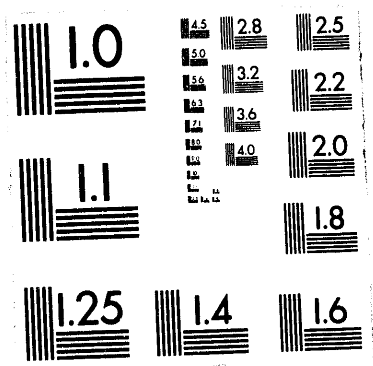
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STATIC ANALYSIS OF A PIPING SYSTEM WITH ELBOWS (U)

by

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STATIC ANALYSIS OF A PIPING SYSTEM WITH ELBOWS

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ABSTRACT

Vibration tests of elbows to failure were performed in Japan [1] in the early 1970s. The piping system included two elbows and an eccentric mass. Tests were run both pressurized and unpressurized. This report documents a static analysis of the piping system in which the elbows are subjected to out of plane bending. The effects of internal pressure and material plasticity are investigated.

DESCRIPTION OF PHYSICAL SYSTEM

The pipe system analyzed consists of three straight pipe segments and two long radius elbows (R = 11.43 cm) as shown in Figure 1. The majority of the pipe in this system is 3 in sch 40S. The thin elbow is 3 in sch 10S and there is a 5 cm tapered section to allow transition from the sch 40S pipe to the sch 10S elbow on each side. The purpose of the

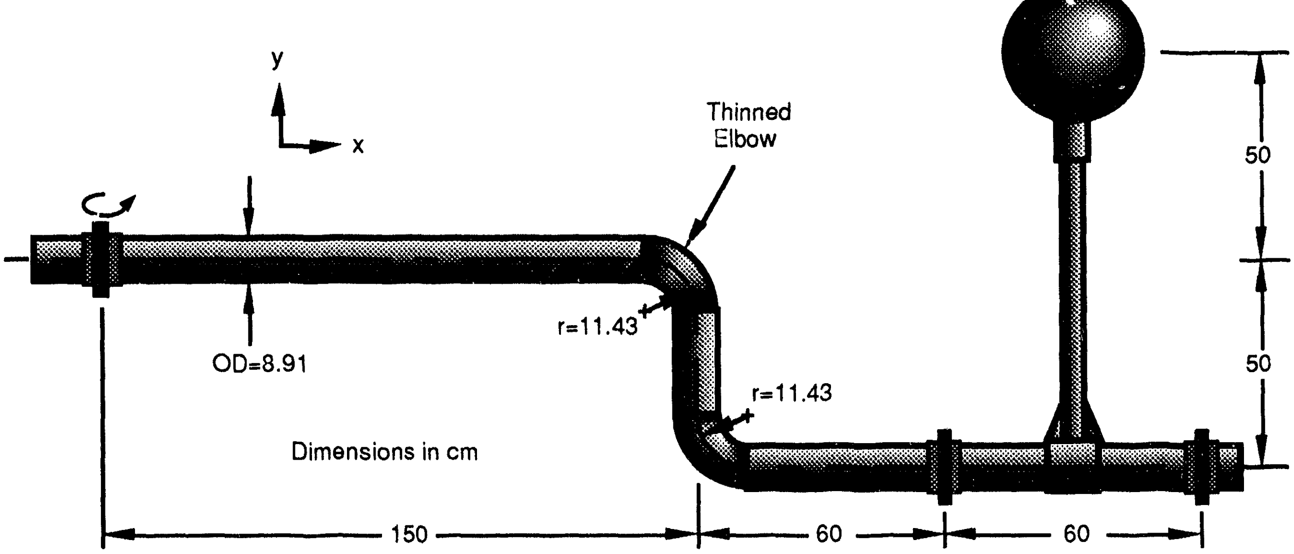

Figure 1: PIPE SYSTEM

1/25 tapered joints is to avoid stress concentrations at the thickness transitions. The diameter and thickness of the piping is shown in Table 1.

	Outside Diameter (cm)	Thickness (cm)
Sch 10S	8.91	0.3
Sch 40S	8.91	0.55

Table 1: PIPING DIMENSIONS

Material Properties

The engineering properties of the 304L stainless steel material are as shown in Figure 2. The material has a yield strength of 2.14 E9 $^{dyne}/_{cm^2}$ and an ultimate strength of 6.12 E9 $^{dyne}/_{cm^2}$ at 31% strain.

