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AN ESTIMATION METHOD OF BEARING STRENGTH OF BOLTED JOINTS IN FIBRE REINFORCED COMPOSITE

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Abstract

Some researchers have estimated the strength of bolted joints in fibre reinforced composite, using simple and efficient engineering procedures. However, for these procedures the effect of clamping due to the strength of bolted joints is not considered. In this paper, a method is presented for predicating critical bearing strength of single-hole bolted joints in composite on the basis of observing and analysing the results of experiments. The clamping effect of bolts is considered. The calculated results correspond to the test data on Glaphic/Epoxy laminates.

I. Introduction

With the application of fibre reinforced composite in aircraft structures it is important to study a deep insight into the failure of bolted joint (determination of failure load and mode, analysis of failure position, etc.). Because of the anisotropism, brittleness and hoterogeneity the stress concentration around the hole in intensified and the probability of local failure may be increased in the area of bolted joint. In [1] some problems, such as potential failure modes of the joint and the effects on joint strength were analysed. By means of the reasonable selection of the geometric parameters w/D and e/D, is able to make the failure mode of joint a bearing failure mode rather than tension or shear failure mode, enhancing the strength of bolted joint. It is very important to study a method for the determination of joint strength.

For the strength analysis of bolted joint, it is necessary to compute the stress distribution of anisotropic composite laminated finite wide plate with a loaded fastened hole and to determine the joint strength by using appropriate failure criterion of static strength according to a certain definition of failure. The closed form solution is intractable for determination of stress distribution in a laminated plate with a loaded hole. Therefore, numerical method must be used to determine the stress state. Joint strength and failure mode for the bolted joint have been extensively studied[2-8]. But up to now no simple method has been developed to calculate strength of bolted joint for all kinds of failure modes. Recently, some researchers have estimated the strength of bolted joint using simple and efficient procedure.

Strength analysis was developed by Wilson and Pipes[9] for the shearout failure mode in composite bolted joint. A Semi-empirical formula for shearout failure strength was obtained, based on two-dimensional plane stress finite element analysis with orthotropic quadrilateral elements. To predicate effect of geometric parameters on joint strength a polynomial stress function in conjuction with a point stress failure criterion is employed in the strength analysis. The characteristic distance

d_0 (for the point stress failure criterion) was determined by the test data for Graphite/Epoxy laminates $[45/0/-45/0_2/-45/0/45/0_2/90]_s$. In the characteristic distance failure criterion, it is necessary to know the value of d_0 for either average or point stress criterion. There is no standard procedure to find it for different materials or hole diameters. Different value of d_0 has been used according to the test results. Furthermore, in these criterion the joint strength is computed only based on a single stress component. In fact, the state of stress at almost all the points around the hole edge is a plane stress state. The stress distribution and the most serious point of stress concentration are also changed with the change of parameters of laminates. The detail can be seen in [16]. Therefore, there is some limitation in application of those empirical formulae for analysing the shearout failure strength of joint based on the characteristic distance failure criterion.

Static strength of bolted joint of composite laminates under combined by-pass tension and bolt load is investigated by Tang[10]. A tension failure factor is proposed for orthotropic thin laminate specimens (thickness less than 0.63 cm) with $w/D \geqslant 6$、$e/D \geqslant 3$. In application of the data obtained from some different symmtric Graphite/Epoxy laminates including some orientation of 0°, 90°, ±45° the failure loads and failure modes are estimated by interpolation for another laminates. The laminates consisting of different proportion of plies are subjected to the combination of tension and bolt load.

The stress analysis of composite joint specimen with bolt-loaded hole has been conducted by Soni.[11,12] The hole is filled with a rigid core to simulate a bolt. An average distributed load is applied to the rigid core. The stress analysis is treated by finite element technique. The strength analysis is based on the tensor polynomial failure criterion applied to each ply. Consequently, ultimate failure strength of laminate is determined.

