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Influence of surface rectangular defect winding layer on burst pressure of CNG-II composite cylinder

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Abstract. To study the influence of composite materials' surface defect on the burst pressure of CNG-II composite cylinder, the surface defect was simplified as a rectangular slot of certain size on the basis of actually investigating the shape of cylinder's surface defect. A CNG-II composite cylinder with a rectangular slot defect (2mm in depth) was used for burst test, and the numerical simulation software ANSYS was used to calculate its burst pressure. Through comparison between the burst pressure in the test and the numerical analysis result, the correctness of the numerical analysis method was verified. On this basis, the numerical analysis method was conducted for composite cylinders with surface defect in other depth. The result showed that surface defect in the form of rectangular slot had no significant effect on the liner stress of composite cylinder. Instead, it had a great influence on the stress of fiber-wrapped layer. The burst pressure of the composite cylinder decreased as the defect depth increasing. The hoop stress at the bottom of the defect in the shape of rectangular slot exceeded the maximum of the composite materials' tensile strength, which could result in the burst pressure of composite cylinders decreasing.

1. Introduction

High-strength fiber is used to wrap pressure vessel, and pressure vessel made of composite materials can be obtained after the fiber being solidified. The composite materials, characterized as high strength, large elasticity modulus, good design property, excellent fatigue resistance, outstanding failsafe performance and superior manufacturability [1], significantly improve the overall performance of the vessel. Therefore, pressure vessels made of composite materials have been widely applied in a variety of fields [2,3,4]. The fiber-wrapped composite cylinder (CNG-II composite cylinder) is a typical type of composite pressure vessel. However, the composite materials also have some drawbacks, such as having a low surface hardness, being vulnerable to scratch, and having poor wearability [5] which cause the fiber-wrapped layer to be unavoidably to generate defect during the production and the usage of CNG-II composite cylinders. It has also been observed that the damage is generally comprised of small-scale scratches, pits or wearing. According to the provisions [6] of Chinese National Standards *GB24162-2009 Periodic Inspection and Evaluation of Metal-lined and Fiber-Wrapped Composite Cylinders for Compressed Natural Gas Used by Automotive Vehicles*, the allowable and repairable defect depth on composite materials' surface is 1.25mm. However, inspectors usually perform the procedures based on experience instead of with a mind to strict compliance to this standard in the periodic inspection and scrapping determination for cylinders. At the same time, the absence of strict computational and experimental verification during the standard execution makes it highly possible that the composite cylinders still have great residual strength [7, 8] even when the defect is deeper than 1.25mm. The investigation of the damage tolerance and residual strength of

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composite cylinders with surface defect of certain size is necessary, and it benefits the safety management of composite cylinders. To obtain the damage tolerance of composite cylinders, it is essential to study the influence of surface defect on composite cylinders' stress.

The research needs to be carried out in the form of experiment and numerical simulation for researching the influence of surface rectangular defect on composite cylinders. Hydraulic burst test was conducted to obtain the ultimate burst pressure of the defective cylinders in the experiment, and numerical simulation was used to study the reason why the defect influenced the burst pressure. Numerical simulation analysis can be applied for defect in different depth, but the accuracy of numerical simulation needs to be verified by experiment. Through comparing the test result and the consequence of numerical analysis, the correctness of the modeling and analysis in numerical simulation was verified. On this basis, calculation was made for composite cylinders with other defect depth by means of numerical simulation. The ANSYS software has won recognition for related researcher with its powerful functions and can be applied to the analysis of composite materials with defect [9, 10].

On the basis of hydraulic burst test for the composite cylinders with surface rectangular defects, the paper used ANSYS software to analyze the stress field of defective cylinders. After verifying the correctness of finite element model by means of experiment, underlying causes were analyzed for the stress changes in the liner and the fiber-wrapped layer as well as changes in burst pressure.

