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Tubular Columns

THE STRENGTH OF AXIALLY LOADED TUBULAR STEEL COLUMNS

DETAILED WORK PROPOSAL

by

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This work is to be carried out as part of an investigation sponsored by the American Petroleum Institute

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I. TESTING PROGRAM OF AXIALLY LOADED TUBULAR COLUMNS

1. DESIGN OF SPECIMENS

The specimens are designed according to the American Petroleum Institute's (API) [1] specification for Fabricated Structural Steel Pipe.

1.1 Materials

The sections used to build up the columns are cold-rolled from A36 steel plates with a 5/16 in. thickness. The original milling direction of the plates is perpendicular to the longitudinal axis of the finished columns.

1.2 Tolerances

The following tolerances are taken from the API Specifications [1] and applies to all specimens:

a) Out-of-roundness The difference between the major and minor outside diameter shall not exceed 1% of the specified nominal outside diameter or ¼ in. whichever is less. Both ends and center of column to be checked. (API Spec. 2B, Sec. 4.2).

b) Out-of-straightness The maximum allowable straightness deviation in any 10 ft length shall be 1/8 inches. For lengths over 10 ft the maximum deviation of the entire length shall not exceed 1/8 inch for each ten foot length, nor be greater than 3/8 inch in any 40 ft. length (API Spec. 2B, Sec. 4.4).

c) 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.

All specimens will be fabricated to the best possible tolerances by McDermott & co. according to standard oilfield practice. It is recognized that it may not be possible to meet the API specifications for the 15 inch diameter specimens.

1.3 Welding

All pipe ends shall be beveled for welding with an angle of 30 deg, both for the longitudinal and circumferential welding surface (API, Spec. 2B, Sec. 4.5. The filler metal should be according to the AWS Specification #5.17. The semi-automatic fabrication setup requires a copper backup bar under the weld. Since this type of setup may not be available to all fabricators, a flux box backup is recommended. This is very easily achieved by simply clamping a small flux filled channel on the underside of the weld. The longitudinal welds will require four passes from the outside. The first should be a GMA (gas metal arc) spray transfer weld and the next three should be SMA (submerged arc) passes. A final inside SMA pass completes the weld. The girth welds are to be made by 4 passes. Three SMA passes following a GMA short arc root pass. A 1/8 in. to 5/32 in. girth weld root opening is to be used. Alternately, a feather-edge jammed joint can be used for the girth welds; if so, a GMA spray are root pass is to be used.

Visual inspection of the weld should be sufficient after completion.

1.4 Machining

The ends of the finished columns and stub columns are to be machined flat, perpendicular to the longitudinal axis of the column.

This will be carried out in a plant near Lehigh to minimize damage from transportation and handling.

2. DESCRIPTION OF TEST PROGRAM

The test program, designated as WTC-series (Welded Tubular Columns), is summarized in Table 1. A series of ten full sized columns together with four stub columns and tensile coupons will be tested. The stub-columns (WCT-S1 and S2) are also listed in Table 1. Two of each diameter size will be made. One additional pipe of about 4 ft. of each diameter size should also be made for residual stress measurements. Tensile specimens should be made both from flat plate and the curved pipe. Two of each should be furnished. The coupons will be tested both with dynamic and static loading.

The procedures of testing of stub-columns [2,3] and of columns which previously have been successfully used in similar studies, [4] will be utilized. Stub-column and column tests will require the use of the 5 million pound capacity universal testing machine at Fritz Engineering Laboratory. Detailed discussion of the test program is given as follows.

2.1 Materials

As mentioned 5/16 in. A36 steel plates, if possible from two heats and under no circumstances steel "downgraded" from a higher quality will be used. Speed of specimen fabrication will, however, take precedence over the requirement to obtain steel from two heat lots.

a) Number of Specimens Two of each identical full sized specimens will be tested together with two stub-columns for each diameter size.

b) Size and Build Up of Specimens All full sized specimens will be made up from 5/16 in. A36 steel and the dimensions are as follows.

