THE COLLAPSE STRENGTH OF A
WELDED KNEE
SUBJECTED TO TENSILE-TYPE LOADINGS

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INTRODUCTION

1.1 SUBJECT

In this test two simple portal frame knees were each subjected to tensile-type loadings applied in such a manner that the angle between the two legs of the knee increased. The two knees were identical with the exception that one had previously been stressed beyond its yield strength while the other had practically no previous strain history.

1.2 PURPOSE

The purpose of this test was to study the behavior of a simple portal frame knee when subjected to a loading which causes an increase rather than a decrease in the angle between the legs of the knee.

1.3 SCOPE

This report covers a theoretical and an experimental study of the knees tested. The study covers total rotation of the knee, average unit rotation over 10" sections of the beam adjacent to the knee, total deflection of the knee, and lateral support load.
SUMMARY OF RESULTS

2.1 The failure of both knees was brought about by lateral buckling.

2.2 The ultimate moment of the knees was 45% greater than the theoretical yield moment of a plain beam 12WF36 Section.

2.3 The knee was 10% stronger under tensile-type loading than under compressive-type loading.

2.4 When rotations became large the unit rotation at a point in the leg just outside the knee proper became greater than the unit rotation at the haunch, the intersection of the centerlines of the legs.

2.5 The lateral support loads were only 0.4% of the theoretical axial yield load of the section until the ultimate strength of the knee was reached. Once the ultimate strength was reached, the lateral support loads increased rapidly.
CONCLUSIONS

On the basis of the tests of the two knees described in this report the following conclusions are made.

3.1 A knee of the type used in this test, type 8B as described in Progress Report 4 (1), will safely withstand the same load under a tensile-type loading that it is designed to withstand under a compressive-type loading.

3.2 A knee of the type used in this test should be provided with lateral support capable of exerting a force on the knee of 1.0% of the theoretical axial yield load of the section. These supports should be located on the inside and outside corners of the knee.

3.3 A knee of the type used in this test if properly supported should be capable of supporting tensile-type loadings 20% greater than its theoretical yield strength and 10% greater than its theoretical plastic strength.
DESCRIPTION OF TEST

4.1 TEST SPECIMEN

A detailed drawing of the test specimens is shown in Fig. 9. They are both knees of the type 8B as described in Progress Report 4 (Reference 1).

4.1.1 History

The two knees tested were cut from a full-sized single bay rectangular rigid frame fabricated from a 12WF66 steel section. The test to failure of this frame is described in Progress Report U (2). A photograph of this frame after being tested is shown in Fig. 10.

4.1.1.1 The Virgin Knee -- The knee which will be referred to as the virgin knee in this report was the windward knee of the frame described in Progress Report U (2). From the plot of its previous strain history as shown in the Moment-Rotation Curves, Fig. 3, it is seen that during the frame test the moment in this knee was at all times below the yield moment. Slight permanent deformation due to Local Yielding did occur, but its effect may be neglected. For practical purposes, this knee may be considered as having no previous strain history.

4.1.1.2 The Deformed Knee -- The knee which will be referred to as the deformed knee was the lee knee of the frame. From the plot of its previous strain history as shown in the Moment-Rotation Curves, Fig. 4, it is seen that during the frame test the
moment in this knee surpassed the plastic moment of the knee and reached the ultimate moment. Excessive permanent deformation of the knee occurred. A photograph of the knee as it appeared after the frame test is shown in Fig. 11.

4.1.2 Section Properties (2)

The steel section used in fabricating the portal frame was a nominal 12WF36, but the actual measurements of the cross-section showed that the section used had properties that varied to some extent from those given in the A.I.S.C. Steel Construction Manual. A comparison of handbook and actual dimensions is given in Table I.

<table>
<thead>
<tr>
<th>TABLE I: PROPERTIES OF 12WF36</th>
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<tbody>
<tr>
<td>Wt. per ft.</td>
</tr>
<tr>
<td>lb.</td>
</tr>
<tr>
<td>Actual</td>
</tr>
<tr>
<td>Handbook</td>
</tr>
<tr>
<td>Variation</td>
</tr>
</tbody>
</table>
4.1.3 Mechanical Properties (2)

The mechanical properties of the steel used were determined by standard coupon tests (both tension and compression) taken from several locations in the cross-section of the beam. The steel used was ordered to meet the requirement of A.S.T.M. Designation A7-50T and all pieces needed to form the two knees were cut from a single length.

