RESULTS OF
LOCAL BUCKLING TESTS ON
A-36 TUBULAR SPECIMENS

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by
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1. INTRODUCTION

Results from the tests on tubular specimens fabricated by cold-rolling and welding from 50 ksi steel were used to develop a formula for predicting the local buckling stress of such members (1).* There was acceptably small scatter between the individual test results and many tests on specimens made from other steels seemed to confirm the proposed formula.

However, there have been no consistent test results on tubular members made of 36 ksi steel although this is the most widely used material in offshore construction. The purpose of the tests described in this report is to investigate the local buckling strength of fabricated tubular columns made of 36 ksi steel (ASTM designation A-36) and propose a method which would be suitable for use by designers. This report presents a brief, preliminary summary of the test results on four tubular specimens.

A supplementary test was conducted on a 100 ksi specimen which was made from a specimen previously tested on another research project (2).

*See References.
2. DESCRIPTION OF TEST SPECIMENS

The dimensions and other physical parameters of the tubular specimens tested are listed in Table 1. Test results are shown in the last column. The specimens were all short, the slenderness ratios being less than nine, in order to preclude the effects of overall column buckling.

The specimens were fabricated by cold rolling a flat plate in a pyramid three-roll bending machine and then welding the joint with a multipass submerged arc weld. After welding, the tubes were rerolled in order to reduce the welding distortions. Steel end rings were welded to each end of the specimens to facilitate application of a uniform, concentric load.

Specimen P11 was made from Specimen P9 which had been tested in another project at Lehigh University(2). Specimen P11 was prepared for the retest by removing the length of the tube (approximately 19 inches) that contained the buckles by flame cutting, straightening some out-of-roundness remaining from some of the buckles, and rewelding the end ring to the new specimen.

The yield stresses for Specimens T1 to T4 were obtained as the average static yield stress of three standard eight-inch gage tensile coupons cut in the longitudinal direction of the specimens. A summary of the individual coupon yield stresses and their definitions can be found in Table 2.

The coupons were tested in a 120,000 pound Tinius-Olsen testing machine at a crosshead speed of 0.025 inches per minute. This translates to a strain rate of approximately 51 microinches/microinches/sec. The upper dynamic yield stress, \( F_{ydu} \), was the stress at which the load began to decrease. The lower dynamic yield stress, \( F_{ydl} \), was determined as the average stress obtained by the 0.2% offset and the 0.005 strain methods.
Within the initial 0.010 strain there were three locations at which the crosshead of the testing machine was stopped and load was permitted to stabilize at a lower level. The average of these three stable stresses under zero strain rate was taken as the static yield stress, \( F_{ys} \).

The static yield stress, \( F_{ys} \), of Specimen P11 was assumed to be that of the original Specimen P9 (2).

Measurements were taken to determine geometric imperfections in all specimens for initial out-of-straightness and initial out-of-roundness. These measurements are currently being analyzed. One result of this analysis may be an adjustment of the specimen diameters, and consequently, of the values for D/t ratio, \( \sigma \), and \( c \) shown in Table 1. The diameter reported in Table 1 is the mean diameter calculated from the circumferences measured at the ends of the specimen.
3. TEST SETUP AND INSTRUMENTATION

A schematic presentation of the test setup is shown in Fig. 1 and the actual setup is illustrated in Fig. 2. The specimen stands between the loading head of the testing machine and the machine floor. A layer of gypsum grout ("Hydrostone") between each of the specimen's end rings and the testing machine components assured the transmission of a uniform load to the specimen.

The instrumentation consisted of both mechanical dial and electric-resistance strain gages. Four mechanical gages at the corners of the machine head were used to measure the longitudinal shortening of the specimen. Two additional mechanical gages were attached between the end rings close to the specimen wall and located diametrically opposite one another. Three electric-resistance strain gages located at third points around the circumference and at approximately midheight of the specimen served as a check on the concentricity of the load and as an alternate means for determining longitudinal deformations. Whittemore strain gage readings between the residual stress target holes were taken periodically in specimens T2 and T4 to further check longitudinal deformations.

The lateral deflection of the specimen wall relative to its ends was measured by means of the special movable dial gage rig shown to the right of the specimen in Fig. 2. The rig consisted of eight mechanical dial gages attached to an aluminum truss. The bottom end of the rig sat on the end ring and touched the specimen wall, and an electromagnet held the top of the rig against the specimen. Readings were taken at nine to thirteen locations around the circumference of the tubes by successively repositioning the rig.
4. RESIDUAL STRESSES

Longitudinal residual stresses caused by welding were measured in specimens T2 and T4. The residual stresses induced by the original cooling of the plate and by the cold-rolling during fabrication were not measured. However, they can be assumed to be constant around the circumference and thus should have no effect on buckle location.