Table 1 Test Program

Series	Outside Diameter, D	Length L	L/r Ratio	L/D Ratio
WTC-1	22 in.	36 ft.	56	--
WTC-2	22 in.	25 ft.	39	--
WTC-3	15 in.	36 ft.	83	--
WTC-4	15 in.	26 ft.	60	--
WTC-5	15 in.	18 ft.	42	--
WTC-S1	22 in.	4 ft.	--	2.18
WTC-S2	15 in.	3 ft. 2 in.	--	2.53

The columns will be made up of 10 ft. sections for the 22 in. diameter specimens with the last section shorter to fit the 36 or 25 ft. lengths. For the 15 in. diameter specimens 5 ft. sections will be used with the last section = 6 ft. for the 36 and 26 ft. specimens and 3 ft. for the 18 ft. specimen.

The longitudinal weld seams will be staggered at 90° at the circumferential seams to simulate the normal build-up of tubular columns in off-shore structures.

2.2 Residual Stresses

The "strain gage hole drilling method" will be used if suitable to obtain the necessary information such as residual stresses at the welds, in the surrounding material, and through-the-thickness variation in these stresses. Some initial investigation will be carried out to determine the sensitivity of the measurements at various depths. This will be carried out on annealed plate subjected to a given stress and on annealed and afterwards bent plate which is allowed to spring back. This will be done to arrive a calibration factors before measurements are taken from both inside and outside of the fin shed specimens.

Residual stress measurements will be made on specimens from all heat lots and a brief report will be issued as soon as the measurements have been carried out.

2.3 Testing Procedure

Spherical bearing heads at both ends of the columns will be used. This will give a pinned ended condition and thereby allowing up to 22 in. diameter columns to be tested. It also allows for buckling in the weakest direction.

2.4 Axial Loading Case

For the 10 specimens only axial loads will be considered. Eccentrical loads will give a predetermined buckling direction and the effects of residual stresses cannot readily be observed.

The stub column test results are to be used as a check on the "average" residual stress values found from the detailed measuring work with the actual test specimens.

a) Test specimens should be loaded (within safety and as is practical) to loads well in excess of their "maximum" strength.

An appreciation of the post-buckling characteristics of the specimens is desired.

b) Lateral deflections are to be measured in perpendicular directions at the eighth points between the upper and lower quarter-points of the test specimens.

c) Out-of-roundness and out-of-straightness measurements with the specimens are also to be made subsequent to testing.

3. FABRICATION

The local fabricators have not been able to meet the tolerance requirements of the API code for fabrication of welded tubular columns. Among the companies contacted the Bethlehem Corp. which appeared to be better qualified than any other local fabricator rejected the work for the same reason.

The fabrication will therefore be carried out by J. Ray McDermott & Co., Inc., which is familiar with the production of such columns.

4. EXPECTED PROGRESS BY SEPTEMBER/OCTOBER 1975

It is expected that within the time span allotted the 10 tubular steel column specimens will have been manufactured and tested, preferably to loads well in excess of the failure load. It is also expected that such stub column tests and residual stress measurements as may be possible or necessary will have been completed. Measurements to be made will include axial load, lateral deflections, 2 sets at 90° on D/8 between ¼ pts, and axial strain on the specimens during testing as well as such out-of-straightness, out-of-roundness and residual stress measurements as may be possible on the test specimens prior and subsequent to testing.

It is expected that the results of the experimental testing will be delivered in such a form that they may be inserted at the proper places in the critical stress-slenderness ratio curves at present proposed by CRC. Typical load-strain curves and column curves are shown in Fig. 1 and Fig. 2. Theoretical developments of these curves are given in Part II of this report. It will not be the responsibility of the Lehigh research program to determine or suggest any "safety factors" or "derating factors" which may be necessary to fit the results to design curves.

