LOCAL BUCKLING TESTS ON THREE
STEEL LARGE-DIAMETER TUBULAR COLUMNS

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ABSTRACT

Local buckling tests were conducted on three short, large-diameter tubular columns. The columns were fabricated by cold-rolling and welding, from 6.35 mm (½ in.) high-strength steel plate with a nominal yield stress of 345 MPa (50 ksi). The diameters were 1.20 m (47 in.), 1.53 m (60 in.) and 1.79 m (70 in.), and the diameter-to-thickness ratios (D/t) were 165 to 248. The average buckling stress was limited by the formation either of lobular buckles or of a simultaneous combination of lobular buckles with a ring bulge. The buckling stress values were from 0.814 to 0.941 of the yield stress. The buckling stress and strain, the type of initial buckling, and the post-buckling behavior were found to be functions of D/t. The location of the buckles did not appear to be affected either by the initial geometric imperfections or by the pattern of the longitudinal residual stresses caused by welding. In the post-buckling range the columns could dissipate energy at 15-25% of the buckling stress by the formation of successive sets of lobular buckles. Detailed description is presented of the testing technique and of the column behavior in the prebuckling, buckling and post-buckling ranges. These three tests, together with the five tests previously conducted by the authors (yield stress also = 345 MPa) gave local buckling stress values which, when plotted against D/t, formed a smooth curve with very little scatter. Present design rules were all found to be conservative with respect to these test results.
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1. INTRODUCTION

1.1 Background

Circular columns are equally resistant to buckling in all directions, and this is one reason why they are often used in structures subjected to three-dimensional loading such as offshore oil drilling platforms, elevated storage tanks, transmission towers, and light poles. Tubular members in these structures are mainly fabricated from the flat plate by cold-rolling into a cylindrical shape and welding the joint. The distinction of this fabrication method from the manufacturing in a mill by extrusion, electric resistance welding or spiral cold-forming is significant because fabricated tubes usually have greater geometric imperfections and different patterns and levels of residual stresses than manufactured tubes.

There is significant discrepancy between the present design rules used to compute the local buckling stress of tubular columns. The substantial disagreement between the test results and the classical theory and the wide scatter among the test points have been largely responsible for this discrepancy. The vast majority of tests have been performed on manufactured tubes made from thin gage aluminum or Mylar and very few tests on fabricated tubes made from steel, even though such members are widely used. It is not sound to extrapolate the test results on the

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manufactured tubes to fabricated steel tubes because of the differences between the two groups.

Of particular interest for engineering structures are fabricated members whose diameter-to-thickness ratio (D/t) is such that local buckling can be expected at stresses between the proportional limit and the yield stress. Some of the numerous parameters which are expected to influence buckling within this range are: residual stresses, out-of-roundness, out-of-straightness, and location of the weld seams. Since at the present time these factors are difficult or impossible to consider analytically, there is a need for more experimental studies.

1.2 Present Design Curves

The following current design curves used for local buckling are shown in Fig. 1: Donnell & Wan (5), AISI (American Iron and Steel Institute) (1), Plantema (8), API (American Petroleum Institute) (2), and DNV (Det Norske Veritas) (4). The ordinate is the ratio of the buckling stress to the yield stress ($F_c/F_y$), and the abscissa is the nondimensional parameter $\alpha$ which is inversely proportional to the D/t ratio and is defined by

$$\alpha = \frac{Et}{F_yD}$$

(1)

where $E$ is the modulus of elasticity, $t$ is the wall thickness, $F_y$ is the yield stress, and $D$ is the diameter of the tube (6).

Although the AISI and API curves are most widely used in the United States for design of fabricated members, they exhibit a rather substantial disagreement. The optimistic DNV curve makes the range of
uncertainty even more pronounced. For example, the difference in $F_c/F_y$ between the DNV and API curves is 40% for $\alpha = 3.0$ ($D/t = 200$ when $F_y = 345$ MPa [50 ksi]).

1.3 Previous Work

Results of most of the local buckling tests conducted on fabricated tubes which failed in the inelastic range are plotted in Fig. 1 (7,10,11). The test points shown represent a range of the $D/t$ ratios from 69 to 320 and of the wall thickness from 0.8 mm (0.031 in.) to 12.55 mm (0.494 in.). There is substantial scatter between the test results.

