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Innovative Concepts in Power Piping Design

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FOREWORD

The papers in this year's piping session emphasize both the technical and practical methods being developed today. On the technical side, there are papers describing micro-computer applications for such diverse subjects as piping graphics and system design. On the practical side, we are presenting papers dealing with topics such as water hammer in direct contact heaters and as-built program development. The subjects are a representative cross-section of the work being done today in piping and should be of interest to all engineers in this field.

I wish to thank the authors for their time and efforts in providing the technical papers for this publication. I also wish to thank members of my staff at Cygna for their contribution in the last minute editing, proofing, and paste-up work; in particular, Jerry Wong, Nancy Williams, and Jane Gonzalez. Also, the review committee deserves my personal thanks: John Minichiello, Joseph Santosuosso and James Woodward. The combined contributions have assured another successful meeting session and publication.

Eric van Stijgeren
Cygna Energy Services

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EVALUATION OF FUNCTIONAL CAPABILITY OF ASME CLASS 2 AND 3 CARBON STEEL ELBOW BY FINITE ELEMENT TECHNIQUE

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ABSTRACT

The requirement for demonstration of functional capability of piping components subject to intensified bending stress stems from a concern that at certain ASME Service Limits, significant yielding and inelastic behavior of the component could result. This in turn could impair the fluid transport characteristics, or function, of the piping system through a reduction in flow area.

Theories have been established which provide a basis for evaluating the functional capability of piping components so affected. These theories are based on maintaining "limit loads" which are within the predominantly elastic or transitional plastic range of the material. Small increases in load above these "limit loads" could produce large increases in deformation. When these limit load rules cannot be satisfied, functional capability may still be demonstrated through the application of a more detailed analysis. This paper presents an assessment of the functional capability of elbows by taking advantage of the plastic properties of the pipe material through a finite element analysis (FEM).

INTRODUCTION

Criteria have been established based on limit load concepts, (1), (2),[1] which may be used to assess the functional capability of piping components. Compliance with these criteria assures that moment loadings necessary to produce gross plastic deformation are not present in the piping system.

This paper presents an assessment of the functional capability of piping elbows under loading conditions which exceed these limit loads through the use of a finite element computer program (3). This elastic-plastic finite element analysis was performed on a carbon steel elbow for which experimental test data exists. The analytical results are compared to the experimental test results. These comparisons consist of load-deflection curves, load-strain curves and maximum ovality. The effect of internal pressure on the moment carrying capacity of the elbow was also evaluated and compared to the conclusions reached in Reference (1). Stress-strain curves were developed based on an empirical equation (4) due to works of Ramberg and Osgood and used as input to the finite element routine.

$$\varepsilon = \frac{\sigma}{E} + k\left(\frac{\sigma}{E}\right)^n \qquad (1)$$

The elastic-plastic finite element technique was then applied to a sample problem in order to assess the functional capability of an ASME Class 2 carbon steel elbow under combined pressure and moment loadings beyond the limit load rules.

[1]Underlined numbers in parentheses refer to references at the end of the paper.

NOMENCLATURE

- B_1 = stress index, pressure loading
- B_2 = stress index, moment loading
- D_o = outside diameter
- E = modulus of elasticity
- h = t_nR/R_m^2 = flexibility characteristic
- k, n = constants
- M = resultant moment
- M_z = in-plane bending moment
- P = internal pressure
- R = mean radius of pipe
- R_m = bend radius of pipe
- S_{max} = maximum calculated stress
- Sy = yield strength of material
- t_n = nominal wall thickness
- Z = section modulus of pipe
- ε = strain
- α = bend angle
- ϕ = elbow coordinate angle
- σ = stress
- o——o = represents test results
- x——x = represents FEM analysis results

