LOCAL BUCKLING TESTS ON TWO HIGH-STRENGTH STEEL TUBULAR COLUMNS

Progress Report, AISI Project No. 187

by

A. Ostapenko and S. X. Gunnelman

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1. INTRODUCTION AND PROPOSED PROGRAM

Tubular members are used in the construction of offshore oil drilling platforms, elevated storage tanks, light poles, etc. Design of such members, however, is handicapped by the discrepancies between the current design recommendations for predicting local buckling especially when the tubes are fabricated of high strength steels. Of particular interest are members whose diameter-to-thickness ratio is such that local buckling can be expected in the range between the proportional limit and the yield stress. Local buckling in this range is influenced by many parameters which are very difficult or impossible to take into account analytically. Some of these are residual stresses, out-of-roundness, location of the weld seam, and local imperfections. Thus it is necessary to conduct tests in order to establish more accurate guidelines for the development of practical design rules.

Some work has been done in this area for manufactured tubes and for tubes fabricated of mild structural steel, but essentially no work has been done on tubes fabricated by the cold rolling and welding of high strength steels. The uncertainty of the local buckling strengths of fabricated tubes...
is reflected by the wide variation among the currently available rules shown in Fig. 1.* The ordinate is the ratio of the local buckling (critical, wrinkling) strength to the yield stress, and the abscissa is the non-dimensional parameter $\alpha = \frac{E_t}{F_y}D$ which is inversely proportional to $D/t$. This figure shows most of the available test results and the following curves which have been recommended for design**:

- Donnell & Wan
- Plantema
- AWWA
- AISI
- "Fitted Curve" (CRC)
- Marshall
- DNV (Det Norske Veritas, 1973, Amended).

Of particular interest are the AISI (2) and Marshall (3) curves since these are the ones promoted by AISI and API for practical use in the design of fabricated tubular members in this country. The disagreement between these curves is rather substantial especially in the range of $F_c / F_y = 0.5$ to $0.8$. The optimistic Amended 1973 DNV curve, recommended for offshore construction by Det Norske Veritas, makes the range of uncertainty even more dramatic; for example, the difference in $F_c / F_y$ between the DNV and Marshall curves for $\alpha = 4.0$ ($D/t = 150$ when $F_y = 50$ ksi) is 25%.

*Figure 1 is a modified version of Fig. 10.8 of Ref. 1
**There are more curves in practice, such as the CB&I curve. These generally fall within the extremes of the curves shown. Although the curves are shown nondimensionalized with respect to the yield stress, a direct comparison between them is sometimes ambiguous since some of them were originally developed as allowable stress curves for a particular grade of steel.
The purpose of the proposed research program is to investigate the range of stresses above the proportional limit experimentally and theoretically in order to establish a more conclusive basis for consideration of local buckling of fabricated, high-strength steel, tubular columns. The first part of the program was to consist of testing four specimens within this range. Two values of the non-dimensional parameter \( \alpha \) were selected, 6.7 and 4.0, which respectively correspond to \( \frac{D}{t} = 90 \) and 150 for \( F_y = 50 \) ksi. Two grades of steel were selected: A572 (Grade 50) and A633 (Grade D). Both steels have 50 ksi nominal yield stress. The proposed dimensions of the four test specimens and other parameters are listed in Table 1. The comments below the table give the specifications for specimen fabrication.

