Fabrication and Strength Assessment of Composite Corrugated Expansion Tube

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Abstract. A technique is proposed to develop a composite corrugated expansion tube which can achieve a prescribed axial extension when subjected to an internal pressure. The composite corrugated expansion tube was fabricated using annular carbon fabric/PU sheets via the vacuum-assisted resin transfer process. In forming the tube shape, the edges of each annular fabric/PU sheet are adhesively bound to the other two similar sheets at the outer and inner edges, respectively. A finite element model of the corrugated expansion tube is established using the shell elements of the finite element code ANSYS. To illustrate the applications of the proposed technique, the corrugated expansion tube that can sustain internal pressure of 82.73 MPa is developed and tested to verify the accuracy of the finite element model. It has been shown that compressive stresses are induced at the adhesive layers that are located at the outer edges of the corrugated expansion tube. The occurrence of such compressive stresses at the outer edge adhesive layers can increase the failure pressure of the corrugated expansion tube. The failure strength of the composite sheet dominates the incipient failure pressure of the tube. This type of failure mode makes the expansion tube design feasible for practical applications.

1. Introduction

Corrugated expansion tubes have been used in many industries to absorb energy induced by component/system deformation/movement. A corrugated expansion tube usually consists of a flexible bellow which is formed using a number of flexible annular elements. Corrugated expansion tubes are required to be corrosion resistant, capable of sustaining axial load and/or pressure. Metallic bellows have found wide applications in, for instance, aerospace, chemical plants, power system, heat exchangers, automotive vehicle parts, piping system. Many research works have been devoted to tackle different issues related to metallic corrugated expansion tubes [1-9]. As for composite corrugated expansion tubes, not much work has been done in this respect. In this paper, the development of a composite corrugated expansion tube is presented. The composite expansion tube can sustain internal pressure of 82.73 Mpa in operation. The axial stiffness of the proposed corrugated expansion tube with inner and outer diameters of 37 mm and 51.3 mm, respectively, is lower than 22.8 Kg/mm. The corrugated expansion tube as shown in Figure 1 is used as a water pump in the mechanical braking system of a wind turbine. There are two check valves below the expansion tube, which allow the water to flow in from one conduit and come out from another one when the expansion tube is in operation. The rod above the expansion tube is connected to the rotor of the wind turbine. When the rotor rotates above a specific speed, the rod of the expansion tube can move up and down to pump water into a chamber of the braking system. When the pressure in the chamber reaches a
prescribed value, the break is actuated to slow down the rotor speed. A detail description of the development of the composite corrugated expansion tube is given in the following.

Figure 1. Operation of expansion tube

2. Development procedure of corrugated expansion tube
The configuration of the composite corrugated expansion tube is shown in Figure 2. The expansion tube consists of a bellow, a driving rod, an inlet valve, and an outlet valve.

Figure 2. Configuration of composite corrugated expansion tube

The development procedure of the composite corrugated expansion tube is shown in Figure 3. The expansion tube is fabricated using carbon fabric/PU sheets. The development procedure includes design, analysis, fabrication, and testing of the composite corrugated expansion tube.

Figure 3. Development procedure of composite corrugated expansion tube

3. Fabrication of corrugated expansion tube
The corrugated expansion tube is manufactured in the following manner. Prepare a piece of rectangular carbon fibre woven fabric sheet of 90mm x 140mm and cut two crosses of 38mm x 38mm on the sheet as shown in Figure 4.
Figure 4. Carbon fabric sheet

Use a #20 iron wire of 165mm long wire to make a ring by welding as shown in Figure 5. The iron rings will be used to exert compressive force along the outer boundary of the flexible elements of the bellow. Such compressive force will prevent the opening failure mode to occur at the outer boundary of the bellow.

Figure 5. Ring forming from iron wire

The carbon fabric sheet coated with PU is placed in a vacuum bag which is then placed in an oven for curing as shown in Figure 6. The composite sheet is cured in an oven at 100 ° C for 12 hours until the PU becomes hardened. Two flexible annular elements can be attained from the cured composite sheet. A pair of cured flexible elements is shown in Figure 7.

Figure 6. Carbon fiber fabric/PU sheet together with vacuum bag laying in mold
Figure 7. Two cured carbon fiber fabric/PU bellow elements

There are different ways to fabricate the bellow. For instance, a pair of flexible elements can be first adhesively joined together at their inner edges as shown in Figure 8. Next, consider the joining of two similar pairs of flexible elements of which the flexible elements of each pair have been adhesively bound at their inner edges. In binding the two pairs of flexible elements together, the outer edge of the top element of the first pair is joined adhesively to the outer edge of the bottom element of the second pair.

Figure 8. Flexible elements adhesively joined at their inner edges

In Figure 9, it shows that two pairs of flexible elements have been adhesively joined together at the outer edges. Also, iron rings have been placed at the outer edges to exert contracting forces to the flexible elements so that the through thickness compressive stress can be generated at the interface between the top and bottom elements.

Figure 9. Design of edge adhesive joint
After fabrication, a bellow consisting of three pairs of flexible elements after fabrication is shown in Figure 10.

