Composite Structures 195 (2018) 211–218

Contents lists available at ScienceDirect

Composite Structures

journal homepage: www.elsevier.com/locate/compstruct

Experimental and numerical investigation of loading speed effect on the bearing strength of glass/epoxy composite joints

F. Nazari, M. Safarabadi*

School of Mechanical Engineering, College of Engineering, University of Tehran, Tehran 11365-4563, Iran

A R T I C L E I N F O

Keywords:
Loading speed
Strain rate
Bearing strength
Energy absorption
Delamination
GFRPs

A B S T R A C T

Polymer-matrix composites have a variety of uses in industry. However, their failure behavior is not well characterized yet. Specially, the bearing response of mechanical composite joints is very complex and needs further study. One of the important parameters influencing the bearing strength is loading speed that has not been investigated thoroughly and lacks sufficient data. In this research, effect of loading speed on bearing strength has been investigated empirically on glass-epoxy composites. Samples have been tested in different loading speeds in batches of five. The finite element model has been developed for this experiment in Abaqus. Considering that there is no specific amount to show the mechanical behavior of joint, using statistical analysis is essential. Empirical results based on ASTM D 5961 Standard have been fitted to Weibull distribution. The effect of loading rate on the probability of failure and survival have been analyzed. The results demonstrate that by increasing the loading rate, survival reliability and bearing strength increases, absorbed energy increased to a specific loading rate, then decreases and also the sigma of statistical charts is increases. In comparison between experimental results and finite element result, by increasing the loading speed the error of FE result will increase.

1. Introduction

Nowadays because of mechanical properties like high strength to weight ratio, corrosion resistance and oriented properties, polymer matrix composites have become popular in aerospace, marine and automotive industry and rapidly replacing metals. Despite of near net shape manufacturing composite parts, machining operations are still needed to achieve the final dimensions and also mechanical joints. For a mechanical joint, there is a need to make a hole to insert bolts, pins or rivet in which drilling is the most common operation for that purpose which leads to lots of defects such as matrix fraction, fiber crack, fiber pullout and delamination. Delamination is the most common defect during the drilling of composite materials which is the result of local bending in the contact zone with drill tip and changes the mechanical properties and reduces the bearing strength of the joint.

Numerous studies have been done on drilling and delamination of composites. But effect of loading speed on the bearing strength of a delaminated composite joint, have not been investigated enough. In practice, a composite part will undergo different loading conditions and may experience varying load speed. Ismail et al. studied on the machinability of fiber reinforced composites (FRCs) [1,2]. They investigated the effect of drilling parameters, drill diameter and chip formation on delamination and surface roughness on hemp fiber reinforced polymer (HFRP) and carbon fiber reinforced polymer (CFRP) composite laminates. The result shows that increasing feed rat, thrust force or drill diameter leads to higher delamination surface roughness in both materials. Therefore, low feed rate and high cutting speed leads to lower delamination. They also found lower delamination in HFRP laminates than CFRP. They determined the 0.05–0.10 mm/rev feed rate and 30 m/min cutting speed as optimal drilling parameters.

Vangrimde and Boukhili have investigated the relationships between laminate architecture, macroscopic damage and bearing response of glass fiber reinforced plastics (GRP) bolted joints [3,4]. They used specimens in three coupon geometry from six different laminates. The standard coupon had the most diverse failure behavior. Specimens with high end distance showed higher bearing strength and specimens with low width may fail due to tensile failure. Also they showed that adding off-axis reinforcement results in high bearing strength. Ascione et al. have studied the effects of the fiber inclination angle and laminate stacking sequence on the bearing failure load of glass fiber/epoxy laminate bolted joints [5]. They have concluded that the fiber inclination angle to the external load direction has a high effect on the bearing load failure. They also showed the bearing failure is almost independent of the stacking sequence where the results show the maximum 5% difference.

