STUDY ON THE SALVAGE OF AN AXIAL PENETRATED CRACK ON THE COMPOSITE CYLINDRICAL SHELL WITH A REINFORCED OPEN HOLE

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Abstract

A study on the salvage of a composite cylindrical shell with a reinforced open hole, containing an axial penetrated crack, was carried out. The finite element method was used to establish an analysis model for the original structure with defects and employed to analyze its compressive buckling strength and model. The relationship between the length of the penetrated crack and the buckling strength of the cracked cylindrical shell was established. This buckling strength was compared with that of a shell with no crack. Naturally the results show that the buckling strength of the cracked cylindrical shell becomes lower than that of the cylindrical shell without crack. As the length of the crack exceeds a certain range, the buckling region is shifted from the area around the hole to the area around the crack, resulting in a sharp drop of buckling strength. Proper repair should be carried out to salvage the structure by improving the shear load carrying capacity in cracked region of the shell. After repair, a buckling analysis was again carried out and it was found that, the buckling mode of the repaired shell was resumed to that of the shell without any crack, with a slight increase in buckling strength. This illustrates the salvage method is effective.
Keywords: Polymer-matrix composites; Buckling; Salvage; Finite element analysis

1. Introduction

Cylindrical shells are extensively used in aircrafts, ships, oil and gas pipelines as critical load-carrying components. Compared to commonly used metals, cylindrical shells made from composites offer some weight reduction and better corrosive properties while achieving the same strength [1, 2].

Composite cylindrical shells are generally integral forming structures, the cost is high, and the design process is not allowed to be greatly repeated due to research schedule. If cracks or deformations are found on these composite cylindrical shells, remedial measures should be taken to keep them usable. Therefore it is of special importance to study the influence of cracks on composite cylindrical shells and establish proper remedy solutions [3, 4].

There are several different kinds of cracks found on composite cylindrical shells. These cracks can be sorted by their locations into surface crack, internal crack, penetrated crack, etc. In addition, they can be sorted by their directions into circumferential crack, axial crack, inclined crack, etc. The buckling mode of a composite cylindrical shell changes with the directions, locations and length of the crack, loads and ply sequences [5].

Study on cylindrical shells containing cracks began at the end of the 70s in the last century, when Krenk established the Shell Theory to solve the problems of cylindrical shells containing circumferential and axial cracks under different loads. At the same time, he also considered orthotropic materials [6]. Rong Liu et al. also studied orthotropic properties of composite materials, and found that axial cracks are greatly affected by orthotropic properties, while circumferential cracks are seldom influenced [2]. To simulate different kinds of

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cracks, different methods shall be used. For example, elliptical cutouts are recommended to simulate surface cracks or partly through cracks. The cracks can be well imitated by taking the crack length as the longer axis and crack depth as half of the shorter axis with a semi ellipse cutout [1, 2, 8]. As for penetrated cracks, narrow slots are generally used for imitation [5, 7, 9, 10] and the grid mesh should be refined in order to improve accuracy [7]. To simulate the growth of penetrated cracks using the Finite Element Method, there are generally two ways. One is to calculate a series of cases, each with different crack lengths [11]; the other one is Dual Boundary Element Method [12]. Elements around the crack do not need to be re-meshed using the latter way. After a number of studies performed regarding the influence of cracks, people now have started to consider proper ways to repair the cracks to salvage the structures. Study on the cracked cylindrical shell after repair shows that, with smaller angle between crack direction and axis of cylinder, the repair is more effective [13]. Usik Lee et al. put forward a way to identify the damage of cylindrical shells [14], Christos C. Chamis et al. studied about the damage tolerance design of cylindrical shells [15].

Most of the studies above are about cracks on intact cylindrical shells, few of them have taken open holes into consideration. This paper presents studies about the compressive behavior of a cracked composite cylindrical shell with a reinforced open hole. The Finite Element Method is used for the buckling analysis of the composite cylindrical shell without any crack. Then cracks of different lengths are added to the cylindrical shell and each case was analyzed. The results related to the cracked cylindrical shells are compared to that of the cylindrical shell with no crack. According to the influence of the crack, a salvage scheme is proposed and buckling analysis was carried out again after repair. Using the results of the buckling analysis, the effectiveness of proposed salvage scheme is estimated.