Residual strains were determined from the change in the distance between pairs of target holes. The holes were drilled into the inside and outside surfaces of the specimen wall after the plate had been rolled but before it was welded. The holes were located as shown in Fig. 3, approximately 10 inches apart and 30 inches from one end of the specimen. The inside and outside pairs of holes were located opposite each other, and were circumferentially spaced closer near the weld in order to obtain more readings in the more highly stressed region. The distances between the pairs of holes were measured after rolling but prior to welding the longitudinal seam and then again after welding. A Whittemore mechanical strain gage with a 10-inch gage length was used.

Welding residual stress distributions for Specimens T2 and T4 are shown in Figures 4 and 5, respectively. For the purpose of presentation, the stress distribution around the circumference of the specimen is shown on a tube visualized to have been cut, unfolded, and laid out flat. The vertical line through the center corresponds to the weld seam, and the right and left edges correspond to the line which is diametrically opposite the weld. The distance from the weld is given by the abscissa, and the stress is given by the ordinate. The averages of the stresses on the inside and outside surfaces are connected with a smooth curve.
The band of compressive stress extends from approximately 1 to 25 inches on either side of the weld. Beyond this, the magnitude of the stress diminishes and tends to fluctuate between tension and compression in a wave-like pattern. The average maximum compressive stress was approximately 8 ksi for Specimen T2 and 10 ksi for T4.

The band of compressive stress appears to be slightly wider than the 8 to 12 inch band determined in the previous tests at Lehigh University and the maximum compressive stress is slightly lower than the average 12 ksi stress determined then (2,3). The 36 ksi nominal yield stress of the material as opposed to the 50 ksi nominal yield of the previous tests is a likely contributing factor to these differences.

As in previous tests (2,3), no correlation could be detected between the residual stress pattern and the location or pattern of buckles.
5. TEST RESULTS

The load-deformation curves for Specimens P11 and T1 to T4 are shown in Figures 6 to 10, respectively. The load is given as the average axial stress nondimensionalized with respect to the static yield stress of the material (ordinate) and deformation is given as the axial longitudinal deformation determined from the four corner dial gages (abscissa). No deflection comparisons have been made as yet based on readings from the other two dial gages or from the electric-resistance strain gages.

All specimens followed a basically linear load-deformation path to a value of approximately 0.8 $F/F_{ys}$. All specimens except T1 deviated only slightly from linearity up to the attainment of maximum load. As shown in Figure 7, Specimen T1 yielded extensively, and showed a larger nonlinear region before reaching its ultimate load. Specimens T1, T2, and T3 reached ultimate capacities near or slightly above the yield capacity.

For all specimens except T4, the ultimate load was reached during a loading increment. This indicates that perhaps a stress closer to the lower dynamic yield stress ($F_{ydl}$) rather than the static yield stress, $F_{ys}$, may be a more appropriate nondimensionalizing parameter.

For Specimen T4, the loading had been stopped and readings were being taken when the load suddenly started to drop. Thus, the static yield stress, $F_{ys}$, is completely appropriate for this case.*

In Specimen P11, the ultimate load was accompanied by sudden buckling with an explosive bang. Specimens T1 through T4 all buckled gradually,

*Coordination between the particular testing conditions and the maximum (ultimate) load may explain some of the inconsistencies observed in the research that has been reported.
first through the formation of a ring bulge at one end (both ends for T1, although one eventually disappeared) and then, the formation of the alternating ("checkerboard") buckled pattern. A typical ring bulge is shown in Fig. 11.

As shown in Figures 6 to 10, the postbuckling region of all specimens indicates load stability at approximately 15-25% of the ultimate capacity. Continued load application resulted in the specimen wall folding over on itself, as indicated in Figure 12, thus enabling it to carry slightly increased load until a second set of buckles formed. Specimen T4 was the only specimen whose walls cracked during the postbuckling load application.
6. COMPARISON WITH DESIGN CURVES

The nondimensional buckling stresses for all five specimens are plotted against parameter $\alpha$ in Figure 13 together with several other test results and some current design curves. Specimens T1 and T3 fall above and P11 falls to the left of all of the ultimate design curves. Specimen T4 falls on the planemtha curve while T2 falls near a group of curves.