Progress of this work has been marked by success in the acquisition of the material for the test specimens, but there have been some complications with fabrication. It was found that the A633 steel plate contained rolling laminations which would have adversely affected the behavior of the test specimens and thus the plate had to be replaced. This introduced an unforeseen delay in the fabrication of the test specimens, and it was decided to fabricate and test A572 specimens first and the A633 specimens later. At this time, the A572 specimens (P1 and P3) have been fabricated and tested, and the fabrication of A633 specimens (P2 and P4) is in progress. Presented in this progress report are the description of the fabrication and testing procedures for the A572 specimens, the method of measuring welding residual stresses, the test results, and a proposal for future work.
2. TEST SPECIMENS

2.1 Gross Plates and Material Properties

The material was selected to be of one piece of plate for each grade of steel so that the same material properties would exist in specimens P1 and P3, and P2 and P4, respectively. Each plate measured 12 by 20 feet. The large and small specimens were cut from their respective plates as shown in Fig. 2. The smaller remaining rectangular plate was used for the tensile coupon tests to determine material properties. Immediately upon delivery of the plates, three tensile coupons were cut out as indicated in Fig. 2 and tested. The obtained values of $F_y$ are shown in Col. 3 of Table 2.* Although the static yield stress $F_y = 46.29$ ksi for A572 plate is less than 50 ksi and this lead to $\alpha = 7.51$ for specimen P1 rather than the planned $\alpha = 6.7$ (see Table 1, Col. 8), it was impossible to modify the specimen geometry since the plates were already cut.

2.2 Fabrication of Test Specimens

A typical test specimen is shown in Fig. 3.

The process of fabrication was intermeshed with the steps needed for measuring residual stresses. The general sequence was as follows:

1) Cutting the gross plate.

2) Layout of gage lines for residual stress measurement and drilling of target holes (In the Laboratory).

*The initially delivered A633 plate showed a consistent yield stress level but a very short plastification range. This was found to be due to the rolling laminations in the plate which caused premature fracturing of the coupons. In consultation with some task force members a decision was reached to reject this plate and the supplier agreed to replace it without cost. Table 2 gives $F_y$ of the replacement plate used for the fabrication of test specimens P2 and P4.
3) Survey of the plate surface in the area of residual stress measurements. (Lab)

4) First measurement of residual stress gage lines. (Lab)

5) Repetition of steps (2) to (4) for the other side of the plate.

6) Rolling of the plate into a tube. (In the fabrication shop)

7) Measurement of residual stress gage lines on both surfaces, inside and outside. (Shop)

8) Welding of the tubes. (Shop)

9) Machining the ends flat and square. (Shop)

10) Measurement of residual stress gage lines. (Shop or Lab)

The steps pertaining to the fabrication itself are (1), (6), (8), and (9), and the tolerance requirements and the types of weld are given in the notes of Table 1. The cutting of the gross plate (Step 1 above) was done by shearing rather than by burning in order to avoid introduction of additional residual stresses.

In making the tubes, the plates were first prebent about 12 in. from each end in a press rig and then rolled on a three-roll machine.

Some difficulties were encountered in the fabrication of the first two specimens, P1 and P3 because the shop personnel had to adapt their procedures to working with this relatively thin material (5/16 in.). The tubes had to be rolled several times to achieve the desired out-of-roundness and the larger tube, Specimen P3, had to be rerolled after welding in order to correct the out-of-roundness introduced by the
welding shrinkage (however, no rolling was done over the weld itself so that the welding residual stresses were preserved). A special procedure had to be developed for machining the ends of the specimens flat and square in order to avoid any welding on the specimen for the purpose of holding it in position during the machining process.

Dimensions of test specimens P1 and P3, as fabricated, are given in Table 2.

Careful notes were taken at all stages of fabrication in order to be able to have a better understanding of the specimen behavior during testing.

2.3 Measurement of Residual Stresses Due to Welding

Only the gross longitudinal residual stresses caused by welding the seam are determined in this pilot program. Thus, the gross residual stresses produced in the plate by the manufacturing process are neglected. A comparative study conducted on stiffened plate panels has shown that the latter stresses are relatively small (less than 1 ksi) (4). The residual stresses developing during cold-rolling should be quite substantial, up to \( F_y \) in the circumferential and one-half \( F_y \) in the longitudinal directions, but they vary through the wall thickness and more specialized techniques are required to determine them (see Dr. W. F. Chen's API Project). Since these stresses do not change around the circumference, they should not affect the location of the first local buckles relative to the weld seam as would the gross longitudinal stresses although they may have an effect on the intensity of the buckling stress.
The steps of the general fabrication sequence listed in Art. 2.2 pertaining to the measurement of residual stresses are steps (2), (3), (4), (5), (7) and (10). Figure 3 shows the general layout of the gage lines and target holes on a test specimen. The gage section of 10 in. was chosen to be 24 in. from the end of the specimen so that there would be sufficient distance from one end not to allow a relaxation of the residual stresses and the section could be conveniently reached for readings on the inside surface.

