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Roger A. LaBoube
Missouri University of Science and Technology, laboube@mst.edu

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STRENGTH OF BOLTED CONNECTIONS: IS IT BEARING OR NET SECTION?

by Roger A. LaBoube *

The most critical, and yet the least understood structural element is the connection. Understanding the behavior, and subsequently the design, of a connection requires the knowledge of the various limit states and their interaction. Because of the relative thin sheet steel used in the fabrication of cold-formed steel members, the behavior of connections for such members is very complex, and not as clearly defined as the connections of thicker hot-rolled members.

This paper will present the findings of a research project that investigated the behavior of cold-formed steel connections governed by a limit state that is best defined as bearing or the interaction of bearing and sheet tearing. Based upon available test data generated at either university or industry test laboratories, empirical equations were developed and will be discussed. Considered in the study were the effects of washers, low ductility material, bolt diameter and multiple rows of bolts.

Experimental Studies

The data used in this study was generated from research conducted at the University of Missouri-Rolla, Cornell University, University of Wyoming and Butler Research. References 1, 2 and 3 give a summary of the test programs and results. All test specimens were either single or double shear lap joint connections.

From observations of failed test specimens, the University Researchers classified the failure modes by one of the following:

Type I - longitudinal shear, or tearing, of the sheet parallel to the direction of the load.

Type II - bearing failure, or piling up, of the sheet in front of the bolt.

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

Type IV - failure of the bolt.

The above four limit states serve as the foundation for the design provisions of the 1986 AISI Specification (4). However, based on the author's studies, there is some question as to the definition of these limit states, and the rational nature of the corresponding equations. The two limit states in question are Type II and Type III.

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* Research & Development Manager - Structural Systems, Butler Mfg. Co., Research Center, Grandview, MO.

In the AISI Specification, the limit state for the Type II failure mode, Fp, is defined by a constant relationship with regard to the tensile strength of the sheet, Fp = C Fu,. As indicated by the Specification, the constant C ranges from 2.22 to 3.33 depending upon the type of joint, sheet thickness, and sheet material properties.

Type III limit state, tension on the net section is defined by the following equations in the Specification,

when washers are provided under both the bolt head and nut,

$$F_t = (1.0 - 0.9r + 3rd/s)\ F_u \leq F_u \qquad (3)$$

when washers are not provided under both the bolt head and nut,

$$F_t = (1.0 - r + 2.5rd/s)\ F_u \leq F_u \qquad (4)$$

where r, d, and s are defined in Reference 4. Ft is evaluated on the net section of the member, Anet.

A review of the development of these empirical equations indicates that test data identified as both Type II and a combination Type II and III was used to derive the above equations. This would indicate that these equations address more than just net section, as the Specification indicates. Also, a dilemma that exists with the application of these equations is the choice for the net area. For the flat sheet test specimens, the net area was rather clear, but that is not the case for a C-section having a bolted connection in either the flange or the web. For example, the connection of the C-section column to the C-section roof beam in the endwall of a metal building. Depending upon the choice of the net area, the controlling limit state may, or may not, be precluded.

In Reference 5, the author demonstrated that the limit state of tension on the net section can be accurately predicted by the limit state provisions for hot-rolled steel connections(6).

Because of the above findings and observations, a re-evaluation of the available test data was conducted. This study considered the following parameters, which were perceived to be the significant parameters influencing the bearing capacity of a cold-formed steel bolted connection:

- Material ductility
- Tensile strength, Fu
- Bolt diameter, d
- Use of washers under both bolt head and nut
- Connection geometry.

An important consideration when choosing data points to be incorporated in this study was the failure type. Only failure Types II, III and combinations of I, II and/or III were used.

Without Washers

The 53 data points included in this parametic study were obtained from References 1, 2, 3 and unpublished Butler Research test results. The bearing capacity of a bolted connection is computed by the equation

$$fp = P / (ndt) \qquad (5)$$

where P = the ultimate test load and n = the number of bolts in the connection.
Figure 1 depicts the variation of fp/Fu with respect to Fu, which indicates that as Fu increases, the connection capacity decreases. Using a linear regression, this trend can be represented by the following equation,

$$fp/Fu = 3.41-0.0224(Fu) \qquad (6)$$

Adjusting the fp/Fu ratio for the variation represented by Eq. 6, the strength is recognized to be constant with respect to the ratio of edge distance to bolt diameter, e/d. See Figure 2.