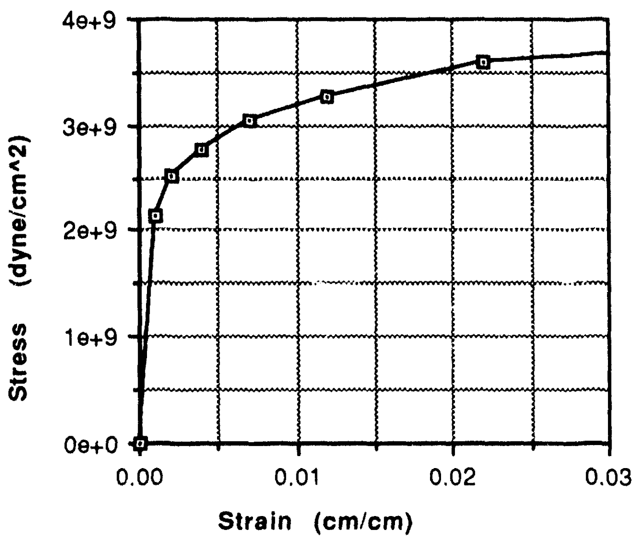

Figure 2: MATERIAL STRESS-STRAIN BEHAVIOR

Loading Conditions

In order to investigate the static response of the pipe system to out-of-plane elbow bending, a load was applied to the top of the shaft at the concentrated mass. The applied load is in the z-dir in Figure 1.

DESCRIPTION OF FINITE ELEMENT MODEL

The finite element model (FEM) of this piping system was compiled using the ABAQUS code Version 5.2. [2]

Elements Used

The elements used for the majority of the FEM are the PIPE31 and ELBOW31 elements as described below.

Pipe Elements. The PIPE31 element is a three dimensional beam which uses Timoshenko beam theory and includes transverse shear deformation. The axial and bending behavior are interpolated linearly and include the effects of material nonlinearity. The shear behavior is treated as if the response is linear elastic, independent of the axial and bending response.

In this analysis the cross-section of the pipe elements are integrated numerically to obtain the generalized force/strain relations. This allows for generality of material response since each integration point in the section is considered by the constitutive routines. However, the cross-section of the element is assumed not to deform except for hoop strain due to internal pressure. The pipe elements in this analysis used eigl integration points around the circumference of the cross-section as shown in Figure 3.

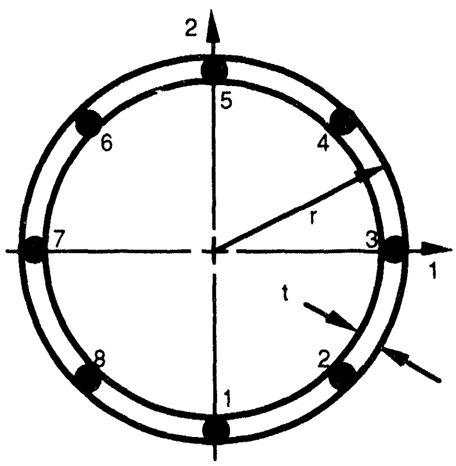

Figure 3: PIPE ELEMENT CROSS-SECTION

Elbow Elements. In the usual approach to linear analysis of elbows, the response prediction is based on semi-analytical "flexibility factors" used to correct results obtained with beam theory. Such factors no longer apply in nonlinear cases and the pipe must be modeled as a shell in order to predict the response accurately. This is the concept behind the ELBOW31 element; although it appears as a beam element to the user, it is comprised of shells which allow complex deformation patterns.

The ELBOW31 is a three dimensional element which allows ovalization and warping of the cross-section. The element uses linear interpolation along the length and Fourier interpolation around the pipe to model the ovalization and warping effects.

The elbow elements in this analysis used five integration points through the thickness and twenty integration points around the pipe as shown in Figure 4. The ovalization and warping effects are modeled using six Fourier modes.