4.1.3.1 Mill Report -- The mill report for the steel is shown in Table II.

**TABLE II: MILL REPORT ON 12WF36**

<table>
<thead>
<tr>
<th>Chemical Composition in Per Cent:</th>
<th>Mechanical Properties</th>
</tr>
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<tbody>
<tr>
<td><strong>C</strong> = 0.18</td>
<td>Yield Strength (upper yield)=42,530 psi</td>
</tr>
<tr>
<td></td>
<td>(Ave. Yield Stress Level by Lab. Tests = 39,100 psi)</td>
</tr>
<tr>
<td><strong>Mn</strong> = 0.65</td>
<td>Ultimate Strength = 67,420 psi</td>
</tr>
<tr>
<td><strong>P</strong> = 0.014</td>
<td>Elongation in 8 in. = 25.2%</td>
</tr>
<tr>
<td><strong>S</strong> = 0.038</td>
<td>Reduction in Area = 50.0 per cent</td>
</tr>
</tbody>
</table>

4.1.3.2 Laboratory Coupon Tests -- The laboratory coupon tests are summarized in Table III. In using these results the yield stress level of those coupons (tension and compression) located in the flanges of the beam were averaged and used to determine the yield moment and plastic moment of the section. This average
yield stress level was 39,100 psi which is somewhat lower than the upper yield strength of 42,530 psi given in the mill report.

TABLE III: SUMMARY OF LABORATORY COUPON TESTS OF 12WF36

<table>
<thead>
<tr>
<th>Location</th>
<th>Tension of</th>
<th>Yield Stress Level—psi</th>
<th>Ultimate Strength—psi</th>
<th>Strain Hardening in/in</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>T</td>
<td>39,230</td>
<td>62,000</td>
<td>0.015</td>
</tr>
<tr>
<td>1</td>
<td>C</td>
<td>38,060</td>
<td>-</td>
<td>0.014</td>
</tr>
<tr>
<td>2</td>
<td>T</td>
<td>45,100</td>
<td>67,800</td>
<td>0.024</td>
</tr>
<tr>
<td>2</td>
<td>C</td>
<td>45,150</td>
<td>-</td>
<td>0.014</td>
</tr>
<tr>
<td>3</td>
<td>T</td>
<td>39,700</td>
<td>62,200</td>
<td>0.018</td>
</tr>
<tr>
<td>3</td>
<td>C</td>
<td>38,090</td>
<td>-</td>
<td>0.015</td>
</tr>
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<td>4</td>
<td>T</td>
<td>41,200</td>
<td>66,200</td>
<td>0.014</td>
</tr>
<tr>
<td>4</td>
<td>C</td>
<td>38,490</td>
<td>-</td>
<td>0.013</td>
</tr>
</tbody>
</table>
4.2 TESTING APPARATUS

The loads were applied to each knee by means of an 800,000-pound capacity, screw-type testing machine. A 3 1/2-in. pin was securely welded to the end of each leg of the knee as shown in Fig. 9. The knee was then suspended between the upper fixed head and the movable head of the testing machine. The upper leg, or beam leg, was securely mounted by its pin to the fixed head; the lower leg, or column leg, was securely mounted by its pin to the movable head. This set-up is shown in Fig. 12 and in the photograph, Fig. 13. All loads were applied to the knee through these two pins. The magnitude of the applied load was read directly from the load-indication lever balance of the machine.

4.2.1 Lateral Support (2)

Past experience in the testing of rigid frame knees into the plastic region has shown that adequate lateral support is essential if the theoretical collapse load is to be attained. Without proper lateral support the entire specimen will buckle as a unit and failure will occur under loads far lower than the theoretical collapse load.

In this test the knees were provided with lateral support in a manner which might be equivalent to that used in actual building construction. The support was given by four struts, two on each side of the knee. An initial tension of approximately 6 Kips was applied to each strut by means of a turnbuckle. This insured that the struts would provide proper support.
4.2.1.1 **Flex Bars** -- In order to insure free movement of the frame in its plane, the lateral support struts were fitted with flex bars at each end.

4.2.1.2 **Strain Gages** -- SR-4 electrical strain gages were attached to one of the flex bars of each lateral support so that the force in each support could be known at any time during the test.