With Washers

Reference 1 provides an excellent summary of the available test data regarding bolted connections with washers.

Assuming the variation of fp/Fu with respect to the material tensile strength (Eq. 6), is also valid for bolted connections with washers, results in a rather large dispersion of the 168 data points. This is shown graphically by Figure 3. This scatter in test results is in part due to the number of connection parameters represented by the data: bolt diameters ranging from 1/4" to 1 1/8"; single shear and double shear configurations; single and multiple rows of bolts; limit states identified as Type II, Type III and combinations of Type I, II and III; and variations in material ductility.

Review of the data revealed that many of the test specimens employed bolt diameters of 3/4 in. or greater. Diameters of this size are unrealistic for typical cold-formed construction. The data is segregated on Figure 3, the solid symbols depict specimens fabricated using bolt diameters less than 3/4", and the open symbols represent test specimens having diameters of 3/4" or greater. Because the two data groups indicate a shift in tested capacity, with the smaller diameter bolt specimens indicating a larger load carrying capacity, the data was evaluated based upon bolt diameter.

Diameters Less Than 3/4"

Figure 4 was constructed using only test specimens having bolt diameters less than 3/4 in. This yields a marked decrease in the amount of available test data (74 data points). The dispersion of test data is somewhat improved, and continues to be attributed to the various connection parameters and limit states which are depicted by different symbols. The contribution of each variable is depicted by Figures 5 through 9. Based on engineering judgement, an ordinate value of 1.5 is chosen as a reasonable value for design.

Figure 5 summarizes the test data identified to have failed by limit state II the combination of I and II, or the combination of II and III. Although the data dispersion is slightly below the 1.5, the vast majority are greater than 1.2, which represents a 20% variation.

The test specimens identified by previous researchers as having failed by tension are depicted on Figure 6. The constant 1.5 provides a reasonable estimation of connection capacity. It is the author's opinion that the actual limit state for these specimens is initially bearing, followed by a tearing of the sheet.

Material having low ductility, as defined by the ratio of tensile strength to yield strength, was also investigated. The data for specimens fabricated from material having a tensile to yield ratio near unity is given by Figure 7. All data fall above 1.5, which is an interesting occurance. One would expect low ductility to have a negative influence on the connection capacity.

Figure 8 depicts test results for double shear specimens. The dispersion of data is such that the choice of the constant 1.5 is a reasonable solution.

For the four test specimens having multiple rows of bolts, very unconservative values are depicted by Figure 9. However, the two values less than unity are for specimens having three rows of bolts. Although alarming, the use of three or more rows of bolts is not typical for cold-formed steel building construction. The limited data for the two rows of bolts would indicate that the ordinate value of 1.5 is acceptable for design. The lower values would appear to indicate that the common assumption of equal sharing of load by all bolts in a connection is inappropriate for cold-formed steel construction.

Diameters of 3/4" and Greater

Figure 10 summarizes the distribution of all test data for specimens having bolt diameters of 3/4" or greater. The distribution of the data is such that the previously assumed ordinate value of 1.5 is too liberal, and therefore based on engineering judgement, a value of 1.2 is chosen.

For data identified as having a limit state of either type II, the combination of I and II or the combination of II and III, the ordinate constant of 1.2 is a lower bound for the test data. See Figure 11.

The specimens identified as having a tension on the net section limit state are given by Figure 12. The data spread is such that the assumed ordinate constant of 1.2 is reasonable to predict the load carrying capacity. Again, this result leads the author to speculate that the limit state was not that of a net section failure, but initial bearing failure with subsequent tearing of the sheet.

The load capacity for specimens having a double shear configuration can generally be conservatively estimated by using the ordinate constant of 1.2. This trend is shown by Figure 13.

For connections having multiple rows of bolts, there is insufficient data to draw conclusions on the best approach to calculating the connection capacity. As indicated by Figure 14, values of less than unity were realized for three of test specimens. Again these three specimens contained three rows of bolts.

Computed Bearing Capacity

Based on the studies discussed herein, the nominal bearing capacity for a bolted connection can be predicted by the following equation:

$$f_p = (3.41 - 0.0024(F_u))\ C\ F_u \qquad (7)$$

where,

$C = 1.0$, washer only under bolt head or nut, or no washer
$= 1.2$, washers under both bolt head and nut, and $d \geq 3/4"$
$= 1.5$, washers under both bolt head and nut, and $d < 3/4"$

Equation 7 enables the evaluation of the connection capacity for the limit state of bearing, and the combination of bearing and sheet tearing. Sheet tearing may be perpendicular to the direction of loading or parallel to the direction of loading.

