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Development of Mathematical Models for Determination of Failure Loads of Glass Epoxy Composite Plates

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***ABSTRACT**: This paper deals with the mathematical study of failure loads of glass epoxy composite plates with two serial holes subjected to traction force by two serial rigid pins. To evaluate the effect of joint geometry on the failure loads the geometrical parameters such as the edge distance of first hole-to-hole diameter (E/D), the width of the specimen-to-hole diameter (W/D), and the distance between center of two holes-to-hole diameter (K/D) were varied from 1-4, 2-4, and 3-4 respectively. Mathematical models have been developed for both wet and dry specimens to determine the failure loads of different geometry plates. Wet specimens are specimens immersed in seawater for 24 hours. The unimmersed specimens are called dry specimens. Here Full Cubic models have proved to be very efficient. A comparison of the results from mathematical models with the experimental results from existing literature shows high values of correlation co-efficient, Root Mean Square Error and Maximum Absolute Error. For estimation of the failure loads within the range of E/D, W/D and K/D considered for the study, the mathematical models developed are found to be efficient.*

***Keywords:** composite plates, pin joint, failure load.*

I. INTRODUCTION

Composite materials have a wide range of applications because of their light weight, high strength to weight ratio, good fatigue resistance, corrosion resistance etc. compared to metals. The applicability of composite materials has increased the demand for high reliability materials in various industries like aerospace, aircraft, and automobile. In building complex structures several parts must be joined together. Most of these joints are formed by using mechanical fasteners such as pins because of their low cost, simplicity and easy assembly and disassembly. Also, multiple fasteners can be used in many applications. The difficulty with this method is that the presence of a hole in a laminated plate subjected to external loading introduces a disturbance in the stress field. Stress concentrations are generated in the vicinity of the hole making the joint a weak one. The knowledge of failure strength of a joint helps in selecting the appropriate joint size in a given application. The capability of a composite structure to withstand any physical load can be evaluated either by physical testing or any advanced computational method. Performing physical tests on composites is destructive and costly. So, implementing advanced computational techniques to determine the failure loads are preferred after some experiments are done.

Owing to the significance of the problem, several investigators have developed procedures to determine the strength of pin joints in composite materials. Chang et al. (1982) developed a computer code to find the failure loads and failure mode of composite joints with different ply orientations, different material properties and geometries. Vyasaraj and Kakhandki (2005) obtained analytical solutions for an irregular shaped hole in an orthotropic laminate. Karakuzu et al. (2006) predicted the failure loads experimentally and numerically on glass vinylester composite plates subjected to pin loading. In the numerical analysis, they used the Hashin failure criterion in order to determine failure loads and failure modes. LUSAS commercial finite element software was utilized during their analysis. Whitworth et al. (2008) investigated the characteristic dimensions in tension and compression using point stress failure criteria and Yamada-Sun failure criteria. Murat Pakdil (2009) has studied the failure analysis of composite single bolted joint subjected to pretension on the bolt. The composite laminated plates are stacked with different ply orientations. It was observed that the failure modes and the bearing strength depend on the stacking sequence, geometrical parameters and bolt pretension. Aktas (2011) performed experimental and numerical study to determine the failure behaviour of glass epoxy composite plates with single and two holes. The numerical study was performed by using ANSYS and Yamada-Sun failure criteria. Ozen and Sayman (2011) investigated experimentally and numerically the first failure load and the bearing strength behaviour of pinned joints of glass fibre reinforced woven epoxy composite prepregs with two serial holes subjected to traction forces by two serial rigid pins. The effect of seawater on the bearing strength of the joints was studied by immersing the specimens for 24hours in seawater. It was observed that immersion in seawater reduces the failure load of the specimens. Ondurucu (2012) has studied the effects of joint geometry and stacking sequence on the bearing strength and damage mode experimentally. Damage progression was later examined by using scanning electron microscopy on specimens loaded up to ultimate failure. Khashaba et al. (2013) has dealt with the failure and reliability analysis of composite pinned-joints using theoretical models based on Weibull distribution function with experimental results for a guideline of safe design strength. Soykok et al. (2013) have carried experiments to understand the effect of thermal condition and tightening torque on the failure load and failure behavior of glass epoxy composite joints. It was observed that the load carrying capacity of the joint decreased by increasing the temperature level. The tightening torque was observed to increase the joint strength.

In the present work, mathematical models have been developed to predict the failure loads of composite pin joints under both dry and wet conditions. The results obtained from the mathematical models are compared with the experimental results of Ozen and Sayman (2011).

II. PROBLEM DEFINITION

To evaluate the effects of joint geometry, the ratio of edge distance to the hole diameter (E/D), the ratio of width of the specimen to the hole diameter (W/D) and the ratio of distance between center of two holes to the hole diameter (K/D) were varied from 1-4, 2-4 and 3-4 respectively. Here specimens are considered dry and wet i.e. specimen held in sea water for 24 hours.