2. Geometrical model

The composite cylindrical shell was processed using the Resin Transfer Molding technique. To ensure its surface quality, steel was used for the outer mold and silicone rubber for the mandrel. During processing, silicone rubber would expand due to heat and pressurize the composite cylindrical shell. The thermal expansion coefficient of silicone rubber was hard to predict and therefore, the expansion was difficult to control. The silicone rubber over-expanded during the curing process and the bolts of one-side deformed plastically. A gap was formed and resin flowed into the gap and formed a flash on this side. When the flash was removed, a penetrated crack was found on the shell as shown in Fig. 1

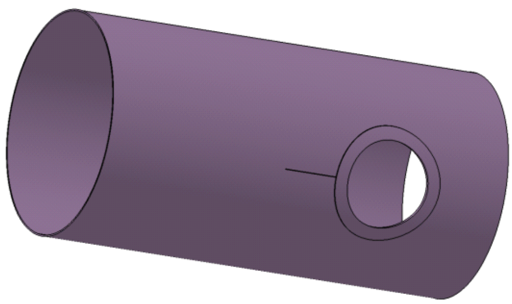

Fig. 1 Cylindrical shell Structural sketch

Consider a cylindrical shell with following dimensions:

External diameter: $d_1 = 514$ mm,

Internal diameter: $d_2 = 507.44$ mm,

Thickness: $t_s = 3.28$ mm,

Height: $h = 1000$ mm.

There is an open hole on the cylindrical shell. To avoid a sharp decrease in the buckling strength, an annular reinforcing frame was added and the crack starts just above the reinforcing frame.

Diameter of the open hole: d_h = 200 mm,

Thickness of the annular reinforcing frame:

t_f = 8.16 mm,

Width of the crack: b = 1 mm,

Length of the crack: l = 0 ~ 320 mm.

The cylindrical shell consists of two kinds of carbon/epoxy materials, one is tape, T300/6808, and another is fabric, G814/6808.

Different parts of the cylindrical shell have different ply sequences:

Shell: $[(0,90)/45/-45/0_2/90/0_2/45/-45/0_2/90/0_2/-45/45/(0,90)_2]$

Reinforcing frame: $[(0,90)/45/-45/0/90_2/0/-45/45/45/-45/0/90_2/0/-45/45/45/-45/0/90_2/0/-45/45]_s$

Repair patch: $[(\pm45)]$

(0,90) and ($\pm$45) stand for fabric

The material properties of T300/6808:

Young's modulus: E_1 = 117 000 MPa; E_2 = 8 000 MPa,

Shear modulus: G_{12} = 4 000 MPa,

Poisson's ratio: ν_{12} = 0.3.

The material properties of G814/6808:

Young's modulus: E_1 = 63 000 MPa; E_2 = 63 000 MPa,

Shear modulus: G_{12} = 4 100 MPa,

Poisson's ratio: ν_{12} = 0.062.

3. Finite element modeling

4-nodes shell element was used to simulate each part of the cylindrical shell and the finite element model established in [16] is used.

To simulate the penetrated crack, a slot of 1mm width is created above the annular stiffener. As the strain around the crack is complex, the elements in this area are refined to achieve better accuracy as shown in Fig. 2.

Boundary conditions: lower end clamped supported, horizontal displacement of upper end restricted.

Loading conditions: unit arc length of upper end loaded with unit pressure.

4. Results and analysis

Firstly, a static analysis is carried out on both the composite cylindrical shells having crack and without crack. The results are shown in Fig.3. It was observed that, the static strength of the composite cylindrical shell remains nearly unchanged as the crack grows.