The above equation should not be applied to connections having three or more rows of bolts in the line of loading. Also, a reduction in the above values should be considered if deformation around the bolt hole is a design consideration.

Summary

This paper presents the findings that resulted from a study of the behavior of cold-formed steel bolted connections governed by the limit state of bearing and the combination of bearing and tearing (Type II).

Three basic limit states (Type I, II and III) need to be considered when designing the base material for a cold-formed steel bolted connection. Design guidelines for the Type I limit state are given in Section E3.1 of Reference 4. The Type III limit state can be predicted using Section D1 of Reference 6 (5). The remaining limit state, Type

II, bearing and the interaction of bearing and tearing, can be estimated using Equation 7 contained herein.

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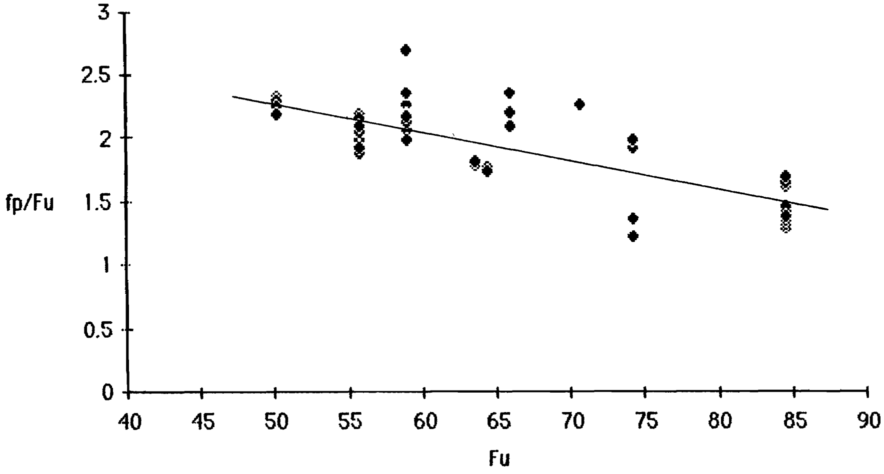