Some tests were conducted by several researchers for investigating the strength of bolted joints.[13-15] From the experimental results obtained the effects of geometric parameters of joint, clampup torque and parameters on the joint strength were shown. To study effects of local reinforced or softened on joint strength many experiments were also conducted by means of extra Titanium-Shim or GFRP plies. More valuable data and experience have been accumulated from these experiments. For single-hole specimen failure load Pmax and maximum deformation of hole are generally obtained by experiments. However, aircraft structure engineers were most interested in the load which is corresponding to a special deformation of hole or the initial failure. This deformation is a critical one, i.e. when the hole deformation exceeds this value, it increases rapidly with the increase of load. In addition to load and deformation, it is necessary to realize the location of initial failure and the possible modes of failure.

In order to develop full bearing strength the minimum value of the w/D or e/D is needed for the design of bolted joint. It is important that how the bearing strength is predicated and how the bearing strength is raised through reasonably designing laminated parameters. Reference materials relating to these problems are not too much. In this paper the finite element analysis technique coupled with classical laminated plate theory is used in computing the stress distribution for single-fastened joint. On the basis of analysing experimental results a method of engineering computing for critical bearing strength of single-hole bolted joint in composite is presented.

II. Analysis Procedure

Symmetric laminates in plane stress state are found to have a wide application in aircraft structure today. Therefore, these laminates are analysed in this paper. Load of single direction is applied on composite laminates with a bolt-loaded hole. In order to simulate the load applied to hole by bolt the assumption of cosine normal load distribution is adopted as Fig. 1. The resultant of decentralized load in x-direction equals to the resultant Q of tension applied to the end of plate.

$$p=\frac{2Q}{\pi R}\cos\theta$$

where p — the contact forct per arc length.

Q — total bolted load.

R — radius of the bolted hole.

θ — measured opposite clockwise from a horizontal axis x through the hole.

For stress analysis of laminated plate with a hole the plane stress 4-node isoparamtric element is used in the structural analysis program. The program can be used to solve: (1) the corrected stress components σ_x、σ_y and τ_{xy} for each node. (2) radial and tangent stress components σ_r、σ_θ and $\tau_{r\theta}$ for each node at the hole or washer edge. (3) stress components σ_x、σ_y and τ_{xy} for each element. (4) On-axis stresses for each ply. The failure criterion-Norris criterion is adopted for strength analysis of each ply. The applied load is increased step by step and the computions above mentioned are repeated until the load of critical bearing is obtained. Equivalent engineering constants of laminate E_x, E_y, G_{xy} and μ_{xy} are obtained by the classical laminated plate theory i.e. the laminate is regarded as equivalent, homogeneous orthotropic plate.

Stiffness matrix of the element is as follows:

$$[K]^e=\int_{-1}^{1}\int_{-1}^{1}[B]^T[D][B]|J|t\,d\xi\,d\eta$$

where $[D]$ — elastic matrix for effective orthotropic material

$$[D]=\begin{bmatrix} \frac{E_x}{1-\mu_{xy}\mu_{yx}} & \frac{E_x\mu_{yx}}{1-\mu_{xy}\mu_{yx}} & 0 \\ & \frac{E_y}{1-\mu_{xy}\mu_{yx}} & 0 \\ \text{Sym.} & & G_{xy} \end{bmatrix}$$

Stress components σ_x、σ_y and τ_{xy} for each element are obtained by the finite element analysis program. They are average stresses of the element. According to the condition of compatible deformation which is satisfied for each ply in every element under the applied load, on-axis stress components can be calculated for each ply then Norris failure criterion is used for analysing strength of each ply.

Norris failure criterion is as follows:

$$\left(\frac{\sigma_1}{X}\right)^2+\left(\frac{\sigma_2}{Y}\right)^2-\left(\frac{\sigma_1\sigma_2}{XY}\right)+\left(\frac{\tau_{12}}{S}\right)^2=1$$

where σ_1, σ_2 and τ_{12} are on-axis stress components respectively for each ply in every element.