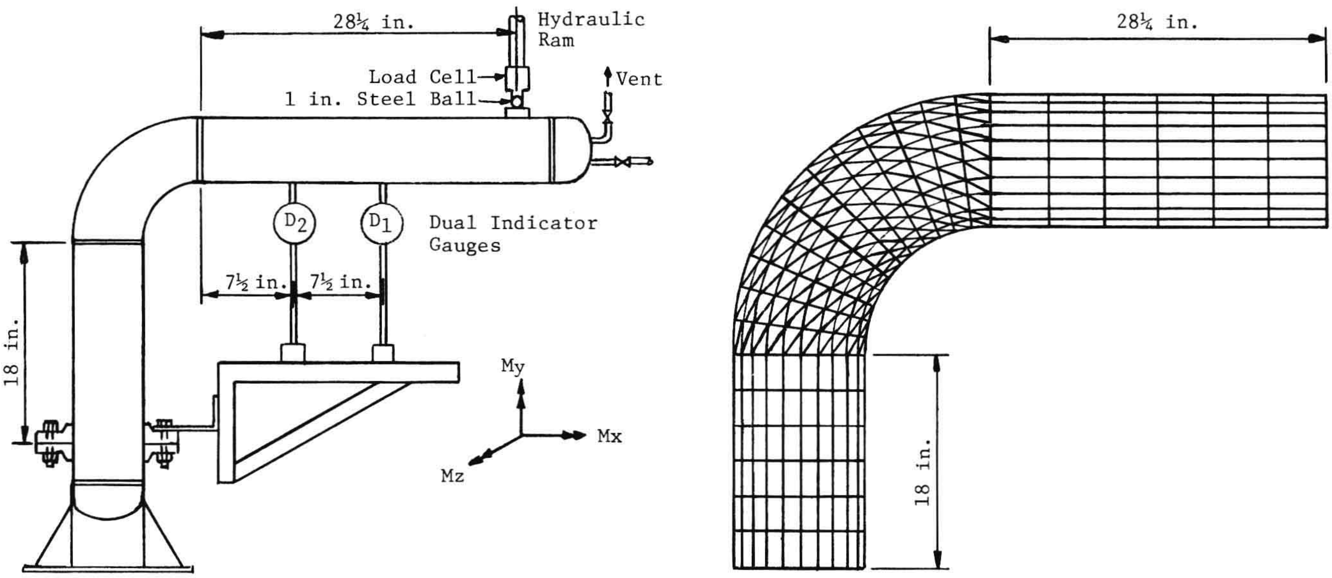

FIG. 1 TEST SET-UP AND ANALYTICAL MODEL

CORRELATION OF TEST RESULTS TO ANALYSIS

Test Set-Up and Analytical Model

Reference (1) contains results of a series of room temperature tests. These tests were performed on twenty commercial butt-welding elbows. Each test consisted of incremental load application with corresponding dial indicator and strain gauge readings for each load step.

Test PE-2 was selected for correlation with the finite element analysis. This test was performed on a 6-inch Schedule 40 long radius elbow. The elbow conformed to ASTM-A-106B. The imposed load for this test produced an in-plane bending moment on the elbow which tends to close the elbow.

The dimensional aspects of the test were duplicated by the finite element model. The straight segments of pipe consisted of elastic quadrilateral shell elements whereas the elbow was made up of plastic triangular shell elements.

The test set-up and analytical model are presented in Figure 1. Figure 2 reflects strain gauge locations.

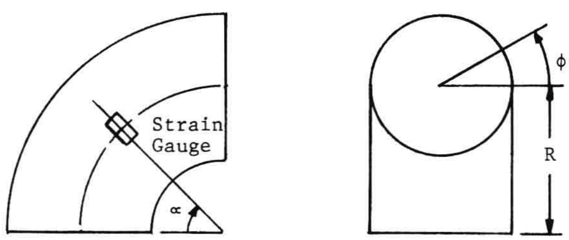

FIG. 2 DEFINITION OF COORDINATE ANGLE (ϕ), BEND ANGLE (α), AND STRAIN GAUGE LOCATION

Comparison of Results

Maximum Stress. For the analytical load step in the elastic range, the maximum stress occurred in the hoop direction at $\phi = 0^o$ at the 45^o angle (α) of the bend. This stress compares favorably with the predicted maximum stress resulting from an in-plane bending moment. This is represented by the equation: (2)

$$S_{max} = \frac{1.8}{h^{2/3}}\left(\frac{M}{Z}\right) \qquad (2)$$

For this load, the maximum stress from the finite element analysis was 47,300 psi compared to the predicted stress from Eq. (2) of approximately 53,000 psi.

Load Deflection. Figure 3 compares the load versus deflection data of the test and that of the FEM analysis. This deflection output is taken at the point corresponding to the D_1 dial indicator location.

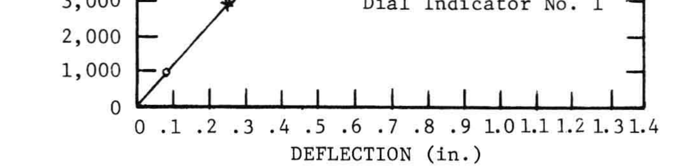

FIG. 3 LOAD-DEFLECTION CURVE FOR IN-PLANE BENDING ($-M_Z$) WITH ZERO INTERNAL PRESSURE

Load/Strain. Figure 4 compares the load versus strain data at the corresponding location. The strain gauges were located on the outside surface at $\phi = 0^o$ and 180^o at the 45^o angle of the bend.

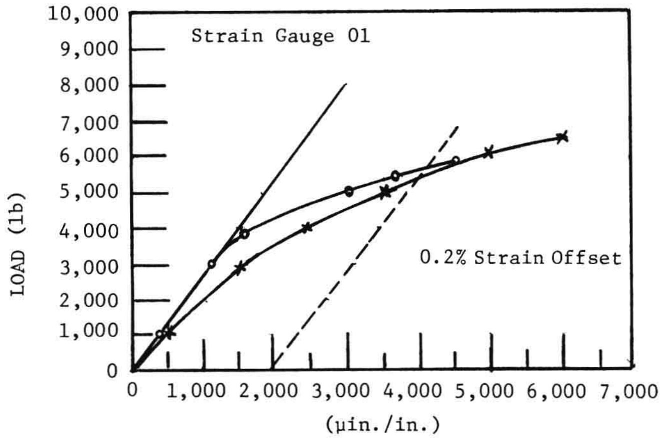

FIG. 4 LOAD-STRAIN DATA FOR IN-PLANE BENDING ($-M_Z$) WITH ZERO INTERNAL PRESSURE

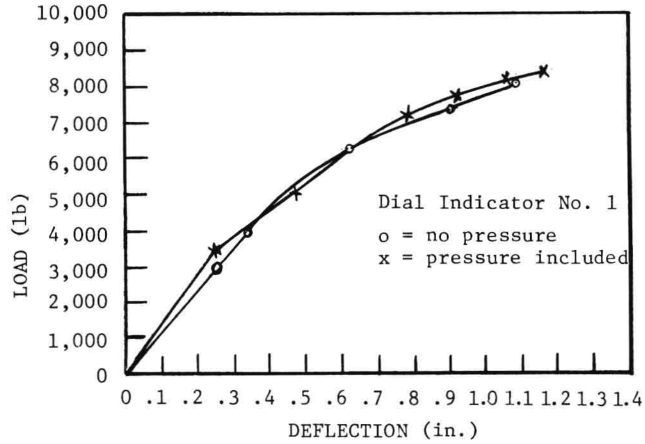

FIG. 5 LOAD-DEFLECTION CURVES SHOWING EFFECT OF INTERNAL PRESSURE

Ovality. An ovality of 3.6% was calculated from the analytical results for the load step corresponding to the maximum test load of 6,000#. Reference (1) does not provide specific post test ovality data for the PE-2 test. It does indicate that the maximum ovality measured for any of the long radius carbon steel elbows tested was 6.5%. The % ovality is defined as:

$$\% \text{ ovality} = \frac{D_o \max - D_o \min}{D_o \text{ avg}} \times 100 \qquad (3)$$

No appreciable loss of rated flow would be expected from this deformation.