![Composite corrugated bellow](image)

**Figure 10. Composite corrugated bellow**

4. **Experimental investigation**

The mechanical behaviour of the composite corrugated expansion tube was studied experimentally. The pull test was carried out using a material testing machine. The two ends of the expansion tube were connected to two plates (Figure 11) which were clamped by the grippers of the material testing machine (Figure 12). During testing, the expansion tube was subjected to the stroke of 30 mm at the speed of 1 mm/sec.

![Composite corrugated expansion tube used for pulling test](image)

**Figure 11. Composite corrugated expansion tube used for pulling test**
Figure 12. Clamping of end plates in pulling test

The measured load-displacement of the expansion tube is shown in Figure 13. It is noted that the corrugated expansion tube behaves nonlinearly when the displacement is larger than 0.015m. Therefore, in order to have an appropriate prediction of the composite corrugated expansion tube, a geometrically nonlinear structural analysis should be performed to analyse the mechanical behaviour of the corrugated tube.

Figure 13. Load-displacement curve of composite corrugated expansion tube

Observing the corrugated expansion tube at the maximum displacement of 0.03m under pulling (Figure 14), it has been found that the 3-round corrugated expansion tube did not fail.
5. Nonlinear finite element analysis

The geometric nonlinearity module of the finite element code ANSYS [10] is used to analyse the deformation of the composite corrugated expansion tube to construct the load-displacement curve. The finite element mesh of a quarter of the flexible bellow element is shown in Figure 15. The convergence test of the mesh is shown in Figure 16. It is noted that the displacement converges when the element size is 0.2mm x 0.2mm. The flexible part with thickness 0.55mm as well as the adhesive layers at the inner and outer edges is modelled using Shell 181 elements while the iron-ring Solid 185 elements. It is noted that due to axis-symmetry, the tangential displacements at the two ends are set as $U_\theta=0$ for $\theta=0^\circ$ and $90^\circ$.

Figure 14. Composite corrugated expansion tube at the state of maximum displacement

Figure 15. Finite element model
Figure 16. Finite element mesh convergence test

In the nonlinear analysis, the deformations of the bellow elements are determined via the stroke control approach. As shown in Figure 17, the vertical displacement at the inner edge of the upper bellow element is increased from 0 to 0.5mm while that of the lower bellow element from 0 to -0.5mm. The incremental technique in which the total stroke is divided into 200 increments is used to trace the load-displacement. The material constants used in the finite element analysis of the composite bellow are listed in Table 1.

Figure 17. Incremental stroke control adopted in the finite element analysis

Table 1. Material properties

|                | Carbon fabric/PU composite | Iron wire |
|----------------|---------------------------|-----------|
| E₁             | 340 MPa                   | E         | 200 GPa |
| E₂             | 340 MPa                   | v₁₂       | 0.28    |
| E₃             | 34 MPa                    | v₂₃       | 0.28    |
| v₁₃            | 0.28                      | v₁₂       | 0.35    |
| G₁₂            | 13.6 MPa                  | G₂₃       | 6.8 MPa |
| G₂₃            | 6.8 MPa                   | G₁₃       | 6.8 MPa |

The theoretical and the experimental load-displacement curves are plotted in Figure 18 for comparison. It is noted that the theoretical load-displacement curve can match the experimental one well. For instance, when the stoke equals to 0.03m, the percentage difference between the theoretically and the experimentally predicted loads is lower than 3.2%.
Figure 18. Theoretical and the experimental load-displacement curves

Now consider the mechanical behaviour of the expansion tube subjected to internal pressure of 8.44kgf/cm². When the top end of the expansion tube goes upward, air will come into the tube through the inlet valve to fill up the tube. On the other hand, when the top end of the tube goes downward, the air in the tube being squeaked out of the tube through the outlet valve will generate pressure in the tube. The loading and boundary conditions of the tube at the final state of the air squeaking process are shown in Figure 19. In the finite element analysis, it has been found that the flexible elements and the adhesive layers at the outer edges of the bellow will not fail. Furthermore, some regions at the adhesive layer of the outer edge produce through thickness compressive stress as shown in Figure 20. Therefore, the proposed design of the composite corrugated expansion tube is feasible and may have the potential for practical applications.

Figure 19. Expansion tube under internal pressure

Figure 20. Stress distribution at adhesive layer of outer edge
6. Conclusion
Carbon fabric/PU composite material has been successfully used to fabricate a corrugated expansion tube. The corrugated expansion tube comprises a flexible bellow made of several carbon fabric/PU curved sheets bound together adhesively. Iron rings are used to exert contracting forces to the bellow so that through thickness compressive stresses can be induced in the adhesive layers at the outer edges of the bellow. These compressive stresses can prevent the opening failure mode of the outer binding edges of the bellow from occurring. A finite element model has been proposed to analyse the mechanical behaviour of the composite corrugated expansion tube. The accuracy and effectiveness of the proposed finite element model have been validated by experimental results. The feasibility validation has made the proposed finite element model suitable to be used to design similar composite corrugated expansion tubes of different sizes.

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7. References
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