Initial imperfections have been most often designated as the cause of the discrepancies between local buckling test results. The methods of analysis which include the effect of initial imperfections are being developed, and a state-of-the-art discussion on this work is presented in Ref. 9. So far these methods have been largely limited to elastic buckling. Despite the advances in the analytical methods, no specific design recommendations can yet be made basing them on theory alone.

1.4 Lehigh Research/Program

The inelastic local buckling of five high-strength steel tubular specimens was investigated previously at Lehigh University (7). The diameter varied from 0.72 m (28 in.) to 1.22 m (48 in.), and the nominal thickness of all specimens was 7.9 mm (5/16 in.). These tests covered a rather limited range of $D/t$ from 85 to 151. To explore the effect of larger $D/t$, three additional tests were conducted, and their results are described here.
2. DESCRIPTION OF TEST SPECIMENS

2.1 Geometric and Material Parameters

A typical tubular specimen and the pertinent notation are shown schematically in Fig. 2. The dimensions and other parameters of the specimens are listed in Table 1. The outside diameter (OD) ranged from 1.20 m (47 in.) to 1.19 m (70 in.) as seen in Column 4 of Table 1, and the wall thickness for all three specimens was approximately 7.2 mm (0.28 in.) as shown in Column 5. The D/t ratios correspondingly fell between 165 and 248. The specimens were short, each having a length of 3.03 m (119 in.), and this resulted in slenderness ratios of less than ten in all cases.

The specimens were made from ASTM A572 steel with a nominal yield stress of 345 MPa (50 ksi). They were fabricated by cold-rolling flat plate in a pyramid three-roll plate bending machine and then welding the longitudinal joint. The submerged arc process was used to place a two-pass, single-vee groove weld seam as shown in Fig. 3.

2.2 Preparation of the Specimen Ends

The ends of the specimens had to be prepared so that the load could be applied uniformly and concentrically. A 127 mm (5 in.) wide by 25.4 mm (1 in.) thick steel ring was welded to each end of Specimens P5 and P6 with the specimens centered on the rings. The end ring at the top of Specimen P6 can be seen in Fig. 4. In the case of Specimen P7, however, the smaller-diameter allowed the ends of the specimen to be milled flat and square, and no end rings were needed.
2.3 Material Properties

Static yield stress values obtained from flat plate coupons at a zero strain rate were used in evaluating the test results. The plate coupons were made in accordance with the ASTM Standards (3), utilizing a 203.2 mm (8 in.) gage length. The yield stress values were taken as the average of 3 to 4 coupon tests, and they are listed in column 3 of Table 1.

3. INITIAL IMPERFECTIONS OF SPECIMENS

Two measures of geometric imperfections were considered: out-of-roundness and out-of-straightness. Local imperfections, such as indentations, are not discussed here since they were indetectably small.

The out-of-roundness at a particular cross section of a specimen is defined either by the absolute value of the difference between the maximum and minimum diameters

\[
\text{ABSOLUTE OUT-OF-ROUNDNESS} = \text{OD}_{\text{max}} - \text{OD}_{\text{min}}
\]

(2)

or by a relative value with respect to the mean diameter

\[
\text{OUT-OF-ROUNDNESS} = \frac{\text{OD}_{\text{max}} - \text{OD}_{\text{min}}}{\text{OD}}
\]

(3)

where \(\text{OD}_{\text{max}}\), \(\text{OD}_{\text{min}}\) and \(\text{OD}\) are the maximum, minimum and mean outside diameters. The out-of-roundness was determined for the top, the bottom, and the mid-height levels of each specimen, and the maximum relative values and their locations are listed in Columns 3 and 4 of Table 2.

The limits set by the American Petroleum Institute Standards (2) for the absolute and relative out-of-roundness of fabricated tubes are
6.4 mm (¼ in.) and 0.01, respectively. Specimen P7 exceeded both of these limits, but Specimens P5 and P6 only slightly exceeded the absolute value.

The out-of-straightness is defined as the maximum offset between a longitudinal straight line and the specimen wall in any 1.52 m (5 ft) length. In all three specimens the maximum out-of-straightness was on a line adjacent to the weld, and the values are given in Column 5 of Table 2. Even the largest value of 1.5 mm (0.059 in.) for Specimen P7 did not exceed the limit of 1.6 mm (1/16 in.) set by API (2).

A comparison was made between Specimens P5 to P7 and the previously tested specimens, but no specific relationship could be found between the magnitude of the initial imperfections and the specimen dimensions.

