Simulation of residual stress measuring process in a fiber material cylinder using slitting method

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Simulation of residual stress measuring process in a fiber material cylinder using slitting method

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Abstract. In order to measure the residual stress in fiber material more conveniently by strain gauge, A measurement scheme based on slitting method and finite element simulation is proposed in this paper. The measurement models with different crack depth are established, and the influence of the distance from crack to strain foil are also investigated. In addition, the residual stress field is estimated by temperature-stress field analogy. Simulation results show that the distance from strain gauge to crack should better be between 0.3 and 0.5 times of the cylinder radius. By counting the difference between different stress-depth curves of the crack slitting, the inner stress in the cylinder with non-uniform stress distribution can be evaluated.

1. Introduction
When considering the cause of cracks in components, residual stress [1] is an important consideration. It is well known that, hole drilling method [2] is the most commonly used residual stress measurement method. However, for fiber material the drilling method is not an appropriate method for measuring residual stress, especially when the hole does not cut the fiber, the method is almost ineffective. In order to better understand the mechanism of material failure caused by residual stress, and further use the artificial residual stress, that is, the principle of pre-stress [3], to increase the crack resistance of the material, there must be an effective method for measuring residual stresses in fiber materials. When selecting the appropriate measurement method[4], considering that the fibers should be cut off from the material, the slitting/crack compliance method [5] is selected. Fig.1 shows the principle of slitting method in measuring growth stress in a fiber material cylinder.

Figure 1. schematic diagram of slitting method measurement

In the measurement, the stress in the cylinder is released by increasing the depth of the crack by manual cutting, and then the residual stress in the cylinder is calculated by a special algorithm. However, there are many questions that need to be answered, such as: (1) Is it better to cut one crack...
or to cut two cracks? (2) How far the strain foil should be from the crack? (3) how deep should the crack be cut? (4) In addition to surface stress, can stress inside the cylinder be measured by strain foils with prefabricated cracks? In this paper, the above questions are answered by numerical simulations.

2. Numerical simulation
On the basis of a cylindrical geometry model, a finite element model is established to simulate the stress release caused by slitting of different cutting depths by generating cracks of different depths in turn. Then the slitting method is combined with the finite element analysis to evaluate the residual stress in the cylinder more effectively.

2.1. Simulation model
The numerical simulation model is shown in Fig.2, and in the simulation, the macroscopic elastic constants are shown in Table.1

![Figure 2. Simulation model in this research](image)

| $E_R$ | $E_T$ | $E_L$ | $G_{RT}$ | $G_{RL}$ | $G_{TL}$ | $v_{RT}$ | $v_{RL}$ | $v_{TL}$ |
|------|------|------|--------|--------|--------|--------|--------|--------|
| 0.8  | 0.4  | 10   | 0.07   | 0.62   | 0.54   | 0.4    | 0.1    | 0.1    |

In the simulation model, the simple unidirectional stress state is simulated by exerting the displacement load directly on the finite element model, and the complex residual stress field is simulated through thermal-stress analogy. The cracks in the measurement process on the cylinder are simulated by prefabricated cracks in the finite element models. In the thermal-stress analogy, a suitable temperature field is pre-defined on the model (usually the temperature near the center is lower, and the temperature near the surface is higher. The two ends of the cylinder are fixed, and then the temperature in the central part is increased by heat conduction). The residual stress field is simulated by forming a stress field with axial compressive stress at the center region of the cylinder and with axial tensile stress at the surface region of the cylinder.

2.2. Simulation results
After establishing a large number of models and simulating different slitting intervals and different slitting cutting depths, some interesting simulation results are obtained.

2.2.1. Comparison of single and double cut. Fig.3 and Fig.4 have compared the percentage of stress measured by strain gauges to the initial stress values of the cylinder by single crack cutting method and double crack cutting method when the crack depth is 15% of the cylinder radius. The simulation results show that the value of strain gauge measured by double crack cutting method is more than twice that of single crack cutting method. The method of double crack can reduce the depth of crack cutting and reduce the damage to the material to a certain extent. The simulation of other crack depths, such as 5mm, 15mm, 20mm, has obtained the same results, all of which show that the double crack cutting method is superior.
Figure 3. Simulation result of single crack cut. (the crack depth is equal to 15% of cylinder radius, the stress relaxation measured by the strain gauge is 18% of initial stress)

Figure 4. Simulation result of double cracks cut. (the crack depth is equal to 15% of cylinder radius, the stress relaxation measured by the strain gauge is 45% of initial stress)

2.2.2. Location of strain foil. In the simulation, the size of the finite element mesh is set to 1/10 of the radius of the cylinder, which is convenient for the result observation.

Figure 5. Influence of strain foil location on measurement. (In this simulation crack depth is equal to 15% of cylinder radius)

From the fitting curve of Fig.6, it can be seen that when the distance from the measuring point to the crack is more than 0.5 times of the cylinder radius, the released stress that can be measured by the strain gauge is no more than 20% of the initial stress. If the measured stress value is too small, the measurement accuracy will decrease. So the distance from the measuring point to the crack should not exceed 0.5 times of the cylinder radius. From the simulation, it is also found that the measuring point should not be too close to the crack. For example, when the distance is less than 0.3 times of the cylinder radius, the stress in-homogeneity and stress gradient near the measuring point will increase. The increasing of the stress gradient will cause large measurement error. Therefore, the optimum distance from the measuring point to the crack should be 0.3-0.5 times of cylinder radius. According to this finding, the distance from the strain foil to the crack is set to be 0.4 times of the cylinder radius in the subsequent simulations.
2.2.3. Crack depth and the measured stress. In addition to the crack with 15% cylinder radius in figure 4, the models with crack depth of 7.5% and 20% cylinder radius are also used to simulate the crack. Simulation results see figure 7 and figure 8, respectively.

