

EFFECTS OF PRE-TIGHTENING FORCE AND CONNECTION MODE ON THE STRENGTH AND PROGRESSIVE DAMAGE OF COMPOSITE LAMINATES WITH BOLTED JOINT

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Abstract. Pre-tightening force and the mode of connection are of great influences on progressive damage of connection. Two three-dimensional (3D) models of composite laminates with bolted joint are developed with the finite element software and compared with the analytical results. Using 3D failure criteria, the influences on the strength and progressive damage of composite laminates with bolted joint are analyzed. The results indicate that the connection strength in single-lap laminated plates increases by a given range of pre-tightening force, but the connection strength will be reduced by excessive level of pre-tightening force. While in double-lap laminated plates, it increases with the addition of pre-tightening force. The connection strength of double-lap laminated plates is higher than that of the single-lap laminated plates. It may be attributed to the secondary bending because of the eccentric load. The initial failure loads of composite laminates are improved with the appropriate pre-tightening force. Delamination and matrix cracking failure load of composite laminates are reduced and the connection strength is improved.

1. Introduction

Composite material is widely used in ship and aerospace structures because of its high material performance. Bolted joint is also widely used in composite structure which can transfer large load and it is easy to be repaired. Joints of composite material are the key point of composite structure, so it is important to study its strength and progressive damage. The load of shear bolt joint is transferred by bolt's shear and small pre-tightening force is effective. While in special structures, large pre-tightening force is used to meet the demand of fatigue life and mechanical seal. At present, a good number of the literatures on the strength of composite laminates with bolted joint are available. Wang [1] analyzed the effects of pre-tightening force on the double-lap bolt joint. Zhang [2] have presented the influencing factors of bolt joint and found that appropriate pre-tightening force could improve the strength of bolt joint. McCarthy [3] carried out a series of tests to study the effects of pre-tightening force on stress around the hole. Kiral [4] characterized the failure modes and the strength of composite material pin joint with different e/d and w/d . Pradhan [5] analyzed the effects of

Table 1. Dimensions of joints.

| L/mm | W/mm | t/mm | e/mm | D/mm | d/mm |
|------|------|------|------|------|------|
| 120 | 24 | 2 | 16 | 10 | 6 |

Table 2. Mechanical properties of T300/1034-C.

| Properties | Value | Properties | Value |
|----------------|-------|----------------------|--------|
| E_{xx} / GPa | 146.9 | σ_{bx} / MPa | 1730.6 |
| E_{yy} / GPa | 11.38 | σ_{cx} / MPa | 1739 |
| E_{zz} / GPa | 12.38 | σ_{by} / MPa | 66.54 |
| G_{xy} / GPa | 6.185 | σ_{cy} / MPa | 268.2 |
| G_{xz} / GPa | 6.185 | σ_{bz} / MPa | 52 |
| G_{yz} / GPa | 5.78 | σ_{cz} / MPa | 280 |
| V_{xy} | 0.3 | σ_{sxy} / MPa | 133.8 |
| V_{xz} | 0.3 | σ_{sxz} / MPa | 133.8 |
| V_{yz} | 0.42 | σ_{syz} / MPa | 100 |

2.2. Failure criterion of progressive damage. Based on Hashin criterion, 3D progressive damage failure criterion is proposed by TSERPES [8-10], 3D progressive damage failure criterion is used in this paper, and the forms are shown as follows:

Matrix tensile crack:

$$\left(\frac{\sigma_{yy}}{\sigma_{by}}\right)^2 + \left(\frac{\sigma_{xy}}{\sigma_{sxy}}\right)^2 + \left(\frac{\sigma_{yz}}{\sigma_{syz}}\right)^2 \geq 1, \quad \sigma_{yy} \geq 0. \quad (1)$$

Matrix compressive crack:

$$\left(\frac{\sigma_{yy}}{\sigma_{cy}}\right)^2 + \left(\frac{\sigma_{xy}}{\sigma_{sxy}}\right)^2 + \left(\frac{\sigma_{yz}}{\sigma_{syz}}\right)^2 \geq 1, \quad \sigma_{yy} \leq 0. \quad (2)$$