Figure 1 Influence of Tensile Strength on Connection Capacity

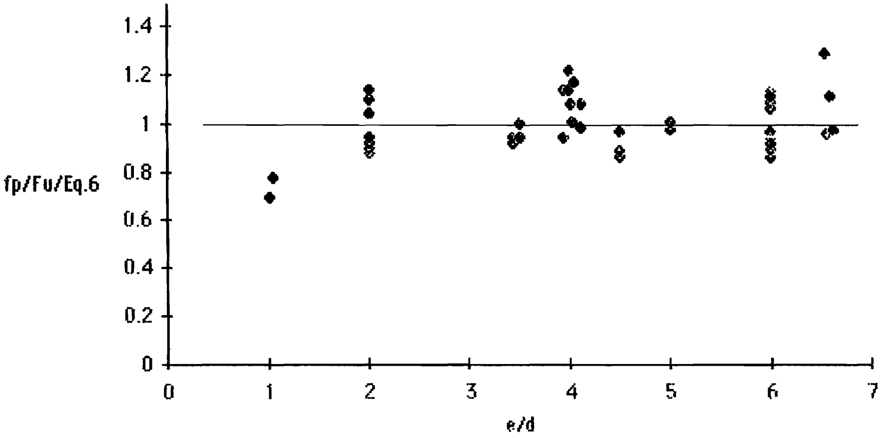

Figure 2 Connection Capacity for Test Specimens Without Washers

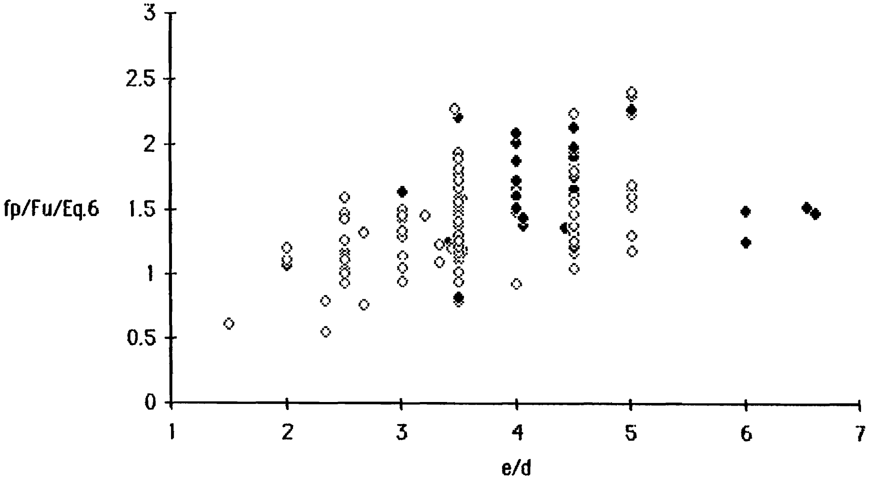

Figure 3 Connection Capacity for All Specimens With Washers

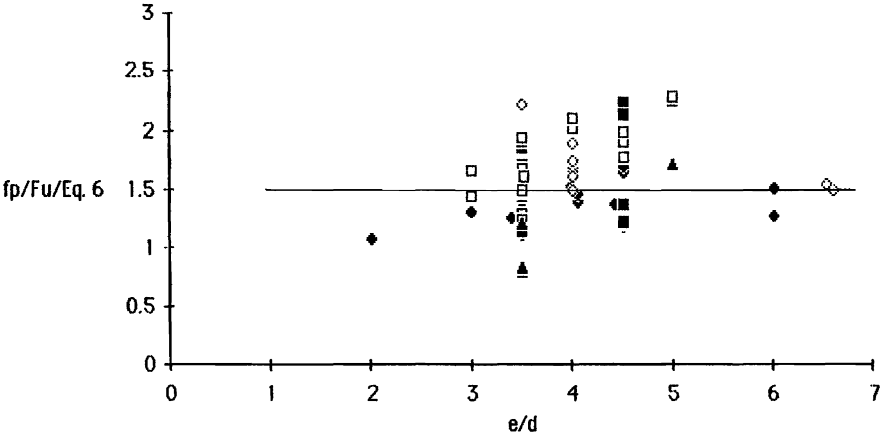

Figure 4 Connection Capacity for Specimens With Washers, d < 3/4"

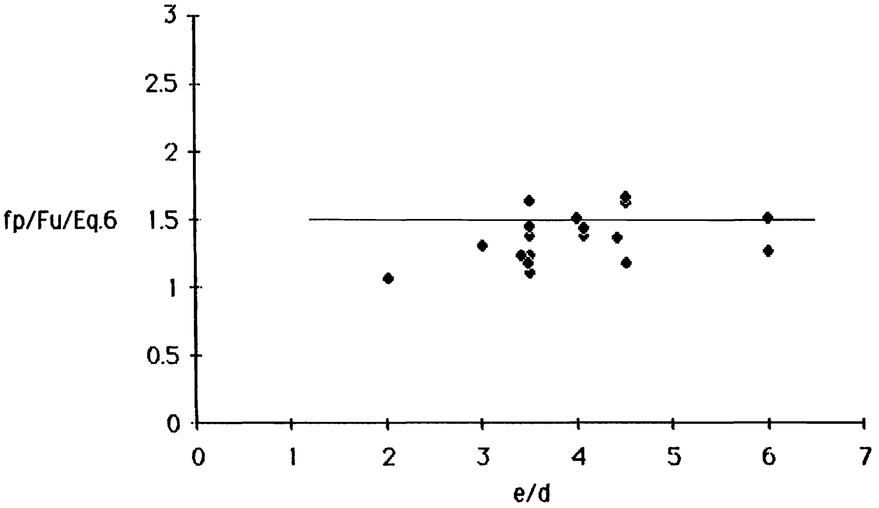

Figure 5 Connection Capacity With Washers - Bearing Failure, d < 3/4"