4.2.2 **Rotation Measurements**

Rotation indicators of the type described in Progress Report 7 (3) and illustrated in Fig. 20 of that report were used to determine rotation. Seven such rotation indicators were used on each knee: one across the knee and three in each leg. The rotation indicator brackets may be seen in the photograph of the test set-up, Fig. 13.

4.2.3 **Deflection Measurements**

Deflection of the knee in the plane of the knee was measured by a single Ames Dial mounted as shown in Fig. 12. A rod was suspended from the upper leg of the knee in line with the upper pin and hung vertically along the line of the force acting on the knee. The Ames Dial was mounted on the lower end of the rod in such a manner that its plunger rested securely on a punch mark set directly in line with the pin of the lower leg of the knee. In this manner the deflection was determined by the vertical change in the positions of the pins through which the load was applied.
4.2.4 Scaffolding

In order to read the deflection and rotation dials and examine the specimen during testing safely and easily, a steel and wood-planked platform was mounted around the knee and securely attached to the testing machine frame. This platform may be seen in the photograph, Fig. 15.

4.3 TEST PROCEDURE

Each knee, virgin and deformed, was tested according to the procedure described herein.

4.3.1 Virgin Knee

The virgin knee was tested continuously for eight hours to failure.

4.3.2 Deformed Knee

The deformed knee was tested for two hours the first day and eight hours the second day. The load applied to the knee at the end of the second hour on the first day was allowed to remain acting on the knee overnight. The test was resumed the following day by first taking all measurements without additional load and then continuing with the test.

The load at which the testing was stopped on the first day was that load at which the Load-Deflection Curve tended to first deviate from the straight-line, elastic curve.

4.3.3 Load Increment Criterion

At the beginning of the test, load was applied in approximately equal increments of about 8% of the calculated yield
load. All Deflection and rotation measurements were taken at each load before the following load was applied. Approximately ten minutes was required to take these measurements.

4.3.4 Deformation Increment Criterion

When the plastic strength of the knee had been surpassed as indicated on the Load-Deflection Curve by a flattening of the curve, the "load-increment" criterion of loading was replaced by a "deformation-increment" type loading of the type developed in Progress Report U (2). During this latter part of the test five minutes was allowed to elapse after application of each load before any data was taken. The purpose of this elapse in time was to allow the knee to "settle down", to allow time for most of the yielding at that load to occur. This five minutes time elapse was established from previous tests which indicated that practically all of the drop in load due to yielding occurs within the first five minutes of application of the strain increment.

4.3.5 Readjustment of Lateral Supports

As the stresses in the knee reached beyond the plastic limit, deformation caused the knee to move several inches towards the line of force. This induced bending stresses in the lateral supports and necessitated their being reset to prevent fracture of the flex-bars and to provide proper lateral support.

4.3.6 Removal of Rotation Indicators

When the ultimate load of the specimen had been reached, as indicated by a drop in load with increased strain as shown on the Load-Deflection Curve, the rotation indicators were removed.
This was done to prevent damage to the Ames dials. The indicators were in danger of binding due to the large deformations accompanying these loads. This binding could cause the Ames dials to slip from their seats and fall to the base of the testing machine.

4.3.7 Removal of Lateral Supports

After the knee had been stressed beyond its ultimate strength, the stress in the lateral bracing became high. In order to prevent fracturing of the flex-bars under increased deformations, the lateral supports were removed.

4.3.8 Removal of the Deflection Dial

As the knee began to fail, deflections became so great that the Ames dial was no longer able to effectively measure them. The dial was removed and further deflection was measured with a six-foot rule.

4.3.9 Failure

Failure was determined by that load at which the knee could not withstand added strain without a rapid drop in load.
5.1 THEORETICAL MOMENTS 

5.1.1 Yield Moment

As shown in Table I the section modulus for the wide flange section was found to be 43.5 in$^3$. Using the average yield stress level of 39,100 psi (see Table II), the theoretical moment, $M_y$, for the knee is found to be:

$$M_y = S_x \times \sigma_y = 43.5 \times 39.1 = 1700 \text{ In. Kips}$$

5.1.2 Plastic Moment

As shown in Table I the plastic modulus for the wide flange section was found to be 48.1 in$^3$. Using the average yield stress level of 39,100 (see Table II), the theoretical plastic moment, $M_p$, for the knee is found to be:

$$M_p = Z_x \times \sigma_y = 48.1 \times 39.1 = 1880 \text{ In. Kips}$$

5.2 THEORETICAL LOADS

Analysis for finding the theoretical loads are based on Diagram I. The length of the arm "a" is found to be:

$$96 \cos 45^\circ = 67.37 \text{ in.}$$
5.2.1 Yield Load

The theoretical yield load is found to be:

\[ P_y = \frac{M_y}{a} = \frac{1700}{67.89} = 25.0 \text{ Kips} \]

