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NUMERICAL STUDIES ON THE PREDICTION OF BEARING FAILURE LOAD AND CORRELATION WITH EXPERIMENTAL RESULTS OF A SINGLE BOLTED JOINT

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***Abstract*: Various parts of the aircraft structure such as wing spar, fuselage frames etc are very big in size. It is always desirable to design a structural member in one piece without joints for a smooth internal stress distribution avoiding stress concentrations. As such it is difficult to fabricate them in a single piece avoiding the structural joints. Hence it is a common practice to adopt splicing of these components using necessary additional members together. Bolts are used to secure the two spliced parts. This spliced joint will be sized to transfer the shear, torque and bending moment at a given section. These bolted joints are generally subjected to 6 modes of failure. By properly designing the various dimensions of the joined members the various modes of failure are avoided. However, it is not possible to avoid the bearing failure completely. Hence this mode of failure of the joint has attracted the attention of researchers across the world to undertake a detailed study. Due to the complicated nature of the interaction between various modes of failure of the composites, various theories have been proposed to understand the bearing failure mechanism. In this paper we have tried to predict the bearing failure load using the various bearing angles of load dispersion. Two failure theories namely, maximum stress and Hashin failure criterion have been used to study the various failure mechanisms. Numerical studies show that Hashin failure criterion shows large reserves of margins of safety in various modes of failure as compared to the maximum stress failure criterion because it considers the interaction of various stresses for prediction of failure of the plies, whereas, Maximum stress criteria only directly compares the induced stress to the allowable stress.**

Keywords—Splice joint; bearing failure; fiber failure; matrix failure; interaction of failure modes; laminated plates

I. INTRODUCTION

Modern aerospace structures require high strength and light weight composite materials to achieve the full potential of recent advances in technology. There may be many possible combinations of various types of composite materials and fiber angles which may manifest in the brittle failure; in addition to the fiber patterns which make the composite bolted joints fail either in a perfectly elastic or perfectly plastic mode.High strength and stiffness ensures durability and further light weight adds to the additional payload [1]. Goswami and others have modeled bearing strength and progressive failure of a pin-loaded Composite. The model used 4-noded shell elements and a rigid pin. Three different failure criteria were used, Hashin's criteria, Maximum stress failure criteria, and Tsai-Wu failure criterion. From the paper it is not clear how the element stiffness properties were degraded after failure. Strength was fairly well predicted whereas the progressive failure was not compared to experiments [1]. Pin or bolt joints are preferred because of low cost, simplicity and facilitation of disassembly for repair [2]. L. J. Hart Smith, studied bolted joints in graphite epoxy composites and produced a NASA report Composite materials are brittle in nature. Thus, bolted joints in composite structures for aerospace applications require a greater analysis capability to predict the failure load and mechanisms than has been necessary for conventional ductile metals like Aluminum alloys [3]. This study was conducted on GFRP/CFRP specimens with varied thicknesses and ply orientations. The thicknesses used were typical representatives of skin thickness in aircraft structures. The pin diameter of 6.35 mm was used in these tests. A detailed analysis of the existing literature in this area has too many fragments to be covered by a simple rational analysis approach that can be directly applied to arbitrary composite bolted joints. However, the previous works have identified three predominant modes of failures viz., net tension, shear out and bolt bearing [4] (Cleavage, bolt pull through and bolt failure are other three modes of failure which are avoided by proper design and detailing of joint. The layups used for the various specimens varied widely [5]. The materials used for the specimens were prepared using GFRP or CFRP [5].

In 2009, Faruk Sen et al, conducted an experimental failure analysis is performed to calculate bearing strength of single bolted joints in laminated composites reinforced unidirectional glass fibers. The main goal of this study was to determine the failure behaviour of bolted composite joints under various preload moments as 0, 2.5, 5 N-m. Furthermore, two different geometrical parameters, the edge distance to hole diameter ratio (E/D) and plate width to hole diameter ratio (W/D) are investigated. For that reason E/D and W/D ratios are selected from 1 to 5 and from 2 to 5 respectively. Besides, the effect of orientation angle of laminates is considered. Therefore, four different ply orientations are selected as $[30^0]_4$, $[45^0]_4$, $[60^0]_4$, and $[90^0]_4$. The experimental results show that the magnitudes of bearing strengths in single bolted composite joints are strictly influenced from increasing value of applied preload moments, changing of (W/D) and (E/D) ratios and also ply orientations [5].