2. Test methods

Hydraulic burst method was adopted to obtain the burst pressure of the composite cylinders with surface defects, and the test apparatus was capable to record pressure automatically. A G300LVE gas-driven pump was used for boosting pressure; a pressure sensor was used for measuring pressure during the pressure-boosting process. The measuring range of the pressure sensor was 0~150MPa, and the accuracy of the pressure sensor was Grade 0.5. The measuring range of the pressure gauge was 0~160MPa and the accuracy of the pressure gauge was Grade 1.6. Corresponding software was used to record the pressure changes during the process of hydraulic burst test.

The CNG-II composite cylinder used in the test was 406 mm in diameter and the size of the liner is shown in Figure 1. The fiber-wrapped layer was 8.4mm in thickness and the cylinder was 100L in volume. The liner was made of 30CrMo, and the composite materials comprised ECR560-2400 glass fiber and epoxy resin. The mechanical properties of the liner and the composite materials is shown in Table 1. The performance parameters of the composite materials are shown in Table 2. And the burst pressure of the defect-free composite cylinders with the same size in the test is 50-55MPa.

The defect on the surface of the composite cylinder were in the shape of a rectangular slot, and the defect was in the center of the composite cylinder. The scratch, which is along the axial direction of the cylinder, was 2mm in depth, 50mm in length, and 3.5mm in width, is shown in Figure 2.

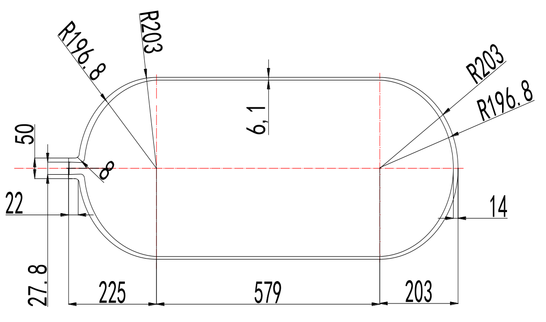

Figure 1. Model geometry

Figure 2. The shape of the defect

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Table 1. The mechanical properties of the liner and the composite layer

Material	Modulus of elasticity (GPa)	Poisson's ratio	Yield strength (MPa)	Tensile strength(MPa)	Elongation (%)
30CrMo	200	0.29	≥720	≥820	≥14
ECR560-2400 glass fiber/epoxy resin composite materials	≥81.49			≥2625	

Table 2. The performance parameters of the composite materials

E_X (GPa)	E_Y (GPa]	E_Z (GPa)	V_{XY}	V_{YZ}	V_{XZ}	G_{XY} (GPa)	G_{YZ} (GPa)	G_{XZ} (GPa)
33	8.97	8.97	0.26	0.05	0.26	6.2	2.0	2.0

The specific test procedures were as follows: The cylinder with scratch defect was fully filled with water first. Then it was fitted with a connector. A blasting machine was used for boosting water pressure. The pressure was boosted after air was exhausted. As the pressure reached approximately 43MPa, it was observed that the fiber-wrapped layer of the composite cylinder was initially broken at the zone of rectangular slot defect with the pressure dropping. Then the pressure was fluctuated and the fiber-wrapped layer continued to rupture with crack. Finally, the liner ruptured at approximately 26MPa. The shape of the burst composite cylinder is shown in Figure 3. The data of the hydraulic burst test was recorded and the time-pressure curve is shown in Figure 4.

