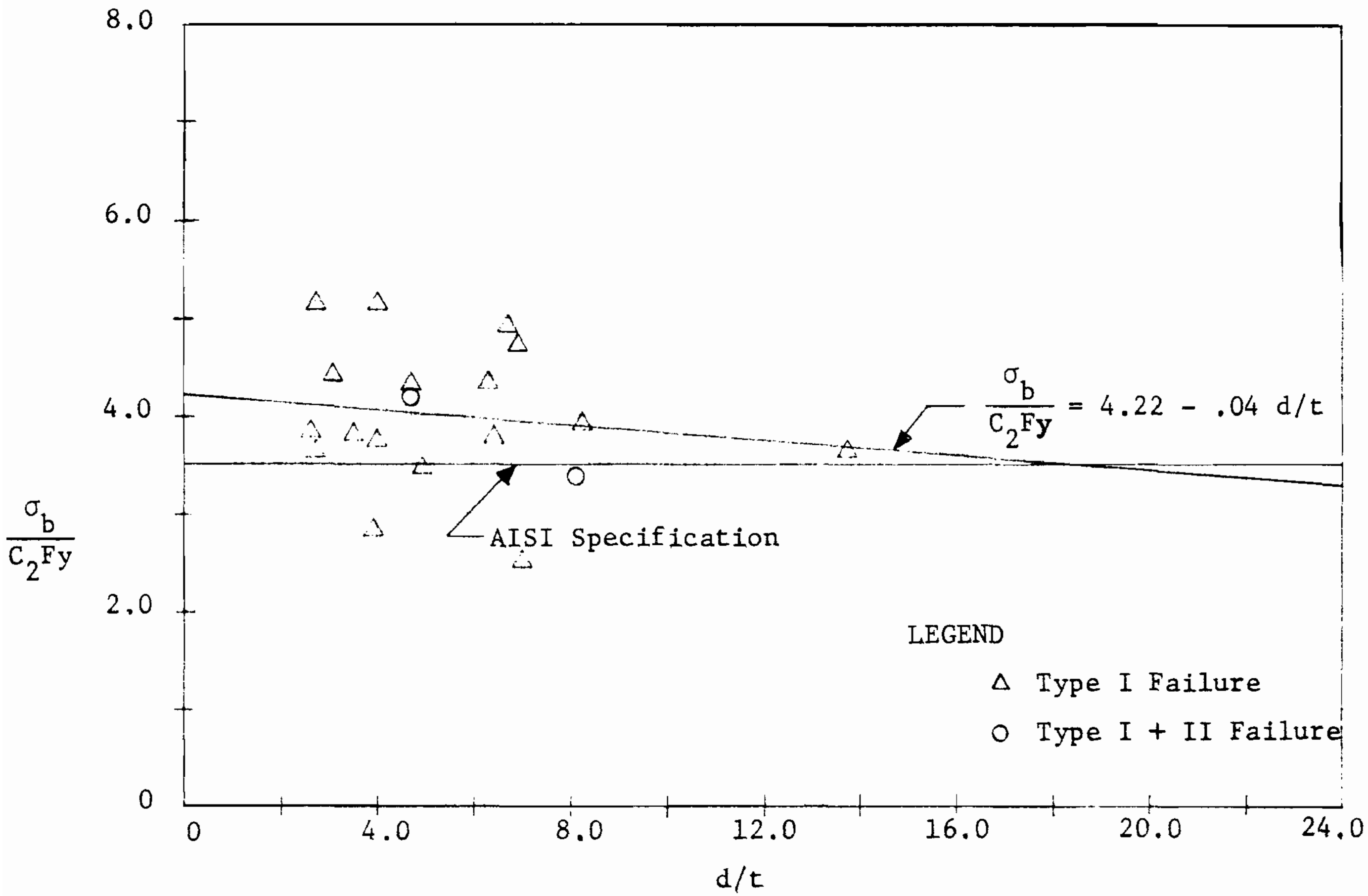

Fig. 15 Effect of d/t on Longitudinal Shear Strength of Steel Sheets (Double Shear e/d = 2.5) [6,9,10]

