1967

Bolted hybrid joints, ASCE, Vol. 93, ST5, October 1967, Reprint No. 67-12

R. Kormanik
J. W. Fisher

Follow this and additional works at: http://preserve.lehigh.edu/engr-civil-environmental-fritz-lab-reports

Recommended Citation
http://preserve.lehigh.edu/engr-civil-environmental-fritz-lab-reports/1895

This Technical Report is brought to you for free and open access by the Civil and Environmental Engineering at Lehigh Preserve. It has been accepted for inclusion in Fritz Laboratory Reports by an authorized administrator of Lehigh Preserve. For more information, please contact preserve@lehigh.edu.
BOLTED HYBRID JOINTS

by

Robert Kormanik
John W. Fisher

This work was carried out as part of the Large Bolted Connections Project, sponsored by the Pennsylvania Department of Highways, the Department of Commerce - Bureau of Public Roads, and the American Institute of Steel Construction. Technical guidance is provided by the Research Council on Riveted and Bolted Structural Joints.

Fritz Engineering Laboratory
Department of Civil Engineering
Lehigh University
Bethlehem, Pennsylvania

September 1966

Fritz Engineering Laboratory Report No. 317.5
# Table of Contents

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABSTRACT</td>
<td>1</td>
</tr>
<tr>
<td>1. INTRODUCTION</td>
<td>2</td>
</tr>
<tr>
<td>1.1 Purpose</td>
<td>2</td>
</tr>
<tr>
<td>1.2 Literature Review</td>
<td>2</td>
</tr>
<tr>
<td>1.3 Calibration Program</td>
<td>3</td>
</tr>
<tr>
<td>2. THEORETICAL INVESTIGATION</td>
<td>6</td>
</tr>
<tr>
<td>2.1 Scope of Study</td>
<td>6</td>
</tr>
<tr>
<td>2.2 Joint Proportioning</td>
<td>6</td>
</tr>
<tr>
<td>2.3 Ultimate Strength of Hybrid Connections</td>
<td>8</td>
</tr>
<tr>
<td>2.3.1 Joint Length</td>
<td>9</td>
</tr>
<tr>
<td>2.3.2 Joint Geometry ($A_n/A_s$ ratio)</td>
<td>11</td>
</tr>
<tr>
<td>2.4 Load Distribution</td>
<td>13</td>
</tr>
<tr>
<td>2.5 Deformation Characteristics of Hybrid Bolted Joints</td>
<td>17</td>
</tr>
<tr>
<td>3. COMPARISON OF ALLOWABLE BOLT STRESSES</td>
<td>22</td>
</tr>
<tr>
<td>3.1 Introduction</td>
<td>22</td>
</tr>
<tr>
<td>3.2 Variation in Factor of Safety</td>
<td>23</td>
</tr>
<tr>
<td>4. SUMMARY AND CONCLUSIONS</td>
<td>28</td>
</tr>
<tr>
<td>5. ACKNOWLEDGMENTS</td>
<td>29</td>
</tr>
<tr>
<td>6. REFERENCES</td>
<td>31</td>
</tr>
<tr>
<td>7. TABLE AND FIGURES</td>
<td>32</td>
</tr>
</tbody>
</table>
A B S T R A C T

This report presents the results of an extensive theoretical analysis of hybrid steel butt joints of A36, A440, and A514 steel fastened with either A325 or A490 bolts. The theoretical studies were designed to determine the effect of various variables on the ultimate joint strength. The major variables studied were joint length and the ratio of net plate area, $A_n$, to the total fastener shear area, $A_s$. The load distribution among the fasteners in a hybrid joint was also investigated.

The analytical studies indicated that the average shear strength of hybrid joints was equal to or greater than the average shear strength of homogeneous joints. Hybrid joints behaved similarly to homogeneous joints in that as the joint length was increased, the average shear strength decreased. Also, a decrease in $A_n/A_s$ ratio in hybrid joints was accompanied by the decrease in average shear strength experienced with homogeneous joints.

It was demonstrated that increasing the allowable stresses from 22 ksi to 30 ksi for the A325 bolt, and from 32 ksi to 40 ksi for the A490 bolt had little effect on the minimum factor of safety in bearing-type connections.
1. INTRODUCTION

1.1 Purpose of the Investigation

In the past, investigations of riveted and bolted structural connections were concerned with only one type of material being connected. As a structure becomes larger, the high forces encountered may demand higher strength steels. The structural connection of interest is the hybrid connection involving two or more steels of different strengths. The primary concern is what effect such differences in strength have on the ultimate strength of the joint.

Previous theoretical and experimental analysis of homogeneous joints, in which only one type of material is connected, have shown that two major parameters affect the ultimate strength of a joint, the relative proportions of the net plate area and the total bolt shear area, and the joint length (number of bolts in line). This study assesses the theoretical behavior of bolted hybrid steel joints. Major attention is given to the ultimate strength of the joint. Since joint length and geometry are the major variables affecting homogeneous joint strength, these same variables were evaluated.

1.2 Literature Review

This investigation is based upon the theoretical solution for mechanically fastened joints developed by Rumpf and Fisher, who
provide a detailed review of previous theoretical studies along with the theoretical development.\textsuperscript{1} The equilibrium and compatibility equations were solved with the aid of a digital computer. Analytical expressions were developed for the stress-strain relationship of plates with holes and for the shear deformation relationship of the high strength bolts. These were used to facilitate the analytical solution, which was said to be applicable to hybrid joints. However, so far as is known, no other solution has been developed nor has the theory previously been applied to studies of hybrid connections.