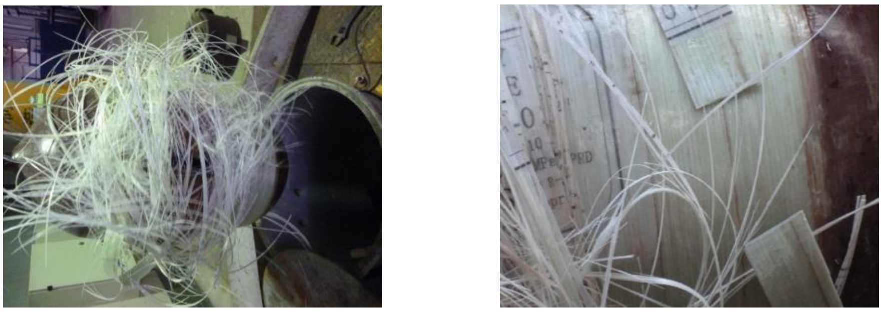


Figure 3. The shape of the burst composite cylinder

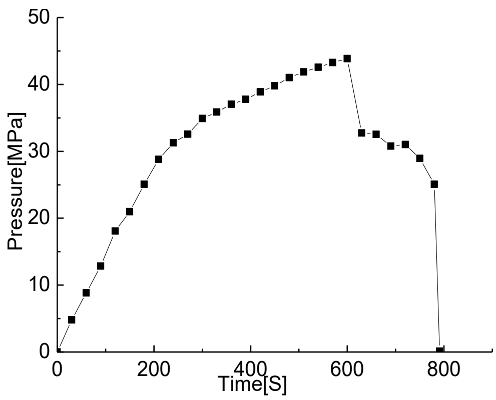


Figure 4. The time-pressure curve

From the test it is evident that the burst pressure of the composite cylinder with the rectangular slot (2mm in depth, 50mm in length and 3.5mm in width) was 43.87MPa. Compared with the burst pressure of the defect-free composite cylinders of the same size, there was a significant decrease in burst pressure for composite cylinders with rectangular slot defect on their surfaces.

3. Finite element analysis

3.1 Model establishment
Numerical analysis method was conducted for composite cylinder with the rectangular slot defect (2mm in depth, 50mm in length and 3.5mm in width). Half of the CNG-II composite cylinder model was established because the defect, which was in the center of the cylinder and along the axial, only affected the local part of the cylinder. The geometric structure and material properties of the CNG-II composite cylinder used in ANSYS was as same as the cylinder used in the foregoing burst test. The geometric model of the defective composite cylinder is shown in Figure 5.

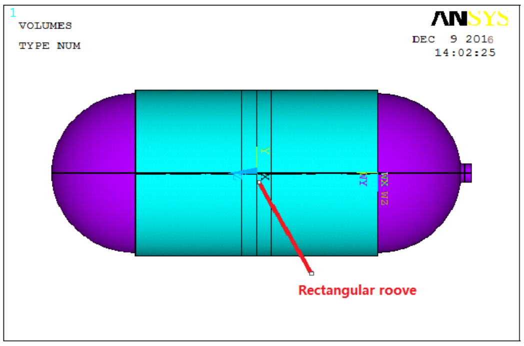


Figure 5. The geometric model of the defective composite cylinder

Finite element software ANSYS was used to make simulated calculation, and appropriate unit was selected according to the different model materials. The liner was made of isotropic material while the fiber-wrapped layer was made of transversely anisotropic material, which therefore meant that an 8-node isotropic unit solid45 was used for simulating the liner, and an 8-node anisotropic unit solid64 was used for simulating the fiber-wrapped layer. Since the cylinder is wrapped circumferentially, the composite fiber-wrapped layer was considered as a whole piece of anisotropic layer laminate, and the X axis of the fiber-wrapped layer unit coordinate system was adjusted along the fiber direction when establishing the model. The finite element model is shown in Figure 6.

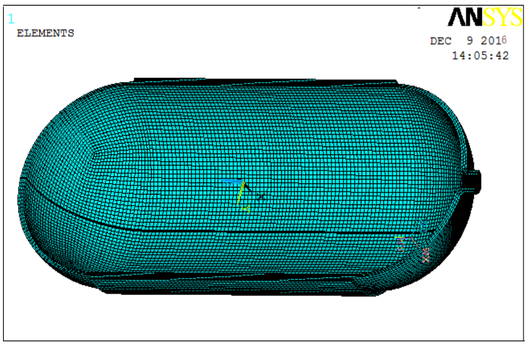


Figure 6. The finite element model

3.2 Constraint and load
The boundary conditions of the cylinder model were set as follows: Symmetry constraint was applied on the profile of the cylinder model. The equivalent tensile stress was applied on the top of the cylinder model and zero of axial displacement was applied at the bottom of the cylinder model.
Both normal load conditions and auto-frettage process should be taken into consideration during the ANSYS numerical simulation. The specific load conditions were as follows: the auto-frettage pressure was set as 34MPa, the operating pressure was set as 20MPa, and the maximal pressure was set as 65MPa to calculate the burst pressure easier. The load was set as: 0MPa→34MPa

→0MPa→20MPa→65MPa during the ANSYS numerical calculation. In addition, certain sub-steps were set for each load-step to ensure that the load was gradually increased.