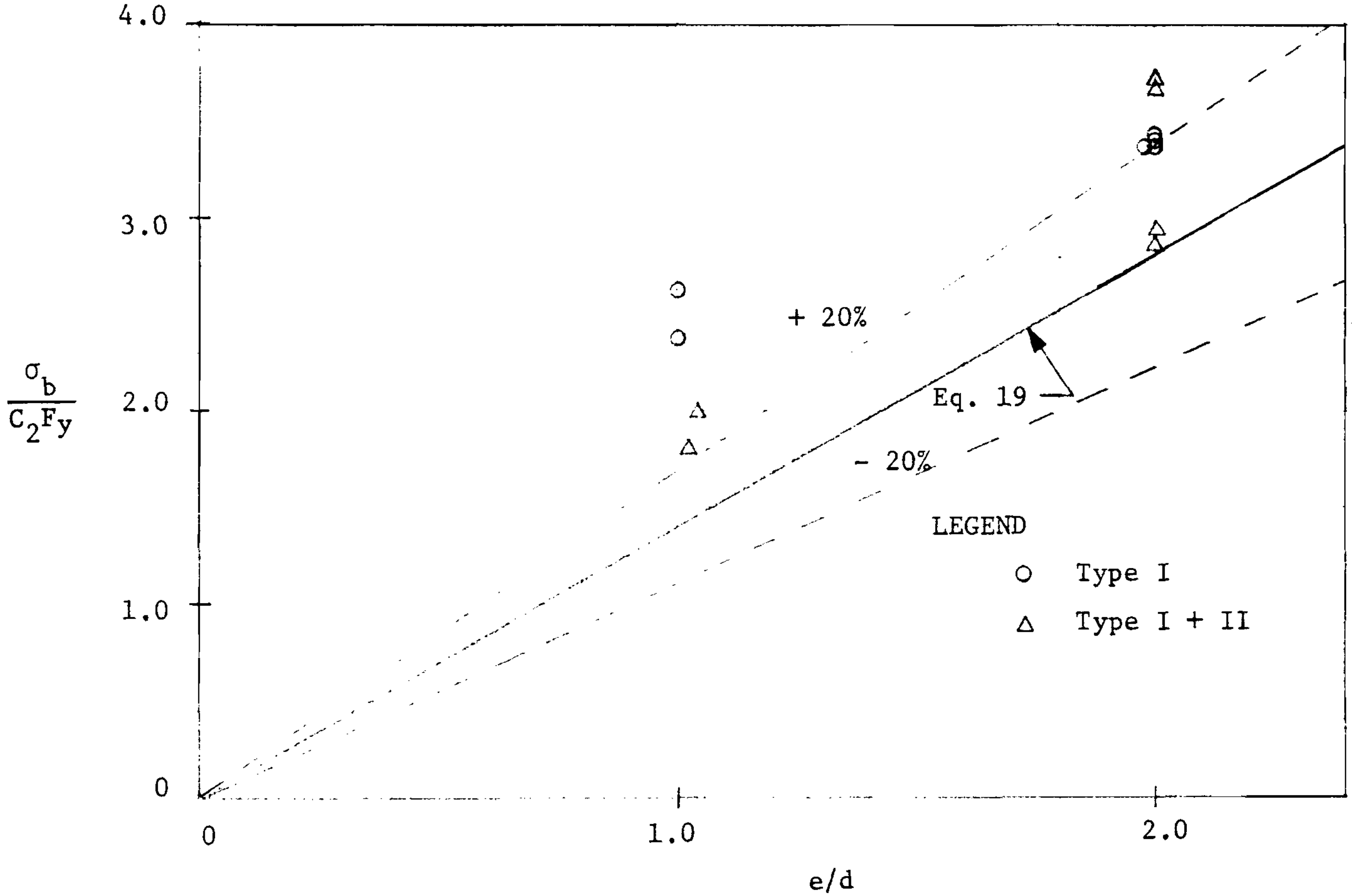

Fig. 16 Effect of e/d on Longitudinal Shear Strength of Steel Sheets in Bolted Connections without Washers[7]

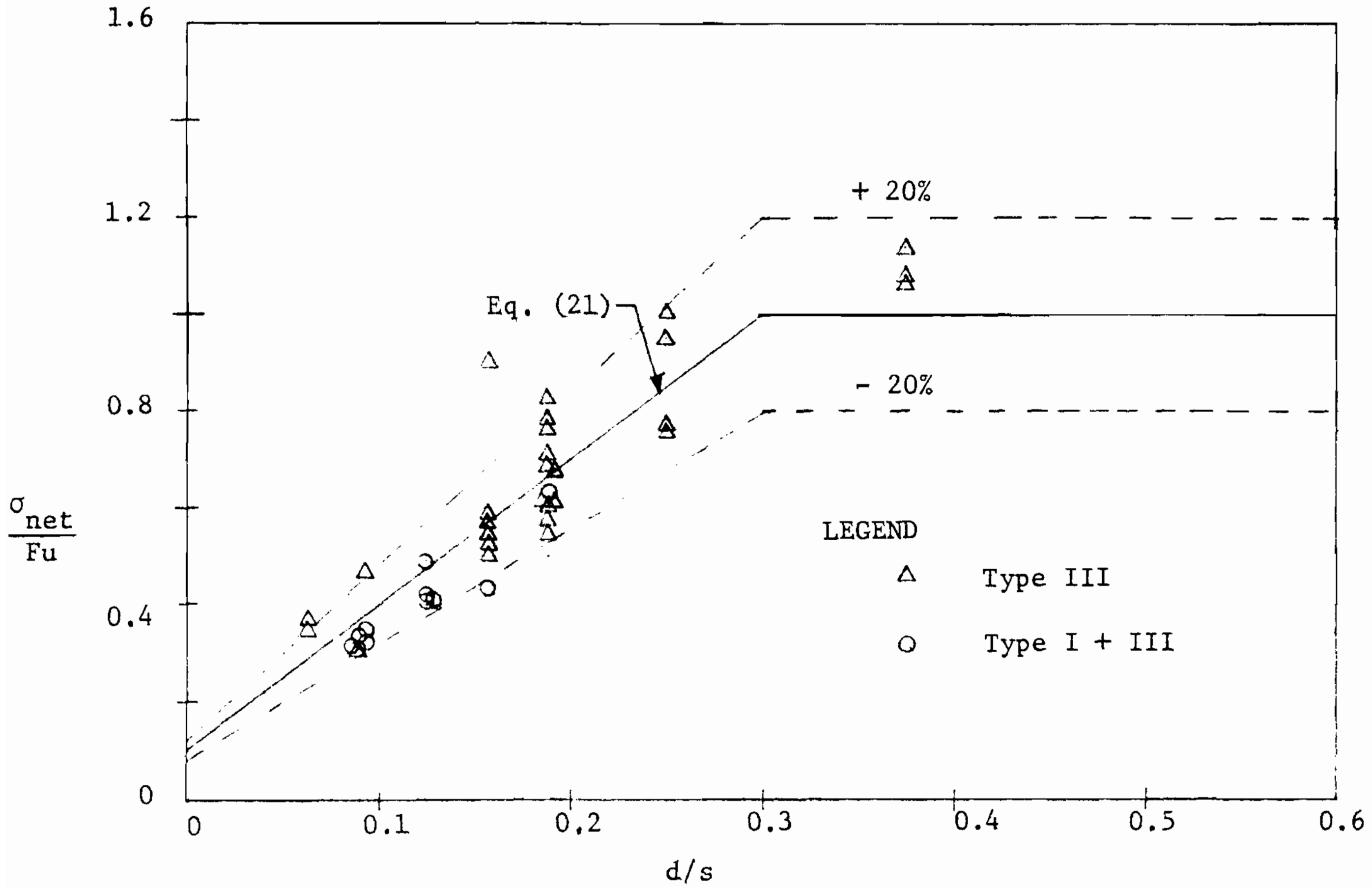

Fig. 17 Effect of d/s on Tensile Strength of Bolted Connections Using High Ductility Steels (Single Shear, One Bolt)[9,10]

