

FINITE ELEMENT ANALYSIS OF METAL TUBES HYDRAULIC BULGING PROCESS

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Abstract

Finite element analysis of hydraulic bulging for metal tubes was performed to investigate the effect of varying process parameters on the internal pressure needed. The effects tube thickness, tube materials and the number of bulges on the internal pressure needed, deformation, stresses and tube thinning were determined. The aluminium and steel tubes with 2 mm and 4 mm thickness by using one and two bulges were studied. The results showed that the 4 mm-thick tube could withstand an internal pressure varying from 425% to 481.4% more when compared with the 2 mm-thick tube. Furthermore, the steel tube could withstand an internal pressure varying from 163.8% to 192.1% when compared with the aluminium tube. Finally, the increase of the number of bulges resulted in a small change varying from 0% to 3.1% when compared with the one bulge tube.

Keywords: Bulge forming, tube-bulging, hydroforming, bellows, finite element (FE) analysis, simulation

Introduction

Bulging process is an expansion of a part of a tube, in the radial direction, by a mechanical or hydraulic means. The main benefit of bulging is to accommodate movement of pipes due to thermal and mechanical changes in the system. The hydraulic bulging of metal tubes is designed to be circumferentially strong enough to withstand the pressure and longitudinally flexible enough to accept the deflection.

A considerable amount of research concerned with three dimensional finite element simulation of various bulge forming processes has been carried out over the past few years. The effect of combined internal pressure and in-plane compressive load on the bulging process, using

the finite element technique, had been analysed (Ahmed and Hashmi, 1998a). On the other hand, the finite element simulation of manufacturing metal bellows from tube was also carried out (Ahmed and Hashmi, 1998b). While, a simulation of the bulge forming of a cross joint from a tubular blank (Mac Donald and Hashmi, 2000) was also reported. In addition, three-dimensional finite-element simulation of bulge forming was also investigated (Ahmed and Hashmi, 2001a). The stress and strain distributions resulting from these loading situations were evaluated. Two loading cases were analysed. In the first case, the internal fluid pressure was raised faster when

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compared with the second case where the pressure was raised at a slower rate. For both cases, the axial compression of the tube ends was applied at an equal rate. It could be seen from the results that although the branch height in the second case was slightly less developed, the stress and strain situation in the formed T branch is small. It was also realised that when the internal pressure is raised slowly when compared with the axial compression, the material would move from the ends due to the less normal force on the die-tube interface. This enables them to raise the internal pressure later in the process and develop more branch height for a comparable thinning. (Ahmed and Hashmi, 2001a).

The simulations of bulge forming using a solid bulging medium was investigated (Ahmed and Hashmi, 2001b) by developing the three-dimensional model required for the process. The history of the development of the bulge and stress conditions in the formed component was analysed. The results of the simulation were then compared with those previously obtained in the simulation of the hydraulic bulging process. The explicit non-linear FE code LS-DYNA3D was used to perform the simulations. In addition, an experimental process for axisymmetrical bulging of thin-walled metal tubes was described in their work. The bulge forming using a polyurethane rod is compared with the hydraulic bulge forming. It was concluded, due to the complexity of analysing the polyurethane forming technique, that the more highly developed hydraulic forming method gave the better results (Ahmed and Hashmi, 2001b). The main tube has stressed a great deal in the simulation for solid medium bulging. This is because the friction between the bulging medium and the tube causing greater axial stress to be imparted on the tube than that present in the hydraulic simulation. An important advantage of the solid medium process, noticed during the comparison, was that it could produce the same branch height as the hydraulic process but with far less reduction in length of the unbulged tube. This is again due to the friction between the bulging medium and the tube causing material to be pulled into the bulging zone (Ahmed and Hashmi, 2001b).

More recently, a finite element analysis of bulge forming of cross branches has also been done (Pipan and Kosel, 2002). The effects of friction and tube thickness variation are examined. The deformations, stresses and tube thinning/thickening behaviour in the formed component were all taken into consideration. The finite element simulations of the manufacture of cross branches from straight tubes, using the bulge forming method, were performed (Pipan and Kosel, 2002) to investigate the effects of varying process parameters. Finite element models were built and validated against experimental measurements. Two different types of loading were employed: the internal pressure load only and the combined internal pressure and axial loading. The effects of various process parameters are examined and presented, with deformations, stresses and tube thinning/thickening behaviour in the formed component. The models were pre and post processed using the ANSYS finite element software and the problems were solved using LS-DYNA. Also, the influences of particular parameters on the stability of the bulging process, showing on a practical example how it is possible to achieve tube bulging without wall thinning was also carried out (Pipan and Kosel, 2002). The process of rotational symmetric tube bulging with inside pressure and axial compression enables the standard tubes to be formed into different rotational symmetric hollow part in such a way that their central part is expanded into a desired shape while the ends remain unchanged.

In addition, a hydraulic bulging machine, with a personal computer and a data logger, was used to monitor the axial force and hydraulic pressure (Thiruvardchevan *et al.*, 1998). They designed and constructed a hydraulic bulging machine, with an independent pressure and axial-force control. This machine consists of a horizontal press frame with two opposed hydraulic units at the ends of two sliding units carrying the die halves. Two sets of three hydraulic cylinders open and close the die halves containing the tube to be bulged. Once the die halves are closed, two differential pistons operating in two pressure vessels attached to the end plates move in and seal the tube. Then the

hydraulic pressure is applied to the tube through the central bore of one of the differential pistons.

