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Inflation of Stressed Cylindrical Tubes: An Experimental Study

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ABSTRACT

The inflation of an initially stressed cylindrical shell provides a good illustration of the phenomenon of the initiation and propagation of an instability, which shares the same mathematical and mechanical features with a variety of other strain localization phenomena in engineering structures and materials. The high speed CCD camera and digital image processing system were used to measure the 3D shape of the inflated cylindrical tube. The localized bulge of a cylindrical tube with closed ends forms when the internal pressure reaches a critical value \( P_{cr} \). As more air is filled into the tube, the pressure drops but the radius at the centre of the bulge will increase until it reaches a maximum value \( r_{\text{max}} \). With continued inflation, the pressure stays at a constant value \( P_p \). The purpose of this study is to investigate the critical and propagation pressures in the tubes and the profile outside when the shells under axial tension and internal pressure were inflating. We focus on the influence of the axial tension on the critical pressure. In this paper the problem is explored through experimental efforts. A series of experiments were conducted on commercially available natural rubber latex tubes involving different geometries and initial axial tensions, which were regarded as isotropic, homogeneous, incompressible and hyper-elastic materials.

Inflation, Cylindrical tube, Critical and propagation pressure, Profile, Localization

1. INTRODUCTION

Hyper-elastic tube structures are widely used in modern engineering and everyday life. Because of some features such as that they are collapsible, low weight and inflatable, they have promising applications in extra-terrestrial use and widely application prospect in the field of spaceflight. Many tissues and organs also consist of hyper-elastic tube structures which form the special bulge under the internal pressure and complex load. Localized bulging of an inflated hyper-elastic membrane tube shares the same mathematical and mechanical features with a variety of other strain localization phenomena in engineering structures and materials. The localized bulge mentioned above would cause harm to engineering safety and functions of biological tissue.

However, an inflation of a hollow rubber-like stressed cylindrical shell provides a good illustration of the phenomenon of initiation and propagation of an initially localized instability. The process of inflation is known as localization can be described as follows. When a cylindrical membrane tube with closed ends is inflated by an internal pressure, it firstly expands in the radial and axially in a uniform fashion. As more air is filled into the tube, the cylindrical configuration becomes unstable, and a local bulge appears somewhere along the length of the tube with the internal pressure drops. Because of the dropping pressure, the part of the tube away from the bulge experience unloading. In real engineering and life, the process shares the same features as a family of other problems, such as propagating buckles in long metal tubes under external pressure\textsuperscript{1}, propagating necks in some polymeric materials when pulled in tension\textsuperscript{2} and stress-induced phase transformations\textsuperscript{3}.

Inflation of membrane tube and associated problem of instability is a classical subject that has been studied in many books and papers. The mechanisms for the initiation and propagation of bulges in an inflated tube were made more transparent through the analysis of Chater and Hutchinson\textsuperscript{4} and experiments and numerical studies of Kyriakides and Chang\textsuperscript{5,6}. Fu et al.\textsuperscript{7} recalculated the solid line in the Figure 9 of Kyriakides and Chang\textsuperscript{5} and found almost perfect agreement between the theoretical limiting pressure and the experimental initiation pressure. Yin\textsuperscript{8} gave a detailed characterization of the propagation state (the kinked state). Additional experimental results are given by Pamplona et al. and Goncalves et al.\textsuperscript{9,10}. In this paper, a series of experiments are carried out to observe the process of bulging. The high
speed CCD camera and digital image processing system were used to measure the 3D shape of the inflated cylindrical tube.

The problem of inflation is explored through experimental efforts and the rest of this paper proceeds as follows. After describe the specimen and experimental setup in the next section, we will present the method and show the results of measurement. In the final section, we make a summary of our findings.

2. EXPERIMENTAL SETUP AND SPECIMEN

The experimental setup used in measuring critical pressure and 3D shape of deformation is shown schematically in Fig. 1. The device had the functions of clamping steadily and providing internal pressure continuously. The initial axial load was applied by hanging a calibrated weight which was placed on a guide pulley. The friction of the pulley was small. The tube was inflated with compressed air from the left end. A pressure gage and a dynamic pressure sensor were used to monitor the pressure timely in the system. The pressure value could be read on the dial, and the output of the pressure sensor was recorded in computer using a data acquisition card at the same time. The test section was clamped the connection and sealing element at the ends of the tube. The rate of inflation was controlled manually through a throttle. A pressure maintaining valve was used to ensure a constant supply of air, moreover, a high speed camera system was used to monitor and record the deformed configurations of the tube during inflation.