Effect of Internal Pressure. The effects of internal pressure were also considered in the analytical approach. The results were evaluated against the observations made in Reference (1). Figure 5 presents a comparison of load versus deflection output at D_1 for a pressurized and an unpressurized model. This figure reflects the conclusions of Reference (1). Internal pressure increases the limit moment although the load at the onset of non-linear response is decreased. It does not reflect the extent of increase in load carrying capacity when compared to test data however.

Interpretation of Results

A review of the test versus analytical data indicates good correlation for the significant factors affecting functional capability. Based on favorable comparison, the FEM analysis method is considered to be an effective analytical tool for predicting the degree of plastic deformation in piping elbows under moment loadings.

Some factors which contribute to the differences are: (1) analytical solution is based on idealized dimensional and material conditions, (2) number of iterations for the inelastic analysis, (3) relatively coarse finite element mesh.

SAMPLE PROBLEM

A sample problem was run using the FEM analytical approach. This problem consisted of a 10-inch Schedule 40 carbon steel elbow (SA-106 Grade B) with an internal pressure of 800 psi. Material properties were taken at 400°F. The moment imposed on the elbow exceeded the maximum allowable as determined by Equation 9 of Reference (5), below.

$$S_{oL} = B_1 \frac{P_{max} D_o}{2t_n} + B_2 \frac{M_A + M_B}{Z} \leq 1.5 \quad S_y \qquad (4)$$

The flexibility characteristic (h) of this elbow is such that the moment carrying capacity is not adversely affected by internal pressure, i.e., $B_1 = 0$. The maximum allowable moment ($M_A + M_B$) from the solution of Equation (4) is 357,000 in-lb. The applied in-plane bending moment for which functional capability was to be assessed was 460,000 in-lb. This corresponds to Equation 9 of Reference (6) using 2.4 S_h as the allowable stress. This is represented by an applied load of 6,500# for the analytical model. Pertinent functional capability results for this load step are:

Stress

The resulting stresses indicate that even though there is inelastic deformation along the $\phi = 0^\circ$ and 180° axis, no significant yielding is evident along the $\phi = 90^\circ$ and 270° axis. The maximum stress intensity differences at the various circumferential locations are presented in Figure 6. These occur at a bend angle (∝) of 45°.

This demonstrates that no gross plastic deformation and subsequent "collapse" of the elbow occurs at this load level.

	STRESS (psi)	
LOCATION φ	INSIDE SURFACE	OUTSIDE SURFACE
0	-34,500.	36,900.
90	24,400.	-12,800.
180	-34,500.	36,900.
270	30,500.	-22,400.

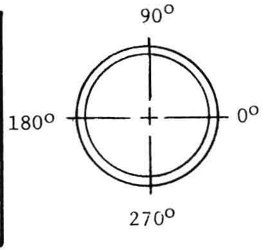

FIG. 6 STRESS DISTRIBUTION

Load/Deflection

Figure 7 presents the load/deflection curve for the sample problem.

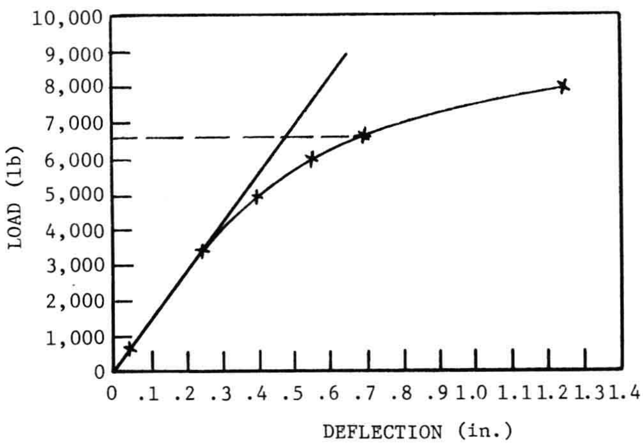

FIG. 7 LOAD - DEFLECTION CURVE FOR 10-INCH ELBOW

The total displacement as a result of the inelastic response of the elbow is only 50% higher than the extrapolated elastic displacement. This would not be expected to completely invalidate the piping system analysis.

Maximum Ovality

The maximum ovality is 4.1%. Essentially, no reduction in flow area occurs as a result of this cross sectional change.

SUMMARY

The FEM analysis method offers an effective analytical tool for assessing the functional capability concerns with plastic deformation of a piping elbow. Results from this method compare very favorably to experimental test data. Using this method on a sample problem, in-plane bending moments were applied which were in excess of certain "limit load" theory and consistent with maximum bending moments allowed at Level D Service Limits as defined in Reference (6).

Interpretation of these results indicate that no loss of functional capability will occur.