4. RESIDUAL STRESSES

The longitudinal residual stresses caused by welding were measured only in Specimen P5. The stresses varied with the distance from the weld and therefore could have affected the circumferential location of the local buckles. Since the circumferential residual stresses and the stresses due to original cooling of the hot-rolled plate are constant around the circumference, they should have had no effect on the location of buckles.

For the purpose of determining the longitudinal residual stresses in Specimen P5, target holes were drilled 0.254 m (10 in.) apart in the longitudinal direction on the inside and outside surfaces as shown in Fig. 5. The distance between these holes was measured before welding.
(but after rolling) and after welding. The residual stress was computed from the change in this distance.

The distribution of longitudinal residual stresses in Specimen P5 is shown in Fig. 6. For the purpose of presentation, the distribution around the circumference of the tube is unfolded and laid out flat. The distance from the weld is given by the abscissa, and the stress is given by the ordinate. The vertical line through the mid-point corresponds to the weld seam, and the right and left ends correspond to the line which originally was diametrically opposite the weld.

The band of greatest compressive stress extends from approximately 0.025 to 0.76 m (1 to 30 in.) on either side of the weld. Beyond this, the magnitude of stress diminishes sharply and swings between tension and compression in a wave-like pattern. The maximum compressive stress points are located at about 0.05 to 0.08 m (2 to 3 in.) from the weld, and the value is 103 MPa (15 ksi).

The residual stress pattern for Specimen P5 exhibits considerable similarity to the patterns found in two 0.71 m (28 in.) and two 1.19 m (47 in.) diameter specimens tested previously in the Lehigh program (7). The differences in the residual stresses of these five specimens can be attributed to the variation of the yield stress, the type of weld, and the wall thickness. However, a careful comparison of the pattern for Specimen P5 with the patterns for the other four, smaller-diameter specimens indicates that the maximum compressive stress was not affected by the diameter, at least over the range of the diameters tested.
5. TEST SETUP AND INSTRUMENTATION

5.1 Test Arrangement for Specimens P5 and P6

A schematic presentation of the test setup for Specimens P5 and P6 is shown in Fig. 7. The test specimen stands between the loading head and the floor of the testing machine. Steel rings were welded to both ends of these specimens to serve in the distribution of the load.

The instrumentation consisted of mechanical and electric-resistance gages. Four mechanical gages at the corners of the machine head were used to measure the longitudinal shortening of the test specimens as indicated in Fig. 7. The electric-resistance strain gages were located at the mid-height level in the longitudinal direction of the specimens, and they served as an alternate means for determining longitudinal deformations. They were mounted on the outside surface at three locations around the circumference.

The lateral deflection of the specimen wall relative to the ends of the specimen was measured by means of the special movable dial gage rig shown to the right of the test specimen in Fig. 8. The rig consisted of eight mechanical dial gages permanently attached to a trussed frame. The bottom end of the rig sat on the base plate and touched the specimen wall, while the top end was held against the specimen by means of an electromagnet. Readings were taken at eleven to thirteen locations around the circumference by successively repositioning the dial gage rig. The reference readings were made on a machined flat surface.

The original geometry of the specimen ends was determined (prior to placement of the specimen in the loading machine) by measuring the
gap between the end rings and a circle scribed approximately 100 mm larger than the outside diameter of the end rings. By also knowing the distance between the outside edge of the end ring and the tube wall, the out-of-roundness at the ends was determined. The geometry at the mid-height was obtained from the readings taken with the dial gage rig.

5.2 Test Arrangement for Specimen P7

A slightly different arrangement was used in testing Specimen P7. The schematic of the test setup for this specimen is shown in Fig. 9. The test specimen is standing between the loading head above and the machine pedestal base below. Between the end of the specimen and the pedestal base is a steel base plate for the distribution of bearing stresses. A thin copper sheet lies between the specimen and the base plate. The copper sheet was intended to accommodate local imperfections in the surface of the base plate and/or in the machined end of the test specimen. The same arrangement was used at the top of the specimen. A practically concentric load was achieved by careful adjustment of the machine head which had a mechanism for controlled tilting.

The use of mechanical and electrical gages was the same as for Specimens P5 and P6 except that the electrical gages also served in the alignment of the specimen.

6. TEST PROCEDURE

6.1 Alignment

The tests were conducted on a 5-million pound hydraulic Baldwin testing machine. The first phase of each test was the alignment of the specimen in the testing machine.
Two methods of alignment were used to account for the different conditions of the specimen ends. For Specimen P7, a practically concentric load could be applied by carefully adjusting the tilt of the loading head of the machine.