The experiments were conducted on commercially available nature latex tubes as shown in Fig. 2. The tube had a nominal outside diameter of 7.5 mm and wall thickness of 1.5 mm and the length ranged between about 30 tube diameters. The tolerance of the diameter and wall thickness was ±0.2 mm. These natural rubber latex tubes were involving different geometries, which were regarded as isotropic, homogeneous, incompressible and hyper-elastic materials. In preparation for an experiment, the test specimens hand-picked were cyclically loaded axially to achieve the required material stability.

3. EXPERIMENTAL METHOD AND RESULTS

When the air is pumped into the tube at a slow rate, the internal pressure monitored by pressure sensor is first increased to a critical value \( P_{cr} \), gradually, then it drops suddenly to a constant value \( P_p \). After inflating uniform, a bulge was formed rapidly along the length of the tube and the radius at the centre of the bulge will increase until it reached a maximum \( r_{max} \). The 3D shape of the inflated tube is recorded at the rate of 2000 fps. In order to record more clearly, the two ends should be fixed steadily but not be free. All the experiments are carried out at the temperature of 28 °C.

3.1 The inflating process and pressure-time history of the tube under axial tension

The apparatus mentioned above fills the tube with air, measures and controls the internal pressure. Fig. 3 shows a series of photographs of the cylindrical tube subjected to increasing volume of air. The corresponding internal pressure shown in Fig. 4 can be observed in the dial of the pressure gage and collected into the computer by the data acquisition unit. In Fig. 3 (a) the tube is stretched. As the air is filled, the tube increases uniformly in Fig. 3 (b) until a maximum value \( r_{max} \) is reached, after which there is a localization of deformation in Fig. 3(c), which is taken just prior to bulge initiation as shown in Fig. 3 (d). Fig. 3 (e-f) show the approximately axi-symmetric bulge spreads in both radial and axial directions. In Fig. 4 the curve section ①, ② and ③ corresponds to Fig. 3 (a-b), (c-d) and (e-f) respectively. In order to get a better look at the edge outside, a light box is used behind the tube.
3.2 The measurement of critical and propagation pressure at different sizes of axial loading

As the air is injected, the localized bulge forms while the internal pressure reaches a critical value $P_{cr}$. With continued inflation, the pressure drops and finally stays at a constant value $P_p$. Fig. 5 presents the pressure-time history recorded in one elastic tube. For the range of axial tension considered, when the cylindrical shells are initially under a set of different axial tensions, it is shown in Fig. 5 that axial tension lowers the initiation pressure observably but the influence of axial loading to propagation pressure is not obvious in the general trend. This is probably due to that the boundary condition has larger effect on the instability but smaller effect on the stable propagation of the localized bulge.
3.3 Measured profiles of the initiation and propagating bulge in an inflating tube

The profile of initiation and propagation of a bulge is measured using the high speed camera and digital image processing system. Fig. 6 shows a picture get through edge extraction, which explains the process involves forming of a localized bulge and unloading of the non-expansion section. This phenomenon is occur in a very short time about 30ms. As shown in Fig. 6 the red line and yellow line represent the shapes before and after the inflation, after uniform expansion, the pressure jump causes a sudden expansion at the point O and a reduction in the diameter of undisturbed section in the green line. In the next moment, the bulge continues to increase in both radial and axial directions.

Fig. 6. The profile of the expansion and unloading section when the bulge is formed

Fig. 7 presents the propagation of the bulge from right to left while the tube radius reaches a maximum value \( r_{\text{max}} \). The small and large diameter sections of the bulged tube remained the same, and the diameter of small section is the same with the unloading part in size. The velocity of propagation depend largely on the rate of inflation. The region which connects the small and large parts moves from location of bulging to both ends and keeps original shape.

Fig. 7. The profiles of a propagating bulge in an inflated tube

Fig. 8 shows a set of real detailed profiles of initiation of a bulge recorded by the camera mentioned above. We can observe the rapid expansion of the bulge, which is not a constant speed. The position of the bulge may differ from one specimen to another. This is probably due to the effect of initial material imperfection. More research will be carried out and relevant results will be reported in separate papers.

Fig. 8 The initiation process of a bulge recorded by the high speed camera
4. CONCLUSION

In this paper the internal critical and propagation pressure and corresponding deformed configurations of an inflated tube are measured. As observed in the experiments, when the air is injected, the whole cylindrical shell deformed symmetrically and the pressure inside increases continuously until a maximum pressure $P_{cr}$ was reached. At this moment, the pressure drops suddenly and a bulge is initiated at a certain position along the tube and then propagated steadily, quasi state propagation of the bulge is constant.

Axial tension lowers the initiation pressure observably but the influence of axial loading to propagation pressure is not obvious in the general trend. The expansion of the bulge in an inflated tube occurs in a very short time, and the velocity is not a constant. In the paper, a detailed process of inflating of a cylindrical shell is studied experimental, meanwhile the pressure inside and shape of the tubes are recorded.

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References