II. THEORETICAL ANALYSES FOR TUBULAR STEEL COLUMN PROJECT

1. INTRODUCTION

There are four possible theoretical approaches to the prediction of tubular steel column behavior, varying from a crude formula to a sophisticated three-dimensional finite element method. The object of these analyses is to discover which analysis provides the best approximation to the measured results with the least effort, and then to work these theoretical predictions into the multiple column curves recently proposed,[5].

The four available methods are as follows: 1) using the tangent modulus formula; 2) a two-dimensional column bending analysis, 3) a three dimensional column bending analysis; and 4) a complete three-dimensional finite element analysis. Each of these methods varies in the extent to which the effects of residual stress, initial imperfections, and eccentricity of load application may be taken into account, and each of these is discussed briefly below.

It must be emphasized that the extent to which each of these analyses can be investigated will depend largely on the project duration. During the first year it will only be possible to investigate the tangent modulus formula and probably the two-dimensional and three-dimensional column bending analyses. It will probably be possible to derive the moment-axial load-curvature relations from the bending analyses, assuming that there is no initial out-of-roundness in the column. During successive year(s) it will be possible to develop the more refined finite element analysis, if this proves necessary.

2. THEORETICAL METHODS

2.1 Using Tangent Modulus Formula

A common method of determining the critical buckling load of a column is given by

$$f_{cr} = \frac{\pi^2 E_t}{\left(\frac{KL}{r}\right)}$$

where f_{cr} = critical buckling stress of the column

E_t = tangent modulus of elasticity for the material at its critical buckling stress

KL = effective unbraced column length

r = radius of gyration of the circular section.

In order to accurately determine the predicted critical buckling stress it will be necessary to conduct either a stub-column test for a tensile test in order to evaluate E_t. As Bouwkamp [6] noted, the residual stresses are accounted for if the tangent modulus, E_t, values are obtained from a stub column test. This formula cannot, however, adequately cater for initial imperfections such as out-of-roundness and out-of-straightness. Nevertheless, it is a classical formula, and thus provides a first estimate.

2.2 A Two-Dimensional In-Plane Column Bending Analysis

A perfectly straight tubular steel column in which there is no welded seam can be assumed to have no preferred direction of buckling. However, the presence of the welded seam predefines the axes of buckling for the same perfectly straight column. This is as a result of the residual stresses induced in the column during the welding process. Also, intuitively, the welding process will induce distortions in the length of the column such that the bending properties of the column about an axis perpendicular to the diameter which includes the welded seam will be different from the bending properties of the column about all other axes. Thus it is that there is likely to be a well-defined direction of bending for the welded, perfectly straight column, and hence a two-dimensional analysis may well be sufficient to adequately predict column properties.

Moment-Curvature Relations

Santathadaporn and Chen [7] reported development of a computer program using tangent stiffness method to find the moment-curvature relationships for wide flange sections of unit length. Dividing the cross-section into finite elements, and using a reasonable approximation for the observable residual stresses in the section, they loaded the section in load increments, iterating to equate the internal and external loads at each load increment. For convenience, an elastic-perfectly plastic stress-strain relationship for steel was assumed, and the elastic unloading of yielded fibers was ignored.

It is anticipated that this method will be adopted for use in analyzing tubular steel columns. While a new computer program will need to be developed, the method will remain similar. It is not advisable, at this stage, to consider initial out-of-roundness. The longitudinal and circumferential residual stress distributions including their variations through the thickness of the steel plate will be included in the development of moment-curvature relations.

Long Column Analysis

A long column may be imagined as stacking up these unit length columns in such a manner that a whole column length is built up. The behavior of a long column is therefore characterized by the behavior of each of its individual unit length columns. The analysis is two-dimensional (in-plane), since only axial load and bending moment in one direction can be applied. It is now possible to include some initial out-of-straightness of the column length, provided it is in the same plane as the bending plane. Chen and Atsuta [8] proposed a method whereby assumptions about the form of the moment-curvature curves allowed exact solution of the differential equations of column behavior and, with the aid of the computer, production of column curvature relationships. It is likely that this method of solution may be readily applicable to the tubular steel column study.