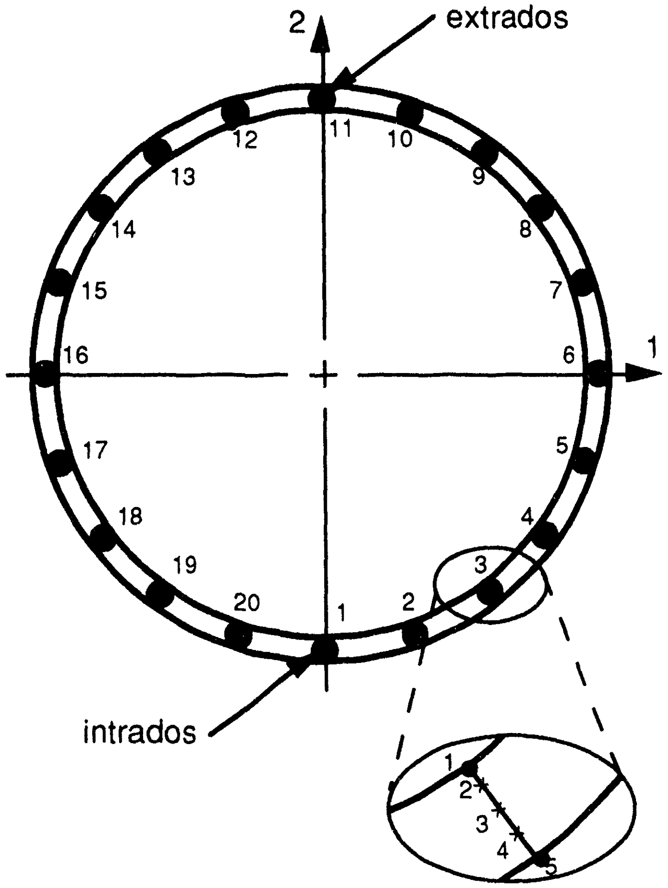

Figure 3: ELBOW31 ELEMENT CROSS-SECTION

Other Elements. There are also MASS and B31 elements used in this analysis. The shaft which connects the eccentric mass to the pipe is modeled using B31 beam elements. The B31 element is formulated identically to the PIPE31 element except for the internal and external pressure aspects. The MASS element allows the introduction of a concentrated mass at a point.

Node and Element Discretization

In physical piping systems any cross-sectional distortion of an elbow will be propogated a finite length down the pipe. So for the pipe system under investigation, the elbow elements with ovalization and warping capabilities were used to model not only the 90° arc of the elbows, but also the straight pipe about ten cm beyond on each side. At the points where the model transitioned from elbow elements to pipe elements (which do not have ovalization or warping capability) boundary conditions are imposed which force the element cross-section to remain undistorted and therefore compatible with the adjacent pipe element. In this fashion end effects which could artificially restrain elbow ovalization are avoided.

In order to provide a smooth transition between the straight pipe segments and the elbows, elbow elements were used to model the straight pipe adjacent to the elbows. See Figure 5. Each 90° elbow is modeled using six elbow elements. If two curved elements have normal directions within 20° a single normal is defined for the common node. Six elements were used in order to maintain a single normal definition at each node and a node at the center of the 90° arc.

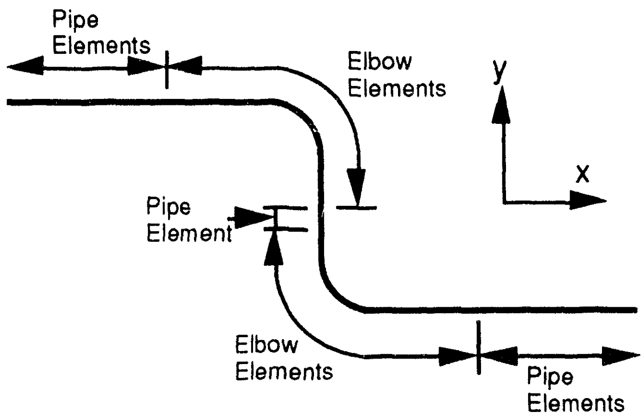

Figure 5: ELEMENT DISCRETIZATION

The PIPE31 elements used in this analysis have a length of about five cm. The pipe element in the vertical section of straight pipe was included to facilitate the extraction of output data.

Boundary Conditions

The boundary conditions associated with this model include both physical constraints and restraints to provide a smooth transition between the pipe and elbow elements. The boundary conditions which model physical constraints are shown in Figure 1. The boundary condition on the left side of the figure is a constraint of all degrees-of-freedom except rotation about the vertical axis (ry). The two boundary conditions on the right side of Figure 1 constrain only the translations. The boundary conditions which provide element continuity between the pipe and elbow elements are discussed above.

Nonlinearities

The effects of two nonlinearities are included in this analysis: pressurization effects and material plasticity.

Pressurization Effects. Pressurization has at least two effects on a pipe system: tension stiffening and reduced cross-sectional distortion. Tension stiffening occurs when the response of a structure to load in one direction is affected by load in another direction. This phenomenon is demonstrated by a guitar string. When the tension on the string is increased, the natural frequency (or pitch) of the out-of-plane vibration is increased. A similar response is seen in piping systems. In addition to tension stiffening internal pressure tends to reduce ovalization and warping of the pipe cross-section. Ovalization reduces the area moment of inertia and thereby reduces the bending stiffness in the direction of the applied moment. When internal pressure is applied the bending stiffness of the pipe system is increased. Pressurization Effects are studied in this paper by running the static load case with and without internal pressure.