The theoretical method of estimating the parameters such as internal pressure, axial load and clamping load required for the forming of tubular components as well as for the design of dies and tools were all discussed (Ahmed and Hashmi, 1997). The development in bulge forming of tubular components was considered by using different parameters. In their discussion, typical values of these parameters for particular tube size and material were developed and their implications on the design and operation of the process are noted.

A practical test method for determining the flow stress of tube materials was also suggested (Sokolowski *et al.*, 2000). This tool set, a simple stand alone hydraulic bulging fixture, was developed to expand the tubes under the bi-axial loading conditions. Tube material properties are required for an accurate design of the parts and tooling for the hydroforming process. A practical test method for determining the flow stress of tube materials (Sokolowski *et al.*, 2000) was done for the better control of the process.

Afterwards, the increasing acceptance and use of hydroforming technology within the automotive industry demands a comprehensive understanding of related issues such as material characteristics, tribology, part and tooling design are all studied (Koc *et al.*, 2000).

An application of finite element (FE) simulation will greatly reduce the expense involved in the development phases. The finite element analysis would also provide more data results when compared with the experimental techniques. Hence, a testing method, which defines the stress-strain behavior of tubular material, based on the bi-axial stretching, is necessary to improve accuracy in prediction of process parameters and deformation. A concise material database would simplify the selection of the proper material. These data may include expansion characteristics, consistency of strength, characteristics of the tubing (circumferentially), bursting pressures, flow stress, etc.

The main objectives of this present investigation are 1) to determine the effect of tube thickness on the bulging pressure; 2) to evaluate the effect of tube metal type on the bulging pressure; and 3) to determine the effect of the number of bulges on the bulging pressure

needed. Steel and Aluminum tubes were selected to be the base materials for this study. These tubes were having 25 mm outer diameter with 2 mm and 4 mm wall thickness. One and two bulges for each tube were analysed. This study has been carried out using LUSAS finite element software (FEA Ltd., 1998) and defining the materials as an elastic plastic solution.

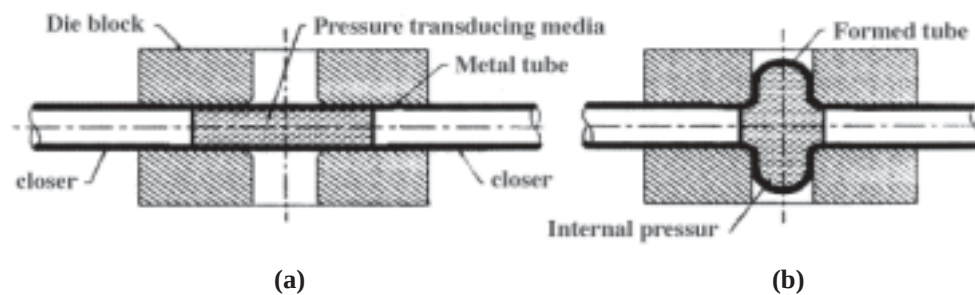
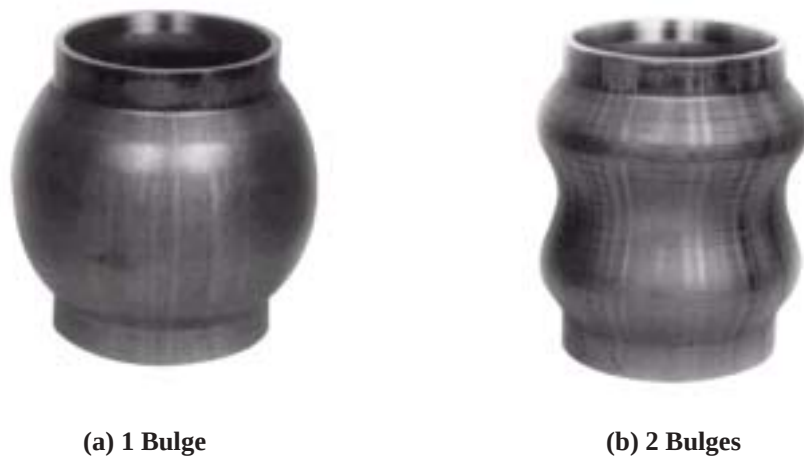
Materials and Methods

Eight different models were created and used to analyse the bulging process using an internal pressure. The models, in general, were done to make one and two bulges. Each one was done for Steel and Aluminum tubes. These tubes, for each material, were of 25 mm outer diameter. Two wall thickness values were used for each material and case as 2 mm and 4 mm. The main dimensions of these models are given in Table 1. A schematic drawing for the bulging process using an internal pressure medium, for one bulge, is shown in Figure 1. In addition, the final tube shape after bulging is shown in Figure 2 (Pipan and Kosel, 2002) for one and two bulges.

LUSAS finite element software has been used to create the models needed. An axisymmetric type of elements (QAX4M type) was used to generate the mesh. Material definition was done using the mechanical properties for each of the steel and aluminum tubes used. High strength forming dies were defined with little or no deformation assumption. Boundary conditions of tubes ends support and slide-lines between the tube and the die were also defined. Loading then applied as a pressure loading type. Two samples of the meshes created for one and two bulges are shown in Figure 3(a) and 1(b). It could be noticed here also that the dies are also supported from x and y directions for their free ends. The tube length was taken as 100 mm and 200 mm for one and two bulge cases respectively. Furthermore, the bulge width, for all the models, was kept as 25 mm. For the two bulge models, the distance between the center line of the first bulge to the next one was taken as 75 mm.