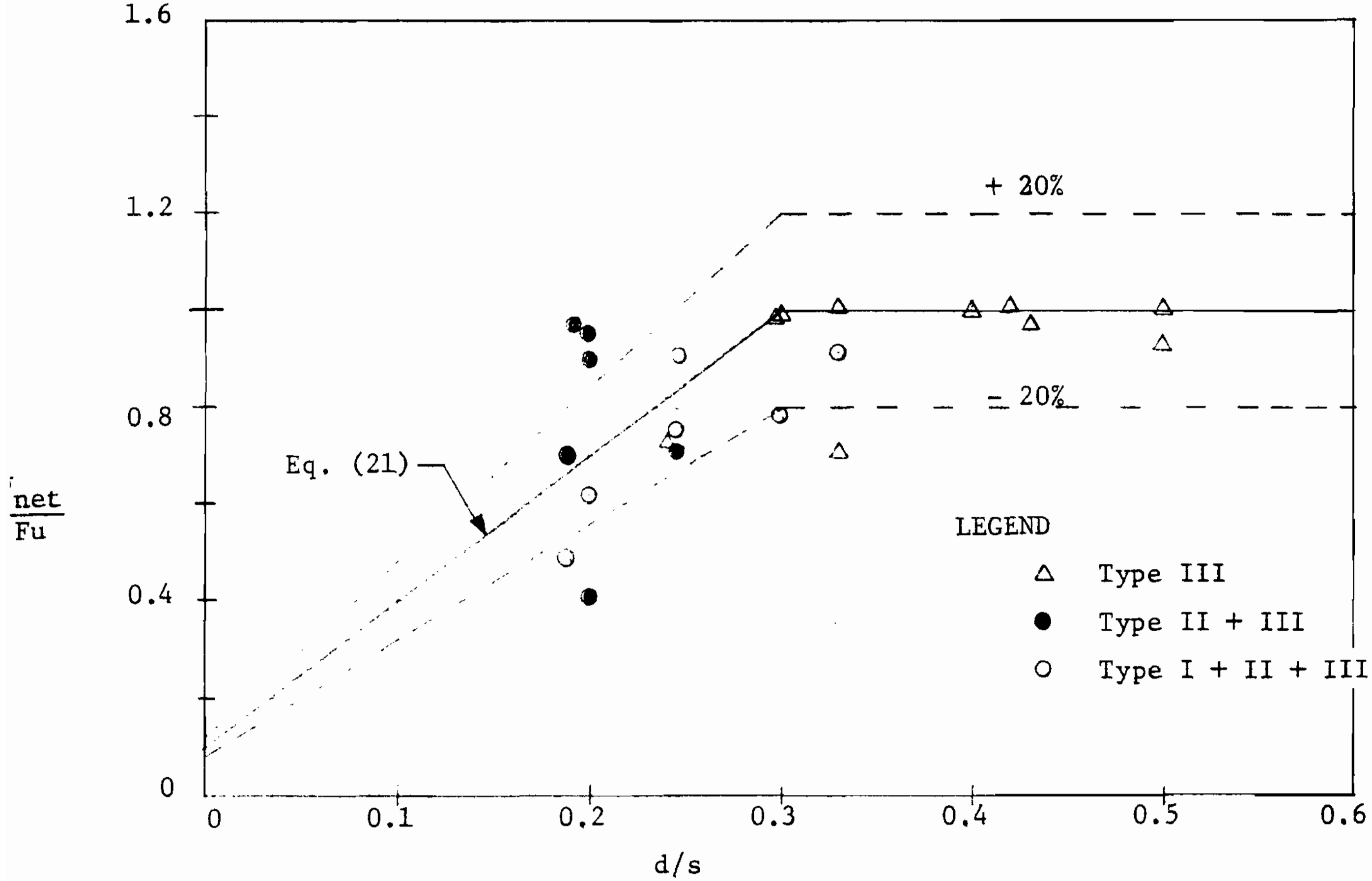

Fig. 18 Effect of d/s on Tensile Strength of Bolted Connections Using Low Ductility Steels (Single Shear, One Bolt)[6]