5.2.2 Plastic Load

The theoretical plastic load is found to be:

\[ P_p = \frac{M_p}{a} = \frac{1880}{67.89} = 27.7 \text{ Kips} \]

5.3 Actual Moment at Haunch

The actual moment at the haunch, the intersection of the center-lines of the two legs, is seen from Diagram I to be simply the applied force, \( P \), times the moment arm, \( a \). However, as the length \( L \) between the pins increases as the knee deflects, the moment arm, "\( a \)" decreases. The following derivation shows that that the decrease in the moment arm is equal to one-half the increase in length \( L \) between the pins.
5.3.1 Derivation for $\Delta a$

By the Pythagorean Theorem:

$$b^2 = a^2 + l^2$$

where: $b$ is the length of the leg of the knee  
$a$ is the original moment arm  
$l$ is one-half the original length between pins, or $L/2$

As the knee deflects:

$$b^2 = (a + \Delta a)^2 + (\frac{L}{2} + \Delta l)^2$$

where: $\Delta a$ is the change in length of moment arm  
$\Delta l$ is one-half the change in length between pins  

$$b^2 = a^2 + 2a(\Delta a) + (\Delta a)^2 + \left(\frac{L}{2}\right)^2 + 2\left(\frac{L}{2}\right)(\Delta l) + (\Delta l)^2$$

$$(\Delta a)^2 \approx (\Delta l)^2 \approx 0$$

$$b^2 = a^2 + 2a(\Delta a) + \left(\frac{L}{2}\right)^2 + 2\left(\frac{L}{2}\right)(\Delta l)$$

$a(\Delta a) = -\frac{L}{2}(\Delta l)$

$$a = -\frac{L}{a} (\Delta l)$$

Since $\alpha = 45^\circ$, $l = a$

$$\Delta a = -\Delta l$$

5.3.2 Moment Arm

The actual moment arm is now found to be:

$$\text{moment arm} = a + \Delta a = a - \Delta l = a - \Delta L/2$$

where: $a$ is the original moment arm  
$\Delta L$ is the change in length between pins, the total deflection.
RESULTS

6.1 GENERAL DISCUSSION OF VIRGIN KNEE TEST, TEST NO. 1

6.1.1 Yielding

The first signs of yielding occurred in the web of the knee near the full stiffener when the moment at the haunch was 1283 In-Kips, 26% less than the Theoretical yield moment. Further increase in load developed yielding in several other points of the knee as evidenced by spalling of the whitewash. When the moment at the haunch had reached 2140 In-Kips, yielding was evident in both flanges of the beam and in the web of the beam near the tension flange. Yielding was also evident at this moment in both flanges of the column and in one diagonal stiffener. The photographs of Fig. 14 show these yield lines. As this yielding developed, both the Load-Deflection Curve, Fig. 1, and the Moment-Rotation Curve, Fig. 3, began to break away from a straight line. There were no signs of either local buckling or lateral buckling at this point in the test.

6.1.2 Local and Lateral Buckling

When the moment in the haunch had increased to 2291 In-Kips there were indications of both local buckling in the compression flange of the beam and lateral buckling of the beam. As the moment was increased further, the lateral buckle became more pronounced and eventually led to the failure of the knee. There was no noticeable change throughout the remainder of the test in the size of the local buckle, which was actually a direct
result of the lateral buckle rather than an independent action. At this point in the test both the Load-Deflection Curve, Fig. 1, and the Moment-Rotation Curve, Fig. 3, had flattened.

6.1.3 Ultimate Strength

The ultimate moment carried by the knee was 2291 In-Kips, which is 55% greater than the theoretical yield moment. This moment occurred simultaneously with the ultimate load of 34.75 Kips. The ultimate strength was reached just as the lateral buckle began.

6.1.4 Failure

As the lateral buckle developed, the knee began to twist about a line through the lateral support connections as its axis. This twisting action caused the loads in the lateral supports to increase rather rapidly.