A consequence of the stacking of unit column lengths is that the circumferentially varying position of the longitudinal weld cannot be considered, nor can the effect of the circumferential welded section joints. The analysis might therefore be expected to be a more correct analysis of a tubular column formed of one length only of welded pipe (if this is considered to be the central portion of a long column, then the applicability is obviously wider). Nevertheless, the method does allow the inclusion of eccentric load application to the section, and has a more analytical approach to the inclusion of residual stresses which is reflected in the development of moment-curvature relations. Furthermore, it is possible to obtain load-deformation behavior of tubular column throughout the entire range of loading up to maximum load.

For these reasons it is considered a worthwhile improvement on the tangent modulus formula.

2.3 A Three-Dimensional Biaxial Column Bending Analysis

Clearly, the two-dimensional in-plane analysis just described is limited by the fact that the plane of bending must be predetermined and furthermore, both the plane of bending and any initial out-of-straightness must be in the same plane. It is therefore probable that a better representation of actual column behavior will be obtained if a three-dimensional biaxial bending analysis is considered. This method allows inclusion of axial load and applied biaxial bending moments in two directions to the cross section, an increase of one degree-of-freedom over the two dimensional in-plane analysis described above.

With the more general derivation of the moment-curvature curves (now really families of curves) it is possible to build up a column length in a similar manner to that described above. Now, however, it is possible to consider column out-of-straightness in any direction as well as twisting of the section [9]. The column length is assumed to have uniform properties over its whole length, as before, and so it is still not possible to consider variations in residual stress over the length of the column, as of circumferential welded seams, or of longitudinal weld staggering.

It is anticipated that some variation of circumferential residual stresses through the thickness of the column wall will be included, by division of the cross-section into finite elements both radially and circumferentially. The extent to which this approach will be developed, will, however, depend on the facilities available, as well as the requirements which will become evident as the program progresses.

All three methods described thus far have approached this problem from a strength of materials approach, i.e., with the implicit assumption that plane sections remain plane. In each of the column bending analyses, attempts are made to establish load-deflection curves throughout the entire range of loading up to maximum load.

It is understood that copies of the computer program and results will be in reports at the end of the first year of the project, in such a form that the programs may be readily used and the results may be compared with CRC curves. As is widely recognized, the budget for computer analysis allotted to the project is at present very small, and this could well hamper any attempt to generate any widely representative sets of results, particularly if families of maximum strength interaction curves of the type P/P_y vs. M/M_y (with ℓ/r fixed) are required for practical design [10].

2.4 Three-Dimensional Finite Element Method

If it proves necessary to obtain a more realistic analytical model of the tubular steel column behavior, it is possible to conduct a complete finite element analysis of each specimen. In this manner it would be possible to include variations in the structural properties of the column along its length. In particular, it would be possible to include the effects of longitudinally varying residual stresses, circumferential weld stresses and weld staggering. Once again, out-of-roundness could be considered, but only with difficulty.

This approach is fundamentally different from the other methods described in that it approaches the problem from a continum mechanics viewpoint, considering each element as an entity with its own equilibrium equalties.

This method has been programed for the case of the I-section in the elastic range [11], but extensive modifications would be required to adapt it for the case of the tubular column including elastic-plastic range and thus it is beyond the scope of the first year of this project.

2.5 Factors to be Considered in Analysis

With progressive refinement of the theoretical analysis comes the opportunity to consider in greater detail progressively more factors affecting the column behavior. It is appropriate to mention here some of the initial assumptions usually made in theoretical analysis, although it is intended that these be replaced by measured values when these became available. A comparison of the results of the analyses, and comparison with experimental data, should enable interesting conclusions about the effect of each factor considered.