The layout of the gage lines and drilling of the target holes was made on the flat plate (Step 2). As shown in Fig. 4, a typical target hole has a countersunk shoulder which seats the tip of the gage. In this way the reference points (the shoulders) are made very uniform and are not subject to easy mechanical damage during handling and rolling as they would have been without countersinking. Protection against rusting was provided by painting the holes with a silicon solution. This has proven to be a very simple and effective means.*

The distance between the target holes on each gage line was measured with a Whittemore Gage. Great care was paid to position the gage perpendicularly to the plate surface, and, to achieve better accuracy, several readings were taken by repositioning the gage (Step 4). The effect of ambient temperature was taken into account by making

*Readings made on the protected holes, even at long time intervals, showed very good repeatability. On the other hand, some sample holes allowed to rust only slightly were found to have their readings altered significantly.
intermittent control readings on a temperature insensitive reference bar made of Invar.

The plate surface was surveyed to determine its out-of-planeness so that the changes in gage lengths due to the subsequent straightening out during fabrication could be taken into account (Step 3). A polynomial finite difference surface approximation was used for the computation of the curvatures and length changes from the surveyed points. (Surveying was made for both sides of the plate since the support conditions could have changed somewhat due to a different support pattern being used on one side than was used on the other side.)

This procedure of readings was repeated for the other plate side. (Step 5)

The next set of readings was made in the fabrication shop after rolling the tubes but before welding (Step 7). Strictly speaking, this set of readings should give the same results as the readings on the flat plate before rolling corrected by the survey data. The only obvious new effect was the ovalization of the originally round holes, and the intent was to establish the error if any. (This study has not yet been completed.)

The final set of readings was made after the specimens were welded (before or after machining of the ends depending on the convenience of the time schedule). (Step 10)

The residual stress due to welding for a particular gage line (pair of holes) was then computed from
where \( \sigma = \) Residual stress

\[ \sigma = \frac{L_A - L_B}{L_B} E \]  

(1)

\( L_A \) = Distance between holes after welding

\( L_B \) = Distance between holes before welding*

\( E \) = Modulus of elasticity \( (E = 29.5 \times 10^3 \text{ ksi was used}) \)

The resultant residual stresses are plotted for Test Specimens P1 and P3 in Figs. 5 and 6, respectively. The plots are made with respect to an unfolded circumferential line centered on the weld seam and ending at a line located directly opposite the weld seam. A plausible residual stress distribution representing the average between the stresses measured on the inside and outside surfaces is shown by the curves. Actually, the averages were approximately adjusted to make the integral of residual stresses in the circumference and the moments about both axes of the cross section equal to zero.

The residual stress patterns of the two specimens are quite similar, and only the pattern for Specimen P1 in Fig. 5 will be discussed in detail. A narrow tension band of about 3-4 inches in width reaches and exceeds the yield stress**. Then, the stresses change to a compression band.

*Data from measurements on the flat plate (Steps 3, 4 and 5) could be also used, but the computations have not yet been completed.

**Although no measurement of this portion could be made by the method used, previous research, the requirements of equilibrium, as well as current test observations, substantiate it.
approximately 13 inches wide with a maximum of 10.5 to 11 ksi. Next, in a diminishing wave pattern, the stresses reverse back to tension of about 1 ksi intensity and then again to compression. The pattern for the larger specimen, P3, differs somewhat in the stress intensities in the respective waves and in the fact that the wave pattern in this longer circumference has one more wave of tension.