SI CONVERSION

1 in. = 0.0254M
1 lb. = 4.448N
1 psi = 6.895kPa

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SECONDARY STRESSES IN PIPE AND COMPONENT SUPPORT STRUCTURES

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ABSTRACT

It has been the practice of some designers to omit secondary bending moments from evaluation of truss-type pipe support structures. Bolted and welded component supports have bending moments at their joints even when the structure is designed as a pin-connected truss. For those members in compression, these secondary moments will reduce the axial load capacities. Hence, it is important to consider secondary bending in component support members which are loaded in combined compression and bending.

Revisions to the ASME Boiler and Pressure Vessel Code, Section III, Division 1, Appendices XVII-2000 and XVII-4000 should rectify this situation by requiring evaluation of the secondary moment in the well-known beam column interaction formulas. The wording was changed in the Winter 1981 Addenda of the code to require designers to account for secondary moment in the stability criteria. An increased limit is allowed in the formula which guards against plastic-hinge formation when the moment is secondary; this does not affect the stability of a member.

This paper discusses the classification of stresses into the primary and secondary categories for linear support structures. The importance of taking secondary moments into account when analyzing beam columns is emphasized.

INTRODUCTION

In a nuclear power plant, typical support structures are reasonably simple for pipe supports and somewhat more complex for components. Pipe supports may be no more than simple beams or even tension rods in which the most complex portions are the connections to the building structure and the pipe. Indeed, the pipe clamp or the clevis detail for a strut may involve more engineering than the main element of the pipe support. More complicated support structures for piping include knee braces, of which there may be hundreds for safety-related piping. Although supports for components (pressure vessels) may be more complicated, they too are often "linear" supports, i.e., they are composed of beam and column elements.

The ASME Boiler and Pressure Vessel Code, Section III, Division 1, Subsection NF (1) governs the design of nuclear power plant linear component supports as well as other types of supports. It has often been noted that Subsection NF design requirements are very similar to those in the AISC Specification (2) for the design of structural steel for buildings. However, differences do exist. The AISC provides rules for two loading conditions, design deadweight and live load, and design deadweight and live load combined with wind and seismic loads, whereas Subection NF provides rules for four levels of service loading in addition to design loads. Regarding structural elements in compression, Subsection NF is more conservative than the AISC specification by providing a load or stress limit which is two-thirds of the critical buckling load or stress regardless of the service limit or source of load. Another difference between the AISC specification and the ASME code, Subsection NF, is the recognition, by the latter code, of the differences between primary and secondary stresses in structures. However, the proposed AISC Specification for Nuclear Facilities (3) does define primary and secondary stresses and it also provides increased stress limits for combined primary and secondary stresses.

Because there is some confusion about the categorization of primary and secondary stresses in linear pipe and component support structures, this paper discusses the differences between the two categories. Also, while designers are aware of the reduction in column load capacity due to primary bending moments, the effects of secondary moments are not quite as clear. These effects are taken into consideration by Subsection NF as discussed herein.

PRIMARY AND SECONDARY FORCES, MOMENTS AND STRESSES

The ASME code (1) has long recognized that certain internal moments and forces in pressure vessels need not be limited to the elastic stress range. These are the secondary moments and forces induced by "structural discontinuities", such as a change in material thickness, or the junctions of two or more structural elements. On the other hand, primary moments and forces, those which maintain equilibrium of the component, must have greater restrictions to avoid catastrophic failure on the first application of load or pressure. If stresses due to primary loads exceed yield, then large distortions may result or the component may fail. The basic characteristic of a primary load is that deflections resulting from this load are not self-limiting, whereas those resulting from a secondary load are self-limiting. Secondary forces and moments result from restraint of free expansion or restraint of free rotation at a joint. Clearly, distortions of the component or structure redistribute and relieve secondary moments and forces, and, therefore, the loads are self-limiting.

Primary forces and moments can be distinguished from those which are secondary in beam and column structures such as linear component supports. The above criteria can be used to separate primary from secondary internal loads. For bending moments, the primary moment can result in formation of a plastic hinge causing instability, whereas stability is retained by redistribution of forces and moments for the secondary moment. As an example, the bending moment at the center of a simple beam is primary because the formation of a plastic hinge at this point will cause collapse and load redistribution will not occur. On the other hand, bending moments at the ends of a fixed-ended beam subjected to a uniform load are secondary; if the bending stresses reach yield and a plastic hinge begins to form, the fixed-ended beam has adequate redundancy to maintain equilibrium. Two other examples are shown in Fig. 1. The rigid frame subject to joint translation in Fig. 1(a) has primary moments and shears at the ends of the individual members. When the cross-bracing in Fig. 1(b) is added, however, these bending moments and shears are secondary; they are induced by restraint of free rotation of the member ends.

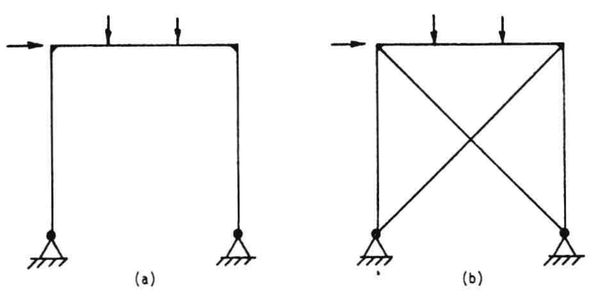

FIG. 1. RIGID FRAME - UNBRACED (a) AND BRACED (b)

These considerations lead us to the present definitions of primary and secondary stresses given in NF-3121.2 and NF-3121.3, respectively. The definitions, which apply to both linear and plate and shell supports, are given as follows.