An extensive review of experimental studies on large bolted homogeneous joints has also been given in Ref. 1 and 2. A7 and A440 steels fastened with A325 and A490 bolts were considered. Several small joints fastened with A325 bolts were tested to evaluate the slip resistance when different steels were combined, but the ultimate strength of these hybrid joints was not determined.\textsuperscript{3}

1.3 Calibration Program

Analytical relationships for the load-displacement characteristics of the two components of a joint were required for the computerized solution. The two components required are the tension behavior of a steel plate with holes and the load-deformation characteristics of a single bolt in double-shear. A mathematical model has been developed to predict the inelastic behavior of an A36 or A440 steel plate with holes.\textsuperscript{4}
This model was modified slightly to predict the behavior of AS14 steel. The modified relationship between stress and strain for AS14 steel was:

\[ \sigma = \sigma_y + (\sigma_u - \sigma_y) \left[ 1 - e^{-(\sigma_u - \sigma_y) \frac{e}{d}} \right]^{3/2} \]  \hspace{1cm} (1)

Equation (1) is a function of:
1. \( \sigma_y \), the yield point,
2. \( \sigma_u \), the tensile strength,
3. \( g/g-d \), the plate-hole geometry, and
4. \( e/p \), total deformation in pitch/pitch length.

This model was modified slightly to predict the behavior of A514 steel. The modified relationship between stress and strain for A514 steel was:

\[ \sigma = \sigma_y + (\sigma_u - \sigma_y) \left[ 1 - e^{-(\sigma_u - \sigma_y) \frac{e}{d}} \right]^{1/3} \]  \hspace{1cm} (2)

Equations (1) and (2) are applicable to the inelastic region, i.e., \( \sigma_y < \sigma < \sigma_u \). The yielded region for A36 and A440 steel extends over the full pitch length. With A514 steel, the yielding occurs only adjacent to the holes so that the plate material in the gross section remains elastic. In the elastic range the deformations were computed from elastic theory,

\[ e = \Sigma \frac{Pl}{AE} \]  \hspace{1cm} (3)

The mathematical model developed for the behavior of a single bolt in a double shear is described as:

-4-
\[ R = R_{ult} \left(1 - e^{\mu \Delta}\right)^\lambda \]  

where \( R_{ult} \) = ultimate shear strength, 
\( R \) = shear load of fastener, 
\( \mu, \lambda \) = regression coefficients, and 
\( \Delta \) = total deformation of bolt and bearing deformation of the connected materials.

The parameters \( \mu \) and \( \lambda \) were evaluated by regression analysis and the boundary conditions.

Because the load-deformation characteristics of the high-strength bolts were required for the various hybrid joint combinations, calibration tests were made to evaluate the empirical parameters for each combination of materials. Hybrid shear jigs of A36 and A440 steels, A440 and A514 steels, and shear jigs of A36 and A514 steels were used to evaluate the behavior of 7/8 in. A325 bolts. In addition, hybrid jigs of A440 and A514 steels were used to evaluate the behavior of 7/8 in. A490 bolts. The ultimate load and deformation, and the regression coefficients are summarized in Table 1 for the various combinations.
2. THEORETICAL INVESTIGATION

2.1 Scope of Study

The analysis in this report is concerned with the ultimate strength of hybrid bolted connections loaded in tension with the load carried by the bolts in shear and bearing. The two major variables examined in detail are joint length (the number of bolts in line) and the $A_n/A_s$ ratio (the ratio of the net area of steel material to the total bolt shear area).

Minimum strength properties were assumed in the analysis for the steel materials and the high strength bolts. The pitch was maintained at 3.5 in., and the gage was kept constant in both main and lap plates, with the thickness varied to maintain joint geometry. The diameter of all bolts was 7/8 in. Previous studies have shown that there is no apparent influence of bolt diameter on ultimate shear strength.\textsuperscript{1,6}

The general compatibility and equilibrium equations which lead to the solution of the ultimate strength capacity of a given joint will not be described in detail in this report, but are discussed at length by Fisher and Rumpf.\textsuperscript{1}

2.2 Joint Proportioning

The material with the lowest yield point in the hybrid joints was selected as the base material, and for computation
purposes was considered to be the main plate. Thus in a hybrid A36-A440 steel joint the A36 steel was the main plate. The hybrid joints were proportioned so the components (the main and lap plates) resisted the same allowable load. Because the width of the components of the joints was maintained constant, the thickness of connected steel varied. Naturally, the net areas for the main and lap plates also varied.

For each hybrid joint analyzed, a joint length was chosen (with a given number of fasteners and shear area) and an initial $A_n/A_s$ ratio was selected for the base material. Each plate component and the bolts resisted the same load. Hence

$$F_v A_s = A_n^m \cdot F_a^m = A_n^l \cdot F_a^l$$

(5)

where $F_v$ = allowable bolt shear stress,

$F_a^m$ = allowable plate tensile stress of main plate,

$F_a^l$ = allowable plate tensile stress of lap plate,

$A_n^m$ = net area of main plate,

$A_n^l$ = net area of lap plate, and

$A_s$ = total bolt shear area.

Since a ratio of $A_n/A_s$ was selected along with the number of fasteners, the net areas of the main plate and lap plates were given by
and

\[ A_n^m = \frac{F_v A_s}{P_{m}} \]  \hspace{1cm} (6)

and

\[ A_n^t = \frac{P_{m} \cdot A_n^m}{P_{a}} \]  \hspace{1cm} (7)

2.3 Ultimate Strength of Hybrid Connections

Previous studies have demonstrated the effects of joint length and geometric proportions (as defined by the \( A_n/A_s \) ratio) on the ultimate strength and behavior of homogeneous steel joints.\(^1,7,8\) As joint length is increased the average shear strengths of the fasteners were decreased. Changes in the joint geometry as described by the ratio of the net plate area to the bolt shear area \((A_n/A_s)\) also affected the load distribution and ultimate strength of the joints. As this ratio is decreased for a given joint length, the connected material has greater flexibility and the average shear strength of the fasteners decreases. These effects were noted for both A325 and A490 high strength bolts.