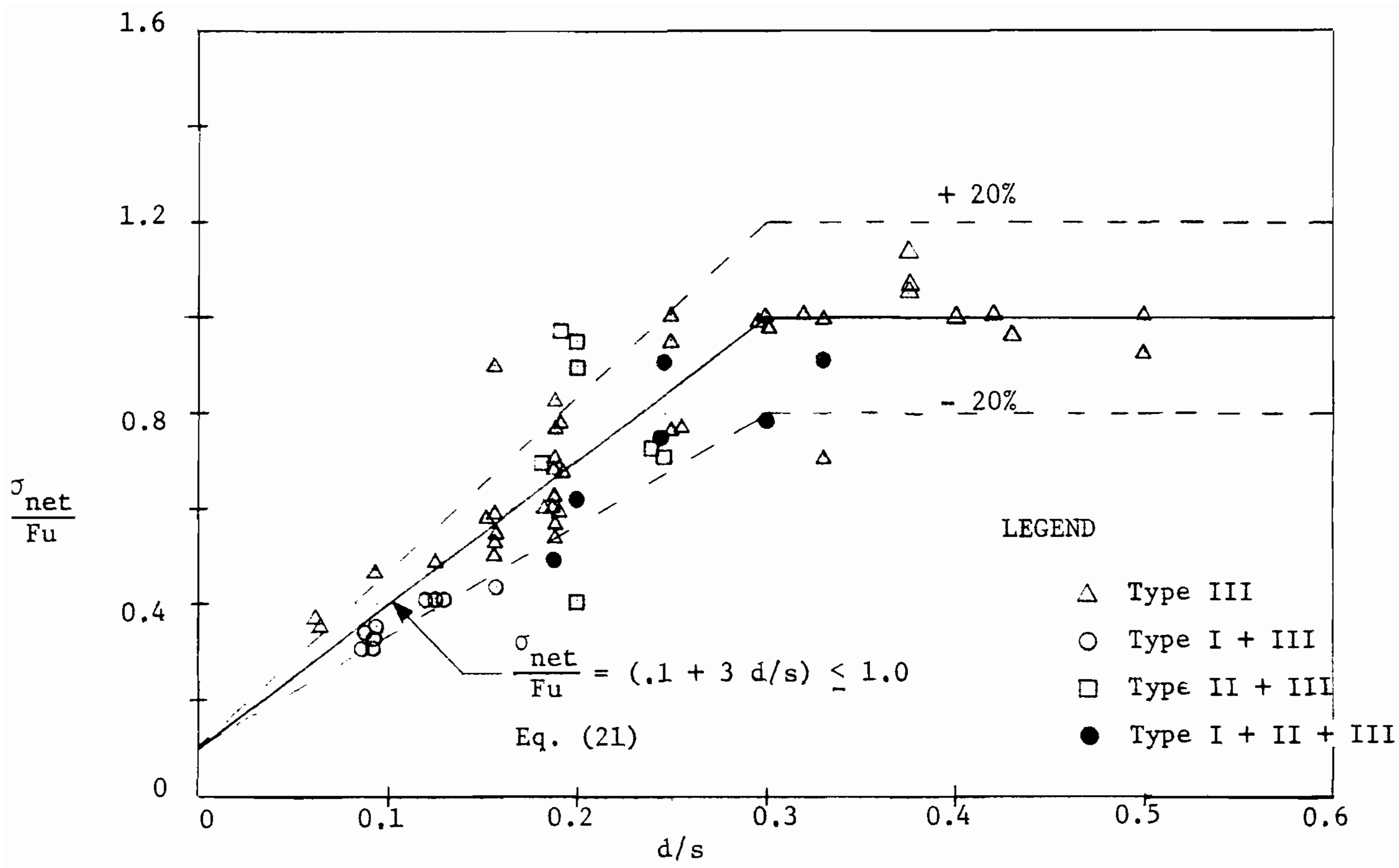

Fig. 19 Effect of d/s on Tensile Strength of Bolted Connections (Combination of the Data Shown in Figs. 17 and 18) (Single Shear, One Bolt) [6,9,10].

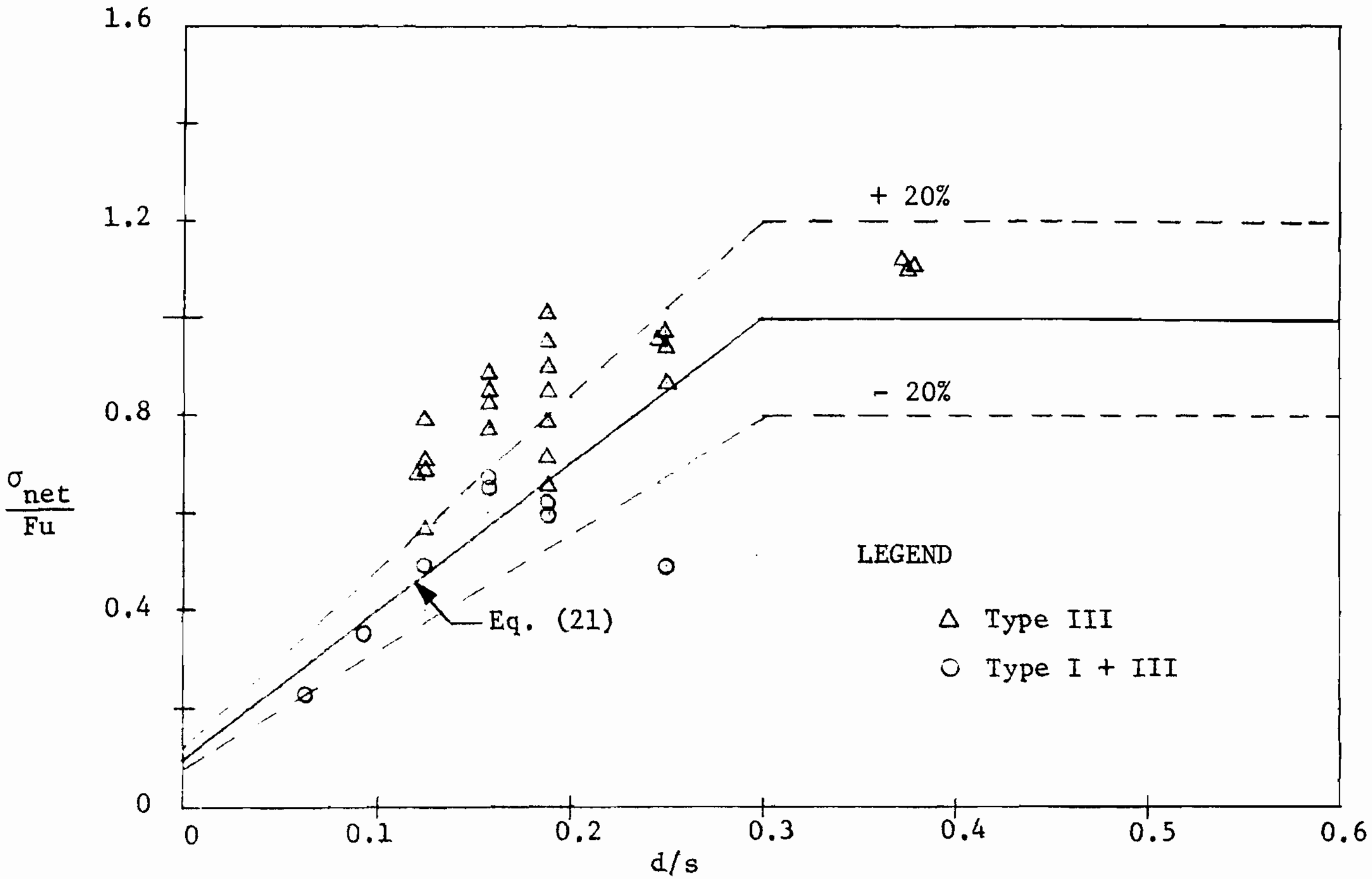

Fig. 20 Effect of d/s on Tensile Strength of Bolted Connections Using High Ductility Steels (Double Shear, One Bolt)[9,10]