The procedure for Specimens P5 and P6 was different than for P7 since the tilting of the loading head was not sufficient for achieving a proper alignment because the steel rings at the ends of these specimens were not truly flat. Therefore, a layer of gypsum grout ("Hydrostone") was placed between the bottom steel ring and the test floor. The specimen was lowered, and the grout spread evenly under the weight. After the grout set, a layer was placed on the top steel ring and the machine head was lowered to spread this layer evenly. After hardening overnight, the grout could transmit the load uniformly to the specimen without any further adjustments. The leveling grout on the top steel ring of Specimen P6 is shown in Fig. 10.

6.2 Test Sequence

Following the alignment, the test began with the application of 90 KN (20 kips) of load and the attachment of the four longitudinal dial gages as shown in Figs. 7 and 9. The readings taken at this load were used as the initial reference condition for all subsequent readings.

Generally, load increments of 890 KN (200 kips) were used. At each load increment, readings were taken of the longitudinal dial gages and of the electric-resistance gages. The lateral displacement readings of the dial gage rig were taken at the initial load of 90 KN and at several times prior to buckling. In addition, the dial gage readings were taken after the formation of the initial buckles in Specimens P5 and P7.
7. TEST RESULTS

The description of test behavior has been separated into three segments: pre-buckling, buckling, and post-buckling. The phenomena common to all the specimens are discussed first, and then individual items of interest are pursued.

7.1 General Behavior of Specimens

7.1.1 Pre-Buckling Behavior

The behavior up to and including buckling of Specimens P5, P6, and P7 is shown in Fig. 11. The load is given as the average axial stress nondimensionalized with respect to the static yield stress of the material (ordinate), and the deformation is given as the average longitudinal strain (abscissa).

After some initial nonlinearity due to self-adjustments in the grouted ends of Specimens P5 and P6 or squashing of the copper in the case of P7, the test curves followed a linearly elastic path. The proportional limit for all three specimens was approximately 0.80 $F_y$.

7.1.2 Buckling Behavior

The maximum stress ranged from 0.941 $F_y$ for P7 to 0.814 $F_y$ for P5 thus decreasing with a reduction in $\alpha$ (an increase in D/t). The maximum stress values are given in Column 9 of Table 1.

In all three specimens, local buckling was sudden and it occurred at the attainment of the maximum stress. For Specimens P5 and P6, the buckling was accompanied by an explosive sound which was louder for the specimen with the larger D/t, P5.
7.1.3 Post-Buckling Behavior

The post-buckling behavior of Specimens P5, P6, and P7 is shown in Fig. 12. The nondimensionalized stress (ordinate) is plotted against the longitudinal deformation (abscissa). Note that in Fig. 11, strain was used for the abscissa rather than the deformation. However, in the post-buckling range, strain is not a valid parameter for plotting because the post-buckling deformation is not uniform over the length of the specimen, but rather concentrated in the buckled portion.

After the initial buckling, there was an immediate and drastic reduction in stress as seen in Fig. 12. Then, the load stabilized, and the stress-deformation curve levelled off. The amount of deformation sustained between buckling and the stabilization of the load after buckling varied inversely with the value of $\alpha$. The deformation values were about 2.5 mm (0.1 in.) for P7, 5.5 mm (0.22 in.) for P6, and 8 mm (0.31 in.) for P5.

7.2 Initial Buckling of Specimens P5, P6, and P7

7.2.1 General Comments

The initial buckling occurred in Specimens P6 and P7 ($2.4 < \alpha < 3.6$) by the simultaneous development of a ring bulge and lobular buckles and only of lobular buckles in Specimen P5 ($\alpha < 2.4$). The buckles formed adjacent to the ends in Specimens P5 and P6 and 0.50 m from one end in Specimen P7.
7.2.2 Initial Buckling of Specimen P5

In Specimen P5, the lobular buckles formed near the bottom end as seen in Fig. 13. The eight lobes alternated inward and outward in a symmetrical pattern around the circumference as shown by the plan view in Fig. 29. A side view of an inward lobe is shown in Fig. 14. This photograph clearly points out the absence of the ring bulge buckles. In the longitudinal direction, the lobular buckles typically took the form shown in Fig. 15. The axial length of the lobes was approximately 0.45 to 0.50 m (18 to 20 in.).

