1114007: ELASTO-PLASTIC COLLAPSE ANALYSIS OF PIPE BENDS USING FINITE ELEMENT ANALYSIS

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Abstract

When an external load is applied to one of its ends, a pipe's bends cross section tends to deform significantly both in and out of its end plane. This shell type behaviour characteristic of pipe bends and mainly due to their curves geometry accounts for their greater flexibility. This added flexibility is also accompanied by stresses and strains that are much higher than those present in a straight pipe.

The primary goal of this research is to study the elastic-plastic behaviour of pipe bends under out of plane moment loading. It is also required to study the effects of changing the value of the pipe bend factor and the value of the internal pressure on that behaviour and to determine the value of the limit moments in each case.

The results of these analyses are presented in the form of load deflection plots for each load case belonging to each model. From the load deflection curves, the limit moments of each case are obtained. The limit loads are then compared to those computed using some of the analytical and empirical equation available in the literature. The effects of modelling parameters are also studied. The results obtained from small displacement and large displacement analyses are compared and the effects of using a strain hardened material model are also investigated.

To better understand the behaviour of pipe elbows under out of plane bending and internal pressure, it was deemed important to know how the cross section deforms and to study the distribution of stresses that cause it to deform in a particular manner. An elbow with pipe bend factor h=0.1 to h=1 is considered and the results of the detailed analysis are thereof examined.

Keywords-Elasto-plastic, finite element analysis, pipe bends, simulation

I. INTRODUCTION

Large pipelines and pipe networks are part of almost every industrial setup today. These are most commonly found in petroleum rigs, refineries, factories producing chemicals andpharmaceuticals, and in power plants. In these and other industrial applications, pipes are veryoften used to carry substances that, by virtue of their pressure, temperature, physical andchemical characteristics, can have serious negative effects on health, property and theenvironment, if released into the atmosphere. Examples of such substances include steam, oil, and sulphurand chlorine gas. Failure in a piping system could cause problems, like an unscheduled, and hence costly, plant shut down for maintenance; or even a catastrophe, like exposing the core of a nuclear reactor. Therefore, the integrity of pipes in industrial contexts is of paramount importance. This integrity relies heavily on the correctness of design codes and practices, which can only be achieved through a thorough understanding of the behaviour of piping components and systems under different types of loads.

Stresses in piping systems are developed as a result of sustained loads, like the weight of the pipe itself and the pressure of the fluid running inside it. The effects of this kind of loads are minimised by selecting an adequate type of supports and using a sufficient number of them.Dynamic loads of seismic origin or generated by a defective attached device (e.g. pump or compressor), and thermal loads, which cause different pipe segments to expand, also create stresses within the piping system. Generally, dynamic and thermal loads are more important and more complex to deal with. Hence, it is vital that some means or mechanism, for relieving these stresses, be present in the design of a piping system, to avoid overloads which might in turn lead to failure of a pipe segment, or cause damage to an attached device, vessel or support.

A. AIM

To investigate the effect of internal pressure on the elastic-plastic behaviour of pipe bends using Finite Element Analysis.

B. OBJECTIVES

- To study, with different values of bend factors, the behaviour of pipe bends
- To investigate the limit pressures beyond which the pipe bend will collapse, using finite element analysis

II. LITERATURE SURVEY

A. THEORETICAL ANALYSIS OF PIPE BENDS

First demonstrated by Bantlin (1910), curved pipes behave differently under load than predicted by simple beam theory. The first theoretical explanation of this discrepancy was presented by Von Karman (1911), and much of the theoretical work done subsequently was an extension of his work, or at least based on the same principle of potential energy minimization. Other closed-form solutions were based on the mechanics of materials principles, or thin shell theory. All these solutions acknowledge the fact that pipe bends have higher flexibility and stresses,and a different stresses distribution, from the ones predicted by simple beam theory. The general approach followed in piping system flexibility calculations, and still widely adopted indesign codes, relies on theuse of "flexibility factors" and "stress-intensification factors", which are simply the ratios of actual flexibility and stress to those predicted by simple beam theory. The different approaches aim at providing more accurate estimates of these correction factors, in a form that can adequately be simplified, to become readily usable in design context.