> "**NF-3121.2 Primary Stress.** Primary stress is any normal stress or a shear stress developed by an imposed loading which is necessary to satisfy the laws of equilibrium of external and internal forces and moments. The basic characteristic of a primary stress is that it is not self-limiting. Primary stresses which considerably exceed the yield strength will result in failure or, at least, in gross distortion. A thermal stress is not classified as a primary stress. A general primary membrane stress is one which is so distributed in the structure that no redistribution of load occurs as a result of yielding. Examples of primary stress are general membrane stress in a circular cylindrical shell due to a uniformly distributed axial load, and bending stress in a cantilever beam due to a normal end load. In addition to the above, for piping and component supports, stresses induced in the support by restraint of free end displacement (NF-3111(e) and (f)) and anchor motion of piping are considered primary stresses.
>
> **NF-3121.3 Secondary Stress.** Secondary stress is a normal stress or a shear stress developed by the constraint of adjacent material or by self-constraint of the structure. The basic characteristic of a secondary stress is that it is self-limting. Local yielding and minor distortions can satisfy the conditions which cause the stress to occur, and failure from one application of the stress is not to be expected. An example of secondary stress is bending stress at a gross structural discontinuity."

Peak stresses, those concentrated stresses caused by notches, holes or other local discontinuities, and which fatigue the metal, should not be confused with secondary stresses, which occur over the entire cross section. Also, the analyst and designer should not consider load conditions to be either primary or secondary. For instance, the thermal expansion of piping may impose self-limiting loads on a pipe support because of the nature of thermal expansion. However, for support design it is necessary to consider this load as any mechanical or weight load in order to retain the linear deflection response (stiffness) of the support which is required to maintain the validity of the piping analysis. In this paper we are discussing the primary and secondary forces, moments, and stresses within the support, and not the sources of the applied load.

To summarize, the secondary stresses in a linear support are those resulting from self-constraint of the structure. Designers may not consider the secondary stresses in their preliminary design, nor may they want them. For instance, the knee brace shown in Fig. 2 may be designed considering only axial loads in the two members. Unfortunately, the welded connections at the ends of the members are not frictionless

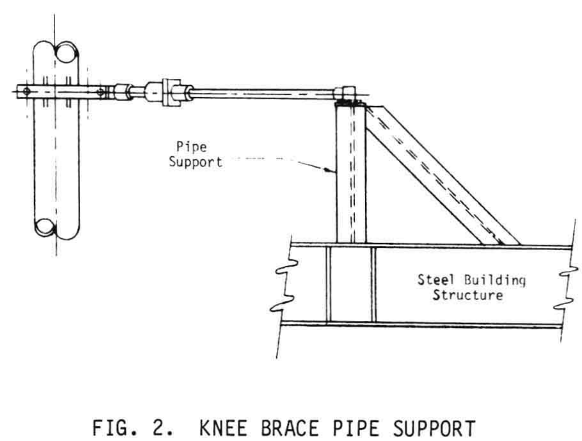

FIG. 2. KNEE BRACE PIPE SUPPORT

pins. Hence, bending moments are induced at the ends of the members since the members can't rotate freely. In the tension member, the bending moment will have little effect. But, for the compression member, the bending moment reduces the axial load capacity.

LINEAR SUPPORT ANALYSIS AND EVALUATION

There are two accepted methods of analyzing linear support structures: one is by elastic methods and the other is by limit analysis. Subsection NF provides evaluation criteria for these two analysis procedures in Appendices XVII-2000[1] and XVII-4000[1], respectively. Also, evaluation limits are given in Subsection NF for load-rating, a test procedure.

Evaluation by the working stress (elastic analysis) method provides increased stress limits for secondary stress. But, for beam columns, those linear members in combined axial compression and bending, and also for centrally loaded columns, special consideration must be given to internal support loads which may buckle a member. Otherwise, secondary stress limits are more liberal than primary stress limits.

The separation of primary and secondary stresses is a moot point if the analyst has chosen the limit analysis method in Appendix XVII-4000 of the ASME code. In this method the lower bound collapse load is determined and the formation of plastic hinges by secondary moments is allowed. Of course, very little or no plasticity is developed in the structure under its actual load conditions, but this method recognizes the fact that material ductility provides redistribution of internal structure loads if some plasticity were to occur in the structure.

The axial load in a linear member is usually a primary load but it may be secondary if the load is induced by a temperature rise in the member. If this is an elastic column which experiences thermal buckling, then the support may lose its load-carrying ability. In other situations, the designer may not consider the compressive load if his support has redundant cross-bracing such as that shown in Fig. 1. The brace which is in tension will maintain the structure's stability.

The bending moment which is applied to a compression element may be primary or secondary. It will be primary if it results from eccentricity of the axial force or if it is induced by lateral external loads applied to the member. On the other hand, it will be secondary if it is caused by constraint of the structure or restraint of free rotation due to welded or bolted joints. The torus columns for the Mark I containment structure are shown in Fig. 3. Various internal loads deform the ring girder but the columns are designed only to resist axial loads. Secondary bending moments are induced at the tops of columns by deformation of the ring girder.