Figure 7. Simulation result of double cracks cut. (the crack depth is equal to 7.5% of cylinder radius, the stress relaxation measured by the strain gauge is 13% of initial stress)

Figure 8. Simulation result of double cracks cut. (the crack depth is equal to 20% of cylinder radius, the stress relaxation measured by the strain gauge is 75% of initial stress)

The simulation results show that when the crack depth reaches 15% of the cylinder radius, the strain gauge can measure 45% of the initial stress; if the crack depth reaches 20% of the cylinder radius, the strain gauge can measure 75% of the initial stress. However, in order to avoid damage of the cylinder, the shallower the crack, the better. But the crack depth should not be too small, for example, when the crack depth is 7.5% of the cylinder radius, the strain gauge can only measure 13% of the initial stress. Therefore, it is suggested that the crack depth of 15% cylinder radius should be used in the actual measurement.

2.2.4. Method of internal stress measurement. Through numerical simulation, it is found that the anisotropic mechanical properties of fiber material will lead to the uneven distribution of the internal stress of the cylinder (usually resulting in the axial tensile stress of the outer surface being greater than the internal axial tensile stress).
Figure 9. Simulation result of internal stress distribution in a long cylinder

Through anisotropic material model and thermal-stress analogy, the initial stress distribution in the cylinder is shown in figure 9. Suppose that there are two cylinders, one of which has uniformly distributed axial tensile stress, the other has a similar stress distribution pattern to the cylinder in figure 9. When using slitting method to measure the stress, suppose the surface stress of the two cylinders is the same, the measurement result of the two cylinders by slitting method will be different. Thus the inner stress distribution pattern in the cylinder can be evaluated according to the comparison of the two different measurement results.

Figure 10. The cylinder with non-uniform initial axial stress (the crack depth is equal to 15% of cylinder radius, the stress relaxation measured by the strain gauge is about 33% of initial stress)

For example, in the simulation the initial stress on the surface of the two cylinders is set the same (+30 MPa, see figure 10 and 11). However, the axial stress in the center region of cylinder in figure 10 is lower than that of cylinder in figure 11. Simulation results show that the stress relaxation in cylinder in figure 10 is about 33% of the initial surface stress, and this value is 45% in the cylinder in figure 11. This shows that different internal stress distribution leads to significant difference in surface stress relaxation. So that, by combining simulation model with measured stress comparison, the non-uniform stress field in the cylinder can be deduced from the simulation.

Figure 11. The cylinder with uniform initial axial stress (the crack depth is equal to 15% of cylinder radius, the stress relaxation measured by the strain gauge is about 45% of initial stress)
Figure 12 has compared the curves of cylinders with uniform initial stress field and non-uniform initial stress field. The larger the distance between the two curves, the greater the difference of stress field between the two models. As long as the measured curve is compared with the existing curve, the stress field in the cylinder can be estimated according to the amount of deviation.

3. Conclusion
Based on FEA, residual stress measuring process in fiber material cylinders using slitting method can be simulated. In the course of simulation, the models with different crack depth are established, and the influence of crack depth on measurement and the influence of crack-strain foil distance is investigated as well. In addition, a measurement technology of the internal stress field of cylinders by combining strain gauge measurement and FEA simulation of slitting method is discussed. In the simulation, the residual stress field model is established by temperature-stress field analogy, and the effect of anisotropic material properties on the corresponding stress field is considered. Simulation results show that the optimum distance from strain gauge to crack should be 0.3 - 0.5 times of the cylinder radius. As for crack depth, when crack depth reaches 15% of cylinder radius, the strain gauge can measure 45% of the initial stress; if the crack depth reaches 20% of the cylinder radius, the strain gauge can measure 75% of the initial stress. By counting the difference between the stress-depth curves of the crack slitting, the inner stress in the cylinder with non-uniform stress distribution can be evaluated.

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References
[1] A.Baldi, Full field methods and residual stress analysis in orthotropic material. II: Nonlinear approach, International Journal of Solids and Structures, 44(2007) 8244-8258.
[2] R.Seifi, D.Salimi-Majd, Effects of plasticity on residual stresses measurement by hole drilling method, Me chanics of Materials 53(2012) 72-79.
[3] B.H.Kim, Evaluation of prestress force on bonded tendons using practical formula, Experimental mechanics,55(2015) 439-447.
[4] N.S.Rossini, M.Dassisti, K.Y.Benyounis, etc., Methods of measuring residual stresses in components, Materials and Design, 35(2012) 572-588.
[5] G.U Sosa, B.R Angeles, L.HH Gomez, etc., GU Calderon, Crack-compliance method for assessing residual stress due to loading/unloading history: Numerical and experimental analysis, Theoretical and Applied Fracture Mechanics, 56(2011)188-199.