Of primary concern are the compression bands immediately adjoining the tensile band at the weld since they were expected to have significant influence on local buckling.

3. TEST SETUP AND INSTRUMENTATION

Figure 7 shows a schematic arrangement for testing the tubular specimens. The test specimen is seen to be standing on the machine pedestal. Between the end of the specimen and the pedestal is a steel base plate for the distribution of high bearing stresses and a thin layer of copper. The copper sheet is intended to accommodate local imperfections in the surface of the base plate and/or in the machined end of the test specimen and thus to provide uniform end stress. The same arrangement is used at the top where the load from the head of the testing machine is applied to the specimen through a base plate and a copper sheet. The head has a mechanism for controlled tilting, and, by careful adjustment, this mechanism allowed the application of a practically concentric load.

The instrumentation consisted of mechanical and electric-resistance strain gages. Four longitudinal mechanical dial gages located at the
corners of the pedestal base, as shown in Fig. 7, were used to determine the displacement of the machine head relative to the pedestal and thus the overall shortening of the test specimen. The lateral deflection of the specimen wall relative to the ends of the specimen was measured by means of a special movable dial gage rig as shown in Fig. 8. The dial gages are permanently attached to the rig frame which was placed alternately at twelve locations around the circumference of the test specimen for each load increment. The bottom end of the rig touched the specimen wall and the top end was held against the specimen by means of an electromagnet. If local buckles had appeared between the fixed dial gages of the rig and/or between the gage lines, a movable dial gage would have been applied between the surface of the specimen and the vertical bar of the rig.

The original and subsequent geometry of the specimen ends was determined by measuring the gap between the specimen wall and the edge of a circular cutout in a Masonite plate (labeled Masonite ring in Fig. 7) attached to the base plate at each end of the specimen. The diameter of the cutout was made approximately four inches larger than the nominal diameter of the test specimen thus providing a two-inch gap which was convenient for measurements by means of calipers. This gap was also adequate for the placement of the dial gage rig.

The layout of the electric-resistance strain gages can be seen in Fig. 9. There were outside and inside longitudinal gages at four diametrically opposite locations at the top and at the mid-height as well as four outside transverse gages at the mid-height. The purpose of the electric resistance strain gages was dual -- first, to serve in the
alignment of the specimens, that is, in the centering of axial load and, secondly, to provide an alternate means for determining longitudinal deformations. The combination of the longitudinal and transverse gages at mid-height provided a source for analyzing wall deformations in addition to the transverse deflection readings from the dial gage rig.

4. TESTING PROCEDURE AND RESULTS

4.1 Testing Procedure

The alignment of the specimens in the testing machine was performed by applying a series of load increments up to 35% of the estimated failure load. Only the longitudinal strain gage readings were taken during alignment. When, after an initial non-linearity due to seating disturbances (slight unevenness of the base plate, dirt, and squashing of the copper plate), the strain increments at the four circumferential locations stabilized and the degree of the needed head tilting was determined, the load would be taken off and the tilting adjustment made. This process was repeated until the stabilized strain increments were in acceptably close agreement indicating the absence of load eccentricity.

The actual testing started by applying a load of 20 kips and attaching the four longitudinal dial gages (see Fig. 7). This then was used as the initial reference condition for the readings of all gages. At this point also, the measurement of the gap between the specimen end and the Masonite rings was made. The testing procedure for the two specimens was the same except that the load increment for P1 (28.2 in. dia.) were 50 kips and for P3 (47 in. dia.) 200 kips.
4.2 Test Results and Discussion

Flaking of the whitewash painted on the test specimens prior to testing gives a visual indication of yielding. For specimen P1, the first yield lines were observed at approximately 50% of the maximum load. Just beyond this point, P1 showed an increasing nonlinearity in its overall axial deformation. The spread of yielding became more intense in the area of the compressive residual stress bands near the weld seam than at any other location around the tube. Finally, just prior to local buckling, the yielding intensified at the top end where the buckling was about to occur.