3.3 Finite element calculation of burst pressure

It was first necessary to determine the burst criteria to calculate the burst pressure of the composite cylinder using numerical calculation method. The maximum stress criterion and the maximum strain criterion were used most popular. In the paper, it was concluded [11] that the maximum stress criterion had higher accuracy than the maximum strain criterion. At the same time, in light of that fact that the defect could give rise to discontinuity of the cylinder structure, stress singularity might occur to the local part of defect and consequently, calculation based on stress could potentially result in inaccuracy. Maximum strain criterion was therefore adopted for judgment. The basis of judgment for maximum strain criterion [12, 13] was the following.

$$\varepsilon_t = \varepsilon_f^h \tag{1}$$

Where, ε_t represents the maximum strain of the circumferential fiber layer; ε_f^h represents strain limit. Multiple burst tests for the composite cylinders indicated that the hoop facture strain of the fiber-wrapped layer at the time of cylinder burst was 85% of that of pure fiber. The fracture strain of the pure glass fiber provided by the glass fiber manufacture r was 3%, and that therefore the fracture strain of the circumferential fiber was 0.0255.

Finite element calculation was carried out for the composite cylinder with the rectangular slot defect (D×L×X=2×50×3.5mm), and the curve of relation between the stress changes of the winding layer and the load changes is shown in Figure 7.

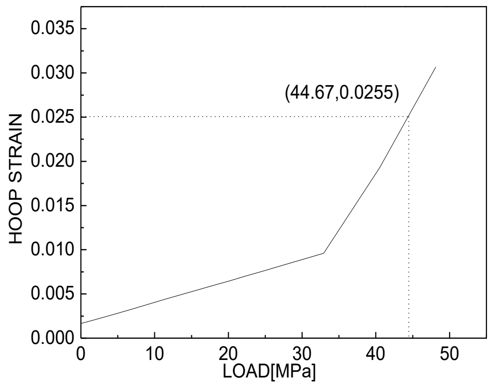


Figure 7. The curve of relation between the stress changes of the winding layer and the load changes

It can be seen from Figure 7 that while the facture strain was 0.0255, the corresponding load was 44.67MPa. Therefore, the burst pressure of the composite cylinder with rectangular slot defect (2mm in depth, 50mm in length and 3.5mm in width) was 44.67MPa. The starting point of the Y-axis in the Figure was not 0 owing to the fact that the previous auto-frettage treatment caused partial deformation to the fiber-wrapped layer.

Through comparison, the deviation between test result and the consequence of numerical calculation was 1.82%. This indicates that the finite element modeling was correct and that numerical calculating result was relatively accurate. So the same method can be adopted to calculate the burst pressure of the composite cylinders with the rectangular slot defect at different depth.

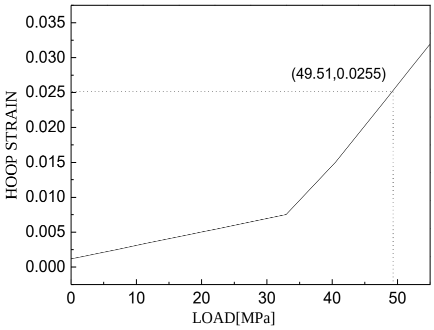
3.4 Burst pressure of the cylinder with various defect depths

The cylinder model above-mentioned was used for numerical calculation to evaluate the influence of rectangular slot defect with different depth on the burst pressure of CNG-II composite cylinder. The size of rectangular slot defect on the surface is shown in Table 3.