For the study purpose of this paper, the test specimen designated as 30DE5W5 [5] is chosen for further studies. This specimen was tested for bearing failure in the test program. In this paper, a finite element model is used for predicting the bearing stress based on the first ply failure criteria and the results are compared to the experimental results stated in the literature [5].

II. Description of the Problem

The test specimen 30DE5W5 is considered for a detailed study using finite element analysis. Specimen description is given below.

1. Name: 30DE5W5
2. Material: GFRP UD epoxy laminate
3. No. of layers: 4
4. Orientation of fibers: 30^0 to the axis of the laminate
5. Layer thickness: 0.4 mm
6. Total thickness of laminate: 1.6 mm
7. E/D = 5 and W/D = 5
8. Diameter of bolt: 5 mm
9. Preload moment: 0 N-m

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The geometrical dimensions of the model are shown in Fig. 1.

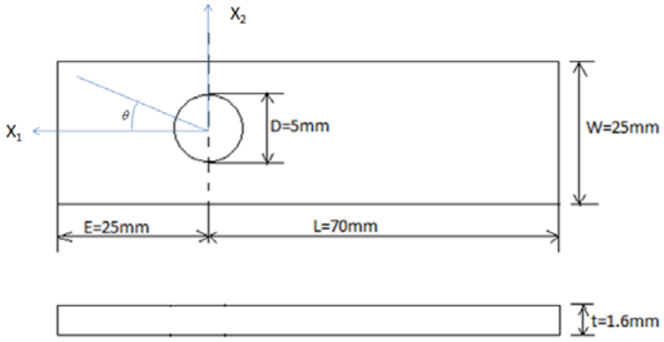

Figure 1: Dimension of the specimen under study

The test specimen with designation is shown in Fig.2.

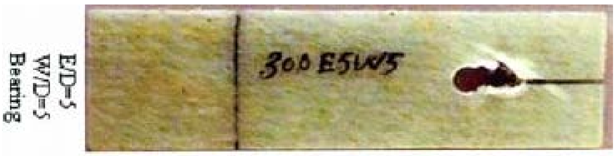

Figure 2: Test Specimen under study (E/D = 5 and (W/D) = 5

III. Analysis and FE Modeling

1. FE Modeling

From [6], ultimate failure of a joint is generally divided into three modes of depending on the failure location θ, as follows,

$0 \leq \theta \leq 15^0$ Bearing Failure mode
$30^0 \leq \theta \leq 60^0$ Shear-out Failure mode
$75^0 \leq \theta \leq 90^0$ Net Tension Failure mode .... (1)

In this case study, we are investigating the bearing failure mode. Hence θ will vary between ±15 degrees with respect to axis X_1.

2. Experimental Results

The experimentally determined bearing failure load for three torque values (0, 2.5 and 5 N-m) are shown in Fig. 3 [5].

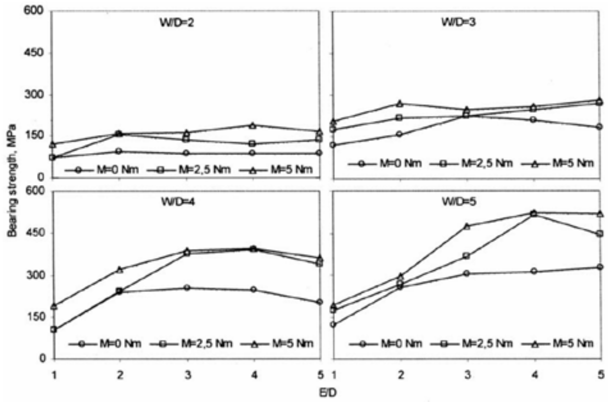

Figure 3: Bearing strength of 30 deg. Laminates (experimental)

Reading from the Fig.3, for (E/D) = 5 and (W/D) = 5
Experimental bearing stress,

σ_{exp_brng} = 322.5 MPa ……….. (2)

3. Finite Element Analysis

The geometric model shown in Fig. 1 was modeled in ANSYS using SHELL181 element. The bearing load was applied from θ = 2 to 14 degrees on either side of the axis X_1 (Fig. 1). This model doesn't take into account friction and contact between the pin and the laminate. It is proposed to introduce these effects in the further study. Finite Element Mesh used for the analysis is shown in Fig. 4.