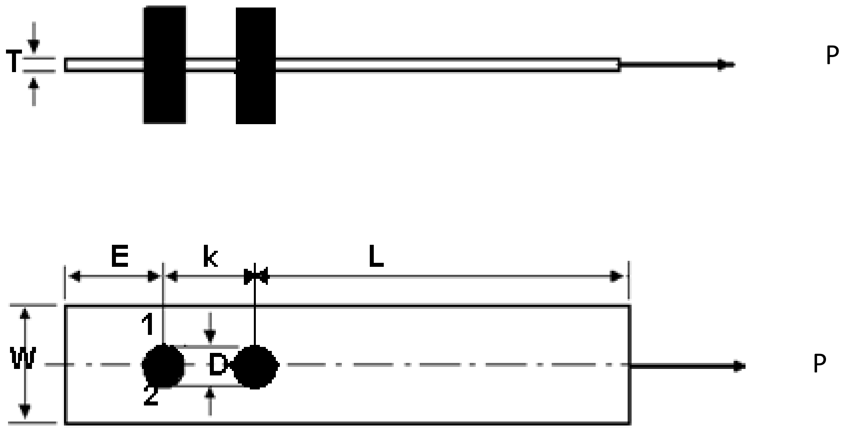

Fig. 1. Geometry of the specimen

The geometry of the composite specimen is shown in Fig. 1. Here W represents the width of the plate, E the edge distance of the first hole from one end of the plate, K is the distance between the two holes and T is the thickness of the plate. The diameter of the holes is shown as D. The total length of the plate is L+K+E. The diameter of the holes, thickness of the plate and the total length of the plate are taken constant as 5mm, 0.8mm and 80mm respectively. A load P is applied to the plate along the longitudinal axis. The plate is symmetric with respect to the longitudinal axis.

The material properties considered, that are given by Ozen and Sayman (2011), are shown in Table 1. Different models are obtained by varying E/D, W/D and K/D but keeping the parameters D, T and total length as constant. Mathematical models are developed to obtain the failure loads of different specimens. A comparison with experimental results is made and correlations are observed.

Table 1: Material properties of the composite plate

E_1 (GPa)	G_{12}(GPa)	μ_{12}	X_t (MPa)	X_C (MPa)	S(MPa)	V_f(%)
22.3	7.5	0.14	295.6	143.9	83.9	57

III. MATHEMATICAL MODELLING

Mathematical models have been developed to predict the failure loads of specimens with different geometries using curve expert. The models are built with the available experimental results. The equation has two independent variables in W/D ratio as x_1 and E/D ratio as x_2. The dependent variable considered here is the failure load P. The thickness of the specimen and the diameter of the hole are constant for all the specimens. Full Cubic model is found to be best suited to determine the failure loads for the existing problem. Equations are developed for dry and wet specimens with K/D ratios equal to 3 and 4 wherein each case W/D varies from 2-4 and E/D varies from 1-4.

These equations can be used to predict the failure load of specimens with other geometric parameters within the given range i.e. for E/D and W/D ratios for which experiments have not been done. It thereby saves the cost and time in carrying out the tests. Hence, the mathematical models are best suited to obtain the results for failure loads. The Full-cubic equation developed is found to be

$$P = a + b*x_1 + c*x_2 + d*x_1^2 + e*x_2^2 + f*x_1^3 + g*x_2^3 + h*x_1*x_2 + i*x_1^2*x_2 + j*x_1*x_2^2$$

Wherein the value of the co-efficients a, b, c, d, e, f, g, h, i and j are given in Table 2. Here model 1 represents dry specimens with K/D=3, model 2 for wet specimens with K/D=3, model 3 for dry specimens with K/D=4 and model 4 for wet specimens with K/D=4.

Table 2: Co-efficients of the full cubic model developed

Model	a	b	c	d	e	f	g	h	i	j
1	-6181	8230	-1440	-2886	248	329	-42	798	-125	-1.5
2	1083	261	-890	-196	1.8	26.8	9.5	706	-72.1	-42
3	1018	-483	-490	451	-6.02	-79.9	18	334	1.15	-52.9
4	6473	-4582	-2921	1317	321	-124	-12	1626	-191	-91.6

IV. RESULTS AND DISCUSSION

Composite specimens with two serial pin holes subjected to traction forces by rigid pins are studied. The specimens are considered both dry and wet i.e. soaked for 24hours in seawater. Mathematical models have been separately developed for both dry and wet specimens. Fig. 2 represents the graphs showing the comparison between the results obtained from the mathematical models with the existing experimental results for different E/D, W/D and K/D ratios. Mathematical models follow the same trend as that of experimental results.

- For a constant W/D ratio, the failure load P increases with increase in E/D ratio and when E/D ratio is maintained constant, the failure load P increases with increase in W/D ratio. This is because when the width of the specimen is increased keeping the edge distance constant the normal and bearing strength increases. Similarly when the edge distance of the hole is increased keeping the width of the specimen constant, the shear strength of the specimen increases.
- With the increase in K/D, for constant W/D and E/D ratios the value of failure load P increases as the distance between the holes increases.
- The failure loads of wet specimens have been observed to be low when compared to the failure loads of dry specimens. So, seawater has a negative effect on the joint strength.