X, Y and S are on-axis ultimate strength for selected uni-directional composites material.

The flow diagram of the analysis program is as follows:

III. Failure Definition for Bolted Joint in Composite Laminate

One of the characteristics for aircraft structures is in repeated service. It is required that the apparent damage will not occur. Due to this reason for bolted joint in composite laminate the

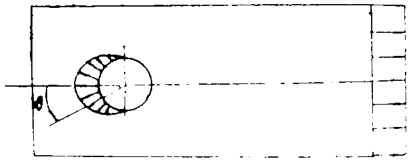

Fig. 1. Load distribution applied to bolted hole

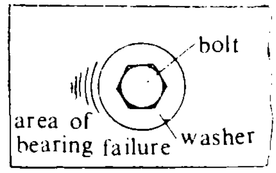

Fig. 3. Figure of bearing failure for bolted joint

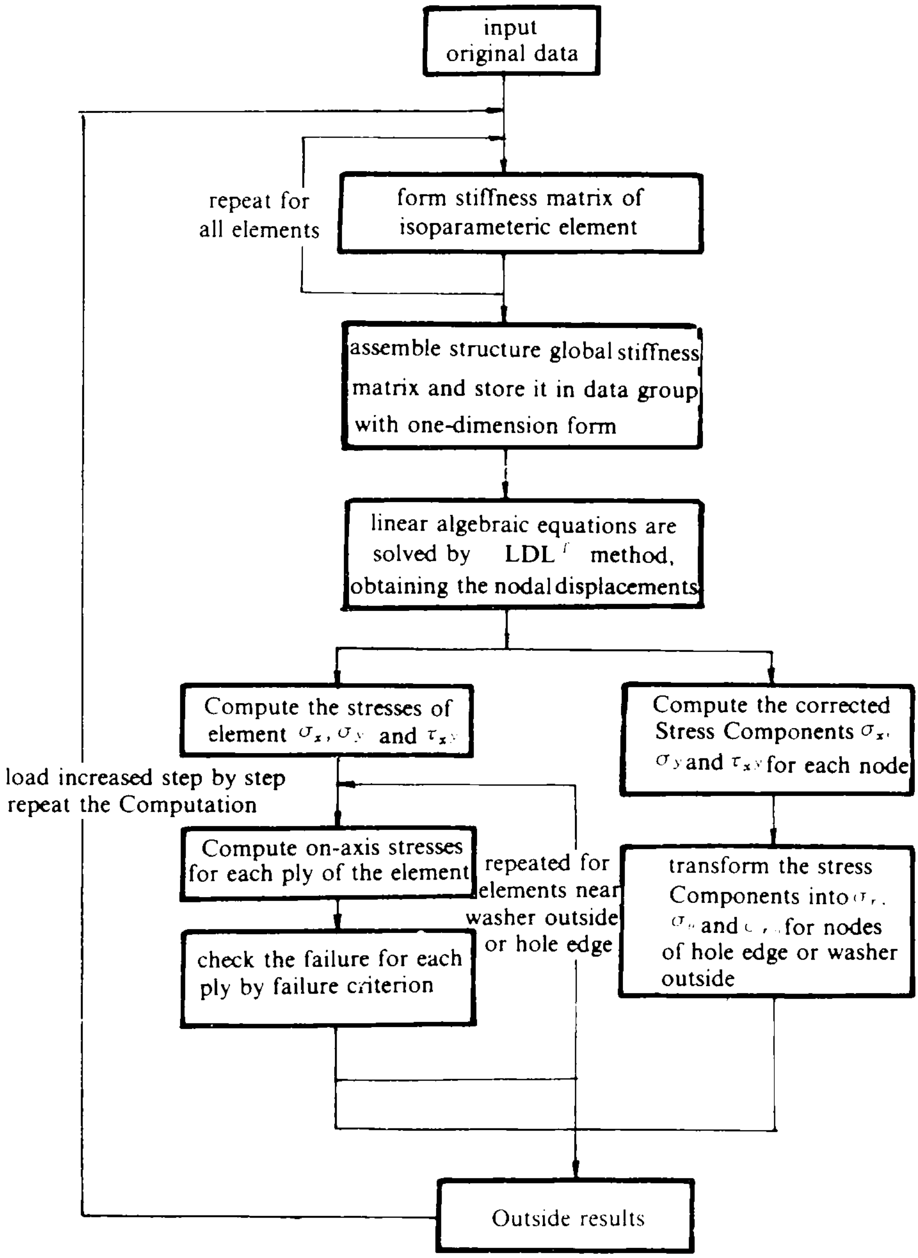

Fig. 2

apparent damage will not be allowed to occur in the vicinity of the hole. Therefore, failure definition is certainly concerned in analysis strength of bolted joint.

By the aid of observing and analysing results of experiment it can be seen that no lateral pressure exists on the laminate in pin-loaded case. Local failure was arised at the hole edge by the pin applied to the hole (delamination or crack). However, due to bolt clampup there exists lateral pressure through washer acting on the laminate under the washer in bolt-loaded with metalline washer case. Consequently, first failure occurs outside the washer (delamination or material piledup and local rise) as shown in Fig. 3. Therefore, when clampup torque reaches the required value the first occurence of the laminate failure under the washer is impossible. Because in the finite element analysis the element is small enough (for example the area of each element is only 1 mm^2 for hole edge and washer outside), the property of global stiffness will not be changed when a ply failure occurs in a certain element of washer outside (bolt-loaded) or hole edge (pin-loaded).