A common drawback of most theoretical solution however, is that they are based on elastic analysis concepts, and cannot be used for the purpose of nonlinear analysis, which is required to predict the response of a pipe bend correctly, especially in accident conditions where plasticity behaviour dominates. Nonlinear theoretical analysis has been explored by a small number of workers, like Spence (1972). However, these efforts did not realize enough success to warrant their use in design. In addition, theoretical solutions are only useful in the analysis of pipe bends of circular cross-section.

Von Karman (1911) publish the first theoretical stress analysis of the problem of the problem of the problem of in-plane bending of pipe bends, which was later generalised by Vigness (1943), to include out of plane bending. In both of these analyses, the deformation of the bend's wall was represented by a trigonometric series whose coefficients were determined by minimizing the total potential energy.

Major simplifying assumptions were made in these analyses:

- Internal pressure effects are ignored.
- The pipe bend is not connected to any straight pipes or flanges. In other words, end-effectsare ignored and a standalone pipe bend is assumed.
- The ratio of the pipe radius to the bend radius (r/R) is negligiblerelative to unity, i.e. longradius elbows (R/r>>1) were assumed.
- The pipe bend's cross-sections remain plane and perpendicular to the bend'scentreline evenafter deformation. This precludes warping effects from the analysis.
- Under torsional moment loading, the pipe bend was assumed to behave like a straight pipe,keeping a circular cross-section.
- The hoop membrane strain in the circumferential direction was assumed to be nil, whichmeansthat the cross-section ovalizes without any changes in the length of its circumference.

Both of the analyses, agreed with Bantlin's results (1910), by indicating that longitudinal tensile and compressive stresses in the tube's wall, produce component forces acting towards and away from the centre of curvature, respectively. These forces result in the flattening of the cross-section into an oval shape, as shown in the figure below which in turn accounts for the increased flexibility and the different stress distribution compared to those predicted by simple beam theory and those found in straight pipes.

They also showed that the bend's maximum stresses and its deformation,namely its end rotation, are higher than those of a straightpipe of the same size and material. These results,expressed as flexibility and stress-intensification factors that are greater than unity, depend on a dimensionless parameter, the pipe bend factor (h), defined as:

$$h = \frac{R.t}{r^2}$$

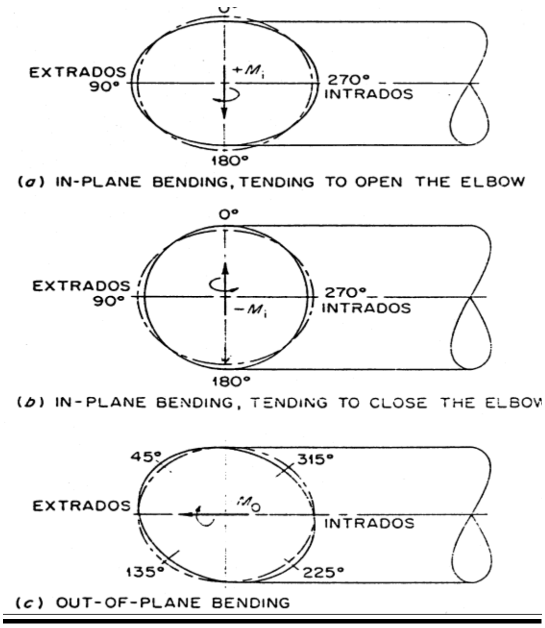

Fig 1. Cross-Sectional Deformation of a Pipe Bend under In-Plane and Out-of-Plane Loading (Dodge and Moore, 1972)

III. EXPERIMENTAL INVESTIGATION ON PIPE BENDS

The most comprehensive study, and the one that is referred to most frequently in the literature, is the one conducted by Greenstreet (1978), at the Oak Ridge National Laboratory (ORNL). In this study, load-deflection responses were determined for twenty 6-inch nominal diameter commercial pipe elbows, sixteen of which were made of ASTM A-106 grade B carbon steel and the remaining four were made of ASTM A-312 type 304L stainless steel.