7.2.3 Initial Buckling of Specimens P6 and P7

For Specimens P6 and P7, the width of the ring bulge buckles was about 0.2 m (8 in.), and the axial length of the concurrent lobular buckles was approximately 0.5 m, that is, the same as for Specimen P5.

In Specimen P6, buckling took place near the top end as shown in Fig. 16. The ring bulge was located about 0.10 m (4 in.) from the top, and it was generally uniform around the circumference. Six lobular buckles emanated from the bottom side of the ring bulge, and the pattern formed by these buckles around the circumference is shown in Fig. 30.

In Specimen P7, the buckles developed at two levels as shown in Fig. 17. One level was located 0.58 m (23 in.) from the top of the tube, and the second (lower) level was 1.17 m (46 in.) from the top. The buckles of the upper level extended about two-thirds of the way around the circumference, while the buckles of the lower level covered the remaining one-third with a slight overlap. At each level, lobular buckles emanated from both sides of a ring bulge in such a manner that an outward lobe above the ring bulge lay opposite an inward lobe below it.
Plan views of the lobes located on the bottom side of each ring bulge in Specimen P7 are shown in Fig. 31a and 31b. The lobes possessed a half-wavelength in the circumferential direction of approximately 58°. This configuration could be interpreted as resulting in either five or seven lobes around a full circumference.

7.3 Post-Buckling Behavior

7.3.1 General Comments

The amplitude of the initial lobular buckles could be only measured after the load had stabilized at a reduced level following buckling. In Fig. 12 the stabilized loads are given by the first set of plotted points after the sharp drop in stress. The magnitudes of the initial inward lobular displacements averaged about 40 mm (1.60 in.) for Specimens P5 and P6 and about 25 mm (0.95 in.) for Specimen P7.

After initial buckling, the size of the ring bulge in Specimens P6 and P7 did not change, and all the post-buckling deformation occurred in the lobular buckles. For Specimens P5 and P6, an inward lobe formed across the weld seam in a manner similar to the specimens reported in Ref. 7.

The two levels of buckles in Specimen P7 had a dividing line at the longitudinal weld seam as shown in Fig. 17. The other dividing line was located about one-third of the circumference from the weld as shown in Fig. 18. At this stage of loading, Specimen P7 had been shortened by about 9.1 mm (0.36 in.). Later, when the specimen was shortened by 12.7 mm (0.50 in.), the two buckled levels were joined by the "Z-shaped" buckle shown in Fig. 19. No such connection developed at the dividing line of the weld.
The tests for Specimens P6 and P7 were terminated at deformations of 19 mm (0.75 in.) and 23 mm (0.9 in.), respectively, but for Specimen P5 the test was continued until the specimen was shortened by 0.40 m (15.6 in.).

7.3.2 Post-Buckling Behavior of Specimen P5

The complete stress-deformation curve for Specimen P5 is shown in Fig. 20. After initial buckling, P5 continued to lose stress until it reached a low point of 0.10 $F_y$ at a deformation of 0.11 m (4.3 in.) which is 20 times the initial buckling deformation. Beyond this point, the specimen regained some strength and achieved another peak in stress, equal to 0.22 $F_y$, at a deformation of 0.24 m (9.5 in.), which is 44 times the initial buckling deformation.

Shortly before the second stress peak was reached, a second set of lobular buckles formed adjacent to and above the first set. The new set of lobes was generally staggered with respect to the first set so that an inward lobe of the second set formed opposite an outward lobe of the first set. However, just seven lobes formed in the second set as compared with eight in the first set. The relative position of the two sets was as shown in Fig. 21. A view of the first set of buckles at an advanced stage is given in Fig. 22, and of the second set, at the same circumferential location, in Fig. 23.

The second set of lobes was initially observed at an axial deformation of about 0.20 m (7.9 in.). However, these new buckles were not due to a bifurcation phenomenon; they appeared to result from a gradual deformation of the specimen wall. This continuous process is depicted
in Fig. 24 where an inward lobe from the second set of buckles is shown at various stages of development.

Following the attainment of the second stress peak and the subsequent reduction in load, the test was terminated. Had the test been continued, it is expected that, as additional sets of lobular buckles formed, the stress-deformation curve would have continued to rise and fall with the stress fluctuating between the low value after the first set and the high value of the second set.