Tensile delamination:

$$\left(\frac{\sigma_{zz}}{\sigma_{bz}}\right)^2 + \left(\frac{\sigma_{xz}}{\sigma_{sxz}}\right)^2 + \left(\frac{\sigma_{yz}}{\sigma_{syz}}\right)^2 \geq 1, \quad \sigma_{zz} \geq 0. \quad (3)$$

Compressive delamination:

$$\left(\frac{\sigma_{zz}}{\sigma_{cz}}\right)^2 + \left(\frac{\sigma_{xz}}{\sigma_{sxz}}\right)^2 + \left(\frac{\sigma_{yz}}{\sigma_{syz}}\right)^2 \geq 1, \quad \sigma_{zz} \leq 0. \quad (4)$$

2.3. Applied pre-tightening force. Two methods of applying pre-tightening force are widely used in composite laminates with bolted joint. One is that taking a section of bolt to make it pre-tensile grid, then the corresponding load is applied on it. The other is based on the principle of expand on heating and contract on cooling. Reducing the bolt temperature is used to simulate the pre-tightening force. In this paper, first method is taken to simulate the pre-tightening force.

Pre-tightening force of bolt can be obtained from the nut torque and the expression is shown as

$$P = \frac{M}{kd}. \quad (8)$$

Here M, k, d represent nut torque, torque coefficient and bolt diameter. The lateral compressive stress around the hole of composite laminate [12] is written as:

$$\sigma_2 = \frac{P}{\pi/4(D^2 - d^2)}. \quad (9)$$

Here D, d are the washer diameter and bolt diameter. The value of lateral compressive stress σ_2 plays an important role in initial failure load and affects the whole structure strength.

3. Model validation and analysis of result

3.1. Model validation. To validate the correctness of the present model, firstly, the results are compared with the experimental results of reference [13] and the errors between the analytical results of reference and the present results are shown in Table 3 which are in the permitted range. Comparative results are as follows: failure modes of joint are identical, as are all the tensile failure. The experimental value is 195.2 MPa, while the present one is 190 MPa. The error is 2.66 % .So the present model can be used for the strength prediction of composite laminates with bolted joint.

Table 3. Comparison results of analytical results and computation results.

| Case | stacking sequence | reference, MPa | paper results, MPa | errors |
|------|---|----------------|--------------------|--------|
| 1 | [(0/90) ₆] _s | 180 | 200.03 | 10.0 % |
| 2 | [(±45) ₆] _s | 120 | 127.6 | 5.96 % |
| 3 | [(0/±45/90) ₃] _s | 250 | 229.8 | 8.79 % |
| 4 | [(90 ₂ /±60/±30) ₂] _s | 170 | 165.4 | 2.78 % |

3.2. Strength analysis of two connection styles. Three-dimensional models of composite laminates with bolted joint are developed with the finite element software. A series of pre-tightening force which are shown in Table 4 are applied and discussed the effects on the elements around the hole.

From Fig. 5 in double-lap joint, the maximum stress reduces with the increase of pre-tightening force. When the torque increases to 5 Nm, the maximum stress value become stable. But in single-lap joint, at the beginning the maximum stress reduces with the increased of pre-tightening force, and the torque increases to 5 Nm, the maximum stress reduce to minimum value. The maximum stress increases if the torque continues to increase.

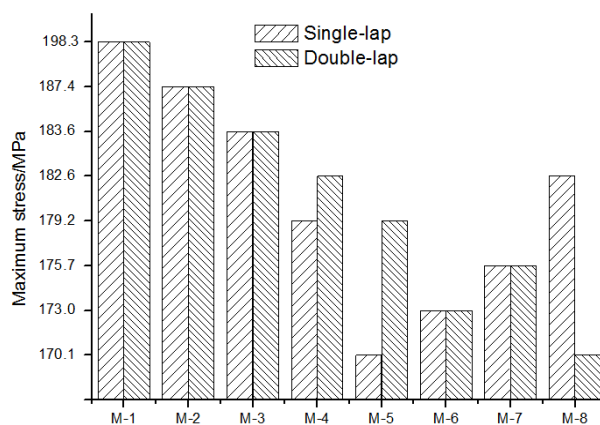


Fig. 5. The comparison of maximum stress between single-lap and double-lap.