An anomalous situation exists for support structures like that used for the Mark I containment. The ring girder is very heavy and has much greater stiffness than the column. Its restraining effect tends to increase column axial load capacity. On the other hand, the girder deformations impose a rotation at the top of the column; this, in turn, imposes curvature in the column which decreases compressive load capacity. The author has performed finite difference studies (4, 5) for situations of this type. Interaction curves were developed, and it was determined, as one would

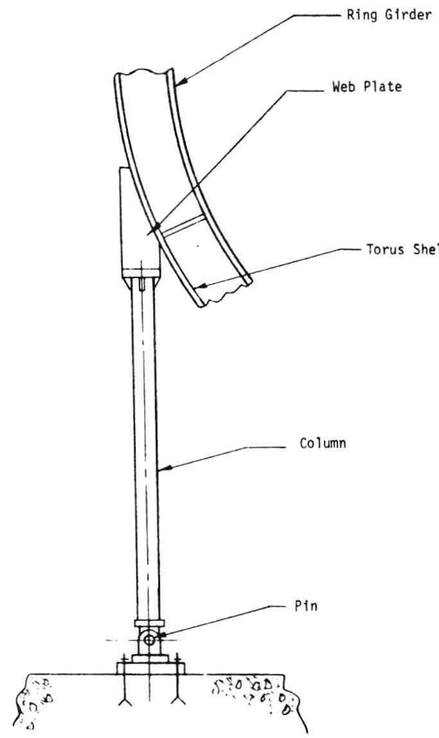

FIG. 3. MARK I CONTAINMENT COLUMN

expect, that for low values of secondary bending moment, the girder's restraining effect enhances column load capacity, whereas high values of secondary moment decrease the axial load capacity so that it doesn't make much difference whether the moment is primary or secondary. Figure 4 illustrates the interaction curves. In that figure P/P_y is the ratio of applied axial load to yield load, M/M_y is the ratio of applied moment to yield moment, R_c is the assumed compressive residual stress equal to zero in this illustrative example, and ℓ/r is the slenderness ratio. The effective length factor, K, used in column strength formulas is not applied to ℓ/r because the end effects are taken into account by the boundary conditions in the finite difference solution.

INTERACTION FORMULAS FOR BEAM COLUMNS

It is not always practical to perform finite difference solutions for columns with combined axial compression and bending moment. So approximate interaction formulas have been developed. It has been noted (6) that the initial curvature, regardless of whether the applied end moment is primary or secondary, is amplified by the so-called P-Δ effect[2]. Lateral deflections from the column centerline are amplified approximately by the factor (6)

$$\frac{1}{1-P/P_e}$$

[1] The Winter 1982 Addenda incorporated Appendix XVII into Article NF-3000.

[2] Some texts refer to the additional bending moment as secondary. That is not the case in the ASME code, nor in this paper, since that moment is not self-limiting.

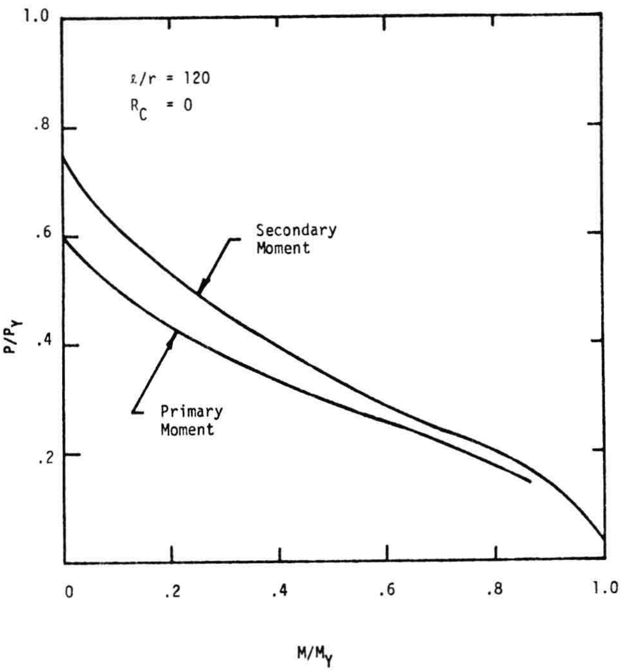

FIG. 4. INTERACTION CURVES FOR W8 x 31, MOMENT AT ONE END, OTHER END PINNED

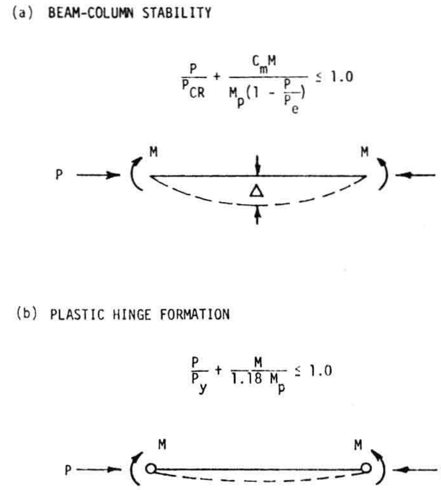

FIG. 5. STABILITY AND YIELD CRITERIA

where P is the applied axial load and P_e is the Euler buckling load.

This is the basis for the well-known beam column stability criterion.

$$\frac{P}{P_{CR}} + \frac{C_m M}{M_p(1 - \frac{P}{P_e})} \leq 1.0 \tag{1}$$

This empirical formula gives good agreement with numerical solutions of beam columns (7). In the event that Eq. (1) shows the member to be stable, another criterion is applied to determine if plastic hinges will form at the ends of the member. For a wide-flange section with bending about the strong axis, this criterion (6) is

$$\frac{P}{P_y} + \frac{M}{1.18\ M_p} \leq 1.0 \tag{2}$$

The stability and hinge criteria are illustrated pictorially in Fig. 5.