Two types of outward lobes were observed during the test. In one case, the outward lobe remained vertical and rigid and tended to shear or punch through the folded section of the buckle beneath it as shown in Fig. 25. The fracturing of steel was accompanied by loud, popping sounds. In the second case, the outward lobe folded over on itself as shown in Fig. 26. It appeared that, when enough outward lobes of the second type folded to the point where unbuckled sections of the tube made contact, the specimen regained strength for another set of buckles.

8. DISCUSSION OF TEST RESULTS
8.1 Comparison with Design Curves

The buckling stresses of Specimens P5 to P7 are plotted against $\alpha$ in Fig. 32. The results of the five tests conducted previously on this program are also given as solid circles (7). Together, these eight test points form a smooth curve with very little scatter. The small magnitude of scatter points out the reliability of these tests, especially in view of the considerable scatter exhibited by the other test points in the figure.
All the design curves, including the AISI and API curves, lie below these eight test points and are therefore conservative. However, the DNV curve comes close to matching these points.

8.2 Effect of End Conditions

In comparing the maximum stresses of the Lehigh specimens in Fig. 32, it should be noted that the end conditions were not the same for all of them. For four of the previously tested specimens, the ends were milled and bearing flat on the end fixtures and the wall was forced to rotate and then slide laterally by the lobular buckles developing adjacent to the ring bulges at the ends (7). However, this edge movement was observed only after reaching the maximum stress and thus is believed not to have affected the maximum stress. Specimen P7 also had milled ends, but the buckles developed away from the ends. Specimens P5 and P6 had the ends fixed by welding to the end rings with the buckling taking place near one of the ends. In spite of all these differences in end conditions the test values fall on a smooth curve thus indicating that the end conditions played no detectable effect on the local buckling stress.

8.3 Comparison of Specimen P5 with the Previously Tested Specimen P3A

The stress-deformation behavior of Specimens P5 and P3A is shown over the full test range in Fig. 27. Specimen P3A was tested previously and had the nominal value of $F_y = 345$ MPa (50 ksi), $D = 1.19$ m (46.85 in.) and $D/t = 142$ (7). Since it buckled at the end which was welded to a plate and thus had the same end conditions as Specimen P5, a comparison of these two specimens offers an indication of the effect of $\alpha$ on the post-buckling behavior ($\alpha = 4.50$ for P3A vs. $\alpha = 2.17$ for P5).
As shown in Fig. 27, the patterns of behavior of the two specimens are quite similar. Both reached a low point in stress at about 20 times their deformations at initial buckling. The second stress peaks for P3A and P5 were achieved at 50 and 44 times their initial buckling deformations, respectively. However, the levels of the post-buckling stress were significantly different as P3A carried approximately 50% higher stress than did P5, for example, at the second stress peaks, 0.34 F for P3A vs. 0.22 F for P5. Thus, it can be concluded that the post-buckling strength is a direct function of $\sigma$ and this relationship can be expected to continue during the formation of additional sets of lobular buckles.

Since the post-buckling strength could maintain its level as the specimens went through the formation of successive sets of buckles, it can be concluded that tubular members are capable of dissipating large amounts of energy at approximately 15-25% of their initial buckling stress.

8.4 Effect of Residual Stresses

The pattern of longitudinal residual stresses due to welding and the pattern of lobular buckles for Specimen P5 are superimposed in Fig. 28. The inward and outward displacements corresponding to the alternating pattern of lobular buckles is shown in the bottom part of the figure. Since no direct correlation between the two patterns can be observed, it can be concluded that the welding residual stresses had no detectable effect on the location of the buckles. This observation can be extended to Specimens P6 and P7 since residual stresses in these specimens were expected to be of the same general pattern and magnitude as measured in P5.
8.5 Effect of Initial Imperfections

The original cross-sectional shape and the shape after initial buckling are superimposed for each specimen in Figs. 29 to 31.

For example, for Specimen P5 these shapes are shown in Fig. 29. The light solid line labeled "reference circle" indicates a circle with a circumference equal to the actually measured circumference of the specimen. The original shape of the specimen is shown by the dotted line and the shape after buckling by the heavy solid line. The displacements are plotted radially relative to the reference circle, but they cannot be directly compared for the original and buckled shapes since, for the sake of clarity, different scales were used for the two shapes.

The original shape was generated from the set of dial gage rig readings taken at the beginning of the test (prior to loading). The readings of the dial gages located nearest the level of buckling were used for this purpose. Since it was generally impossible to use the rig after buckling because of the magnitude of the deformations, the buckled shape was obtained from the measurements of the distance between a straight edge and the points of peak inward and outward displacements around the circumference.