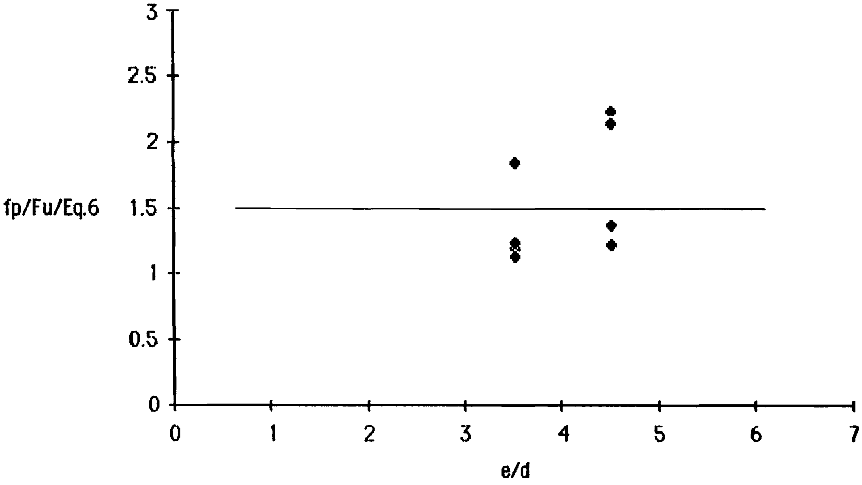

Figure 6 Connection Capacity With Washers - Tension Failure, d < 3/4"

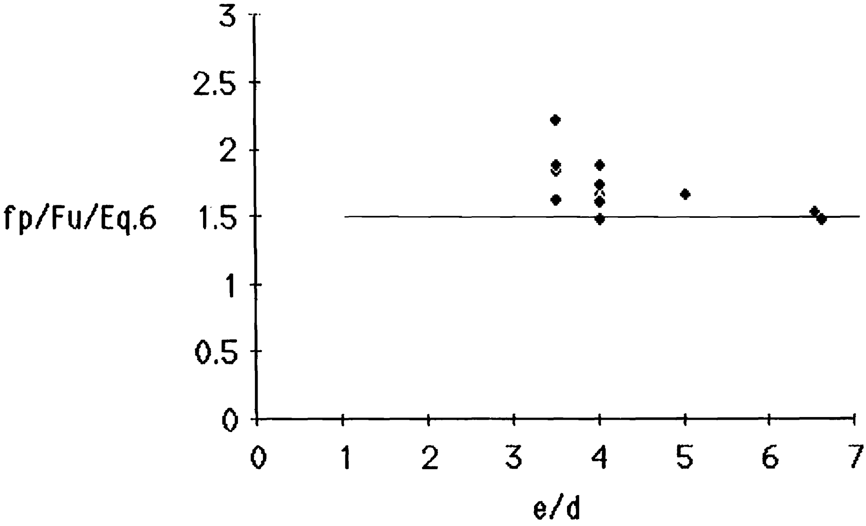

Figure 7 Connection Capacity With Washers - Low Ductile Material, d < 3/4"

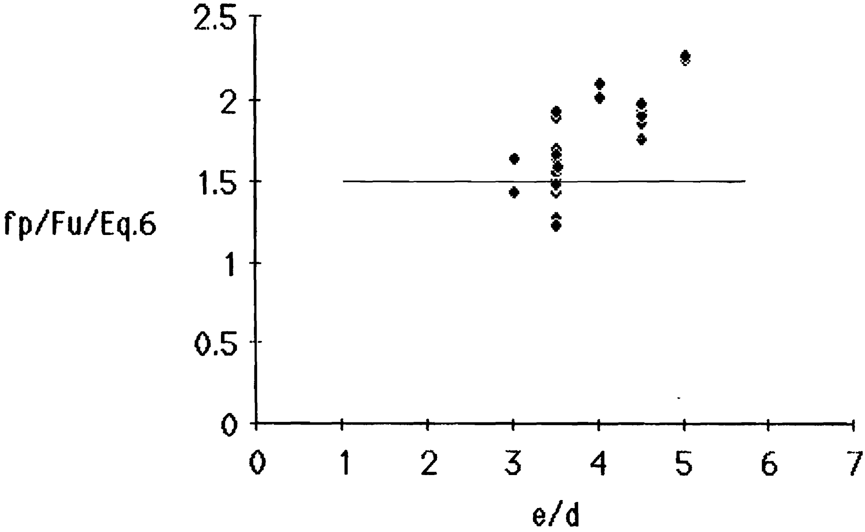

Figure 8 Connection Capacity With Washers - Double Shear, d < 3/4"