This section evaluates the influence of these parameters on the ultimate strength of hybrid joints.
2.3.1 Joint Length

A comparison between the homogeneous joints of A36 and A440 steels and hybrid joints of A36-A440 steels is made in Fig. 1. The joints were proportioned for an allowable bolt stress of 30 ksi, which corresponds to an $A_n/A_s$ ratio of 1.36 for the A36 steel and 1.09 for the A440 steel. Homogeneous A440 and A36 steel joints were examined for the same $A_n/A_s$ ratio that was used in the hybrid joints. The values of the average shear strength of the fasteners at failure are plotted for the various joints. Also shown in Fig. 1 is the shear strength of a single bolt.

It is apparent that as the joint length was increased, the average shear stress for both the homogeneous and hybrid joints decreased. The figure shows that the behavior of the hybrid joint was bounded on either side by one of the homogeneous joint curves. As was noted in previous studies, the milder steel joints achieved better load distribution and higher strength than the higher strength steel joints. Hybrid joint behavior closely parallels that of the lower strength connected material.

In Fig. 2, the behavior of hybrid joints with A36 steel having an $A_n/A_s$ ratio of 1.00 is compared with that of homogeneous A36 steel joints of the same ratio. The A440 steel components had a corresponding $A_n/A_s$ ratio of 0.80. These curves correspond to the allowable bolt shear stress of 22 ksi. Since the $A_n/A_s$ ratio is decreased, the joints are more flexible for a corresponding number of fasteners in a line (length of joint). The influence of
this increased flexibility can be demonstrated by comparing Figs. 1 and 2.

Figure 2 shows a behavior similar to Fig. 1. As the joint length is increased in the hybrid joints, the average shear strength decreases. The behavior of hybrid joints is nearly the same as that of homogeneous A440 steel joints for the allowable shear stress illustrated. The major difference in the behavior of the hybrid steel joints for the allowable bolt shear shown is the length to which bolt failure controls. For these geometric proportions, an increase in joint length is accompanied by a rapid decrease in the average shear strength of both A36 and A440 homogeneous steel joints. In the hybrid joints, there was enough redistribution so that plate failure rather than fastener failure occurred out to joint lengths of about 50 in. Then fastener failure mode became critical and the hybrid joint behaved much the same as a homogeneous A440 steel joint.

The combination of A36 steel with the higher-strength A514 steel was also studied. Equation 7 shows that a substantial change in the net area of lap plate results from the use of the higher-strength steel as the stronger joint material. Bolt failures commenced earlier in the A36-A514 steel combinations than in the homogeneous A514 steel joints. This was not the case with A36-A440 steel hybrid joints (Fig. 2), which developed better redistribution than the homogeneous A440 steel joints. Plate failure controlled for a greater joint length in the hybrid joint than in the homogeneous joints.
The A440-A514 combination was the third connected by A325 bolts to be studied. As with the A36-A440 hybrid, these joints were bounded by the homogeneous joint curves.

Similar analyses were made on hybrid steel joints fastened by A490 high strength bolts. Since the bolts are primarily for use with high strength steels, only the A440-A514 hybrid joints were evaluated. These hybrids are compared with A440 and A514 homogeneous joints fastened with A490 bolts in Figs. 3 and 4. The comparisons are for two $A_n/A_s$ ratios. For the A440 steel, $A_n/A_s$ ratios. For the A440 steel, $A_n/A_s$ ratios of 1.45 and 1.16 were selected. The corresponding $A_n/A_s$ ratios for the A514 steel are 0.66 and 0.53.

As the joint length was increased, the average shear strength of both hybrid and homogeneous joints decreased, just as it did with the A325 bolt for the same combination of steels. Again, the strength of the hybrid joints was not less than that of the corresponding homogeneous joints. Most homogeneous A514 steel joints, like most of the hybrid joints, failed in the plate. Only for extremely long joints did bolt failure become the controlling factor. Thus it is concluded that the manner in which the plate failure boundary shifts is primarily dependent upon the materials fastened.

2.3.2 Joint Geometry ($A_n/A_s$ Ratio)

It has been theoretically predicted and experimentally verified that for homogeneous joints as the $A_n/A_s$ ratio for a joint
is increased for any given joint length, the average shear strength also increases. This is true with either A325 or A490 bolts. Similar behavior was expected of hybrid joints.

Figure 7 shows the results of analytical studies of A36-A440 steel hybrid joints fastened with A325 bolts. An increase in the $A_n/A_s$ ratio corresponds to an increase in the net tensile area relative to the fastener shear area. For this combination, four different $A_n/A_s$ ratios were investigated and are illustrated in the figure. The shear strength of a single bolt for comparison and the plate failure boundary for the hybrid combinations are also shown. When the $A_n/A_s$ ratio was decreased for a given joint length, the average shear strength was decreased.

The results of studies of the A36-A514 hybrid joints are shown in Fig. 6. Two $A_n/A_s$ ratios were compared, 1.70 and 1.65. It is apparent that bolt failure occurs only at considerable joint length. Because of the large differences in tensile strength and yield point, the A36 steel plate is considerably stiffer beyond yield. Also, the inelastic deformations in the A514 steel are small since yielding occurs only near the net section. Because of these factors better redistribution occurs in the shorter joints and the bolts are not critical.