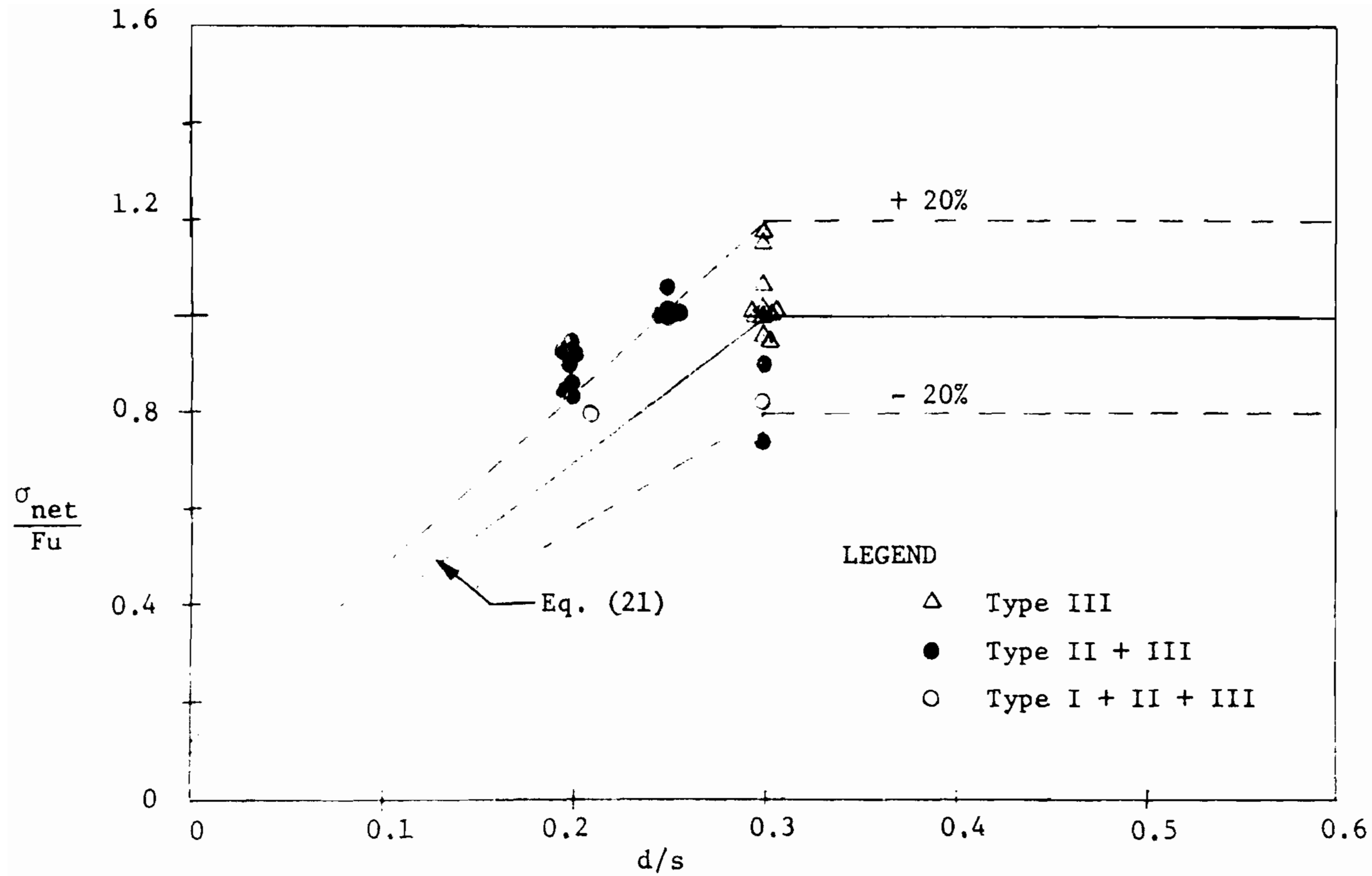

Fig. 21 Effects of d/s on Tensile Strength of Bolted Connections Using Low Ductility Steels (Double Shear, One Bolt)[6]