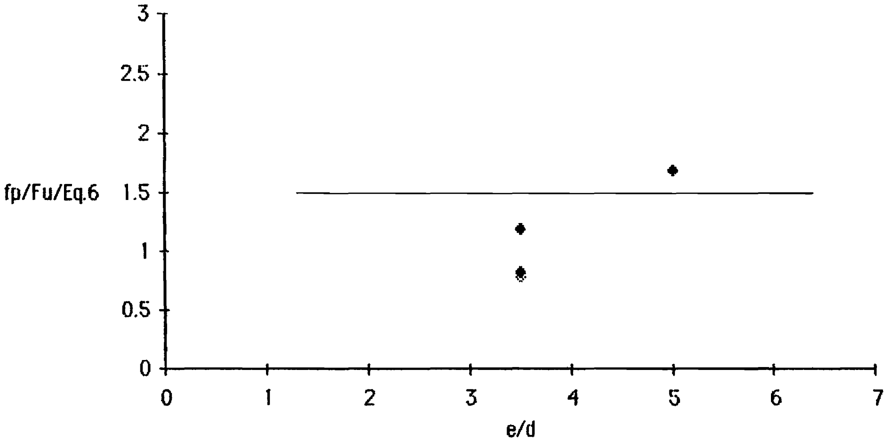

Figure 9 Connection Capacity With Washers - Multiple Rows, d < 3/4"

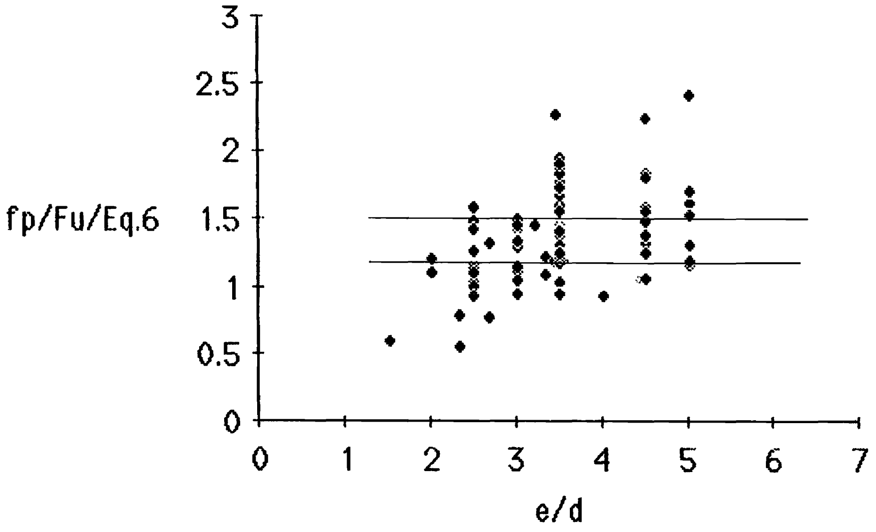

Figure 10 Connection Capacity for Specimens With Washers, d ≥ 3/4"

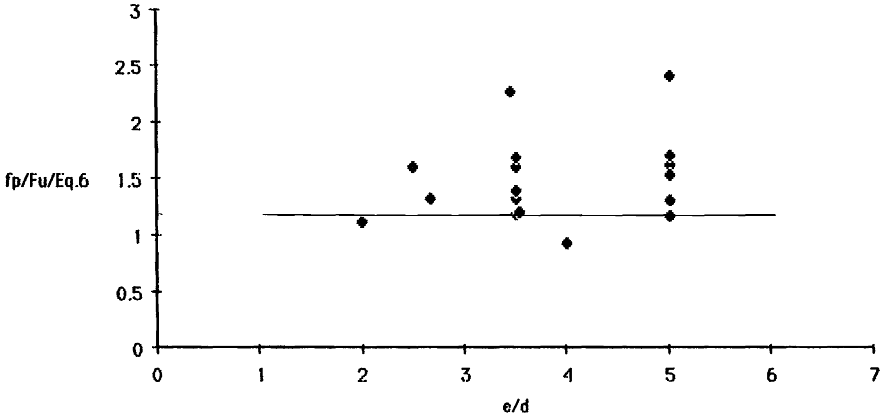

Figure 11 Connection Capacity With Washers - Bearing Failure, d ≥ 3/4"