These two criteria are given in Appendix XVII-4000 for limit analysis, but the moment capacity, M_p, in (1) is replaced by M_m which accounts for lateral torsional buckling, a possibility which the designer must take into account when the major-axis and minor-axis slenderness ratios are significantly different.

$$M_m = (1.07 - \frac{\frac{\ell}{r_y}\sqrt{S_y}}{3160})\ M_p - M_p \tag{3}$$

The above formulas have been converted to stress criteria and another term has been added for weak axis bending. The stress criteria for beam columns are

$$\frac{f_a}{F_a} + \frac{C_{mx} f_{bx}}{(1 - \frac{f_a}{F'_{ex}})F_{bx}} + \frac{C_{my} f_{by}}{(1 - \frac{f_a}{F'_{ey}})F_{by}} \leq 1.0 \tag{4}$$

and

$$\frac{f_a}{.60\ S_y} + \frac{f_{bx}}{F_{bx}} + \frac{f_{by}}{F_{by}} \leq 1.0 \tag{5}$$

These appear in Appendix XVII-2000 of the ASME code as Eqs. (19) and (20), respectively. Of course, the same criteria are given in the AISC code and several texts, including References 6, 7 and 8, give a complete background on the development of these formulae. They were written specifically for wide-flange sections, but they also work well for other sections such as thick-walled tubes. The designer should keep in mind, however, that the moment multiplier, 1.18, in the denominator of the second term of Eq. (2), was derived specifically for strong-axis bending of wide flange members and other factors would be appropriate for other sections.

It is clear that when both the axial compressive load and end moments are primary, the beam column design should adhere to both stability and plastic-hinge criteria. When it is certain that the end moment is secondary and the axial force is primary, then the stability criteria, Eq. (1) or (4) should be applied. But in this case the formation of a plastic hinge at the end of the member will not result in collapse, so the limits of (2) or (5) can be exceeded without violating the integrity of the structure.

Limiting the Right-Hand-Side of (2) or (5) to 1.5 maintains linearity of the support stiffness for Service Levels A and B in those cases in which the bending moment is secondary. It must be emphasized, however, that the stability criteria must be evaluated using 1.0 on the right side for both primary and secondary loads.

The reduction factor, C_m, in the bending term of the stability criterion, Eq. (1) or Eq. (4), accounts for the primary or secondary nature of the bending moment by reducing the moment contribution to the left side of (1) or (4) under certain combinations of end moments when sidesway is prevented (6). When this is the case, moment resistance at the ends of the beam column is not required to maintain equilibrium of the overall support structure. However, the end moment, which is secondary in this case, may affect the column stability. The effects of C_m are illustrated in Fig. 6 which indicates that the plastic hinge criterion will control when the bending moment is secondary. This was borne out in studies by Hooper (9).

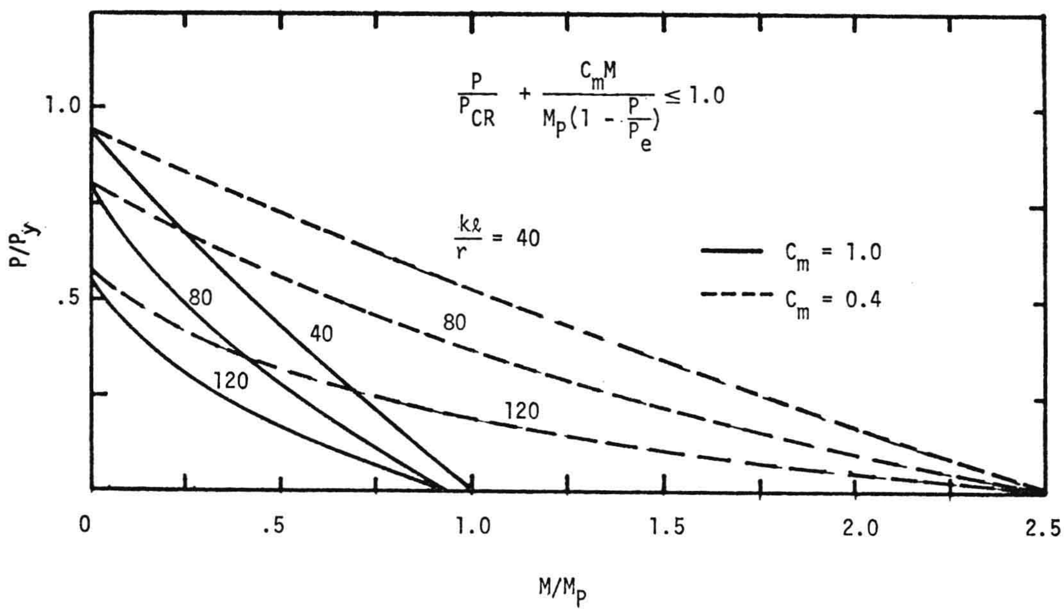

FIG. 6. COMPARISON OF MOMENT REDUCTION FACTORS, C_m

ASME SECTION III, SUBSECTION NF REQUIREMENTS

It has been the practice of some designers to omit secondary bending moments from evaluation of truss-type support structures. Bolted and welded component supports have bending moments at their joints even when the structure is designed as a pin-connected truss. For those members in compression, these secondary moments will reduce the axial load capacities. Hence, it is important to consider secondary bending in component support members which are loaded in combined compression and bending.

Revisions to the ASME Boiler and Pressure Vessel Code, Section III, Division 1, Appendices XVII-2000 and XVII-4000, should rectify this situation by requiring evaluation of the secondary moment in the beam column formulas. An increased limit is allowed in the formula which guards against plastic-hinge formation when the moment is secondary. This does not affect the stability of a member.

Beam column limits are given in Eqs. (6) and (7) of Appendix XVIII-4000 by the well-known interaction formulas. The wording was changed in the Winter 1981 Addenda to require that secondary moment be included in the interaction formulas. But when the designer is assured that the moment is secondary, then the yield criterion is relaxed somewhat by replacing the right side[3] of Eq. (2) or (5), in this paper, with 1.5. In this case plastic hinging will not fail the structure.