Table 1. The main dimensions for the eight 8 models used.

Model no.	Material	Number of bulge	Tube thickness, t (mm)	Tube length, L_o (mm)	Tube outer diameter, D_o (mm)	Bulge width, w (mm)
1	Aluminium	1	2	200	25	25
2	Steel	1	2	200	25	25
3	Aluminium	1	4	200	25	25
4	Steel	1	4	200	25	25
5	Aluminium	2	2	200	25	25
6	Steel	2	2	200	25	25
7	Aluminium	2	4	200	25	25
8	Steel	2	4	200	25	25

**Figure 1.** Bulge forming mechanism using an internal pressure media for (a) before and (b) after bulging.**Figure 2.** General shape of pipes with one and two bulges.

The finite element software used (LUSAS) is a general purpose commercial finite element analysis system which incorporates a variety of analysis facilities. It consists of pre-processing, finite element solver and results processing stages. The first stage of the pre-processing consists of creating two and three dimensional models besides assembling parts together. The mesh generation, material definition, boundary conditions and the type of loading could also be defined in this first stage. While the second stage of solver is able to solve linear and non-linear problems, dynamics, composite and thermal engineering analysis problems. The LUSAS element library contains over 100 element types, enabling a wide range of engineering applications and a variety of materials definition properties. In the last stage, results processing includes a selection of tools for viewing and analyzing the result file produced by the Solver. Many different ways of viewing the results are supported such as contour plots, deformed and undeformed mesh, animated display and graphs.

For the materials used, and defined, the steel tubes were assumed of 210 GN/m² Modulus of Elasticity, 0.3 Poisson's ratio and 320 MN/m² initial uniaxial yield stress. While, for the aluminum tubes used, the Modulus of Elasticity was taken as 70 GN/m², Poisson's ratio

as 0.345 and the initial uniaxial yield stress as 100 MN/m².

Results

The finite element results obtained from this study includes the deformation results, tube wall thickness changes, effect of using two bulges, effect of material and the pressure changes.

The progress deformation for all of the models studied was followed carefully to analyse the change in wall thickness, bulge height and the stress in the tube. The deformation shape and changes for a sample of the one bulge model is shown in Figure 4 and for the two bulge model is shown in Figure 5.

The internal pressure was recorded at each stage of the bulging process. The bulge height (mm) shows an increase as the pressure (MN/m²) increase up to a stable limit as shown in Figure 6 for models 1, 2, 3 and 4 of the one bulge respectively. Furthermore, for the two bulges, the bulge height (mm) related to the change in pressure (MN/m²) is shown in Figure 7 for models 5, 6, 7 and 8. On the other hand, the tube wall thickness change (mm) at the bulge position is shown in Figure 8 for the one bulge models and Figure 9 for the two bulge models. This shows that, at the top point

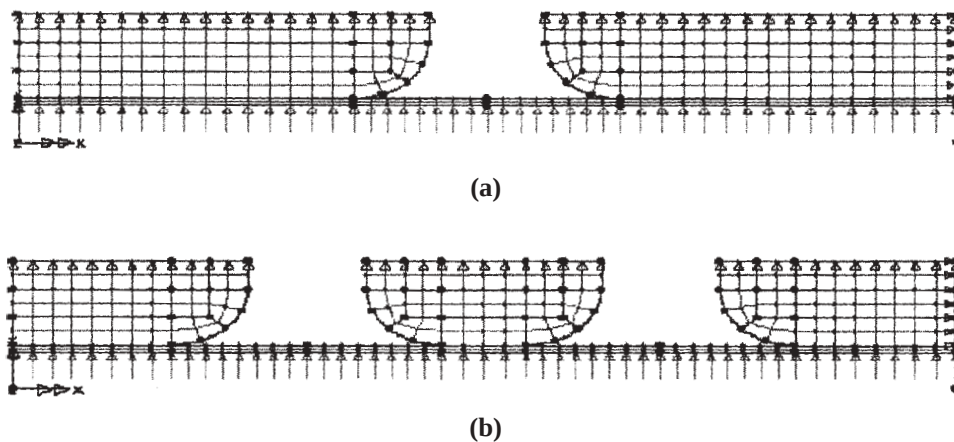
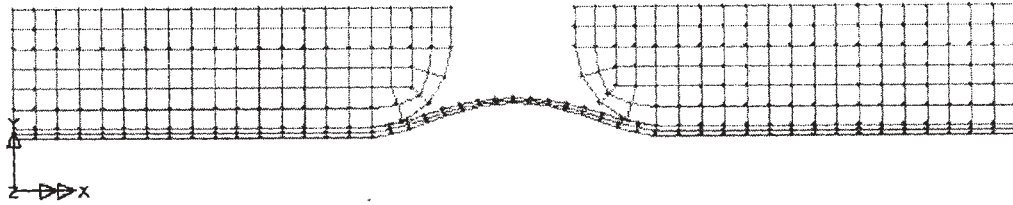
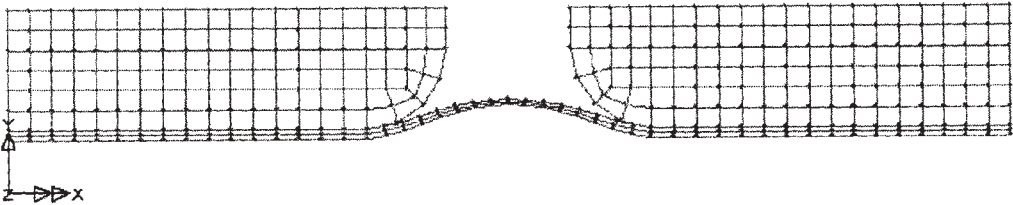