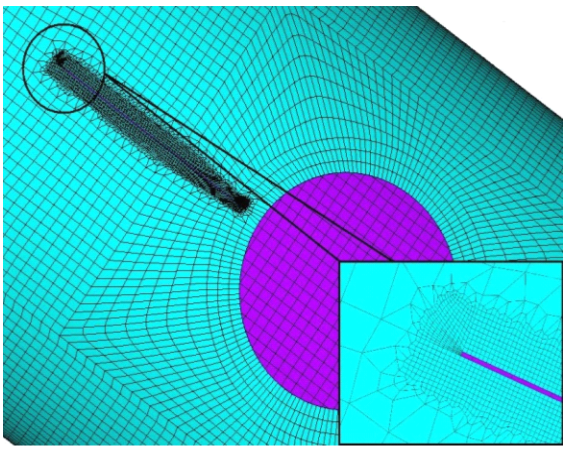

Fig. 2Grid mesh around the crack

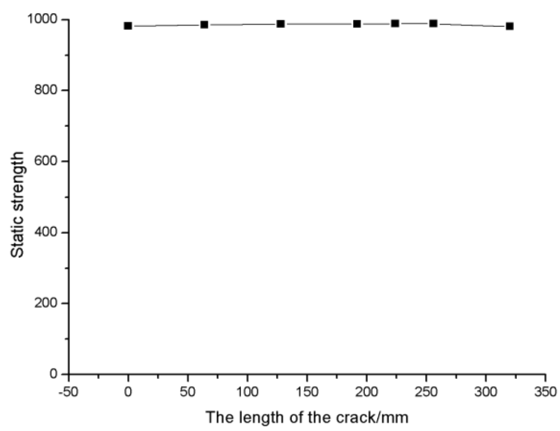

Fig. 3 Static strength vs. crack length

The buckling analysis of the cylindrical shell without crack shows that the buckling strength reaches 631.418 and critical areas are exactly above the open hole on both sides, as shown in Fig. 4

To simulate the growth of the crack, the length of the slot was changed and elements around the crack were re-meshed. Fig. 5.6.7 shows several typical buckling modes of the cylindrical shell as the crack grows longer.

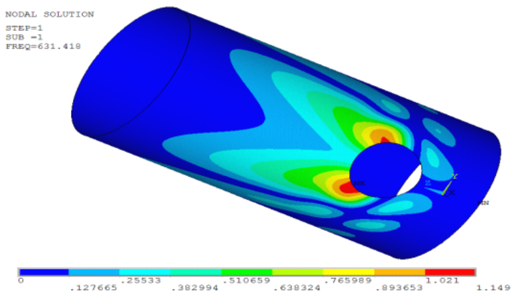

Fig. 4 Buckling modal graph of the cylindrical shell without crack

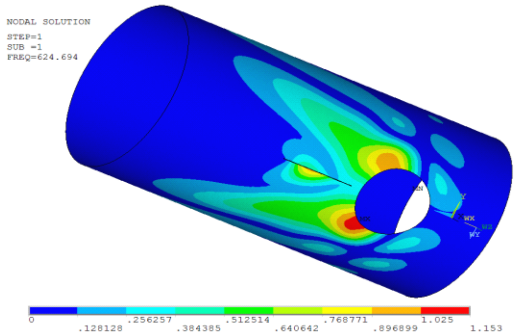

Fig. 6.Buckling modes of the cylindrical shell under 208mm crack

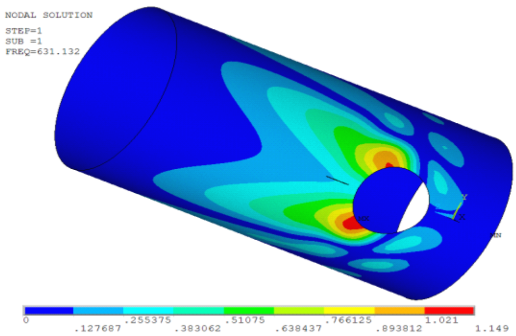

Fig. 5.Buckling modes of the cylindrical shell under 64mm crack

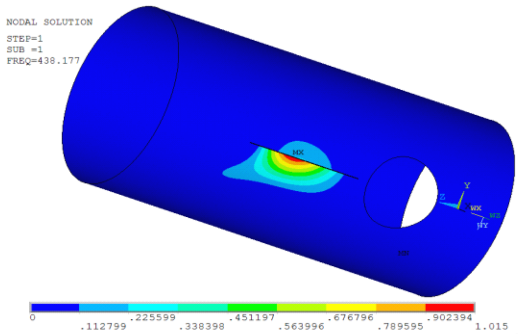

Fig. 7.Buckling modes of the cylindrical shell under 320mm crack

Fig. 8 shows the graphical representation of buckling strength vs. change of crack length. Compare with Fig.3, static strength of the composite cylindrical shell is much higher than buckling strength, in another word, the composite cylindrical shell would always fail in buckling.

When the crack length is shorter than 200mm, the buckling strength is reduced to approx. 1%. Whereas, buckling always occur in the area above the open hole on both sides. While the length of the crack exceeds 200mm, the buckling strength of the cylindrical shell suffers a sharp decrease and the buckling modes start to change. The compressive load may cause the penetrated crack to grow longer. As the buckling strength is reduced with the crack growth, the cylindrical shell would easily fail.