On the basis of above analysis for bolted joint in composite laminate "failure" definition is as follows: when first ply failure occurs in a certain element outside the washer it is considered that the bolted joint fails. Load corresponding with the failure is called ultimate bearing load of bolted joint. For joint in the shape of fork with clearance in the aircraft structure it corresponds to pin-loaded case because it does not exist lateral pressure. Therefore, when first ply failure occurs in a certain element of the hole edge the load corresponding with the failure is called ultimate bearing load of pin joint.

IV. Data and Results

Graphite/Epoxy laminate $[0/45/90/-45/0/45/0]_s$ is selected. The thickness of laminate is 0.2 cm. It was made from 13 plies and with a fibre volume fraction of 62.4%.

The properties of unidirectional composites are as follows:

$E_1 = 9 \times 10^5 kg/cm^2$ $\quad X_t = 11000 kg/cm^2$

$E_2 = 0.8 \times 10^5 kg/cm^2$ $\quad X_c = 8420 kg/cm^2$

$G_{12} = 0.46 \times 10^5 kg/cm^2$ $\quad Y_t = 320 kg/cm^2$

$\mu_{12} = 0.32$ $\quad Y_c = 1300 kg/cm^2$

$s = 670 kg/cm^2$

plies orientation	0°	90°	+45°	−45°
portion of the plies	38.46	15.385	30.77	15.385
thickness of plies	0.0769	0.0308	0.0615	0.0308

Effective engineering constants of the laminate are as follows:

$E_x = 4.62251 \times 10^5 kg/cm^2$, $\quad G_{xy} = 1.28249 \times 10^5 kg/cm^2$

$E_y = 2.83278 \times 10^5 kg/cm^2$, $\quad \mu_{xy} = 0.355$

Geometric parameters of specimen are as follows:

bolt diameter $D = 0.5$ cm, washer diameter $D_i = 1.1$ cm,

width of specimen $w = 3$ cm, edge distance $e = 1.5$ cm,

thus $w/D = 6$, $e/D = 3$.

Finite element model of joint is shown in Fig. 4.