Four ratios of $A_n/A_s$ were investigated for A440-A514 steel joints fastened with A325 bolts. The results of this study are illustrated in Fig. 7. The general behavior was similar to that of the A36-A440 joints. As the $A_n/A_s$ ratio was decreased for a given
joint length, the average shear strength was decreased.

Figure 8 summarizes the results from A440-A514 steel hybrid joints fastened by A490 bolts at $A_n/A_s$ ratios of 1.50 and 1.30. The behavior is similar to that of A36-A514 hybrid joints fastened with A325 bolts. Bolt failure did not occur until a large number of bolts were in line. This was due to the difference in strengths of steels and the resulting deformations in the joint. Plate failure controls over a larger joint length than in similar homogeneous joints.

2.4 Load Distribution in Hybrid Joints

To help evaluate the behavior of hybrid connections, it is important to examine the distribution of load among the individual fasteners. Figures 9 to 12 summarize the distribution of load to the fasteners in homogeneous and hybrid joints having from 15 to 31 bolts in a line. Each figure compares the load distribution of the hybrid joint with the distributions of homogeneous joints having similar geometric proportions. Figures 9 to 11 show the distribution for A325 bolts and Fig. 12 shows the distribution for joints connected by A490 bolts.

In Fig. 9, the load distributions of the A36-A440 hybrid joint and the homogeneous joints of A36 steel and A440 steel with fifteen A325 bolts in a line are compared. The A36 steel had an $A_n/A_s$ ratio of 1.36 and the A440 steel 1.09, both of which correspond to a bolt shear stress of 30 ksi. The height of each bar
in Fig. 9 represents the force carried by the bolt in that location. The homogeneous A36 steel joint is represented by the top of the hatched bars, the hybrid joint by a heavy line in each bar, and the homogeneous A440 steel joint by the top of the clear bars.

It is apparent from Fig. 9 that the hybrid joint distribution agrees more closely with the values obtained for the A36 steel joint than with those for A440 steel joint. Both the hybrid and A36 steel joints have effected a much better load distribution in the bolts than the A440 steel joint because the greater stiffness of the A36 steel plate provides better redistribution. The A36 steel allows more effective redistribution because inelastic deformations occur in the bolts while the plate material is still elastic and relatively rigid. In the A440 steel material, however, inelastic deformation occur nearly simultaneously in the plate material and end fasteners. The inelastic plate deformations in the A440 steel cause the end fasteners to pick up load at a faster rate than the interior fasteners. Thus the end fastener will fail before the interior bolts are able to redistribute the load efficiently.

Observe the load distribution in each joint in Fig. 9. In both homogeneous joints, the load is distributed symmetrically about the center of the joint. However, in the hybrid joint, the end fastener on the end of the joint having the maximum load in the higher strength plate has reached ultimate while the fastener at the opposite end is below its ultimate capacity. This occurs
because the plate deformations are smaller. Also, it is apparent that the bolt forces are not symmetrical about the center of the hybrid joint. This asymmetrical behavior, which predominates in the figures for hybrid joints, is due to the compatibility of the strain in a joint. In a homogeneous joint deformations in the main plate are comparable to deformations in the lap plates, but not in hybrid joints.

A qualitative evaluation of what happens when the $A_n/A_s$ ratio is decreased can be made by comparing Figs. 9 and 10. In Fig. 10 the load distribution of an A36-A440 steel hybrid joint with 15 bolts in line and $A_n/A_s$ ratios of 1.14 for A36 steel and 0.90 for A440 steel is illustrated. Comparison of the distributions in Figs. 9 and 10 shows that the hybrid joint with the large $A_n/A_s$ ratios has a better distribution of load among the fasteners. As was expected, the bolts in the more flexible joint (Fig. 10) have greater variation than those in joints with greater $A_n/A_s$ ratios (Fig. 9). As the $A_n/A_s$ ratio is decreased, the plate material becomes more flexible with respect to the fasteners, and the end fasteners will fail sooner of the differential deformation. The relative differential deformations are more uniform throughout the joint and the bolt forces will be relatively uniform. As the $A_n/A_s$ ratio was decreased from 1.36 to 1.14 the average shear strength decreased from 65 ksi to 57.0 ksi and the ultimate joint load decreased from 1175 kips to 1030 kips.

The non-symmetrical load distribution in the hybrid joint
is more apparent for the lower $A_n/A_s$ ratio. The interior fasteners maintain approximately the same load. However, the end fasteners on the right side of the joint are at greater loads than the fasteners on the left side. This departure from symmetrical load distribution, previously noted in homogeneous joints, becomes more apparent at greater joint lengths.

Figure 11 summarizes the distribution in A36 and A514 homogeneous steel joints and in a hybrid joint with 29 bolts in line. The comparisons are for $A_n/A_s$ ratio of 1.70 for the A36 steel and 0.60 for A514 steel. The A36 steel joint is represented by the top of the hatched bars and the A514 steel joint by the top of the clear bars. The hybrid joint is shown by the heavy solid line in each bar.

In conclusion, then, it is apparent that the differential strains in the hybrid joint are greater and that redistribution is not as effective as it was for the homogeneous joints. Greatly affecting the redistribution is the shear deformation capacity of the bolt. The ultimate deformation capacity of the A325 bolt is about the same in both A514 and hybrid A36-A514 steel joints. The critical joint end is that with the highest load in the more flexible material where a more rapid fall off in load occurs. At the more rigid end of the joint, the deformations in the two materials are more nearly the same and the load partition is more uniform. Plate failure controls the ultimate strength over a much greater range of joint length and $A_n/A_s$ ratios.
The load distribution behavior of A490 bolts is illustrated in Fig. 12, where the hybrid A440-A514 joint, and the homogeneous A514 and A440 steel joints at $A_n/A_s$ ratios of 0.67 and 1.45 respectively, are summarized. The ordinate in Fig. 12 has been magnified to clarify the load distribution in the various joints. Each joint consisted of 31 bolts in line. The hybrid joint is represented by a heavy dashed line in each bar, the A440 steel joint by the heavy solid line in each bar, and the A514 steel joint by the light line. The A514 steel joint has a deep U-shaped symmetrical load distribution. The non-symmetrical load distribution in the hybrid joint is very evident. Although the distributions differed greatly, the loads carried by the various steel joints differed by only 0.5%. The A514 steel joint carried 2935 kips, the A440 steel joint 2920 kips, and the hybrid joint 2930 kips.