For specimen P3, the first yield lines were observed at approximately 80% of the maximum load. The spread of yielding, in this case, was rather general around the circumference of the tube, but it was concentrated in the middle third of the tube length. Surface yielding in the buckled zone of P3 developed only when the buckling actually took place.

The ultimate capacity was reached in both specimens immediately after the formation of the ring bulges at the top end in P1 and at the bottom end in P3. The initial buckling process was relatively sudden. Following the ring bulge formation, the second phase of buckling set in with large checkerboard (lobular) buckles gradually emanating from the bulges. In turn, this checkerboarding caused the tube wall to break friction with the copper sheet (at the buckled end) and to slide alternately inwards and outwards around the circumference. This wall movement most probably affected the post-buckling behavior of the tubes.
Figures 10 and 11 show the two specimens after testing. Surprisingly, both specimens exhibit the same type of buckle deformations although P3 had a D/t = 142 and P1 only a D/t = 85. P3 was actually expected to develop checkerboard buckles in the middle portion, and the spread of yielding in this specimen indicated that the tube may have wanted to buckle there, but the bulging at the end apparently took over.

In both specimens, no yielding occurred in the narrow bands adjoining the weld which corresponds to the high tensile residual stress zone shown in Figs. 5 and 6. The photograph of Fig. 10 clearly shows this non-yielding zone for specimen P1 between reference lines 11 and 12. Although residual stresses affected the surface yielding of the specimens, it appears they had no influence on the initiation or distribution of the local buckles. Nor apparently did the initial imperfections have any effect. This is particularly notable for specimen P3 which had a flattened-out portion near the weld due to an inaccurate initial crimping of the plate during rolling.

Figure 12 depicts the test behavior of the specimens via the plots of the overall axial strain vs. average stress. The most remarkable result is that in spite of the quite different D/t ratios, both specimens attained essentially the same ultimate stress and this was very close to the yield stress (Table 2 shows $P_E / P_y = 0.998$ for P1 and 0.989 for P3).

Although the ultimate stress of the two specimens was essentially the same, the post-ultimate behavior was very different as can be seen
in Fig. 12. Whereas specimen P1 with D/t = 85 had an extended gradual reduction of the axial capacity, specimen P3 with D/t = 142 had a very rapid dropoff. For example, at the strain of $5 \times 10^{-3}$ in./in., the capacity of P1 was reduced by only about 10% from the ultimate while that of P3 was reduced by more than 55%. This difference in behavior may be controlling in establishing factors of safety (or load factors) and in consideration of energy dissipating characteristics.

The ultimate strengths of the test specimens are also shown non-dimensionally in Fig. 1. P1 falls at the yield stress and agrees well with the more optimistic curves (AWWA and DNV). P3, having practically the same strength as P1, shows considerably greater capacity than the majority of design curves.

At present, no conclusive explanation of the higher-than-expected capacity of specimen P3 can be offered. One explanation could be that the yield stress affects the local buckling stress differently than in a direct proportion as has been assumed in the development of the non-dimensional parameters of Fig. 1. However, more test data on high strength steel tubes is needed to arrive at a more accurate relationship. It is also possible that the increase in the yield stress due to coldworking in the process of fabrication may account for the apparent higher strength since specimen P3 was subjected to more rolling operations than P1 and the reference yield stress for nondimensionalizing was obtained from flat plate coupons. (This idea is being investigated by hardness testing; also tensile coupons will be cut out from the test specimens at a later date and tested.)
5. **FUTURE WORK**

Future work is planned to consist of the completion of the tests originally planned for the first year (remaining Specimens P2 and P4, see Tables 1 and 2 and Fig. 13) and of the new work proposed for the second year.