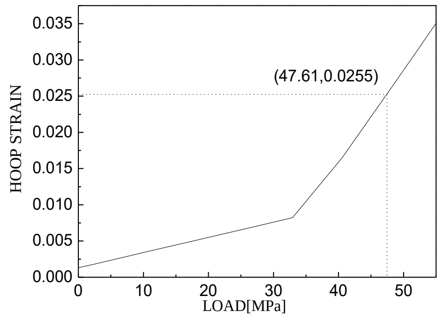
Table 3. The size of rectangular slot defect on the surface

The number of the defect	Length (mm)	Width (mm)	Depth (mm)	Analysis type
1	50	3.5	1.25	Numerical analysis
2	50	3.5	1.50	Experiment and Numerical analysis
3	50	3.5	1.75	Numerical analysis
4	50	3.5	2.00	Numerical analysis
5	50	3.5	2.25	Numerical analysis

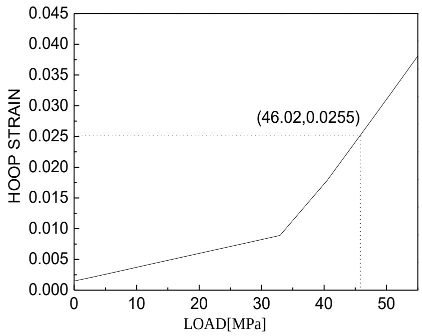
Through ANSYS numerical calculation for the composite cylinder with rectangular slot defect (50mm in length, 3.5mm in width, and 1.25mm, 1.5mm, 1.75mm and 2.25mm in depth respectively), the hoop strain curve of fiber-wrapped layer with the increasing of load is shown in Figure 8.



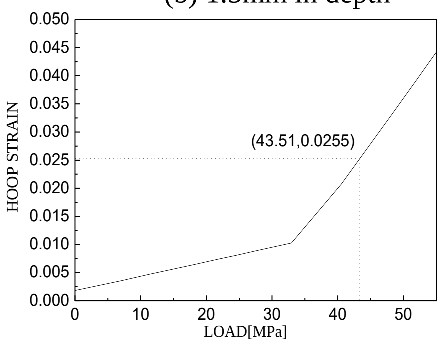
(a) 1.25mm in depth



(b) 1.5mm in depth



(c) 1.75mm in depth



(d) 2.25mm in depth

Figure 8. The curve of relation between the stress changes of the winding layer and the load changes

Figure 8. shows that the burst pressure of composite cylinders with rectangular slot defect (50mm in length, 3.5mm in width, and 1.25mm, 1.5mm, 1.75mm and 2.25mm in depth respectively) was 49.51MPa, 47.61MPa, 46.02MPa and 43.51MPa, respectively. And the burst pressure curve of defective cylinder with the increasing of defect depth is shown in Figure 9.

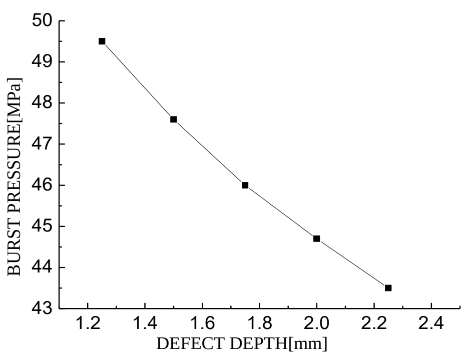


Figure 9. The burst pressure curve of defected cylinder with the increasing of defect depth