Figure 14 shows the stresses plotted with respect to the design curve developed at Lehigh University and based on the buckling tests of 50 ksi specimens (1). A different parameter, $c$, is used here for the abscissa. The test results seem to fall reasonably close to the curve, which was developed to pass through the previous results by a cubic least squares fit. The equation for the curve is

For $c < 0.07$

$$\frac{F_c}{F_y} = 38c - 480c^2 + 2000c^3$$

For $c \geq 0.07$

$$\frac{F_c}{F_y} = 1.0$$

where

$$c = 3\sqrt{\frac{E}{F_y}} \cdot \frac{1}{D/t}$$

Re-evaluation of some of the coefficients may lead to an improved fit which then could extend the application of the curve to tubes fabricated from 36 ksi steel. This and other possibilities will be explored before a recommendation is made for a method of computing the local buckling stress.
7. REFERENCES


## TABLE 1. SPECIMEN DATA

| No. | Steel  | Static $F_{ys}$ (ksi) | Measured |  |  |  |  |  |  |
|-----|--------|------------------------|----------|---|---|---|---|---|
|     |        |                        | $D$ (in.)| $t$ (in.) | $L$ (in.) | $\frac{D}{t}$ | $\alpha$ | $c$ | $\frac{F_c}{F_{ys}}$ |
| PII | A514   | 90.32                  | 60.34    | 0.258 | 77   | 232.8  | 1.40    | 0.029 | 0.826 |
|     | Type B |                        |          |       |      |        |         |      |      |
| T1  | A36    | 35.46                  | 30.01    | 0.389 | 80   | 77.06  | 10.79   | 0.122 | 1.048 |
| T2  | A36    | 29.58                  | 30.03    | 0.266 | 80   | 112.6  | 8.84    | 0.088 | 0.996 |
| T3  | A36    | 29.58                  | 38.10    | 0.266 | 120  | 142.9  | 6.97    | 0.070 | 1.039 |
| T4  | A36    | 29.58                  | 60.03    | 0.266 | 120  | 225.2  | 4.42    | 0.044 | 0.673 |
## TABLE 2. YIELD STRESSES

![Stress Diagram](image)

**STRAIN RATE** \( \approx 51 \text{ min}^{-1} \text{ sec}^{-1} \)

<table>
<thead>
<tr>
<th>COUPON</th>
<th>( F_{ydu} ) (ksi)</th>
<th>( F_{ydl} ) (ksi)</th>
<th>( F_{ys} ) (ksi)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>3/8” PLATE</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T11</td>
<td>39.66</td>
<td>37.01</td>
<td>35.20</td>
</tr>
<tr>
<td>T12</td>
<td>40.04</td>
<td>39.18</td>
<td>35.76</td>
</tr>
<tr>
<td>T14</td>
<td>41.42</td>
<td>38.51</td>
<td>35.43</td>
</tr>
<tr>
<td><strong>AVG.</strong></td>
<td>40.38</td>
<td>38.26</td>
<td>35.46</td>
</tr>
<tr>
<td><strong>1/4” PLATE</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T21</td>
<td>33.42</td>
<td>32.25</td>
<td>29.48</td>
</tr>
<tr>
<td>T22</td>
<td>34.00</td>
<td>32.33</td>
<td>30.01</td>
</tr>
<tr>
<td>T23</td>
<td>34.10</td>
<td>31.68</td>
<td></td>
</tr>
<tr>
<td>T24</td>
<td>35.01</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>AVG.</strong></td>
<td>34.13</td>
<td>32.09</td>
<td>29.61</td>
</tr>
</tbody>
</table>
FIG. 1. SCHEMATIC OF TEST SETUP
FIG. 2.  TYPICAL TEST SETUP
FIG. 3  RESIDUAL STRESS HOLE LOCATIONS
FIG. 4. RESIDUAL STRESSES IN SPECIMEN T4
FIG. 5. RESIDUAL STRESSES IN SPECIMEN T2
FIG. 6. AVG. AXIAL DEFORMATION IN SPECIMEN PII
FIG. 7. AVG. AXIAL DEFORMATION IN SPECIMEN TI
FIG. 8. AVG. AXIAL DEFORMATION IN SPECIMEN T2
FIG. 9. AVG. AXIAL DEFORMATION IN SPECIMEN T3
FIG. 10. AVG. AXIAL DEFORMATION IN SPECIMEN T4
FIG. II. TYPICAL RING BULGE
FIG. 12. BUCKLED SPECIMEN
Fig. 13. Lehigh Tests in Comparison with other Tests and Design Curves

Lehigh University Tests
University of Illinois Tests

$\phi$ Dia. = 0.771 m to 1.778 m
$\Theta$ Dia. = 0.254 m to 1.219 m

-- Lehigh Tests in Comparison with other Tests and Design Curves

\[ a = \frac{E_t}{F_y D} \]

$F_y$, $F_c$, $P_1$, $P_2$, $P_3$, $P_4$, $P_5$, $P_6$ $P_8$, $P_9$, $P_{10}$

Plantema
Donnell & Wan
(D = 0.0006)

Lehigh University Tests
University of Illinois Tests

$F_y$, $F_c$, $P_1$, $P_2$, $P_3$, $P_4$, $P_5$, $P_6$, $P_8$, $P_9$, $P_{10}$
Fig. 14. Plot of Test Results and Proposed Design Curve

\[ C = \sqrt[3]{\frac{E}{F_y}} \cdot \frac{1}{D/t} \]