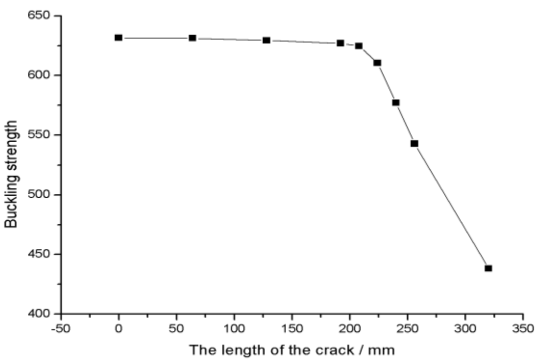

Fig. 8Buckling strength vs crack length

5. Repair

As the cylindrical shell contains an open hole where compressive load cannot be transferred, the area above the open hole actually bears the shear load. The compressive load in the middle area is slowly transferred onto both sides of the open hole. To deal with the penetrated crack present in this area, the solution is to recover the shear-carrying capacity of this area.

The cases in which the lengths of the crack exceed 200mm are considered for repair. A simple fabric patch having several plies of G814/6808 is bonded to this area as shown in Fig. 8. The angle between the fibers and axis is ±45°.

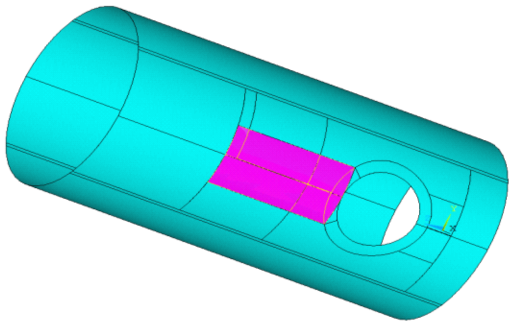

Fig. 8 Sketch of the cylindrical shell after repair

After repair, the shell will be divided into more areas and elements will be re-meshed again to achieve better accuracy. The real constant of this area is also changed to simulate the patch

Fig. 10 shows the buckling mode of the cylindrical shell after repair.

Fig. 11 the buckling strengths of both the unrepaired and repaired cracked shells, as well as that of the crackless shell.

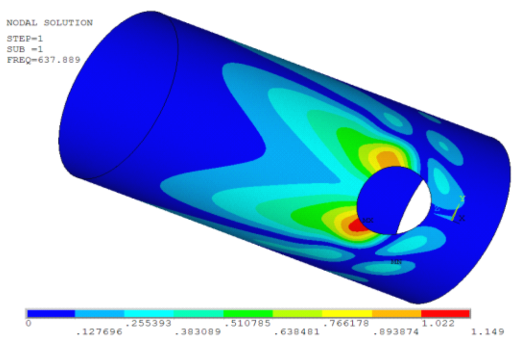

Fig. 10 Buckling modal graph of the cylindrical shell after repair

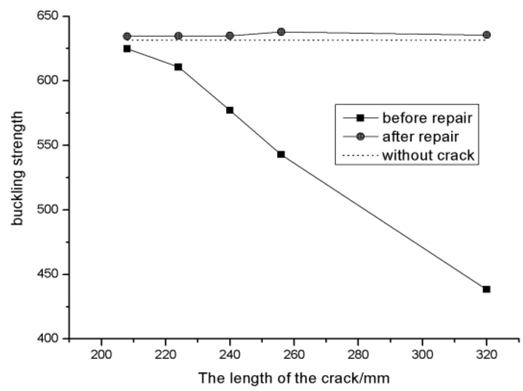

Fig. 11 Buckling strength before and after repair

After bonding a shearing patch on this area, the load-carrying capacity of the cylindrical shell is recovered (independently of the length of crack) comparing to that of the cylindrical shell without any crack. Fig. 11 shows that a small increase in the buckling strength was achieved and the buckling mode returned to that of the composite cylindrical shell without any crack. The buckling strength almost stays unchanged while adding more plies to the patch, showing that one ply of G814/6808 is enough. Overall, the repairs proved to be effective.

6. Conclusions

As the composite cylindrical shell is a thin shell, loaded in compression, it generally fails in buckling and critical areas are around the open hole.

No matter how long the penetrate crack is, once it occurs, the buckling strength of the composite cylindrical shell decreases, and the longer the crack is, the lower the buckling strength becomes.

With the crack length in certain range, the buckling strength is decreased but only to a smaller extent. It almost has no influence on the load carrying capacity of the composite cylindrical shell and the crack only needs to be bridged.

When the crack length exceeds a certain range, the critical region is shifted towards the area around the crack. Buckling strength drops sharply and proper measures must be undertaken to salvage the structure.

To deal with the penetrated crack in a composite cylindrical shell with a reinforced open hole, the shear-carrying capacity of the region above the open hole should be recovered. Bonding a shearing patch in this area is a way worth considering.

After proper repair, the buckling strength is increased slightly when compared to that of the cylindrical shell without any crack. The buckling mode is also resumed showing the repair is effective.

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