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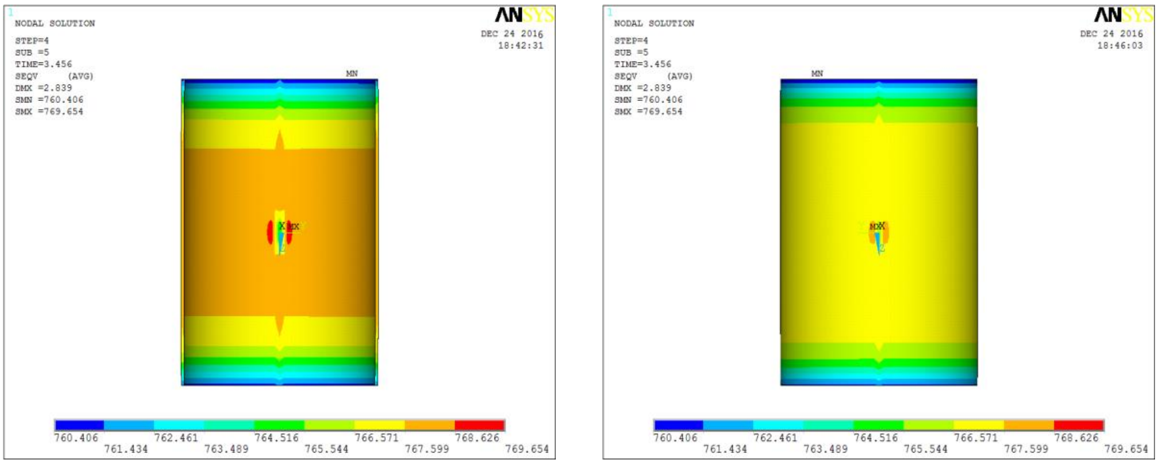
As seen from Figure 9, the burst pressure of defective composite cylinder decreased as the defect depth increasing. The stress analysis of liner and fiber-wrapped layer was taken into consideration to explain the fact that the burst pressure of defective composite cylinders decreased with the increasing of defect depth.

3.5 Stress analysis

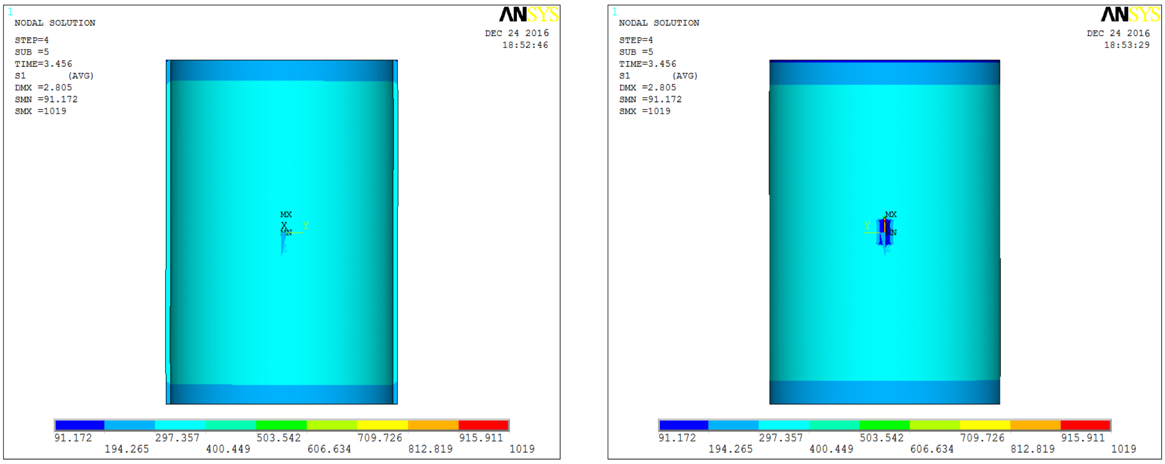
Both the test result and the consequence of ANSYS numerical simulation indicated that the burst pressure of cylinder decreased because of the defect. Through analyzing the stress of the composite cylinder with rectangular slot defect (50mm in length, 3.5mm in width and 2mm in depth), it was calculated that the burst pressure of the defective cylinder above-mentioned was 44.67MPa.

When the cylinder was under burst pressure 44.67MPa, the Mises stress nephogram of the cylinder liner is shown in Figure 10, and the hoop stress nephogram of the fiber-wrapped layer is shown in Figure 11.