At this stage it is not proposed to consider out-of-roundness of the column, but some account of this could be taken if necessary. However, it would be intended that both the two-dimensional in-plane and the three-dimensional biaxial analyses would include the out-of-straightness of the column in some form. The theoretical assumption is usually made that the column adopts a half-sine wave shape, and that the initial out-of-straightness is the maximum allowable under the API Specifications [1].

The residual stress distribution also needs some consideration, for there are three possible factors which may influence this. The rolling of the plate will introduce characteristic stresses (which will vary through the plate thickness), while the longitudinal seam (which will produce stresses characteristic of the cross-section) and the circumferential seams (which will introduce stresses which hopefully will be localized) will introduce residual stresses due to the welding procedures. Each of these factors should be considered separately. However, the elastic-plastic analysis originally contemplated for the in-plane or biaxial bending analysis will allow inclusion of the residual stresses due to the longitudinal welded seam, for which it is proposed to include an initial residual stress distribution similar to that proposed by Marshall [12]. If it proves necessary, the analysis could be modified to include residual stresses introduced by plate rolling. Only the full finite element analysis will be able to include the effects of the circumferential weld residual stresses.

2.6 Reports

a) Periodic informal progress reports (written or verbal) are to be made. b) A final report is to be submitted in the Fall of 1975 giving:

1. A summary of all experimental data gathered to that date.
2. A summary of the theoretical approaches used (complete with relevant experimental correlations) and the results attained therefrom.
3. A detailed interpretation of the results developed and recommendations as to how these might be used in practice by designers.
4. Recommendations as to continuing experimental and theoretical research and data interpretation work needed.

Development of items 3. and 4. will require in-depth discussions between the Advisory Committee and research personnel. Of course, these discussions will have to await the development of both theoretical and experimental research results.

c. Copies of developed computer programs, complete with sufficient documentation so that they can be readily used by others.

III. FUTURE RESEARCH

Although only tentative discussions were held, some opinions on the nature of future research were expressed at the December 9 meeting. Particular emphasis was laid on the need for more experimental testing, particularly of specimens with higher ℓ/r ratios. (It was recognized that, due to the limitation in the size of the testing machine, this would involve the use of smaller diameter specimens.)

Some interest was also evident in the proposal to develop a complete finite element representation of the column specimens, which would allow variations of structural properties along the column (including offsets of longitudinal welded seam, and girth welds) to be considered.

It is recognized that recommendations for future research cannot be made with any degree of certainty until the outcome of the current research is known. The comments above are only speculative, therefore, and more concrete proposals could be expected at the completion of the current program.

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From Fritz Lab Tests 19 November 1973 and 8 March 1974