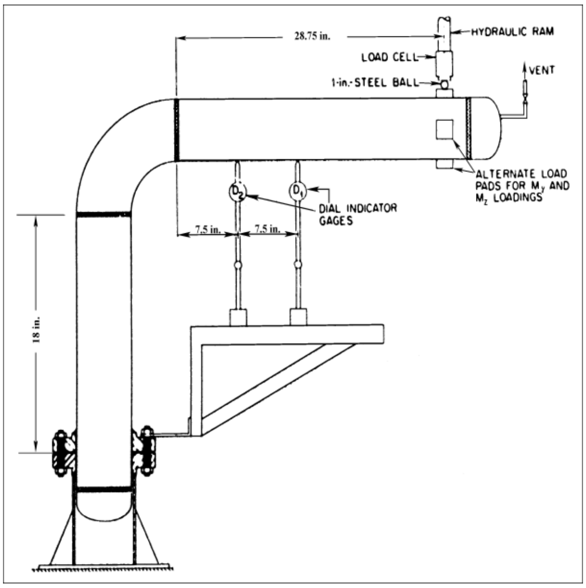

Fig 2: Diagram of the Test Setup Used by

Greenstreet (1978)

They concluded that in the case of in-plane bending in the opening direction, the ovalization of the elbow tends to increase its stiffness, and displace the weak spot in the assembly towards one of the junctions between the elbow and the adjacent straight pipe segments. Failure takes the form of a crease that appears at this weak spot and absorbs all subsequent deformation, preventing the elbow from deforming any further. In-plane bending in the closing direction tends to decrease the stiffness of the elbow, and failure takes the form of excessive ovalization, or flattening of the mid-section. It is reported that this mode of loading is the most critical, since failure takes place at a relative low value of the applied moment.

Hilsenkopf, Bonet and Sollogoub (1988) conducted two series of tests on 90^0 long radius elbows. The first series, which consisted of 10 tests, was conducted on thick-walled TU 42C (equivalent to ASTMA A-106 grade B) ferrite steel elbows, with an outside diameter to wall thickness ratio ($D_0/t=6.7$). a second series of 15 tests was conducted on thin-walled Z2 CN 18-10 (equivalent to ASTM A-312 Type 304L) austenitic stainless steel elbows with $D_o/t=90$.
During the tests, the elbows were subjected to in-plane bending moments, in either the opening or the closing direction, or to out-of-plane moments. From the results obtained, and especially for the thin-walled elbows, Hilsenkopf et al, reported that the cross-section of the elbow tends to ovalize as soon as a bending moment is applied, in any direction, to one of the elbow's extremities. This ovalization keeps increasing applied moment. The tests were extendedsufficiently to observe the ovalization modes under different types of loading and to reveal the failure mode.

Sobel and Newman (1980, 1983 and 1986), conducted three experiments on nominally identical 90^o long radius pipe bends, with an outer diameter of 16 inches and a wall thickness of 0.42 inch. In the first test, which was conducted at room temperature, and in the second test conducted at 1100^oF, (593), an in-plane moment was applied in steps until plastic collapse occurred. In the third test,conducted at 1100^oF, the moment was increased to a value for about 2800 hours, to examine the creep behaviour of the elbow.

IV. METHODOLOGY

The methodology that this project will follow can be summarised by three simple aspects:

- Research formulation and data analysis
- Experimental designs and system modelling
- Complete system simulation

A. Research Formulation and data analysis

The tool that was used in this form of methodology is documents review. Documents containing the information about finite element analysis of pipe bends were looked into to see how the tests were done. This was able to provide a substratum on which to lay the foundation of this numerical analysis of pipe bends. Already published journals were also analysed on subjects on elastic-plastic bending and in particular, pipe bends. This was done as a way to show how analysis of the elastoplastic behaviour of pipe bends is done under different parameters of pressures applied and different materials.