Metal Plasticity. The effects of metal plasticity on the structural response of this pipe system are investigated. For use in the FEM, the engineering properties are translated to true stress-strain properties. The equations for this transformation are as follows:

$$\varepsilon_{true} = ln(1+\varepsilon_{eng})$$

$$\sigma_{true} = \sigma_{eng}(1+\varepsilon_{eng})$$

Both the engineering and true properties are shown in Figure 6.

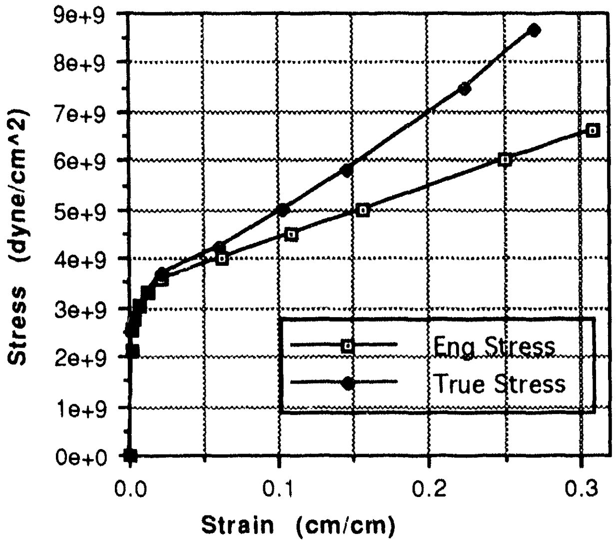

Figure 6: MATERIAL PROPERTIES

RESULTS AND DISCUSSION

In this analysis four cases were studied:

case 1: Elastic properties, unpressurized
case 2: Elastic properties, pressurized,
case 3: Plastic properties, unpressurized
case 4: Plastic properties, pressurized

Plasticity Effects

A plot of the axial strain on the surface of the thinned elbow versus the moment applied to the section is shown in Figure 7 for both elastic and elastic-plastic material properties. (cases 1 and 3). It can be observed that case 3 with material plasticity shows higher strains at applied moments above 2E10 cm-dyne than case 1 with elastic material properties.

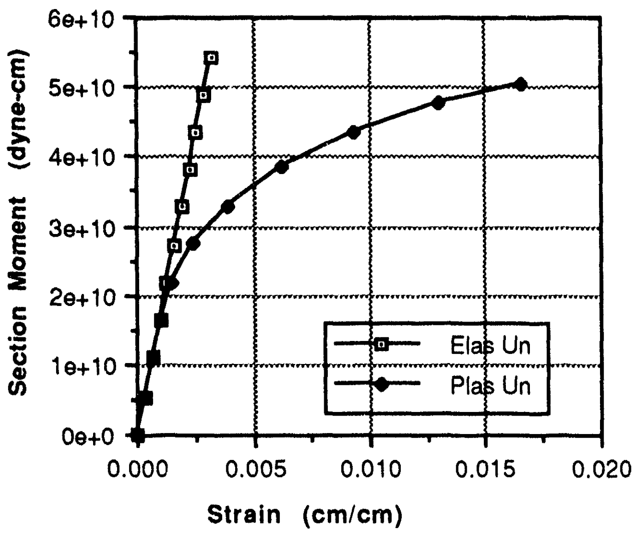

Figure 7: PLASTICITY EFFECTS

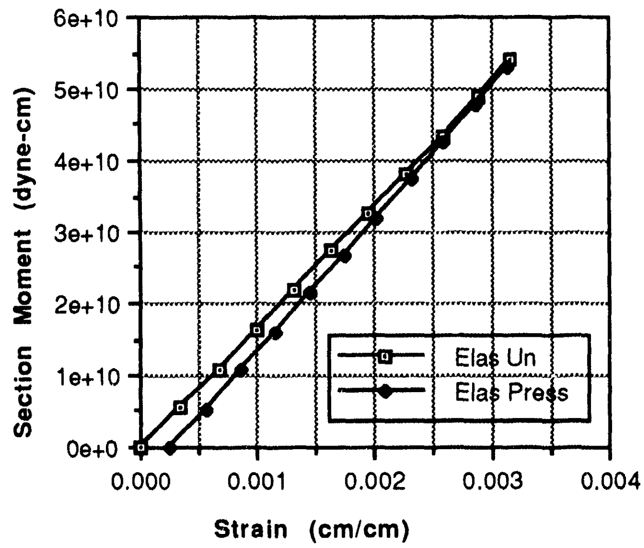

Figure 8: PRESSURIZATION EFFECTS

It should be noted that the points of maximum applied moment for the two cases actually have the same load, 5.53E8 dyne, applied to the concentrated mass. The reason that the section moment is different for cases 1 and 3 is that the plasticity in case 3 allows the applied moment to redistribute away from the part of the structure where the plasticity occurs. The load redistributes to areas of the structure with higher stiffness.