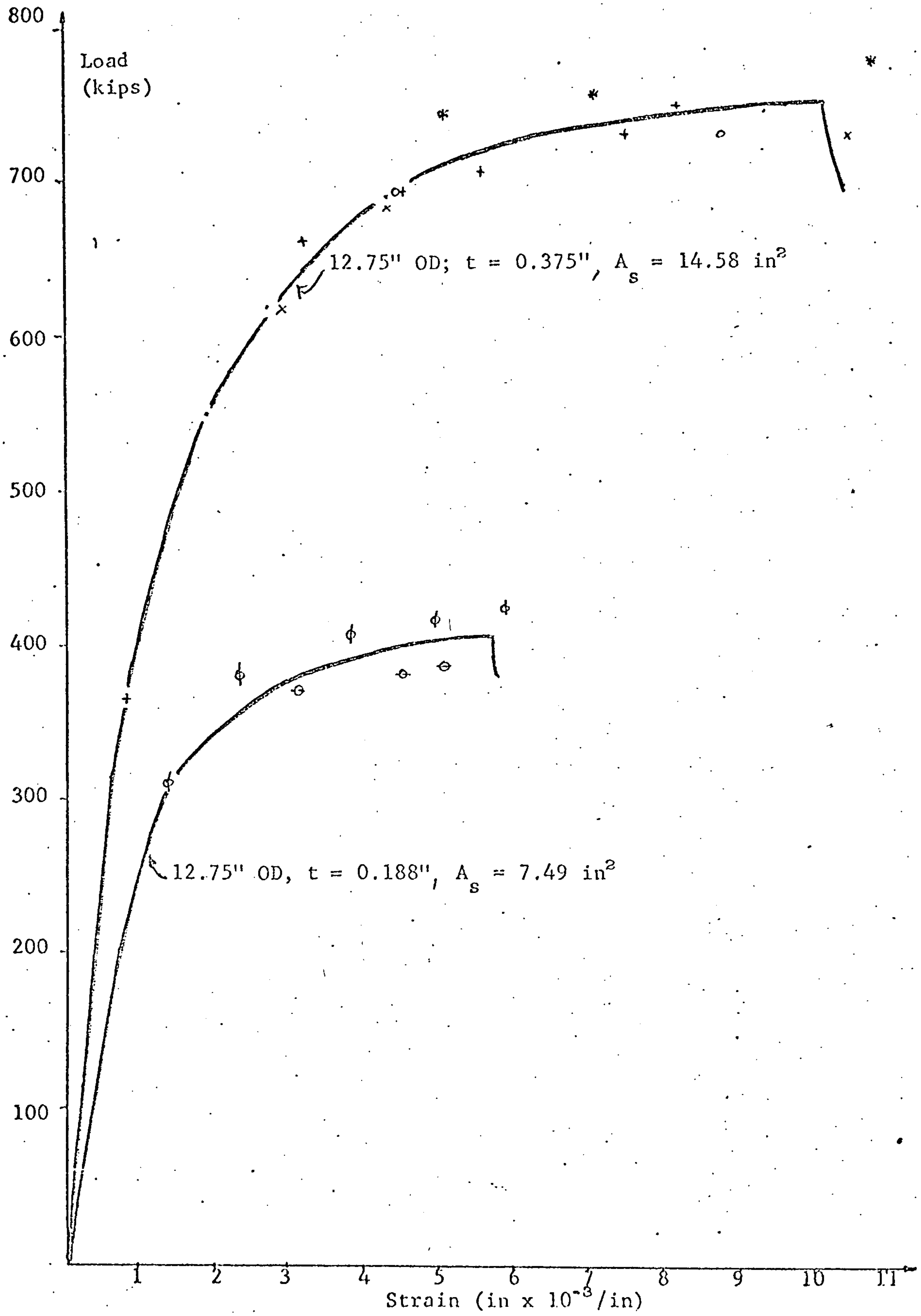
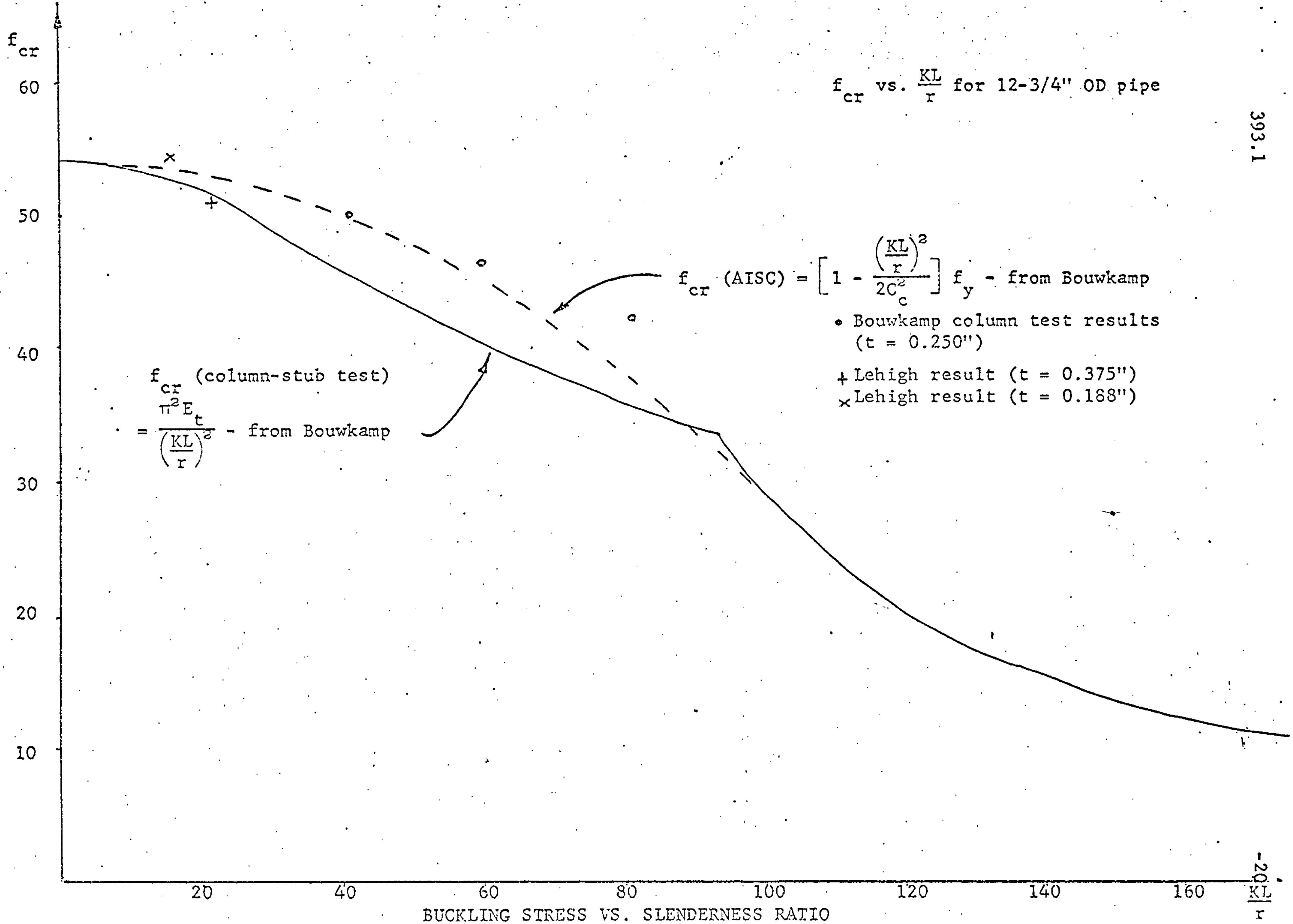


Fig. 1 Load-Strain Curves



BUCKLING STRESS VS. SLENDERNESS RATIO

Fig. 2 Column Curves

API Research Project

THE STRENGTH OF AXIALLY-LOADED TUBULAR COLUMNS

Adivisory Committee Members

L. A. Boston (Chairman) (J. Ray McDermott & Co., New Orleans) principal API representative
R. M. Meith (Chevron Oil Company, New Orleans) API representative
P. W. Marshall (Shell Oil Company, Houston) API representative
J. R. Lloyd (Exxon Production Research, Houston) API representative
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Those attending meeting at Lehigh University, Fritz Engineering Laboratory, Monday, December 9, 1974:

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P. W. Marshall
D. R. Sherman
R. R. Graham
W. F. Chen
D. A. Ross
E. Dahl-Jorgensen
J. Stokes (J. Ray McDermott & Co., New Orleans) welding and fabrication engineer
K. R. Harpel (Fritz Engineering Laboratory Superintendent)
D. Powell (Metallurgist, Fritz Engineering Laboratory)