The corresponding deformations of Specimens P6 and P7 are shown in Figs. 30 and 31.

No definite correlation between the original and buckled shapes for any of the specimens can be observed except at the weld. The initial inward displacement at the weld in Specimens P5 and P6 corresponds to the inward lobe which developed there as shown in Figs. 29 and 30.
In the case of Specimen P7, the two levels of buckling straddled the weld so that no specific buckle can be associated with it (Fig. 31).

There was considerable difference between the imperfections of Specimen P7 and of Specimens P5 and P6. For example, the maximum out-of-roundness of Specimen P7 was about 6 times greater than of Specimen P6. Yet the test point for Specimen P7 falls on the smooth curve formed by the results of the eight tests conducted in the Lehigh program as shown in Fig. 32.

The apparent lack of correlation between the initial imperfections and the buckled shape (except possibly at the weld) and the undetectable effect on the buckling strength must be viewed cautiously. Other researchers have conducted tests in which they were able to link the initial imperfections with buckling (6,9). However, these tests were performed on tubes with very large D/t ratios in comparison to the specimens described here, and the buckling was elastic. Since in this study the buckling was inelastic, it may be that inelastic local buckling is relatively insensitive to initial imperfections in comparison to elastic buckling.

8.6 Effect of $\alpha$

Parameter $\alpha$ and the buckling stress for the three specimens are listed in Columns 8 and 9 of Table 1, and the buckling stress is plotted against $\alpha$ in Fig. 32. In the figure, the eight test points obtained in the Lehigh program form a smooth curve, thereby indicating a consistent relationship between the buckling stress and $\alpha$. 
As can be seen in Fig. 11, the local buckling strain depended on \( \alpha \); the larger \( \alpha \) was, the greater the local buckling strain became. The average local buckling strain was \( 1.82 \times 10^{-3} \) for P5 (\( \alpha = 2.17 \)), about \( 1.90 \times 10^{-3} \) for P6 (\( \alpha = 2.60 \)) and \( 2.20 \times 10^{-3} \) for P7 (\( \alpha = 3.32 \)).

The type of initial buckling also depended on \( \alpha \). A combination of ring bulge and lobular buckles developed in Specimens P6 and P7 (\( 2.4 < \alpha < 3.6 \)), and only the lobular buckles in Specimen P5 (\( \alpha < 2.4 \)).

The axial deformation between the initial buckling and load stabilization after buckling was an inverse function of \( \alpha \). The deformation values varied from \( 2.5 \) mm for P7 (\( \alpha = 3.32 \)) to \( 8 \) mm for P5 (\( \alpha = 2.17 \)).

The peak stress achieved in the post-buckling range after the formation of additional sets of buckles was dependent on \( \alpha \). The larger \( \alpha \) was, the greater was the peak post-buckling stress. This conclusion was reached by comparing Specimens P3A and P5 in Fig. 27.

9. **SUMMARY AND CONCLUSIONS**

Local buckling tests were conducted on three tubular specimens fabricated from high-strength steel plate with \( F_y = 345 \) MPa (50 ksi) by cold-rolling and then welding along the longitudinal seam. The specimen diameters were 1.20 m (47 in.), 1.53 m (60 in.), and 1.79 m (70 in.), and the wall thickness was 7.17 mm (0.28 in.) to 7.26 mm (0.29 in.). The D/t ratios correspondingly fell between 165 and 248. To preclude the effect of overall column buckling, the specimens were made short with a slenderness ratio of less than 10.
The maximum stress achieved in the tests was limited by local buckling which took place above the proportional limit. The behavior of the specimens beyond initial buckling was also studied.

The following conclusions can be drawn from the results of these tests and of the tests previously conducted in this program (7):

1) The design rules for local buckling currently recommended by AISI and API are adequately conservative for tubular members fabricated from 345 MPa (50 ksi) steel and falling within the range of parameters tested: $85 \leq D/t \leq 248$ and $2.17 \leq \alpha \leq 7.51$.

2) The type of initial local buckling is a function of $\alpha$. Approximate guidelines are: ring bulge for $\alpha \geq 3.6$, combination of ring bulge and lobular for $2.4 \leq \alpha \leq 3.6$, and lobular for $\alpha \leq 2.4$.

3) The average strain at local buckling is a function of $\alpha$. The larger is $\alpha$, the greater is the local buckling strain.