The following new work is proposed:

1. **Retesting Specimens P3 (and possibly P4) of the First-year Program**

   Since the buckles of Specimen P3 extend only over a short length, it is proposed to cut it off and to conduct another test on the remaining undeformed portion. If the forthcoming test on Specimen P4 exhibits limited buckling at one end similarly to Specimen P3, it will also be shortened and retested. This way additional experimental points will be obtained in the doubtful range of $D/t = 150$ with a minimum of effort. The geometrical and material parameters of the modified specimens P3A and P4A are listed in Table 3-1 and the tentative location of the test results relative to the nondimensional parameter $\alpha$ is shown in Fig. 13.

2. **New Tests proposed for the Second Year**

   Three new specimens are proposed to be tested. Two of these will be made of steel with $F_y = 60$ ksi (P5 and P6) and one of steel with $F_y = 36$ ksi (P7). These $F_y$ values were chosen to more accurately pinpoint the effect of higher yield stress (60 ksi) and, by using $F_y = 36$ ksi, to "anchor" the results to the Wilson tests and to use the grade of steel most common in present offshore construction practice. The proposed dimensions and other
parameters are given in Table 3-2. These were selected so that the test results would more completely cover the range of parameter \( \alpha \) that is of interest to this project. The intended \( \alpha \)-location of test values for \( P5, \ P6 \) and \( P7 \) is shown in Fig. 13 together with the tests already conducted (\( P1, \ P3 \) and \( P2^* \)), the remaining test \( P4 \), the modified tests \( P3A \) and \( P4A \), and the tests made by Wilson on fabricated tubes (5). Specimen \( P6 \) with \( \alpha = 2.61 \) falls to the left of the other tests to more definitely clarify whether the unexpectedly high buckling value of \( P3 \) was a "freak result" or a logical effect of the high yield stress, among other influences. Specimens \( P5 \) and \( P7 \) more or less fill in the gap between other tests. More importantly, although these two specimens have essentially the same \( \alpha = 5.6 \), their \( D/t \) and \( F_y \) values are very different; \( D/t = 87 \) vs. 147 and \( F_y = 60 \) ksi vs. 36, respectively for \( P5 \) and \( P7 \). Thus, the results should help in arriving at a more accurate parameter than \( \alpha = \frac{E t}{F_y D} \) to be used in the design formulas for fabricated tubes.

3. Analysis of the Test Data Obtained and Preparation of Guidelines for Design Recommendations

This theoretical work will consist of the following:

a) Reduction of the test data and description of the experiments.

b) Analysis of the results. No extensive theoretical analysis can be done within the time available, but a correlation will be made with some simple analytical approaches and other experimental results.

*Test \( P2 \) has been just completed.
c) Preparation of a tentative recommendation for consideration of local buckling in fabricated high-strength tubes. This recommendation is envisioned in the form of a formula or a curve.

d) Preparation of reports describing the work completed.

6. REFERENCES


2. AISI; SPECIFICATION FOR THE DESIGN OF COLD-FORMED STEEL STRUCTURAL MEMBERS, 1968 Edition, AISI, New York, Art. 3.8


5. Wilson, W. M., TESTS OF STEEL COLUMNS, Univ. of Illinois Eng. Exp. Station Bulletin No. 292, 1937 (This is also Ref. 10.113 of Ref. 1)
7. TABLES AND FIGURES
TABLE 1 Proposed Test Specimen Data

<table>
<thead>
<tr>
<th>No. of Specimens</th>
<th>Steel</th>
<th>Col. Dia., D (in.)</th>
<th>Plate Thick., t (in.)</th>
<th>Col. Length, L (in.)</th>
<th>D/t</th>
<th>α</th>
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<td>90</td>
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<td>5/16</td>
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<td>90</td>
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<td>A633</td>
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<td>5/16</td>
<td>120</td>
<td>150</td>
<td>4.0</td>
<td>Butt</td>
</tr>
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</table>

* If the yield strength of the material as received is appreciably greater than 50 ksi, then the geometry of the specimen will be revised to maintain a value of $\alpha = 6.7$, where $\alpha = \frac{E_t}{F_y}$.