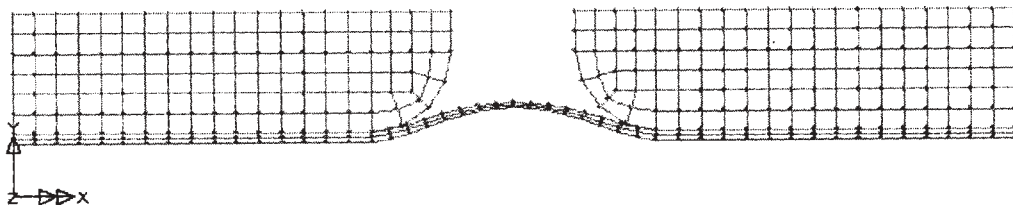
Figure 3. Samples of one (a) and two (b) bulge models created.



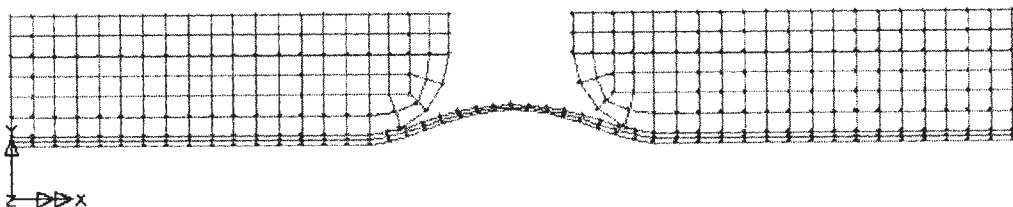
(a): For 30.38 MN/m² internal pressure, 5.77 mm bulge height and 0.94 mm is the top branch thickness.



(b): For 32.87 MN/m² internal pressure, 6.94 mm bulge height and 0.72 mm is the top branch thickness.

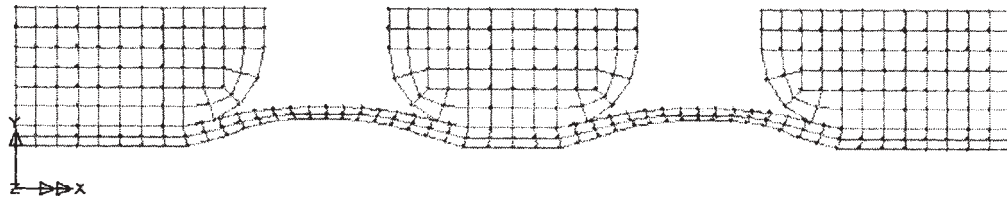


(c): For 34.36 MN/m² internal pressure, 7.82 mm bulge height and 0.56 mm is the top branch thickness.

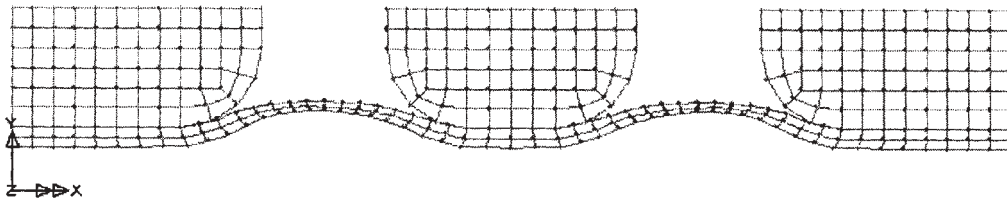


(d): For 36.34 MN/m² internal pressure, 9.05 mm bulge height and 0.33 mm is the top branch thickness.

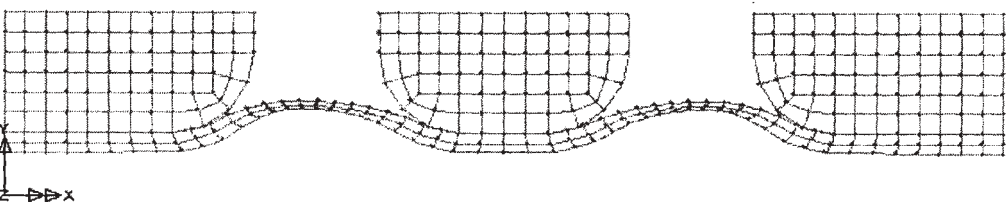
Figure 4. Deformed mesh for model no. 1 of Aluminum tube with 2 mm original wall thickness.



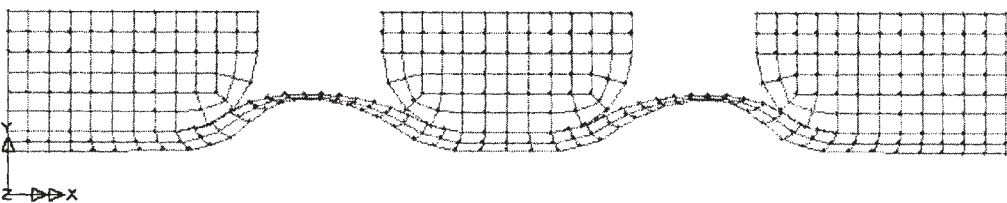
(a): For 400.45 MN/m² internal pressure, 4.03 mm bulge height and 2.37 mm is the top branch thickness.



(b): For 461.06 MN/m² internal pressure, 5.37 mm bulge height and 1.87 mm is the top branch thickness.