2.5 Deformation Characteristics of Hybrid Bolted Joints

In some homogeneous joints having geometric properties ($A_n/A_s$) similar to those of hybrid joints, bolt failure commenced at shorter lengths as illustrated in Fig. 2 while the opposite occurred with homogeneous A514 steel joints. It is of interest to study this shifting of the plate failure boundary in greater detail through an examination of the displacements in joints.

As illustrated in Fig. 13, compatibility of deformations exists between adjacent fasteners in a joint. Reference 1 provides a detailed discussion of the compatibility of deformation. As the
load is applied, the main plates will elongate an amount $e_{MP}$ and the lap plates a different amount $e_{LP}$. The deformation of the bolts, $\Delta$, includes the effects of shear, bending of the bolt, and bearing of the bolt against the plates. The distance between adjacent fasteners gives the following compatibility equation:

$$\Delta_2 + p + e_{LP} + d = \Delta_1 + p + e_{MP} + d$$  \hspace{1cm} (8)

where $\Delta_1 = \text{deformation of the bolt in position 1}$,
$\Delta_2 = \text{deformation of the bolt in position 2}$,
$p = \text{pitch}$,
$d = \text{diameter}$,
$e_{LP} = \text{elongation of the lap plate}$, and
$e_{MP} = \text{elongation of the main plate}$.

Or, upon simplifying terms,

$$\Delta_2 + e_{LP} = \Delta_1 + e_{MP}$$  \hspace{1cm} (9)

The displacement resulting in the fastener adjacent to the critical end fastener is

$$\Delta_2 = \Delta_{ult} + e_{MP} - e_{LP}$$  \hspace{1cm} (10)

Since the factor of safety against yield is the same regardless of the type of steel, the components will yield simultaneously.
The critical location in a hybrid joint is at the end adjacent to the higher strength steel member because tensile strength is not as great as the lower yield material. The higher strength material has been designated as the lap plates of a hybrid joint. The ultimate loads in the main and lap plates are given by

\[ P_{\text{MP}}^u = F_{\text{ult}} \cdot A_{n}^{\text{MP}} = \alpha A_{n}^{\text{MP}} \]  \hspace{1cm} (11)

\[ P_{\text{LP}}^u = F_{\text{ult}} \cdot A_{n}^{\text{LP}} \]  \hspace{1cm} (12)

where \( F_{\text{ult}} \) = ultimate tensile strength,

Substituting for \( A_{n}^{\text{LP}} \) from Eq. 7,

\[ P_{\text{LP}}^u = F_{\text{ult}} \cdot \frac{F_{\text{a}}^{\text{MP}}}{F_{\text{a}}^{\text{LP}}} \cdot A_{n}^{\text{MP}} = \beta A_{n}^{\text{MP}} \]  \hspace{1cm} (13)

Upon substituting appropriate values into Eqs. 11 and 13, it will be found that the lap plates (the higher strength material) control the ultimate load, since \( \beta \) is always less than \( \alpha \). At the plate failure boundary the fasteners and the plate will fail simultaneously. The critical fastener is at the same end as the critical plate material.

In the A36-A440 hybrid steel joints shown in Fig. 2, the A440 steel will control the ultimate load at plate failure. An examination of the deformation characteristics of the components of the hybrid joint is useful in assessing the behavior. Figure 14
depicts the load-deformation characteristics of A36 and A440 steel plate between adjacent fasteners. At the plate failure boundary, the maximum load in the A440 steel lap plate would be reached at a deformation of $e_{LP}^{\max}$. The maximum load in the adjacent A36 steel main plate in the first pitch will be the load corresponding to the ultimate strength of a single bolt. Hence the main plate will be elastic and the lap plate inelastic. The elastic deformation in the A36 steel will be smaller than the deformation in the homogeneous joints because of the greater area of the A36 steel plate.

Besides the differences in plate deformation, the deformation capacity of the fasteners is also critical. In homogeneous A440 steel joints, the ultimate bolt deformation was 0.183 in. In the A36-A440 steel hybrid joints, it increased to 0.245 in. Hence, both the greater stiffness of the connected material and the increased deformation capacity of the fastener allow a more favorable redistribution in hybrid joints of A36-A440 steel. Because of this, fastener failure is not critical at the shorter lengths as it was with the homogeneous joints. Referring back to Eq. 9, it is clear that with the greater ultimate bolt deformation, the interior bolts will deform more than they would in homogeneous joints.

At the main plate end of the joint, the deformations in the end bolts are found by

$$\Delta_{n-1} = \Delta_n + e^{MP} - e^{LP}$$  \hspace{1cm} (14)
Referring to Fig. 14, $e^{MP}$ in the A36 steel for the hybrid joint is considerably less than it would have been in a homogeneous A440 steel joint. Because of this difference, the first several bolts at the main plate end will be deforming approximately the same and hence carry similar loads, as is apparent in the load distribution summarized in Figs. 9 to 11. The end bolt itself will not achieve ultimate load as it would in a homogeneous joint. This non-symmetrical load deformation was observed throughout the investigation as illustrated in Figs. 9 to 12.