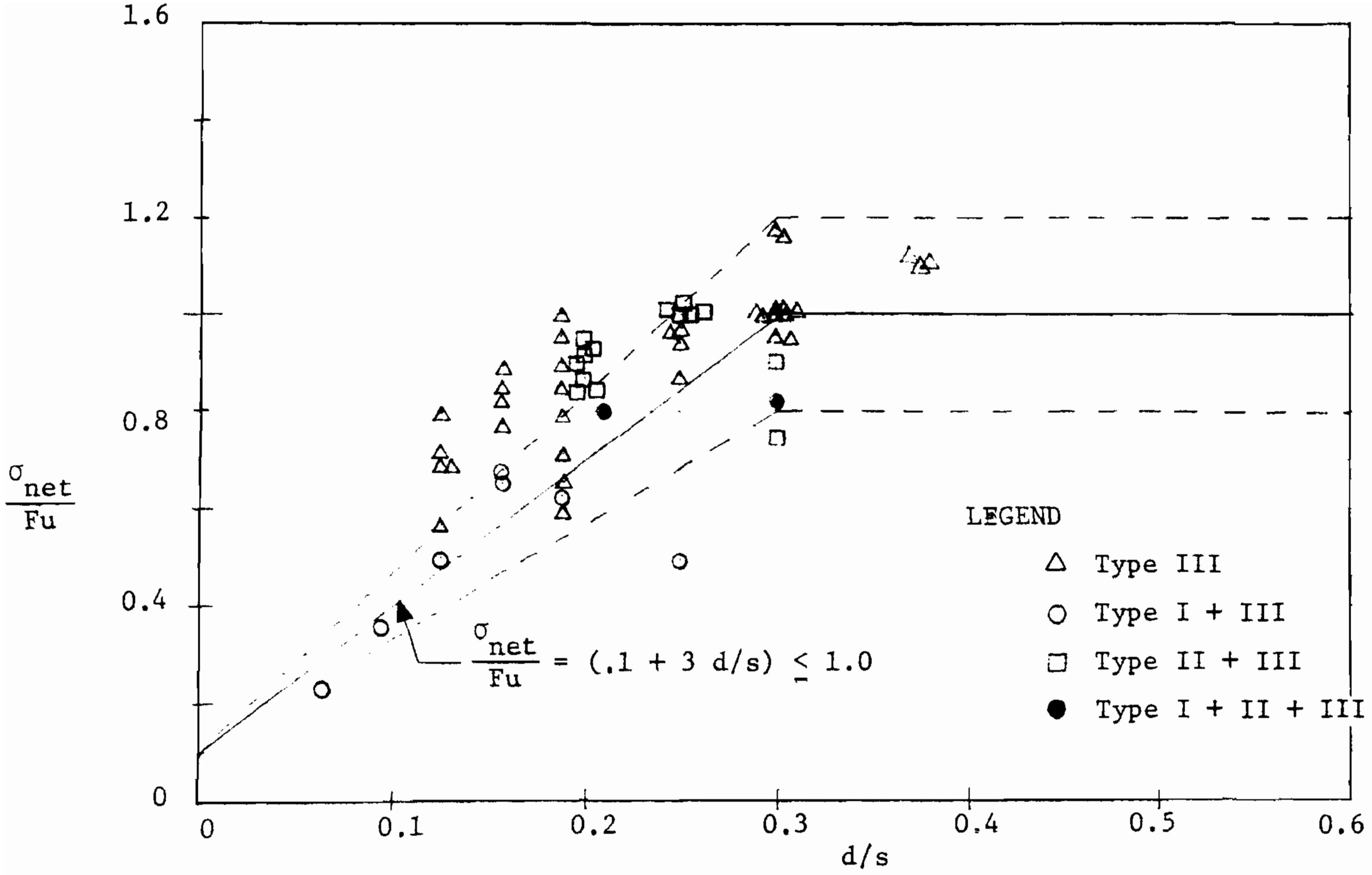

Fig. 22 Effect of d/s on Tensile Strength of Bolted Connections (Combination of the Data Shown in Figs. 20 and 21) (Double Shear, One Bolt)[6,9,10]

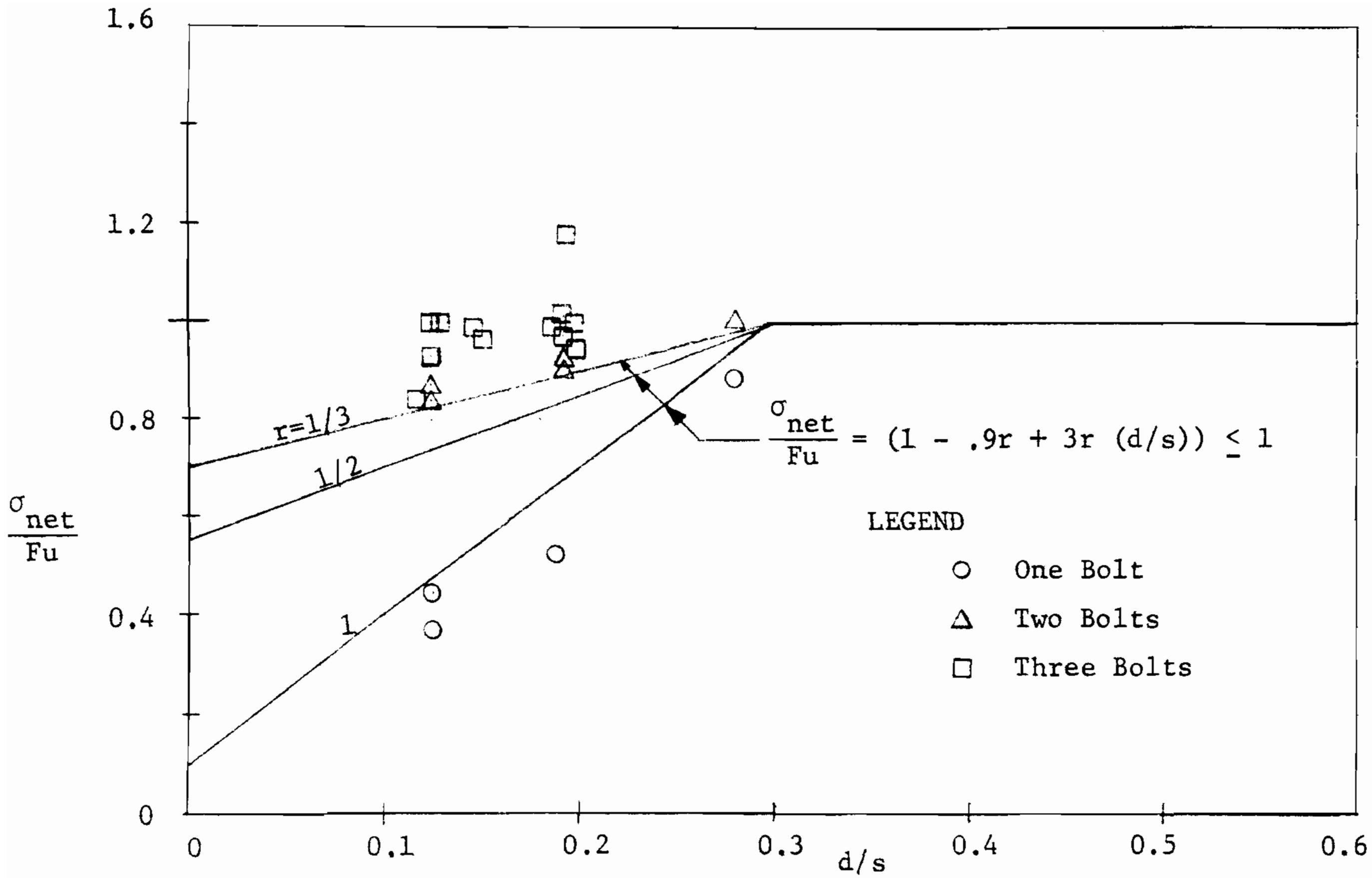

Fig. 23 Effect of d/s on Tensile Strength of Bolted Connections (Single Shear, Multi-Bolt) [5]