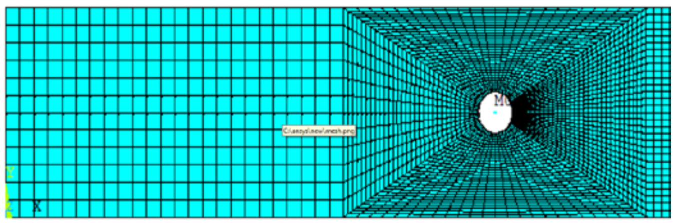

Figure 4: Finite element mesh for load prediction of bearing failure

The load was applied as a distributed load on the nodes arc of the circle which makes an angle of 4 to 28 degrees at the centre of the bolt (Fig. 5).

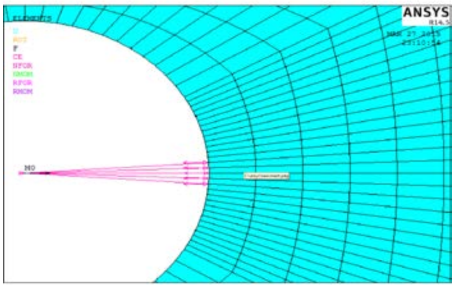

Figure 5: Load application on the circumferential nodes

The model was fixed firmly at one end to simulate the gripping on the specimen under test (Fig. 6).

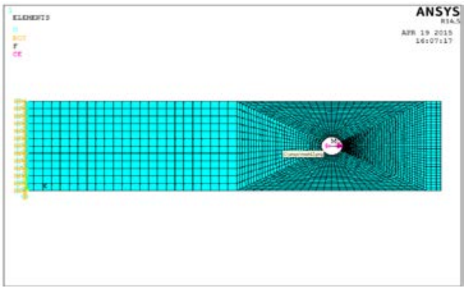

Figure 6: Simulation of boundary conditions on the model

The material properties used in the analysis are given in below [2].

E_x = 45100 MPa Nu_{xy} = 0.25 G_{xy} = 2550 MPa
E_y = 14400 MPa Nu_{yz} = 0.25 G_{yz} = 1550 MPa
E_z = 14000 MPa Nu_{xz} = 0.25 G_{xz} = 1500 MPa

Load applied in the analysis gradually decreased from 800 N (initial guess of failure load) to 195 N (first failure of ply was observed at this load). Then, the bearing stress was calculated due to the applied load of 195 N and compared with the experimentally determined bearing stress. Since no pretension was applied to the bolt, the moment was considered to be 0.0 N-m (M=0.0 N-m). The comparison of the bearing stresses is shown below.

Bearing stress (FEM, load corresponding to no failed elements or one of the failure stresses just reached, bearing angle = 8^0 at the centre of the bolt)

σ_{FEA_brng} = 302.64 MPa ………………….. (3)

IV. RESULTS AND DISCUSSIONS

The results are studied under the following headings.

a. *Comparison of predicted and experimental bearing stresses*: By comparing the experimentally determined bearing stress to that predicted by finite element analysis, it is found that the variation is 6.16% between the two values.

b. *Deformation of the bolt hole*: The Fig. 7 shows the deformation (Blue – undeformed and Red – deformed) of the bolt hole in the plane of the specimen.

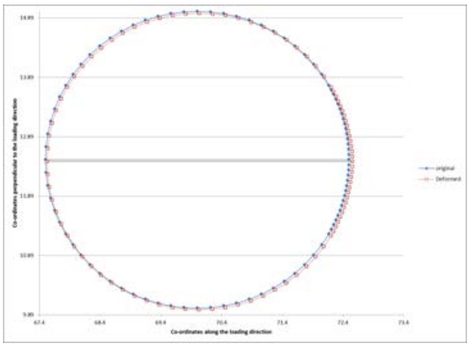

Figure 7: Deformation pattern of the bolt hole

c. *Stress distributions*: Stress distributions (σ_1, σ_2 and τ_{12}) around the bolt hole are shown in the Figure 8 to 10 (layer 1). It is observed that since all the 4 layers oriented at 30^0 to the X_1 axis, the induced stresses in all the layers are exactly the same.