The knee continued to carry a high moment for several more increments of loading. Then, as the lateral buckle and the twisting about the line of the lateral supports became more pronounced, the load began to drop off rapidly with increased strain.

The beam failed.

The photograph of Fig. 13 shows the knee after the test. The lateral buckle may be seen in the upper leg, the beam portion of the knee. With close inspection the local buckle may be seen at the point where the third rotation indicator bracket from the top crosses the upper flange of the beam.
6.2 GENERAL DISCUSSION OF DEFORMED KNEE TEST, TEST NO. 2

6.2.1 Yielding

The first signs of yielding as evidenced from flaking of the whitewash occurred in the tension flange of the beam when the moment at the haunch was 2105 In-Kips, which is 25% higher than the theoretical yield moment. However, the Load-Deflection and Moment Rotation curves, Figs. 2 and 4, indicate that yielding actually began to occur when the moment in the haunch had become approximately 1300 In-Kips, which is 25% less than the theoretical yield moment. This apparent discrepancy is accounted for by the fact that much of the mill scale had flaked from the specimen when it had yielded considerably during its previous test as part of the rigid frame from which it was cut. The steel was thus free of scale in those areas where yielding first occurred.

By the time the moment in the haunch had reached 2263 In-Kips, much of the deformation from the previous test had straightened out. Flaking of the whitewash indicated yielding in both flanges of the beam and in the web of the knee.

6.2.2 Lateral Buckling

When the moment at the haunch reached 2320 In-Kips lateral buckling in the column leg began to develop.

At a moment at the haunch of 2360 In-Kips, considerable yielding occurred in both sides of the compression flange of the beam about five inches up from the stiffener.

With further increase in moment the lateral buckling of the column continued to develop and caused local buckling in
the compression flange of the column about a foot below the knee. At the same time, the knee began to twist about a line through the lateral support connections in a manner similar to that of the virgin knee. The stresses in the lateral supports began to increase rapidly. By this time both the Load-Deflection Curve, Fig. 2, and the Moment-Rotation Curve, Fig. 4, had become flat.

6.2.3 **Ultimate Strength**

The ultimate moment carried by the knee was 2378 In-Kips, 40% greater than the theoretical yield moment. This moment occurred simultaneously with the ultimate load of 34.45 Kips.

6.2.4 **Failure**

The knee continued to carry high moment for several more increments of loading. Then, as the lateral buckle and the twisting about the line of the supports became more pronounced, the load began to drop off rapidly with increase in strain. The beam failed.

6.3 **TOTAL DEFLECTION**

The total deflection of each knee is shown in the Load-Deflection Curves, Figs 1 and 2. Although the curves differ somewhat, with the curve for the deformed knee starting to break from the straight elastic portion of the curve at a load approximately 75% of that for the virgin knee, the ultimate load reached is the same for both. This ultimate load is 40% greater than the theoretical yield load.
6.4 ROTATION ACROSS THE KNEE

The total rotation across each knee for varying moments is shown in the Moment-Rotation Curves, Figs. 3 and 4. Also plotted on these curves are the Moment-Rotation Curves, as taken from Progress Report U (2), showing the previous strain history of each knee.

Although the curves differ slightly, with the curve for the deformed knee starting to break from the straight elastic portion of the curve at a moment approximately 75% of that for the virgin knee, the ultimate moment reached by both is nearly the same, with that of the deformed knee 4% higher than that of the virgin knee. The ultimate moment was 45% greater than the theoretical yield moment for the 12WF36 section.

6.4.1 Virgin Knee

The Moment-Rotation Curve from Progress Report U indicates that in that test, although the knee was not stressed beyond its theoretical yield point, some inelastic action did occur, resulting in a small amount of permanent set in the knee.

6.4.2 Deformed Knee

The behavior of the knee under first a compressive-type loading and then a tension-type loading was nearly the same as these two curves show. It is significant to note, however, that the knee proved to be 10% stronger under the tension-type than the compressive-type loading.
6.5 UNIT ROTATION

The unit rotations along the leg of the knee for various moments at the haunch are shown in the Unit Rotation vs. Distance from Haunch curves, Figs. 5 and 6. For low rotations the point of maximum unit rotation is in the haunch of the knee. As rotation increases, the unit rotation at a point about six inches outside the knee increases at a faster rate than that at the haunch and for large rotations becomes greater than that at the haunch.