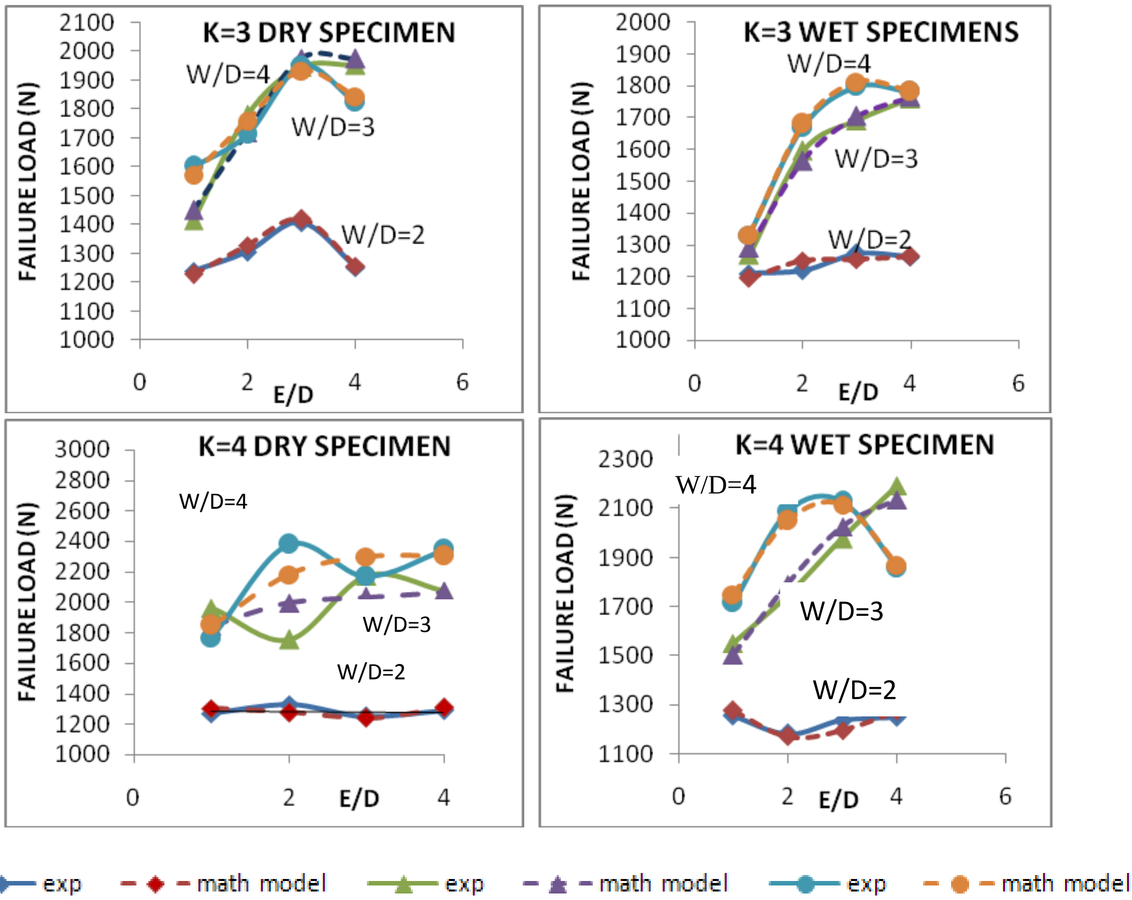

Fig.2 Comparison of Experimental and Mathematical Model Results

- The correlation between the mathematical models and experimental results is found to be high.
  Table 3 shows the correlation coefficient, Root Mean Square error and maximum absolute error.

Table 3: Correlation coefficient, Root Mean Square error and maximum absolute error

MODEL	Maximum absolute error	Root mean square error	Correlation coeffecient
1	60	30	0.994
2	31	16.96	0.997
3	198	116	0.960
4	58	36.56	0.995

V. CONCLUSIONS

In this paper, mathematical models have been developed to predict the failure loads of glass epoxy composite plates with two serial holes subjected to traction force by two serial rigid pins.

- When W/D=2, the increase in failure load with increase in E/D is relatively less compared to when W/D=3 and 4. This is because as the width of the specimen increases, the bearing strength of the specimen increases. So the specimen tends to fail at higher loads. But the margin in the failure loads for W/D = 2, 3 and 4 show that the specimen is weak for W/D=2.
- At constant E/D ratio, as the W/D ratio increases the failure loads increase. The margin in the failure loads for W/D=2, 3, 4 is observed to increase as the E/D ratio increases from 1 to 4. But the maximum failure load in most of the cases is observed to be at E/D=3. Later with increase in E/D, the failure load is found to decrease.
- When the specimens were soaked for 24hours in seawater, then they are found to fail at lower loads compared to the dry specimens. So, seawater was observed to have a negative effect on the failure loads of the specimens.
- Mathematical models show the same trend in the failure loads of specimens, when compared with the experimental models. So, for estimation of the failure loads within the range considered for the study, the mathematical models developed, i.e., Full Cubic Models proves to be efficient with the given values of Correlation Co-efficient, Maximum Absolute Error and Root Mean Square Error.

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