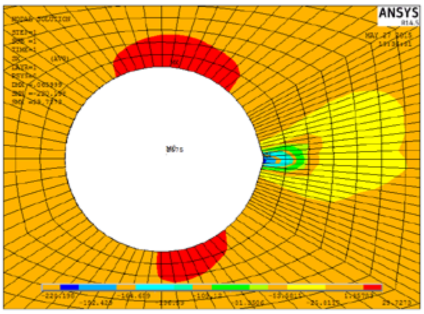

Figure 8: Stress distribution (σ_1) in Ply 1

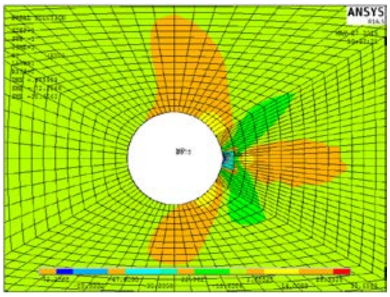

Figure 9: Stress distribution (σ_2) in Ply 1

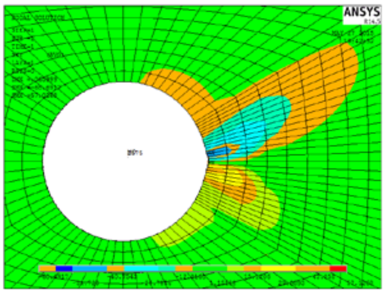

Figure 10: Stress distribution (τ_{xy}) in Ply 1

d. *Comparison of failure modes*: Two failure criteria were selected for the study purpose. The failure indices were computed using the Maximum Stress and Hashin failure criteria to understand the contribution of various stress components towards the prediction of failure of a ply. Fig. 11 shows the comparison of compressive fiber failure stress ratio computed using the two failure criteria for fiber compression failure mode.

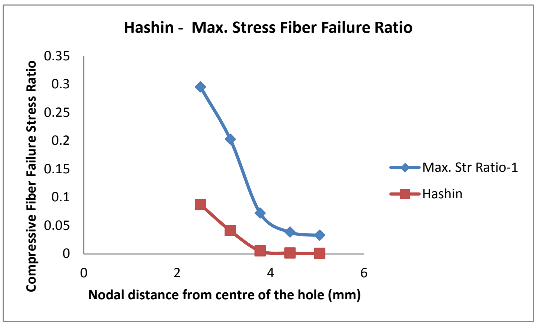

Figure 11: Comparison of Compressive Fiber Failure Stress ratio between two failure theories

Fig. 12 shows the comparison of matrix failure stress ratio computed using the two failure criteria for matrix compression failure mode.

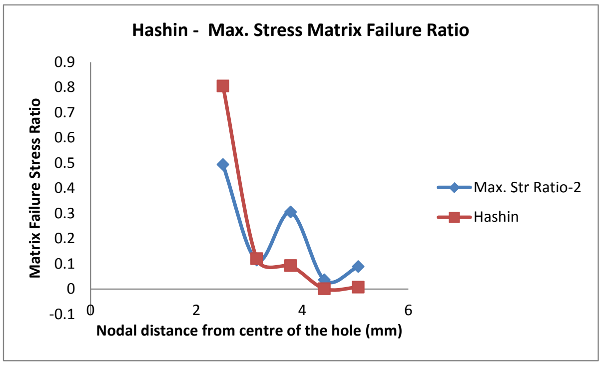

Figure 12: Comparison of Compressive Matrix Failure Stress Ratio between two failure theories

e. *Comparison of degrees of the expression used for predicting the failure*: In predicting the compressive fiber failure, fiber stress ratio as per maximum stress failure theory uses a linear ratio, whereas, Hashin failure criterion uses a squared ratio of the induced stress to the allowable stress. Thus Hashin failure criteria tends to predict the lower ratio. In predicting the tensile matrix failure, maximum stress failure theory uses a linear ratio, whereas, the Hashin criterion uses a failure surface with square terms incorporating contributions from the transverse tensile and in plane and out of plane shear stresses.

f. *Comparison of terms used in the two failure theories*: This two dimensional model doesn't capture the out of plane stresses like σ_{33}, τ_{23} and τ_{13} so that their effect on the mode of failure can't be assessed.

V. CONCLUSIONS

a) This finite element model predicts the failure bearing stress within 6.16% of the experimental results.
b) Maximum stress theory overestimates the failure stress ratios when compared with the Hashin failure criteria.
c) Maximum stress theory doesn't take into account the interaction between the various stress components and any destabilizing or stabilizing actions happening within the laminate as it directly compares the stresses.
d) Two dimensional model doesn't provide enough information for the prediction of failure process of the laminate.
e) Out of plane stresses required for the prediction of failure of a lamina are not generated in a two dimensional analysis. Hence, the prediction of failure using a this model has limited validity.

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