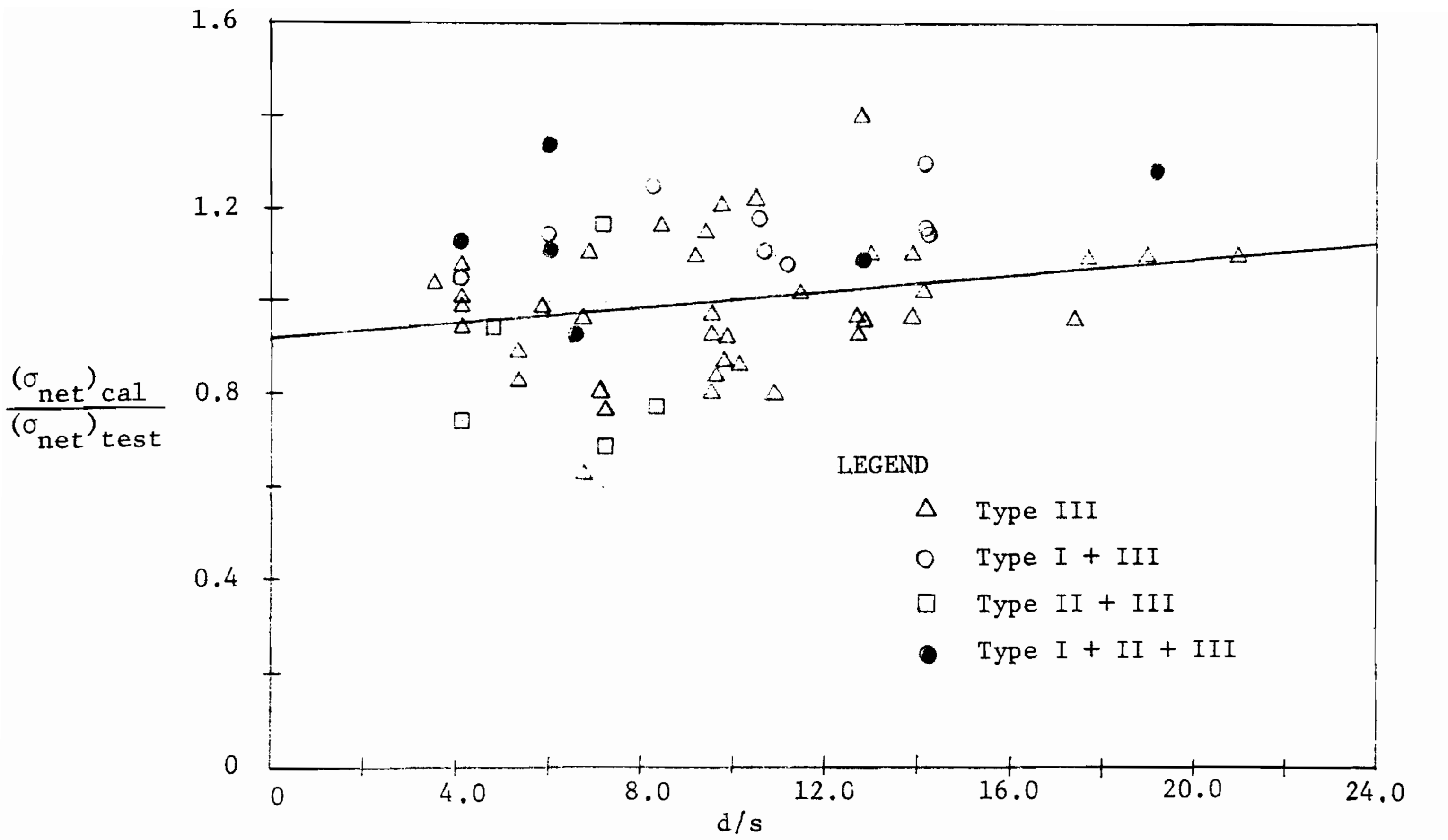

Fig. 24 Effect of d/t on Tensile Strength of Bolted Connections (Single Shear) [6,9,10]