(a) The inner surface of the liner (b) The outer surface of the liner

Figure 10. The Mises stress nephogram of the cylinder liner under burst pressure 44.67Mpa



(a) the inner surface of the fiber-wrapped layer (b) the outer surface of the fiber-wrapped layer

Figure 11. The hoop stress nephogram of the fiber-wrapped layer

Figure 10 shows that the maximal Mises stress of the liner was in the center of the liner's inner surface when the loading pressure reached the burst pressure, namely 44.67MPa. Furthermore, the maximal Mises stress was 769.65MPa, which was less than the tensile strength of the liner materials, namely 820MPa. Therefore, the liner had no danger of bursting under 44.67MPa. Besides, it can be found that

there was a little difference, approximate 1-2MPa, between the maximal Mises stress and the other Mises stress. That is, the surface defect of fiber-wrapped layer had little effect on the liner stress. Figure 11 indicates that the maximal hoop stress of fiber-wrapped layer, which was 1019.00MPa, is located at the defective area. And the maximal hoop stress exceeded the guaranteed value 995MPa of the tensile strength of fiber-wrapped layer, which had resulted in the decreasing of cylinder's burst pressure. The stress at the maximal stress point was, moreover, significantly greater than the stress at locations far away from the defective area. Therefore, the fiber-wrapped layer started to break from the maximal stress point, which conformed to the test observation. It can be concluded that the rectangular slot defect had significant influence on the stress distribution of fiber-wrapped layer.
The correctness of numerical analysis method was verified by the conformance between the test result and the consequence of numerical analysis. To study the influence of different defect depth on cylinder, the analysis method using for defect in 2mm depth was adopted for other defect depth. Figure 12 plots maximal Mises stress of the liner against five different defect depth. And Figure 13 plots maximal hoop stress of the fiber-wrapped layer against five different defect depth.

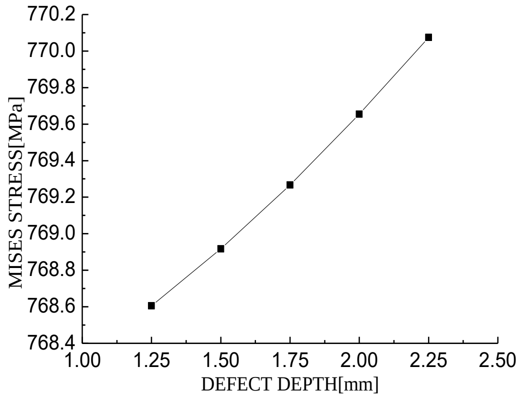


Figure 12. The relation maximal Mises stress of the liner against five different defect depth

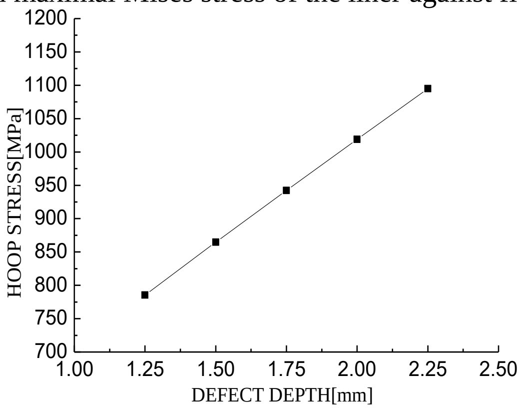


Figure 13. The relation maximal hoop stress of the liner against five different defect depth

Figure 12 indicates that the maximal Mises stress of liner rose, but slowly, as the defect depth increasing. The Mises stress of liner increased by 1.47MPa as the defect depth increasing from 1.25mm to 2.25mm, which further proved the conclusion that the defect had little influence on the liner. Figure 13 illustrates that the maximal hoop stress of fiber-wrapped layer rose, approximately 80MPa, as the defect depth increasing from 1.25mm to 2.25mm. This implies that the defect had larger effect on the fiber-wrapped layer. The maximal hoop stress of fiber-wrapped layer rose with the increasing of defect depth, and it could result in lower burst pressure of composite cylinder.

4. Conclusions

The method of finite element numerical simulation was used to study the influence of the surface defect, which was on the fiber-wrapped layer of composite cylinder, on the burst pressure. Hydraulic burst test was used to verify the correctness of the finite element model. Through analysis of stress changing law for each part of composite cylinder, it was concluded that the burst pressure of composite cylinder decreased because of the existence of surface defect. Surface defect had little influence on the liner stress of composite cylinder. The burst pressure of composite cylinder with surface defect decreased as the defect depth increasing, because the maximal hoop stress of fiber-wrapped layer rose with the increasing of defect depth.

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