(c): For 501.16 MN/m² internal pressure, 6.31 mm bulge height and 1.52 mm is the top branch thickness.



(d): For 552.48 MN/m² internal pressure, 7.57 mm bulge height and 1.05 mm is the top branch thickness.

Figure 5. Deformed mesh for model no. 8 of Steel tube with 4 mm original wall thickness.

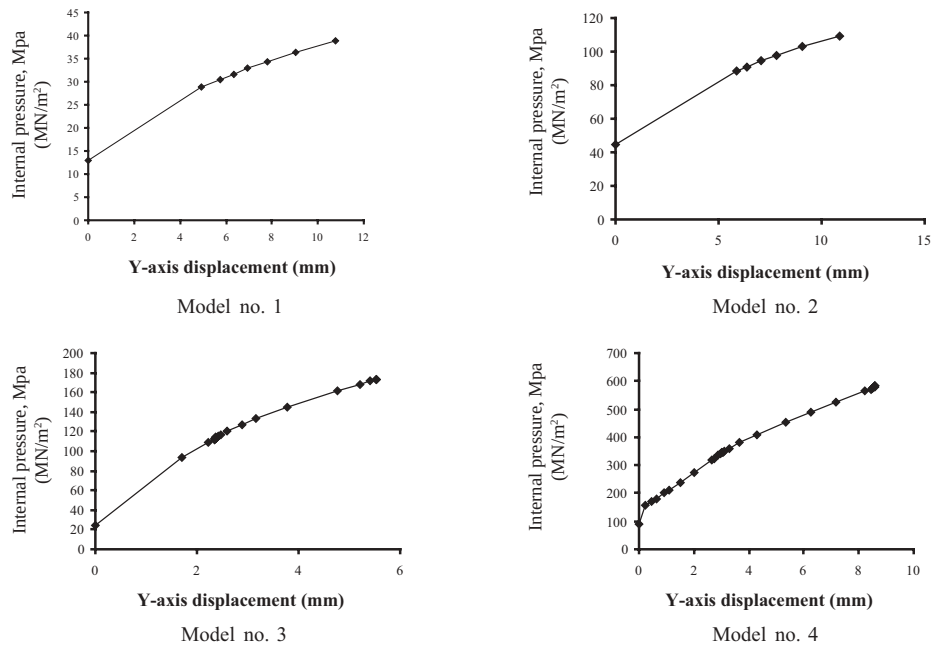


Figure 6. Internal pressure change related with the progress in the bulge height for the one bulge models.

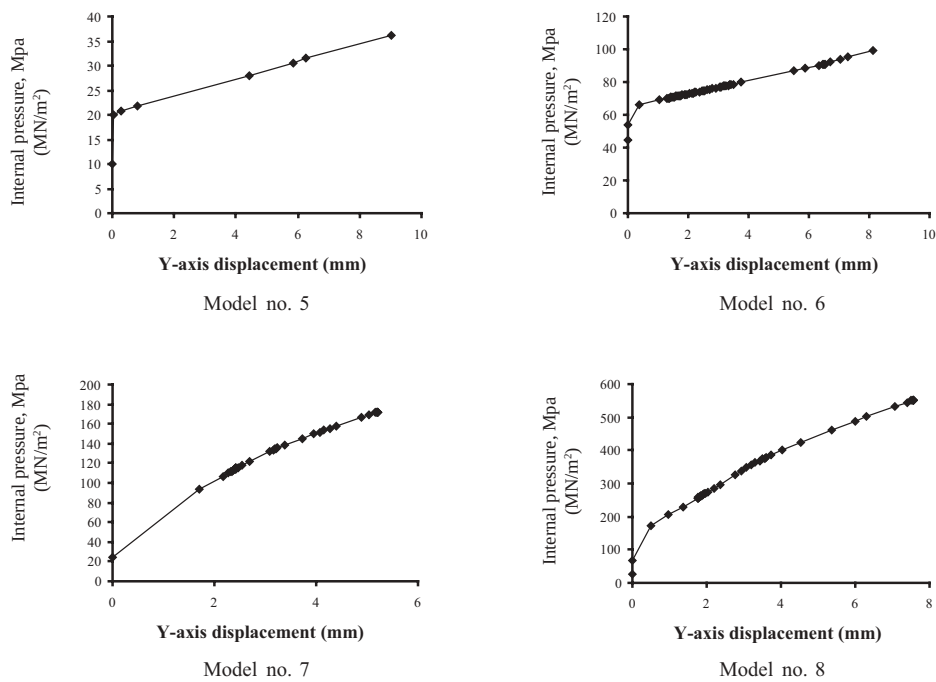


Figure 7. Internal pressure change related with the progress in the bulge height for the two bulge models.