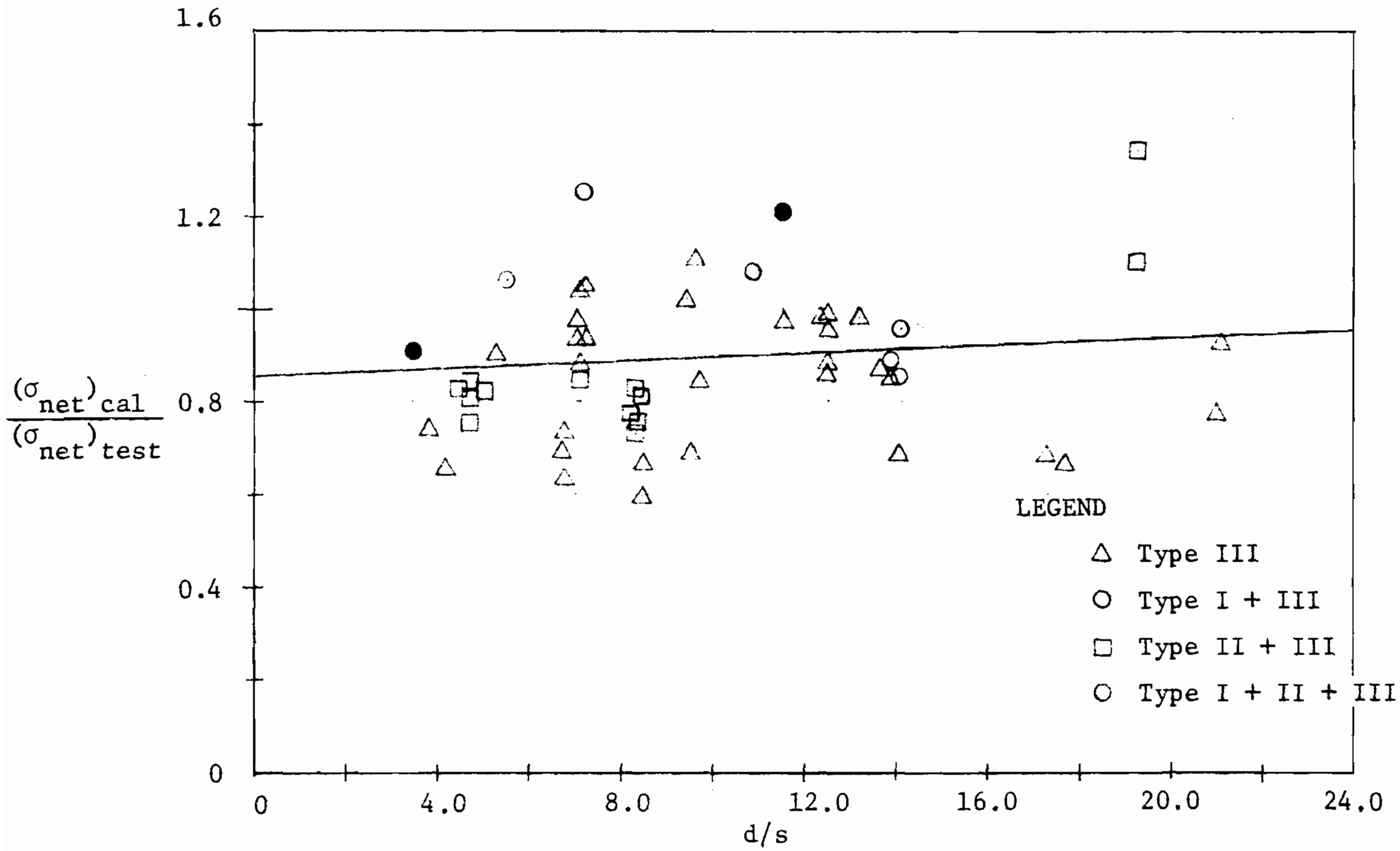

Fig. 25 Effect of d/t on Tensile Strength of Bolted Connections (Double Shear, One Bolt) [6,9,10]

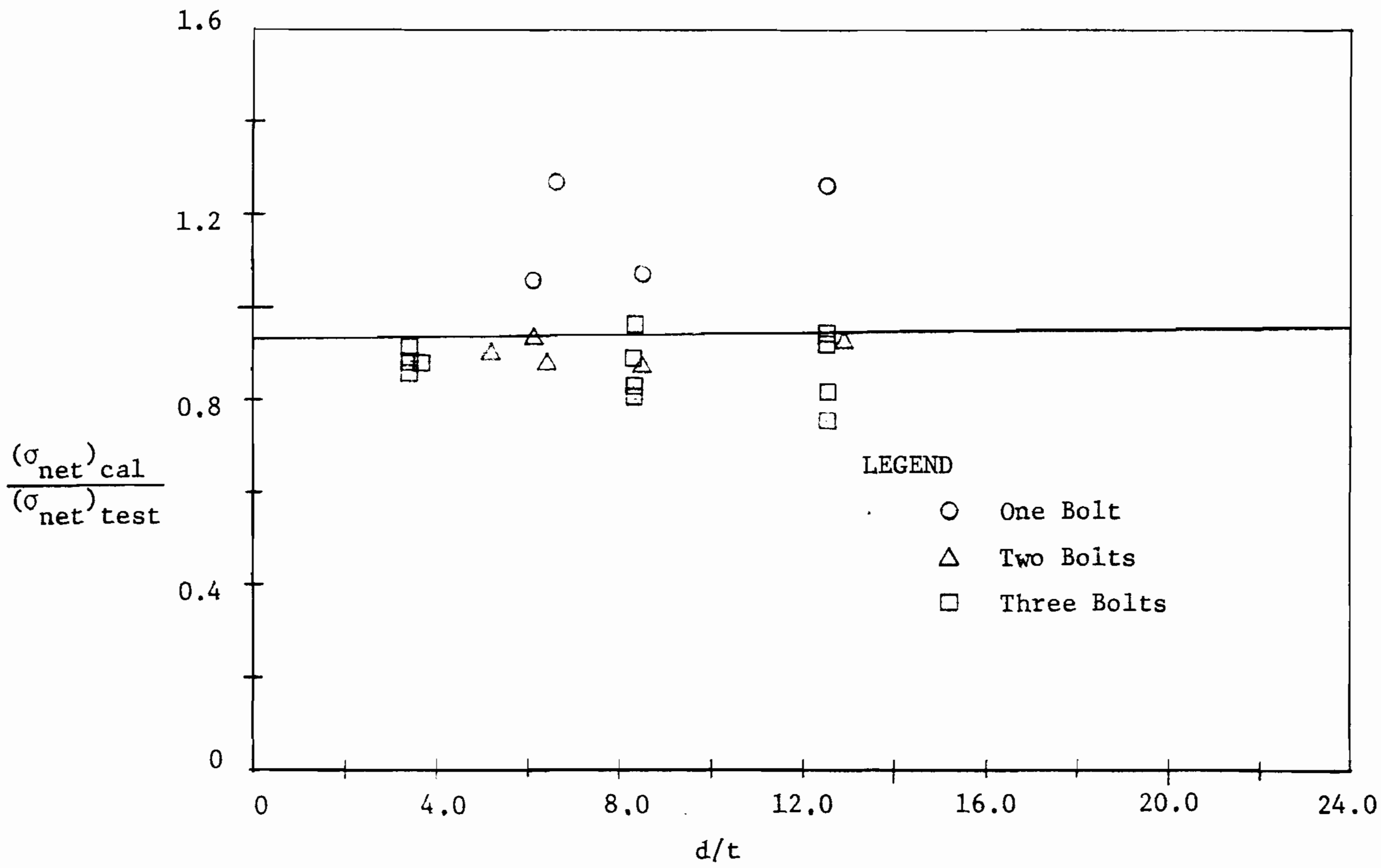

Fig. 26 Effect of d/t on Tensile Strength of Bolted Connections (Single Shear, Multi-Bolt)[5].