The ultimate deformation of A325 bolts was only slightly larger in the homogeneous A514 steel joint (0.1695 in.) than in the A36-A514 hybrid joint (0.1669 in.). Figure 15 presents schematically the load deformation behavior of the steel plates for the A36-A514 hybrid joint. Although the main plate area did increase with a resulting increase in plate stiffness, better redistribution was not obtained as in the A36-A440 combination, due primarily to the small change in the deformation capacity of the fastener. With the smaller $A_{ult}$ and the resulting decreases in $e^{MP}$, the subsequent bolt deformations and forces will be less than in a homogeneous joint. In the A36-A514 hybrid joints, bolt failures started to control at joint lengths between those of A36 and A514 joints. This behavior was noted in all hybrid joints with A514 steel as one of the components. Thus the shifting of the plate failure boundary is chiefly dependent upon the materials being connected and the changing deformation capacity of the fastener.
3. COMPARISONS OF ALLOWABLE BOLT STRESSES

3.1 Introduction

Current design philosophy has drawn extensively on the concept of "balanced design". This concept is based on the precept that at the ultimate load of a joint the strength of the fastener should be equal to the strength of the connected material. Historically, a factor of safety has then been applied to the plate and fasteners in compact joints. It has been demonstrated, however, that by applying the same factor of safety against ultimate to the bolts and plate material, different allowable stresses will result for different materials which is unreasonable.²

Also, due to the redistribution of load among fasteners, a variation in factor of safety was found to accompany a change in joint length. An increase in the $A_n/A_s$ ratio decreased the variation because better redistribution of the fastener forces could occur. A design criteria was suggested to minimize the variation in factor of safety.² It was shown that this could be accomplished by establishing the allowable stress for A325 bolts at about 30 ksi, and A490 bolts at about 40 ksi. The suggestion was based on analytical studies of homogeneous A36 and A440 steel joints and resulted in a minimum factor of safety about 2.0 for A440 steel joints.
In this section, hybrid joints are analyzed to ascertain the effect upon its minimum factor of safety when using the suggested allowable bolt stresses.

3.2 Variation in Factor of Safety

As can be seen in Figs. 16 to 19, the factor of safety varies with joint length in hybrid connections. Figure 16 shows the variation of the factor of safety for the current (1966) allowable shear stress of 22 ksi for A325 bolts. The curves show the factor of safety against shear failure in the bolt (taken as the ratio of the average shear strength divided by the allowable shear stress). The horizontal lines show the limiting factor of safety as governed by plate failure.

Figure 16 shows that for short homogeneous joints the factor of safety is governed by plate failure. The factor of safety inherent in the single bolt is 3.4. However, the limiting factor is failure of the connected plate. As previously noted, plate failure controls to a greater length in hybrid joints than in homogeneous joints. For homogeneous A36 and A440 steel joints, plate failure controls out to joint lengths of 20 and 28 in., respectively. The factor of safety then varies from a maximum governed by the plate down to a minimum of about 2. The higher strength A440 steel joints have the smaller factor of safety at increasing joint length. The hybrid A36-A440 joint provides better redistribution for longer joint lengths, and as a result, the plate
failure boundary shifts so that hybrid joints maintain for longer joint lengths a uniform factor of safety governed by failure of the higher strength A440 steel. This failure mode for the A36-A440 hybrid controls up to a joint length of about 38 in. In the hybrid A36-A440 joint the plate thickness required for the A440 steel was less than 3/4 in. Thicknesses greater than 3/4 in. were commonly encountered in the homogeneous A440 steel joints, which in the yield point and tensile strength of the A440 steel plate was greater in the hybrid joints than in the homogeneous joints.

The variation in the factor of safety against failure in any of the joints plotted in Fig. 16 indicates the extent to which the material is being utilized efficiently. These variations have been calculated for the single bolt, the homogeneous joints, and the hybrid joints. For the first hybrid, A36-A440 steel, at $F_v = 22$ ksi the single bolt factor of safety is 3.40. The factor of safety against plate failure for the A36 steel homogeneous joint was 2.95, and the minimum against bolt failure was 2.15. The factor of safety for the homogeneous A440 steel joints ranged from 2.35 to 2.00. The factor of safety varied from 2.40 to 2.25 for the A36-A440 hybrid, and the factor of safety curve lies, as expected, between the two homogeneous joints.

The factor of safety vs. joint length is also plotted in Fig. 16 for A36-A514 and A440-A514 joints. Both are identical to the homogeneous A514 steel curve, a horizontal dashed line. Plate failure controls the joint failure over the entire joint length.
shown. Thus a constant factor of safety is maintained at 1.92.
This type of behavior is expected at the lower bolt stress of 22 ksi
when using A514 steel, as explained in Section 2.5. The largest
value obtained was 2.95, and the smallest 1.92. Thus it represents
an overall difference of 34%.

The effect of raising the allowable shear stress of A325
bolts to 30 ksi is illustrated in Fig. 17. Comparison with Fig. 16
shows that the variation of the factor of safety for the joints in­
vestigated has been dramatically reduced by increasing the allowable
bolt shear stress. At this higher bolt stress, plate failure con­
trols the mode of failure over a shorter joint length than it did
at 22 ksi. Bolt failure controls over the entire joint length with
A36 steel and for joint lengths greater than 14 in. with A440 steel.
Plate failure controls out to a joint length of 21 in. in the A36-
A440 hybrid joint, and the variation of factor of safety is less:
the single bolt factor of safety decreased to 2.50. The factor of
safety for the homogeneous A36 steel joints ranged from 2.40 for
plate failure to 2.05 for bolt failure. In the A440 steel joints
it ranged from 2.20 to 1.90, and for the hybrid A36-A440 joints it
varied from 2.35 to 2.00. The percentage variations were 14.5%,
13.5%, and 15%, respectively.