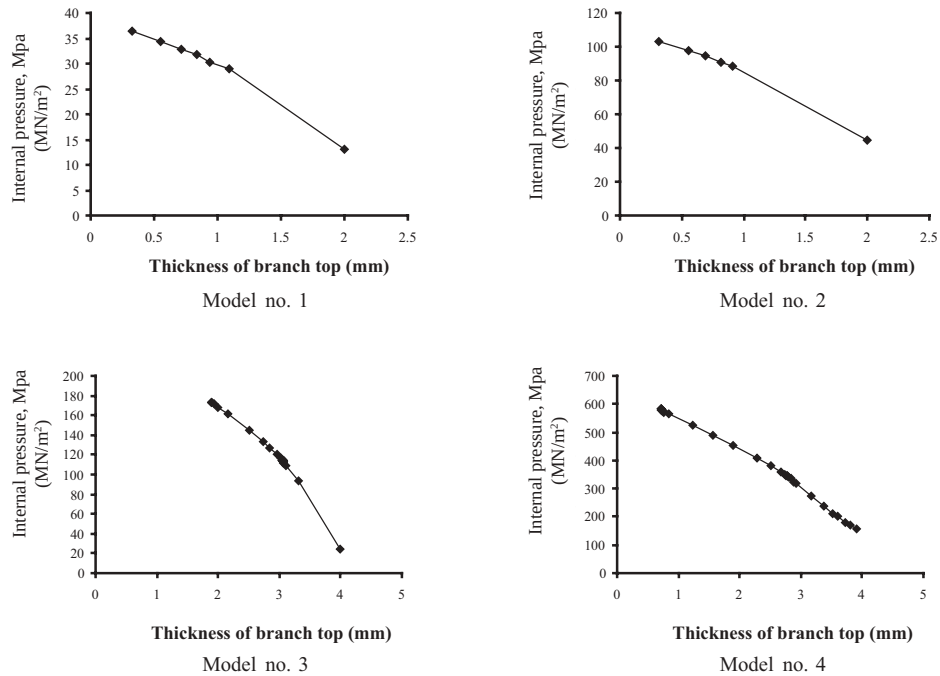


Figure 8. Internal pressure effect on the tube wall thickness of the branch top for one bulge models.

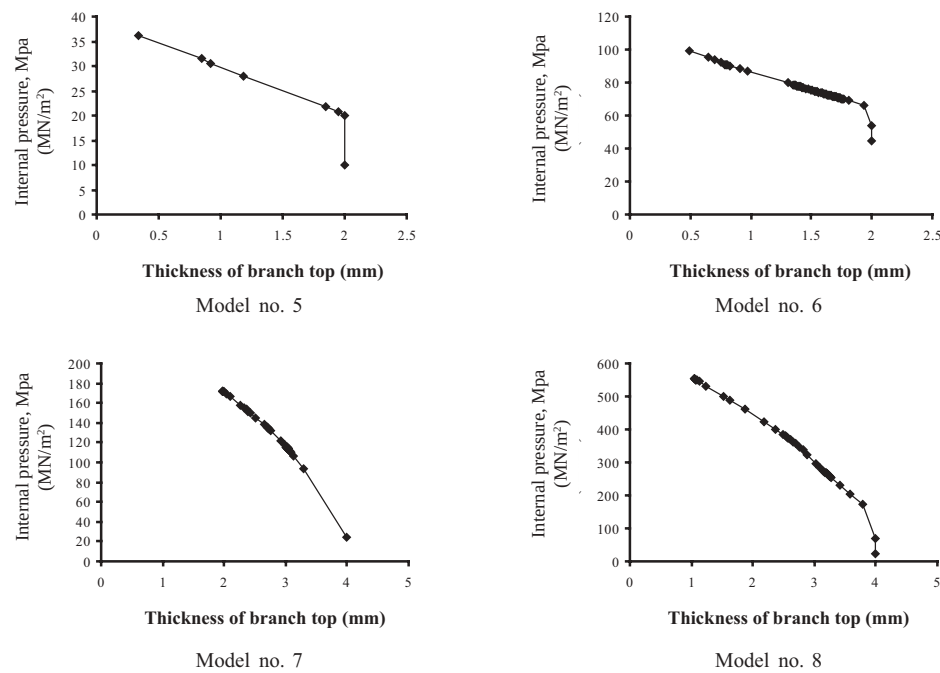


Figure 9. Internal pressure effect on the tube wall thickness of the branch top for two bulge models.

of the bulge, the tube wall thickness reduces as the internal pressure increases.

Comparison

Throughout the investigation, the effect of the tube thickness, tube material and the number of bulges were all studied.

The internal pressure required for a bulge height of 5 mm as the base for the comparison is shown in Table 2. The comparison of the results for the effect of tube thickness, tube materials and number of bulges on the internal pressure needed are shown in Tables 3, 4 and 5 respectively.

The effect of changing the tube thickness (mm) on the internal pressure (MN/m²) is shown in Figure 10. The bulge height of 5 mm was used in order to allow a direct comparison between the results, even though it is obvious that a thicker tube could withstand a higher internal pressure. It can be seen from Figure 10 that the use of a thicker tube resulted in more bulging pressure needed for the same bulge height of 5 mm. The increase of the internal pressure for

the 4 mm thick aluminium tubes is 469% and 481.4% when compared with the 2 mm thick ones for the one and two bulges respectively. On the other hand, for steel tubes, the increase was 436.3% and 425% for one and two bulges respectively. This means that the use of a thicker tube resulted in less bulge height and reduced thinning of the branch top.

The effect of using different tube materials on the internal pressure (MN/m²) for the bulge height of 5 mm is shown in Figure 11. It can be seen from the Figure that, as expected, the use of steel tube resulted in more bulging pressure needed to produce the bulging height of 5 mm when compared with the aluminium tube. The increase of internal pressure for the 2 mm thick steel tubes is 183.1% and 192.1% when compared with the 2 mm thick aluminium tubes for the one and two bulges respectively. Furthermore, for the 4 mm thick tubes, the increase was 166.8% and 163.8% for one and two bulges respectively. This means that the use of higher strength material resulted in the higher internal pressure needed for the same bulge height.

Table 2. Result of each model on the internal pressure needed for the bulge height of 5 mm.