Because of the symmetry about x-axis, half of the laminate has been modelled when using plane stress isoparameters element in stress analysis. Since investigation will be focused on the outside of washer or hole edge, these parts were subdivided into thinner grid. The left side in $\pi/4$ arc length

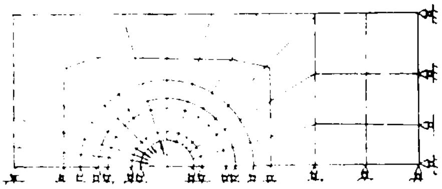

Fig. 4 the finite element model

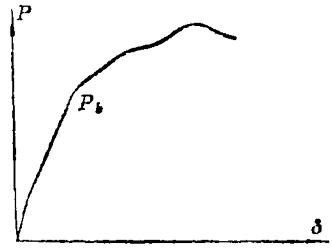

Fig. 5. Load-displacement curve

was also subdivided into thinner grid than the right side. The finite element model has 84 quadrangular elements, 106 nodes, 192 degrees of freedom. Along bottom side of model the nodal vertical displacement is taken zero for symmetry. Along the right edge the nodal horizontal displacement is taken zero for fixture of specimen support. Cosine curve load distribution is translated into components in X and Y direction at nodes around the hole. It is noted that the resultant of components in X direction must equal the applied tension load.

According to failure definition for bolted joint in composite, ultimate bearing loads are calculated for the cases of pin and bolt. Results are listed in Table 1

Table 1

loaded case	calculated value P_c	experimental value P_b	differences %
Pin-loaded	73	75	2.7
bolt-loaded	447	475	5.9

The experimental value in list corresponds to P_b in Fig. 5.

The comparison between the experimental and the calculated value shows that the estimate method of ultimate bearing load is available for bolted joint. The calculated results are satisfied. Of course, it needs to be further verified by a number of computations and experiments.

References

[1] Yang, L. Bolted joint design of composite, N. P. U. Technical Report, SHJ 8217 (1980. 12).

[2] Waszczak, J. P. and T. A. Cruse. Failure mode and strength prediction of anisotropic bolt bearing specimens, *J. of Composite Materials*, 5 (1971), 421.

[3] Jong, Theo. De., Stresses around pin-loaded holes in elastically orthotropic or isotropic plates, *J. Composite Materials*. **2** (1977), 313.

[4] Eisenmann, J. R., Bolted joint static strength model for composite materials, NASA-TM-X-3377 (1976).

[5] Hart-Smith, L. J., Bolted joints in graphite epoxy composites, *Douglas Aircraft Company, NASA Contract Report*, No NASA CR-144899 (1976).

[6] Collings, T. A., The strength of bolted joints in multidirectional CFRP laminates, *Composites*. 8 (1977).

[7] Quinn, W. J and F. L. Matthews, The effect of stacking sequence on the pin-bearing strength in glass fibre reinforced plastic, *J. Composite Materials*. **2** (1977), 139.

[8] Kim, R. Y and J. M. Whitney, Effect of temperature and moisture on pin bearing strength of composite laminates, *J. Composite Materials*. 10 (1976), 149.

[9] Wilson, D. W and R B. Pipes. Analysis of the shearout failure mode in composite bolted joints, *Composite Structure*. p 34

[10] Tang, S., Failure of composite joint under combined tension and bolt loads, *J Composite Materials*, **15** (1981), 329.

[11] Soni, S. R., Failure analysis of composite laminates with a fastener hole, *Joining of Composite Material*, p. 145

[12] Soni. S. R., Stress and strength analysis of bolted joints in composite laminates, *Composite structure*, p. 50.

[13] Wu, J Q., Strength test and study of stress concentration factor for bolted joint in Graphite/Epoxy composite laminates, *Technical Report*, ministry of Aeronautical industry.

[14] Chen, S. J., Test report in composite joints, *Technical Report*. Ministry of Aeronautical industry

[15] Yang, B. Z., Experimental study of bearing strength for Graphite/Epoxy composite laminates, *N.P.U Technical Report*. SHJ 8289 (1982 11).

[16] Yang, L. Stresses analysis around a hole in CFRP laminated plates, *N.P.U Technical Report*, SHJ 8217