3.3. Progressive damage analysis. Based on previous studies [12, 13] and combined with the finite element model, composite laminates with bolted joint which is loaded a torque of 5 Nm is simulated and analyzed. Progressive damage of composite laminate is obtained with the tensile load. The specific extension process of laminates damage is shown in Fig. 5.

From Fig. 6 when the load increases to 90 MPa, 90° layer appear initial failure and the failure mode is matrix crack. With the increase of load until up to 160 MPa, -45° layer and 45° layer also appear initial matrix crack failure. With the load up to 170 MPa, matrix crack is the only failure mode although the failure element number of 90° layer increases. With the load up to 180 MPa, failure appears in 0° layer and failure mode is fiber breakage instead of matrix crack. With the load up to 200 MPa, -45° layer and 45° layer appear various failure modes (matrix crack and fiber breakage), while 45° layer appears fiber breakage failure mode. It may be attributed to the adjacent 0° layer appears amount of fiber breakage and lead to the 45° layer fiber stress increases. With the load up to 220 MPa, there are two failure modes (fiber-matrix shear and fiber breakage) in 0° layer and 90° layer. Previous matrix crack failure elements turn into matrix crack -fiber-matrix shear failure. With the load up to 240 MPa, every layer's failure element number appears a large increase and quickly expands from the hole to the edge of plate width. Failure mode becomes various and previous single-mode turns into multi-failure. With the load up to 320 MPa, element failure expands to the edge of plate width and the joint lose its function.

From Fig. 7 and Fig. 8, initial matrix cracking load and initial delamination load in double-lap joint increase with the increase of torque. As the torque up to 5 Nm, although the torque continues to increase, the failure load becomes stable. While in single-lap joint, initial matrix cracking load and initial delamination increase with the increase of torque until up to 5 Nm. But the failure load reduces if the torque continues to increase. To some extent,

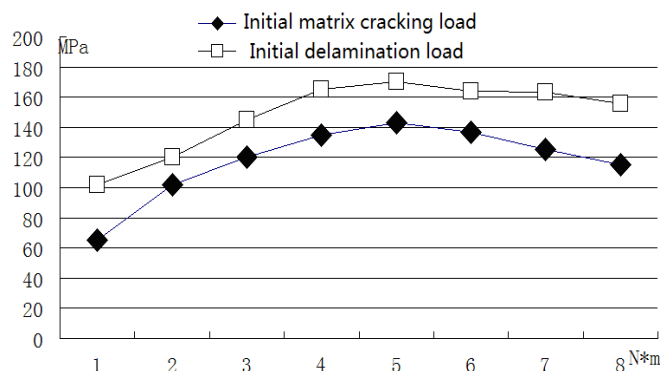


Fig. 8. The initial failure load of single-lap laminated plates.

Table 5. The comparison of final failure load between single-lap and double-lap.

| | | |
|--------------------|------------|---------|
| Final failure load | Double-lap | 320 MPa |
| | Single-lap | 308 MPa |
| | Comparison | 3.9 % |

4. Conclusions

Based on 3D progressive damage theory, the progressive damage of composite laminates with bolted joint models (single-lap and double-lap) is analyzed considering three-dimensional failure modes. Conclusions are obtained:

(1) Comparing the composite laminate double-lap joint with the single-lap, it predicts that strength of double-lap is about 3.9 % higher than single-lap because of the secondary bending caused by eccentric load in single-lap joint.

(2) To some extent, the strength of composite laminates with bolted joint improves with the increase of pre-tightening force double-lap joint or single-lap joint. The strength will decrease if pre-tightening force is too large.

(3) Appropriate pre-tightening force can reduce initial matrix cracking load and initial delamination load, and put off the extension of composite laminate progressive damage. It may be attributed to lateral restraint caused by pre-tightening force.

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