The homogeneous A514 steel joints and the hybrid A36-A514
joints were still controlled by plate failure over the joint lengths
investigated. However, the A440-A514 hybrid combination failed by
shearing of the bolts commencing at a joint length of 84 in. Its
factor of safety changed from 1.92 for plate failure to 1.80 for bolt failure, a 6% variation. The highest factor of safety obtained at $F_v = 30$ ksi was 2.40, and the lowest 1.80 at a joint length of 120 in. This represents a 25% overall variation in factor of safety.

Thus the overall variation in factor of safety against failure was reduced from 34% to 25%, with the minimum value of 1.80. This was achieved while increasing the allowable bolt stress by 36%. The hybrid joints behaved similarly to the homogeneous joints at the two bolt stresses.

Current specifications set the allowable bolt stress equal to 32 ksi for the A490 bolt. As with the A325 bolt, this leads to inconsistent values in the factor of safety. In Fig. 18, a comparison of factors of safety is made between homogeneous joints of A440 steel and A514 steel and the hybrid A440-A514 joints. The bolt shear stress illustrated in 32 ksi. The strengths of the A440-A514 hybrid joints and the homogeneous A514 steel joints are controlled by plate failure. This gave a constant factor of safety at 1.92. The value of the factor of safety for the single bolt was 2.85. For the homogeneous A440 steel joints, the values varied 20% from 2.45 against plate failure to 1.95 against bolt failure. The largest factor of safety obtained was 2.85 and the smallest 1.92, a 33% variation.

By increasing the allowable stress to 40 ksi as illustrated in Fig. 19, the variation is again visibly reduced. The single bolt
factor of safety decreased to 2.30. The A440 steel joint was controlled by bolt failure over its entire joint length, with its factor of safety ranging from 2.30 for compact joints to 1.85 for joints 120 in. long. The homogeneous A514 steel joints had safety factors from 1.90 to 1.85. The variation of safety factor was 19.5% for the A440 steel joints, and 2% for the A514 and the hybrid joints. At the shear stress of 40 ksi, the highest factor of safety obtained was 2.30 and the lowest 1.85, giving a 19% overall variation. This represents a substantial reduction from the 33% variation obtained at the current shear stress of 32 ksi. This reduction was accomplished by increasing the allowable bolt stress by 25%.

By raising the allowable bolt stress in both the A325 and A490 bolts the variations in factor of safety against failure were minimized. In both cases the minimum factor of safety did not change appreciably. The minimum factor of safety of 1.80 for A325 bolts designed for 30 ksi occurred in A440-A514 hybrid joints. This compares with 1.92 for the currently used allowable shear stress of 22 ksi. The minimum factor of safety of 1.85 for A490 bolts with a 40 ksi allowable bolt shear stress occurred in A440-A514 hybrid joints and homogeneous A440 steel joints. This compared with a minimum factor of 1.92 when the allowable shear stress is 32 ksi.
The following summarizes the behavior of hybrid joints fastened by A325 and A490 high strength bolts. The conclusions are based upon the theoretical analysis discussed in this report.

1. The hybrid joints behaved similarly to homogeneous joints. An increase in joint length produced a decrease in the average shear strength. As the $A_n/A_s$ ratio decreased, the average shear strength also decreased.

2. The shear strength of A325 bolts in A36-A440 hybrid joints was equal to or greater than that obtained in homogeneous joints. The shear strength of the A325 bolt in hybrid joints using A514 steel was equal to or slightly less than in homogeneous joints. The reduction in shear strength was less than 5%. There was no reduction for the A490 bolt in the A440-A514 hybrid joints.

3. The major effect observed in the analytical studies was a shifting of the location of the plate failure boundary. The direction and amount of shift depended directly upon the connected materials and the changing deformation capacity of the fastener.

4. Increasing the allowable bolt stress for the A325 and A490 bolt had no adverse effect in hybrid joints. The increase studied for the A325 bolt was from 22 ksi to 30 ksi; and for the A490 bolt, from 22 ksi to 40 ksi. In both cases, the variation in factor of safety against failure was substantially reduced with little change in the minimum factor.
5. ACKNOWLEDGMENTS

This study has been carried out as part of the research project on "Large Bolted Connections" being conducted at Fritz Engineering Laboratory, Department of Civil Engineering, Lehigh University. Professor L. S. Beedle is the Director of the Laboratory, and Acting Chairman of the Civil Engineering Department.

The project is sponsored financially by the Pennsylvania Department of Highways, the United States Department of Commerce - Bureau of Public Roads, and the American Institute of Steel Construction. Technical guidance is provided by the Research Council on Riveted and Bolted Structural Joints through an advisory committee under the Chairmanship of Mr. T. W. Spilman.