6.6 LATERAL SUPPORT

The lateral force required to prevent the knee from buckling over its entire length at loads far lower than the theoretical collapse load is shown in Figs. 7 and 8. To obtain a plot based upon the characteristics of the section the ratio of the lateral force to the theoretical axial yield load of the section was used as the abscissa.

Until the knee reached its ultimate strength, approximately 40% greater than the theoretical yield moment for the section, only a small lateral force was required to insure stability. For the deformed knee the force required remained essentially constant at 0.4 Kip, or 0.1% of the theoretical axial yield load of the section. For the virgin knee the force required varied, but at no point was it greater than 1.5 Kips, or 0.4% of the theoretical axial load. Once the knee had reached its ultimate strength and begun to fail, the lateral force required increased rapidly.
REFERENCES


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The specimens for this project were taken from the project on "Welded Continuous Frames and Their Components" at Fritz Engineering Laboratory.
Figure 1: Load-Deflection Curve of Virgin Knee

Project 242  Test 1

UL
$P_p = 27.7_k$
$P_v = 25.0_k$

Load in Kips

Deflection in Inches

Deflection Gage
FIGURE 2: LOAD-DEFLECTION CURVE OF DEFORMED KNEE

PROJECT 242    TEST-2

U.L.

$P_p = 27.7^k$

$P_k = 25.0^k$

DEFLECTION GAGE

LOAD IN KIPS

0 4 8 12 16 20 24 28 32 36

DEFLECTION IN INCHES

0 1 2 3 4 5 6 7 8 9 10 11 12 13
Figure 3: Moment-Rotation Curves for Virgin Knee

Project 242 Test 1

Location of Knee Rotation Indicators

Rotation Indicator Brackets

Moment-Rotation Curve: Progress Report U

Moment-Rotation Curve: This Test

Knee Moment in Inch-Kips

Knee Rotation in Radians
FIGURE 4:

Moment-Rotation Curves for Deformed Knee

Project 242 TEST-2

Rotation Indicator Brackets

Moment-Rotation Curve - Progress Report "U"

Moment-Rotation Curve - This Test

Location of Knee Rotation Indicators

Knee Moment in Inch-Kips

Knee Rotation in Radians

0 0.005 0.010 0.015 0.020 0.025 0.030 0.035 0.040

2400

2000

1600

1200

800

400

0
FIGURE 5:

UNIT ROTATION VS. DISTANCE FROM HANCH
FOR
VARIOUS HAUNCH MOMENTS

PROJECT-242
TEST-1

\[ M_h = 1.18 M_p \]

\[ M_h = 1.22 M_p \]

\[ M_h = 1.04 M_p \]

\[ M_h = 0.90 M_p \]

\[ M_h = 0.62 M_p \]

12°

22°

2.9" 96" P"
FIGURE 6

UNIT ROTATION vs DISTANCE FROM HAUNCH FOR VARIOUS HAUNCH MOMENTS

Project 242 TEST-2

\[ \theta \text{ IN} \ 10^{-4} \text{ INCHES} \]

\[ M_u = 1.24 M_p \]
\[ M_u = 1.26 M_p \]
\[ M_u = 0.98 M_p \]
\[ M_u = 0.89 M_p \]
\[ M_u = 0.46 M_p \]

12" 22" 29"

96" To Pin

Figure 6
Figure 7

\[
\frac{P}{R^2} \times 10^3
\]

\[
P_i = \frac{(F_2 - F_1) + (F_3 - F_4)}{2}
\]

\[
P_i = A \sigma_f
\]
Figure 8

Ratio of lateral force to yield force vs.
Ratio of haunch moment to yield moment
Project 242
Test-2

\[ \frac{M_H}{M_Y} \]

\[ P = \frac{(F_2 - F_1) + (F_3 - F_4)}{2} \]

\[ P_Y = A \sigma_Y \]
KNEE DETAILS
PROJECT 242
FIGURE 9
12WF FRAME AFTER TESTING

FIGURE 10
DEFORMED KNEE AFTER FRAME TEST

**Figure 11**

View of Inside Flange

Side View
TEST SETUP

FIGURE 12
VIRGIN KNEE IN TESTING MACHINE
AFTER FAILURE

FIGURE 13
YIELDING IN VIRGIN KNEE

\[ M_x \approx M_y \]

FIGURE 14