Each specimen is to be rolled from one piece of flat plate (one longitudinal and no transverse welds).

Specimen Fabrication

a) Tolerance

The following tolerances were established for all four specimens:

1) Out-of-roundness shall not exceed 1/4 in. (based on provisions of API Code, Section 2b). Both ends and center of column to be checked.
2) Out-of-straightness shall not exceed 1/8 in. in any 10 ft or 1/16 in. in any 5 ft (API Code, Section 2b).
3) Local deviations, such as dents, shall not exceed 1/16 in. in any 6 in. If this requirement proves to be too severe for fabrication, then 1/8 in. in any 6 in. will be acceptable.

b) Welding

All welds shall conform to the provisions of AWS, D1.1. Welding shall be done using the submerged arc process. The fabricator shall use the prequalified joint as specified in AWS, D1.1.

c) Machining

Both ends of each specimen are to be machined flat and square.
Table 2 Actual Test Specimen Data

<table>
<thead>
<tr>
<th>No.</th>
<th>Steel</th>
<th>Coupon $F_y$ (ksi)</th>
<th>Measured</th>
<th>Exper. $P_E$ (k)</th>
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$\alpha = \frac{E_t}{F_y D}$  
$E = 29.5 \times 10^3$ ksi  
$D = O.D. - t$
Table 3 Test Specimens Proposed for Second Year

<table>
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<tr>
<th>No.</th>
<th>Steel</th>
<th>Coupon O.D. (in.)</th>
<th>O.Dia. Thickn.</th>
<th>Length L (in.)</th>
<th>D/t</th>
<th>α</th>
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1) Modified Test Specimens

| P3A | A572 Gr50 | 46.29 | 46.85 | 0.3287 | 90 | 141.53 | 4.50 | Modified P3 |
| P4A | A633 Gr D | 50.75 | (47)  | 0.3164 | 90 | (145.3)| (4.0) Modified P4 (Note 1) |

2) New Specimens

| P5  | Note 2 | 60   | 28.2  | 5/16  | 80 | 87   | 5.65 | Note 2 |
| P6  | "      | 60   | 47.0  | 1/4   | 120| 188  | 2.61 | "      |
| P7  | A36    | 36   | 47.0  | 5/16  | 120| 147  | 5.57 | "      |

\[ D = O.D. - t \quad \alpha = \frac{E}{F_y} \cdot \frac{D}{t} \quad E = 29.5 \times 10^3 \text{ ksi} \]

Notes:

1. Values in parenthesis ( ) depend on the actual measurements of Specimen P4 after fabrication.

2. Steel designation and welding procedure to be established by the Task Force of the AISI Project 187.
Note

Equation and Ref. Numbers in this Fig. are those of Chapter 10 of Ref. 1.

Fig. 1 LOCAL BUCKLING CURVES
(a) Layout of A572 Steel Plate

(b) Layout of A633 Steel Plate

Fig. 2 Plate Cutting Layout
WELD SEAM

SEE TABLE 2 FOR DIMENSIONS
D AND L

FIG. 3 LOCATION OF RESIDUAL STRESS
MEASUREMENTS
Fig. 4 Detail of Target Hole for Residual Stress Measurements
Fig. 5 Gross Residual Stresses in P1
Fig. 6 Gross Residual Stresses in P3
Fig. 7  Test Setup
Fig. 8 Location of Strain Gages
Fig. 9  Specimen Pl in Testing Machine and Dial Gage Rig
Fig. 10 Buckled End of specimen P1

Fig. 11 Specimen P3 after Test
Fig. 12 Test Behavior of Specimens
Avg. Stress vs. Avg. Strain
Fig. 13  AISI Project No. 187 Tests  
Completed and Planned