Thanks are also due J. M. Gera for preparing the tracings, to Mrs. Carol Kostenbader for typing the manuscript and to W. A. Digel for reviewing the manuscript.
6. REFERENCES

1. Fisher, J. W., Rumpf, J. L.
   ANALYSIS OF BOLTED BUTT JOINTS, Journal of the Structural Division, ASCE, Vol. 91, ST5, October, 1965

2. Fisher, J. W., Beedle, L. S.
   CRITERIA FOR DESIGNING BEARING-TYPE BOLTED JOINTS,
   Journal of the Structural Division, ASCE, Vol. 91, ST5, October, 1965

   THE COEFFICIENT OF FRICTION IN BOLTED JOINTS MADE WITH VARIOUS STEELS AND MULTIPLE CONTACT SURFACES,
   Department of Civil Engineering, University of Washington, 1964

4. Fisher, J. W.
   BEHAVIOR OF FASTENERS AND PLATES WITH HOLES, Journal of the Structural Division, ASCE, Vol. 91, ST6, December, 1965

5. Project Staff
   SUMMARY REPORT TO THE RESEARCH COUNCIL ON RIVETED AND BOLTED STRUCTURAL JOINTS,
   Fritz Engineering Laboratory Report 288.25, Lehigh University, November, 1964

   SHEAR STRENGTH OF HIGH STRENGTH BOLTS, Journal of the Structural Division, ASCE, Vol. 91, ST3, June, 1965

7. Fisher, J. W., Kulak, G. L., Beedle, L. S.
   BEHAVIOR OF LARGE BOLTED JOINTS, Fritz Engineering Laboratory Report 288.31, Lehigh University, August, 1965


9. Research Council on Riveted and Bolted Structural Joints of the Engineering Foundation
   SPECIFICATIONS FOR STRUCTURAL JOINTS USING ASTM A325 OR A490 BOLTS, September, 1966

-30-
7. TABLE AND FIGURES
<table>
<thead>
<tr>
<th>Steel Combinations</th>
<th>Ultimate Load (kips)</th>
<th>Ultimate Deformation (inches)</th>
<th>( \mu )</th>
<th>( \lambda )</th>
</tr>
</thead>
<tbody>
<tr>
<td>7/8 in. A325 Bolts</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A36-A36</td>
<td>90.3</td>
<td>.2580</td>
<td>18.0</td>
<td>1.000</td>
</tr>
<tr>
<td>A440-A440</td>
<td>90.3</td>
<td>.1833</td>
<td>25.0</td>
<td>0.950</td>
</tr>
<tr>
<td>A514-A514</td>
<td>90.3</td>
<td>.1695</td>
<td>20.0</td>
<td>0.370</td>
</tr>
<tr>
<td>A36-A440</td>
<td>90.3</td>
<td>.2456</td>
<td>10.0</td>
<td>0.356</td>
</tr>
<tr>
<td>A36-A514</td>
<td>90.3</td>
<td>.1669</td>
<td>17.5</td>
<td>0.445</td>
</tr>
<tr>
<td>A440-A514</td>
<td>90.3</td>
<td>.1625</td>
<td>23.5</td>
<td>0.562</td>
</tr>
<tr>
<td>7/8 in. A490 Bolts</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A440-A440</td>
<td>110.0</td>
<td>.2019</td>
<td>23.0</td>
<td>0.400</td>
</tr>
<tr>
<td>A514-A514</td>
<td>110.0</td>
<td>.1400</td>
<td>25.0</td>
<td>0.400</td>
</tr>
<tr>
<td>A440-A514</td>
<td>110.0</td>
<td>.1830</td>
<td>25.0</td>
<td>0.608</td>
</tr>
</tbody>
</table>
**Figure No. 1 - Effect of Joint Length Upon Ultimate Strength - A36 and A440 Steel**

- **A36 Steel**
  - $F_v = 30$ ksi
  - $A_n/A_s = 1.36$

- **A440 Steel**
  - $F_v = 22$ ksi
  - $A_n/A_s = 1.09$

**Figure No. 2 - Effect of Joint Length Upon Ultimate Strength - A36 and A440 Steel**

- **A36 Steel**
  - $F_v = 30$ ksi
  - $A_n/A_s = 1.36$

- **A440 Steel**
  - $F_v = 22$ ksi
  - $A_n/A_s = 1.09$
Figure No. 3 - Effect of Joint Length Upon Ultimate Strength - A440 and A514 Steel

Figure No. 4 - Effect of Joint Length Upon Ultimate Strength - A440 and A514 Steel
A36 - A514 Hybrid Joint

A36 - A440 Hybrid Joint

Figure No. 5 - Effect of Variation of $A_n/A_s$ on Ultimate Strength - A36 and A440 Steel

Figure No. 6 - Effect of Variation of $A_n/A_s$ on Ultimate Strength - A36 and A514 Steel
Figure No. 7 - Effect of Variation of $A_n/A_s$ on Ultimate Strength - A440 and A514 Steel

Figure No. 8 - Effect of Variation of $A_n/A_s$ on Ultimate Strength - A440 and A514 Steel
Figure No. 9 - Load Partition in A36-A440 Hybrid Joints, A325 Bolts, 15 fasteners in line, $A_n/A_s = 1.50$

Figure No. 10 - Load Partition in A36-A440 Hybrid Joint, A325 Bolts, 15 fasteners in line, $A_n/A_s = 1.25$
Figure No. 11 - Load Partition in A36-A514 Hybrid Joint, A325 Bolts, 29 fasteners in line, \( \frac{A_n}{A_s} = 1.70 \)
Figure No. 12 - Load Partition in A440-A514 Hybrid Joint, A490 Bolts, 31 fasteners in line, $A_n/A_s = 1.50$
Figure No. 13 - Compatibility of Deformations in a Bolted Joint

Figure No. 14 - Load-Deformation Behavior of Main and Lap Plates of A36-A440 Hybrid Joint

Figure No. 15 - Load-Deformation Behavior of Main and Lap Plates of A36-A514 Hybrid Joint
Figure No. 16 - Variation of Factor of Safety in A325 Bolts, $F_v = 22$ ksi
Figure No. 17 - Variation of Factor of Safety in A325 Bolts, $F_v = 30$ ksi
Figure No. 18 - Variation of Factor of Safety in A490 Bolts, $F_v = 32$ ksi

Figure No. 19 - Variation of Factor of Safety in A490 Bolts, $F_v = 40$ ksi