Model	Pressure (MN/m ²)	Bulge height (mm)
M1 1 Bulge Aluminium thickness = 2 mm	29	5
M2 1 Bulge Steel thickness = 2 mm	82.1	5
M3 1 Bulge Aluminium thickness = 4 mm	165	5
M4 1 Bulge Steel thickness = 4 mm	440.3	5
M5 2 Bulge Aluminium thickness = 2 mm	29	5
M6 2 Bulge Steel thickness = 2 mm	84.7	5
M7 2 Bulge Aluminium thickness = 4 mm	168.6	5
M8 2 Bulge Steel thickness = 4 mm	444.7	5

Table 3. Effect of tube thickness on internal pressure for the bulge height of 5 mm.

Thickness = 2 mm		Thickness = 4 mm		% Increase
Model	Pressure (MN/m ²)	Model	Pressure (MN/m ²)	
M1 Aluminium 1 bulge	29	M3 Aluminium 1 bulge	165	469
M2 Steel 1 bulge	82.1	M4 Steel 1 bulge	440.3	436.3
M5 Aluminium 2 bulge	29	M7 Aluminium 2 bulge	168.6	481.4
M6 Steel 2 bulge	84.7	M8 Steel 2 bulge	444.7	425

The effect of using different number of bulges on the internal pressure (MN/m^2) for the height of 5 mm is shown in Figure 12. It can be seen from the Figure that the increase of the number of bulges resulted in a small change or approximately the same pressure is needed to produce the bulging height of 5 mm when compared with the one bulge tube. The increase of the internal pressure for two bulges of the 2 mm-thick tubes is 0% and 3.1% when compared with one bulge of the 2 mm-thick aluminium and steel tubes respectively. On the other hand, for 4 mm-thick tubes, the increase was 2.2% and 1% respectively. This means that the use of different number of bulges will not affect the pressure needed.

Discussion and Conclusions

The simulation of bulge forming by the internal pressure alone illustrates that the absence of a compressive load, at the tube ends, results in a high pressure. This also would result in excessive thinning of the branch tops, high stress in the bulged region and low bulge heights.

The highest stresses were located at the branch top and this is where failure eventually occurred. This may be due to the excessive thinning and eventually bursting. The results obtained indicate that the finite element model developed behaves in a manner that is agreeable with experimental trials.

It could also be observed, from the results of this study, that using the same loading conditions but increasing the tube thickness resulted in bulge height reduction. It is obvious however that the thicker tube would be able to withstand the higher internal pressure without failing. If higher loads are applied, it is expected that the branch height could be increased.

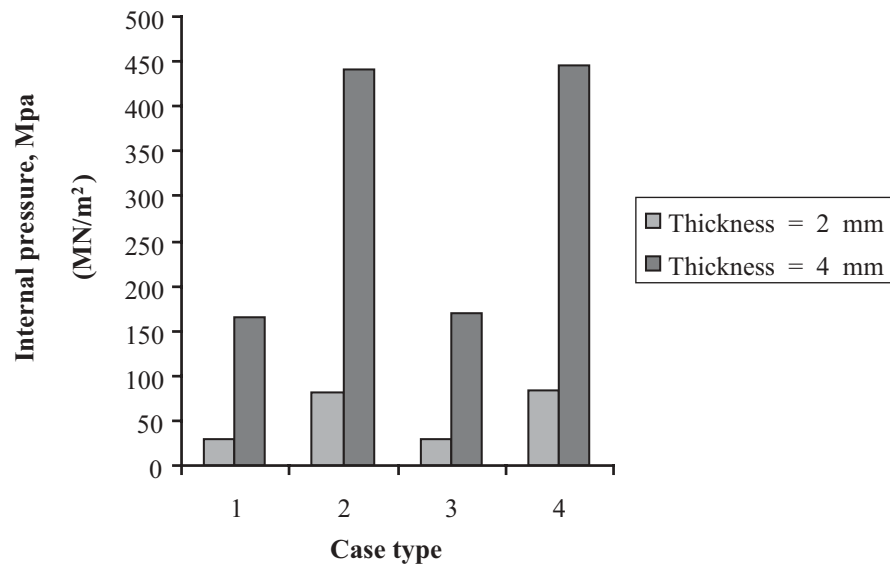
Furthermore, two different materials were used: steel and aluminium. The two materials have different hardening and strength characteristics. Again keeping the same bulge height condition but using the materials with more strength of tube resulted in more internal pressure needed. The use of higher strength materials also had an effect of decreasing the tube wall thickness of the branch top. The same bulge height conditions were used in order to

Table 4. Effect of tube materials on internal pressure for the bulge height of 5 mm.

Aluminium		Steel		% Increase
Model	Pressure (MN/m^2)	Model	Pressure (MN/m^2)	
M1 1 bulge t = 2 mm	29	M2 1 bulge t = 2 mm	82.1	183.1
M3 1 bulge t = 4 mm	165	M4 1 bulge t = 4 mm	440.3	166.8
M5 2 bulge t = 2 mm	29	M6 2 bulge t = 2 mm	84.7	192.1
M7 2 bulge t = 4 mm	168.6	M8 2 bulge t = 4 mm	444.7	163.8