4) The post-buckling strength is a function of $\alpha$. For equivalent end conditions, the post-buckling strength decreases with a decreases in $\alpha$.

5) By forming successive sets of lobular buckles, tubular columns can dissipate large amounts of energy at approximately 15-25% of the buckling stress.

6) There is no apparent correlation between the pattern of longitudinal residual stresses due to welding and the pattern of local buckling. Thus, residual stresses do not appear to be significant in influencing the location of the buckles for the range of parameters tested ($D/t$, $F_y$, etc.).

7) Initial imperfections apparently did not play a significant role in the local buckling of the specimens tested.
Before the results of these tests can be translated into sound design recommendations, it is necessary that more experimental and theoretical work be conducted. Specifically, the following items must be investigated:

1) Yield stresses different from the value of 345 MPa tested.
2) The interaction between local and overall column buckling.
3) The effect of circumferential weld seams.
4) Larger D/t, in order to extend the results of this study to smaller values of $\alpha$.
5) The effect of initial imperfections for larger D/t where there is a transition from inelastic to elastic buckling.

10. ACKNOWLEDGMENTS

This investigation is part of a research project on the local buckling of round tubular steel columns above the proportional limit, sponsored by the American Iron and Steel Institute and conducted at Fritz Engineering Laboratory, Lehigh University. The work was guided by a Task Force of the AISI Engineering Subcommittee of the Committee of Structural Steel and Steel Plate Producers. The chairman of the Task Force is Mr. R. R. Gavin and the AISI coordinator Mr. A. C. Kuentz.

Special thanks are due to K. R. Harpel and the laboratory technical staff who helped plan, set up, and run the tests. The assistance of M. A. Marzullo, Ms. S. Matlock and J. M. Gera and his staff in the technical production of this manuscript is also gratefully acknowledged.
Appendix I - REFERENCES


### TABLE 1: ACTUAL SPECIMEN DATA

<table>
<thead>
<tr>
<th>No.</th>
<th>Steel</th>
<th>Coupon Static $F_y$ (ksi)</th>
<th>Measured</th>
<th>$D/t$</th>
<th>Test $F_c/F_y$</th>
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<tbody>
<tr>
<td>P5</td>
<td>A572</td>
<td>54.70</td>
<td>70.35</td>
<td>0.2821</td>
<td>248.38</td>
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<tr>
<td></td>
<td>Gr50</td>
<td>53.96</td>
<td>60.34</td>
<td>0.2859</td>
<td>210.05</td>
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<td></td>
<td></td>
<td></td>
<td>47.35</td>
<td>0.2859</td>
<td>164.62</td>
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</tbody>
</table>

Notes:  
1 in. = 25.4 mm = 0.0254 m  
1 ksi = 6.895 MPa  
$OD = $ Outside Diameter, $t = $ Thickness, $D = OD - t$  
$L = $ Length, $\alpha = Et/F_D$  
$E = 29.5 \times 10^3$ ksi $= 203.403 \times 10^3$ MPa  
$F_c = $ Critical Local Buckling Stress of the Test
Fig. 1. Design Curves and Previous Test Results for Local Buckling of Tubular Columns
Fig. 2 Typical Test Specimen and Pertinent Notation
Single-Vee Groove, Submerged Arc Weld

<table>
<thead>
<tr>
<th>PASS</th>
<th>ELECTRODE TYPE</th>
<th>DIAMETER (IN.)</th>
<th>AMPS</th>
<th>VOLTS</th>
<th>TRAVEL SPEED</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>EM12K</td>
<td>2.38 mm (3/32&quot;)</td>
<td>460/500</td>
<td>26/30</td>
<td>305/406 mm/min</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>(12/16 in./min)</td>
</tr>
<tr>
<td>2</td>
<td>EM12K</td>
<td>2.38 mm (3/32&quot;)</td>
<td>460/500</td>
<td>26/30</td>
<td>305/406 mm/min</td>
</tr>
<tr>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>(12/16 in./min)</td>
</tr>
</tbody>
</table>

Fig. 3  Welding Details
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Radial Scales:

- 500 mm
- 20 mm
- 200 mm

Buckled Shape
Original Shape
Reference Circle

Fig. 29 The Original and Buckled Shapes for Specimen P5
Fig. 30 The Original and Buckled Shapes for Specimen P6
Fig. 31  The Original and Buckled Shapes for Specimen P7
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