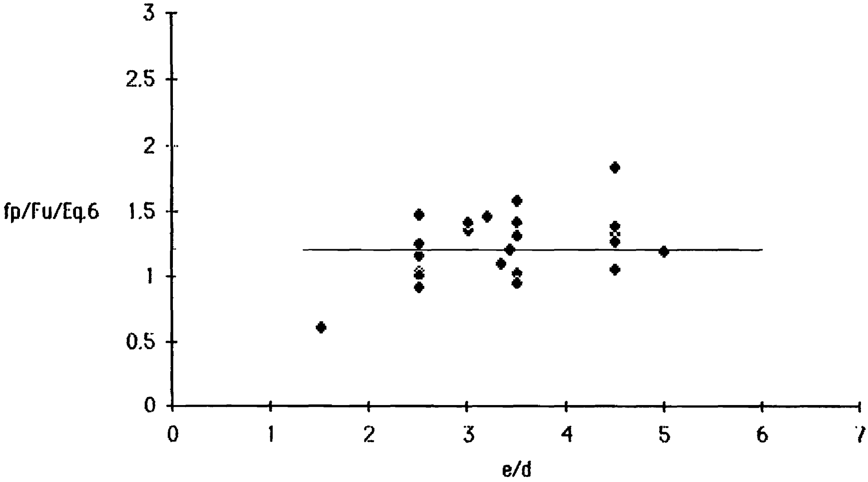

Figure 12 Connection Capacity With Washers - Tension Failure, d ≥ 3/4"

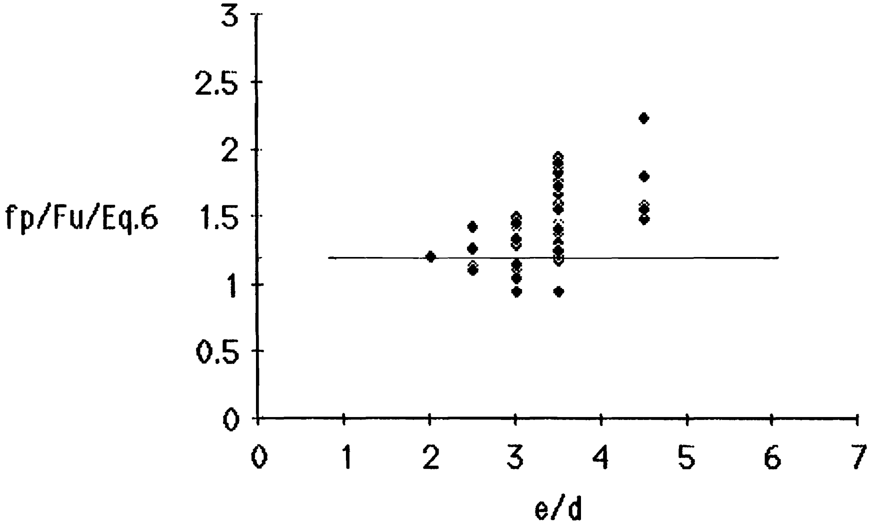

Figure 13 Connection Capacity With Washers - Double Shear, d ≥ 3/4"

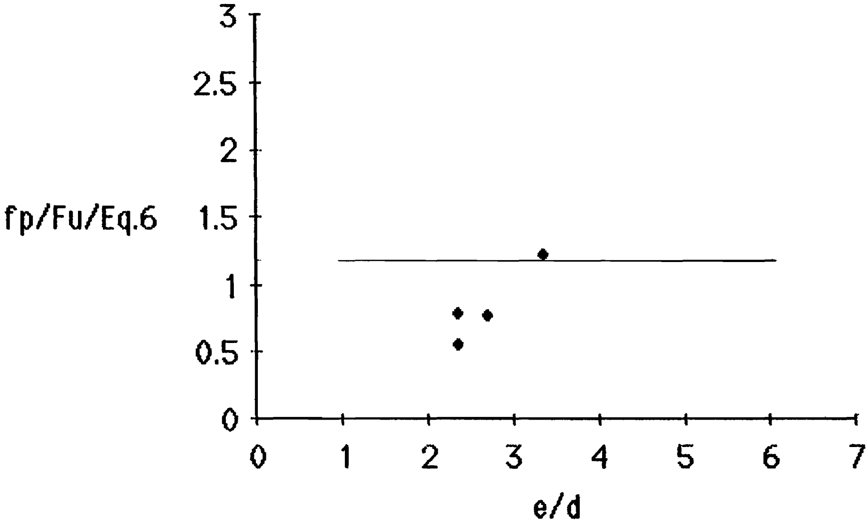

Figure 14 Connection Capacity With Washers - Multiple Rows, d ≥3/4"