Pressurization Effects

Internal pressure tends to stabilize a pipe structure and stiffen the response to loads. Figure 8 is a plot of the axial strain on the surface of the thinned elbow versus the section moment for both unpressurized and pressurized conditions with elastic material properties. (cases 1 and 2)

It is noted that the two curves are linear. Even though the pressurized system (case 2) starts with a higher strain level, the strain increase per unit load is lower. The stiffness is increased by 8% due to tension stiffening and reduced cross-sectional distortion. A measure of the elbow elastic stiffness, in terms of moment per unit strain, is shown in Table 2.

Case	Initial Strain (cm/cm)	Moment at Thinned Elbow (dyne-cm)	Surface Strain at Thinned Elbow (cm/cm)	Stiffness (dyne-cm /strain)
1 - Unpressurized	0	5.42 E10	3.17 E-3	1.71 E13
2 - Pressurized	2.61E-4	5.31 E10	3.14 E-3	1.84 E13
% Difference				8%

Table 2: ELBOW STRAINS

Another effect internal pressure has on a piping system is reduced ovalization and warping. Figure 9 is a plot of the axial strain on the surface of the thinned elbow versus the section moment for both unpressurized and pressurized conditions with elastic-plastic material properties. (Cases 3 and 4) It can be observed from Figure 9 that the two cases respond very similarly in the elastic region, less than 2E10 dyne-cm section moment. However, above 3E10 dyne-cm section moment the pressurized system response is stiffer than that of the unpressurized system. This increased stiffness is attributed to tension stiffening and reduced ovalization and warping of the cross-section. When internal pressure is applied, the elbow it is more resistant to cross-sectional distortion. Warping and ovalization cause additional strains in the thinned elbow. The combined effect of tension stiffening and reduced ovalization and warping causes the axial strain in the pressurized system to be reduced by 35%.

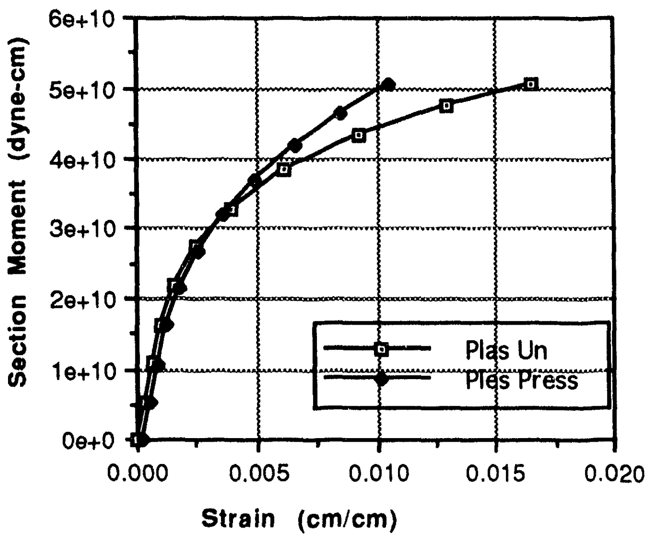

Figure 9: COMBINED EFFECTS

CONCLUSIONS

The effects of pressurization and material plasticity on the response of a pipe system with elbows subjected to an out-of-plane bending load were investigated. Plasticity caused higher strains in the critical elbow. Plasticity also caused load redistribution. Pressurization caused tension stiffening and tended to reduce distortion of the elbow cross section. These effects of pressurization caused reduced strains in the critical elbow.

ACKNOWLEDGMENT

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[1] M. Fujita, K. Shiragi, T. Nakamura, and K. Kitaide, "Vibration Damage Experiments Relating to Earthquake-Resistance; Critical Strength of Curved Pipe", *Transactions of the Japanese Society of Mechanical Engineers*, April 28, 1977

[2] Hibbitt, Karlsson and Sorensen, Inc., *ABAQUS/Standard User's Manual*, Version 5.2, 1992, Pawtucket, RI

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