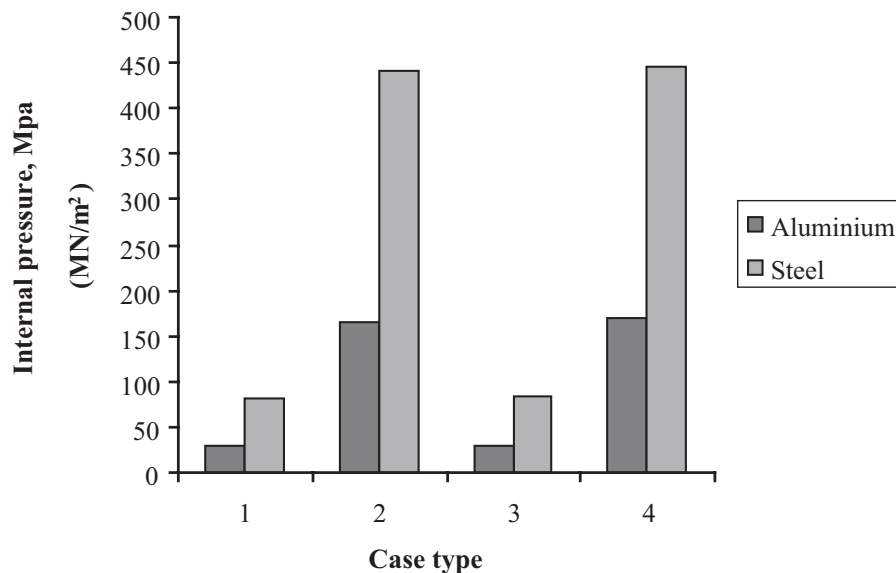
Table 5. Effect of number of bulges on internal pressure for the bulge height of 5 mm.

1 Bulge		2 Bulges		% Increase
Model	Pressure (MN/m^2)	Model	Pressure (MN/m^2)	
M1 Aluminium t = 2 mm	29	M5 Aluminium t = 2 mm	29	0
M2 Steel t = 2 mm	82.1	M6 Steel t = 2 mm	84.7	3.2
M3 Aluminium t = 4 mm	165	M7 Aluminium t = 4 mm	168.6	2.2
M4 Steel t = 4 mm	440.3	M8 Steel t = 4 mm	444.7	1



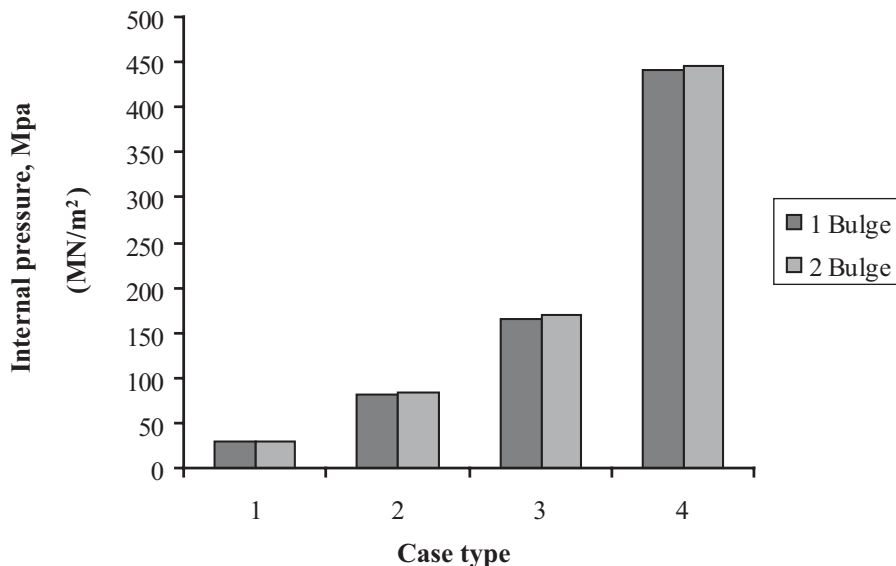
Case 1 = Aluminium 1 bulge, Case 2 = Steel 1 bulge, Case 3 = Aluminium 2 bulge, and Case 4 = Steel 2 bulge

Figure 10. Effect of tube thickness on the internal pressure for bulge height of 5 mm.



Case 1 = 1 bulge Thickness = 2 mm, Case 2 = 1 bulge thickness = 4 mm, Case 3 = 2 bulge thickness = 2 mm and Case 4 = 2 bulge thickness = 4 mm

Figure 11. Effect of tube material on the internal pressure for bulge height of 5 mm.



Case 1 = Aluminium thickness = 2 mm, Case 2 = Steel thickness = 2 mm, Case 3 = Aluminium thickness = 4 mm and Case 4 = Steel thickness = 4 mm

Figure 12. Effect of number of bulge on the internal pressure for bulge height of 5 mm.

allow a direct comparison of the effect of tube materials.

Finally, keeping the same bulge height conditions but increasing the number of bulges will not have an obvious positive effect of reducing the tube wall thickness of the branch top. Increasing the number of bulges of the tube resulted in a small, or negligible, effect on the internal pressure needed when compared with the one-bulge tube.

The main conclusions that could be drawn from this investigation includes :-

1. A thicker tube could withstand a higher internal pressure, the 4 mm-thick tube could withstand an internal pressure varying from 425% to 481.4% when compared with the 2 mm-thick tube. The increase of the tube thickness has positive effects on reducing the tube wall thickness of the branch top at the same bulge height.
2. The use of high strength tube material would be able to withstand the higher internal pressure. Steel could withstand an internal pressure varying from 163.8% to 192.1%

when compared with the aluminium tube. The use of high strength material also has a positive effect on reducing the tube wall thickness of the branch top at the same bulge height.

3. The use of different number of bulges would not affect the pressure needed for the same tube material and bulge height.

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