Typical interaction curves for a short column ($K\ell/r$ = 48.3) are illustrated in Fig. 7. The stability curves will control when moments are secondary. The advantage of using limit analysis per Appendix XVII-4000 rather than working stress analysis per Appendix XVII-2000 should be noted.

CONCLUSION

Traditionally, linear component support structures have been designed and evaluated without separating stresses into the primary and secondary categories. Analysts usually consider all stresses to be primary or in many cases they have neglected secondary stress altogether by assuming that bolted or welded connections in truss-type structures are frictionless pins. However, the forces, moments, and stresses can be separated easily in many cases into

[3] Although this criterion was added in the Winter 1981 Addenda, it was inadvertently omitted in the Winter 1982 Addenda which incorporated Appendix XVII into Article NF-3000.

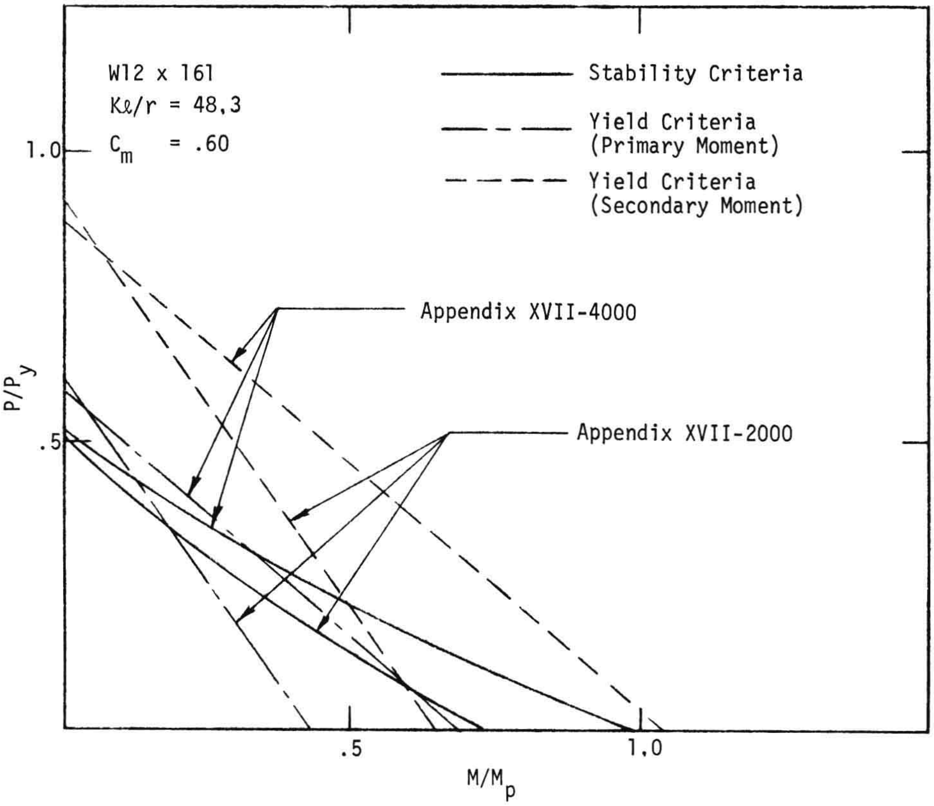

FIG. 7 COMPARISON OF APPENDIX XVII-2000 AND 4000 INTERACTION CURVES FOR FIXED-PINNED COLUMN

these two categories by noting that primary stresses are required to maintain equilibrium and secondary stresses are associated with limited deflections or rotations.

But, it is often difficult to separate the primary and secondary stresses. A linear, elastic computer analysis will not differentiate between the primary stresses and the secondary stresses. When in doubt the analyst can always assume that all of the computed stress is primary; this will ensure a conservative design. The analyst can perform two analyses, one which includes the redundancies associated with secondary stress and the other with all redundant connections released. The first analysis will provide primary plus secondary stress, and the second will only provide primary stress, respectively.

Both primary and secondary bending stress reduce the axial load capacity of columns in compression. Secondary bending moments won't reduce the column strength as much if the restraining members at the ends of the column are very stiff.

The ASME Boiler and Pressure Vessel Code, Section III, Subsection NF, accounts for secondary bending stress in beam column interaction formulas. The limit on the yield criterion, Eq. (2) or (5), is increased to 1.5 to account for the fact that plastic hinge formation will not fail the structure if the moment is secondary.

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NOMENCLATURE

C_m, C_{mx}, C_{my} = Moment Reduction Factors

f_a = Computed Axial Load Stress

F_a = Allowable Axial Compressive Stress

f_{bx} = Bending Stress due to Moment About x-Axis

f_{by} = Bending Stress due to Moment About y-Axis

F_{bx} = Allowable Bending Stress for Moment About x-Axis

F_{by} = Allowable Bending Stress for Moment About y-Axis

F'_{ex} = Elastic Buckling Stress for Buckling About x-Axis

F'_{ey} = Elastic Buckling Stress for Buckling About y-Axis

K = Effective Length Factor

ℓ = Length

ℓ/r = Slenderness Ratio

M = Applied Bending Moment

M_m = Reduced Moment Capacity

M_p = Full Plastic Moment

P = Axial Thrust

P_{cr} = Critical Load for Centrally Loaded Column

P_e = Euler Buckling Load for Buckling in Plane of Bending

P_y = Axial Yield Load

r = Radius of Gyration About Axis of Buckling