The data was therefore analysed, and trends were put down on what has been calculated in experiments by those who carried them out in their journals, articles and papers. All this gave a guide line on how this project was going to be undertaken, having analysed the experiments done in the documents.

The internet was also consulted, which gave quite a number of experiments carried out on this subject. Much emphasis was put on the elastoplastic behaviour of different types of materials, when they undergo some loading. Different pressureswere analysed to see how the different materials behave under different loads.

B. Experimental designs and system modelling

In the subject topic in question, experimental designs and modelling was done. ABAQUS software was used to do experimental design on the pipe bends that are being studied. The experiments were done and were limited to one material (type 304 stainless steel).

The model of the pipe bend was drawn using Solid Edge software. Analysis of the internal pressures was done so as to come up with a finite element analysis that shows the limits beyond which the pipe bend will collapse, in an elastic-plastic manner. Experiments were done and results were given diagrammatically, at each stage, to show the elastic then plastic behaviour of the type 304 stainless steel, when subjected under different loads or pressures.

Graphs showing the elastic-plastic behaviour of the pipe bends were drawn to enable us to see the trends in the elastoplastic behaviour of type 304 stainless steel pipe bends. Computed resulted were used to see the limits to which the bends can hold before they collapse.

C. Complete system simulation

After having modelled the pipe bends, simulation was done and results were shown diagrammatically, for how the system will sustain the pressures they are subjected to before they go elastic and plastic. ABAQUS wasthen used to simulate the model. Results of simulation were analysed and are shown in the document, diagrammatically. This is the finite element analysis.

D. Finite element modelling and analysis

One main goal of this study is to investigate the effect of internal pressure on the behaviour of pipe bends, with different values of the bend factor (h=Rt/r2), under out-of-plane momentloading. A 90□ □ standalone pipe bend, was used throughout this study. This yields moreconservative estimates of limit loads, since the stiffening effect of end-constraints
(e.g. attached flanges or connected straight pipe segments) is neglected.

The pipe bend had a nominal diameter of 16 inches, and the bends axis had a radius of curvature R=24in , to represent a long-radius of radius ratio (R/r=3).

E. Material model

The material used throughout this study was type 304 stainless steel, following the measured response at room temperature reported by Sobel and Newman (1979). This material has the following properties:

Young’s modulus : E = 28.1□ 106 psi (193.74 GPa)

Yield stress : □ y = 39440 psi(271.93 MPa)

Poisson’ s ratio : □ □ = 0.2642

V. CONCLUSIONS AND RECOMMENDATIONS

Shakedown and limit surfaces for pipe bends covering a large range of bend characteristics are presented. Non-dimensionalising the results against limit moments and pressures for an equivalent straight pipe allows trends to be identified with changing R/t, r/t and closing and opening bending. Based on the results presented, the followingobservation and design recommendations are proposed:

- When subject to internal pressure and cyclic in-plane bending, the normalised moment correspondingto the reverse plasticity limit is related to h, for all three modes of bending. The shakedown envelopes show no further trends with h; the ratios R/r and r/t must be considered to ascertain the behaviour.
- Decreasing r/t increases the normalised cyclic bending moment corresponding to the reverse plasticity limit. Decreasing r/t also decreases the margin between the shakedown envelope (for cyclic loading) and the limit load surface (for monotonic loading). Designers must therefore take care to ensure that a sufficient margin is present to prevent an unexpected increase in the cyclic load causing plastic collapse.
- Increasing R/t increases the normalised cyclic bending moment corresponding to the reverse plasticity. Additionally, increasing R/t decrease the margin between the shakedown and limit surfaces, and so care should be taken to ensure sufficient margin is present.
- Opening and closing bending show no difference in the trends displayed, and all those stated above can be equally applied to either opening or closing bending.
- Direct comparison of opening and closing bending shows that closing bending gives a larger limit load surface. The normalised bendingmoment which causes reverse plasticity is not changed for opening, closing or reversed bending. Closing bending shows an increased ratchetting limit over opening bending, with these curves converging with increasing R/r.

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