There is a good data about strain rate dependency of mechanical

* Corresponding author.
E-mail address: msafarabadi@ut.ac.ir (M. Safarabadi).

https://doi.org/10.1016/j.compstruct.2018.04.064
Received 10 September 2017; Received in revised form 1 April 2018; Accepted 19 April 2018
Available online 21 April 2018

properties of the composites in literature review. Ochola et al. have investigated the mechanical behavior of CFRPs and Glass fiber reinforced polymers (GFRPs) at different strain rates and showed that both materials are highly sensitive to strain rate [6]. They concluded the GFRP specimens fail due to fiber kinking, micro buckling and fiber fracture at low strain rates and delamination, separation of interface and spalling at high strain rates. CFRP specimens fail due to kinking and shear at low strain rates and disintegration of the specimen at high strain rates. Naresh et al. have studied the effect of high strain rates on the material behavior of glass/carbon fiber reinforced epoxy laminated composites under tensile loading [7]. Results showed high tensile strength and modulus increase for glass/epoxy composite but not much for carbon/epoxy. They also showed that the material tends to more brittle behavior at higher strain rates, which leads to lower failure strains. They found rough surface, matrix crack, matrix damage, fiber pullout and fiber-matrix debonding in specimens tested in dynamic condition.

Daniel et al. proposed a strain rate dependent criteria for carbon/epoxy composites [8]. They characterized the material at the different strain rates ranging from 10^{-4} to $400\,s^{-1}$, in transverse, compression and shear loading condition. They demonstrated that the moduli and strength have linear dependency to the logarithm of strain rate. Also the transverse to in-plane shear modulus ratio was constant and independent of strain rate. Fitoussi et al. investigated mechanical behavior of short fiber reinforced matrix composites and find it highly strain sensitive [9]. They reported 50% Young's modulus increase which leads to damage onset delay and damage accumulation decrease. Also 500% damage strain and 200% damage strain increase reported. Microscopic observations showed a local zone around the fibers is highly strained due to local matrix rheology which explains the microscopic kinetic damage reduction and dissipates the strain energy and hinders crack propagation. This can be explained by the viscous behavior of the matrix and fiber–matrix interface debonding.

Koyanagi et al. studied time and temperature dependency of fiber reinforced composites [10–12]. They showed that the matrix strength dependency is much higher than the interface strength. They demonstrated that the failure mode in low strain rates is related to matrix failure and in high strain rates to interface failure which is the result of increasing the matrix strength. The transition takes place in the range of 4×10^{-6} to 4×10^{-3} strain rate. Yong Tao et al. investigated the inter-fiber failure of unidirectional glass/epoxy composites and proposed a new strain rate dependent failure theory [13]. They found the matrix dominated strengths strain rate sensitive and modeled the variation by a power-law empirical formula.

The objective of this paper is to determine the bearing response of rectangular GFRP specimens under different loading speeds. For this purpose, specimens have been cut through the laminate and drilled according to ASTM D 5961 Standard and have been tested in different loading speeds. After statistical analyzing data, results were compared with finite element model.

2. Specimen preparation and experiment

Laminate used in this research is built via hand layup from 16 layers of woven epoxy glass fabrics with the weight text of $203\,g/m^2$ and average thickness of 0.1 mm in 64 × 34cm. The epoxy resin employed is (Araldite LY 5052/Aradur 5052) in the weight proportion of 62 to 38 with the gel time of 420–500 min in the temperature of 25 °C. The Vacuum Infusion Process (VIP) is used to drive resin into the laminate. Dry materials are laid into the mold and the vacuum is applied before resin is introduced. Once a complete vacuum is achieved, resin is literally sucked into the laminate. A void measurement is carried out based on ASTM D2734 standard and an average void volume fraction equal to 4% is achieved. Considering the failure modes of the present study specimens, the measured void volume fraction may not have significant impact on test results. More than five specimens are needed for each loading speed so that in case of voids impact on any specimen and leading to reduction in strength, that specimen could be neglected. In this way, effect of probable voids could be eliminated.

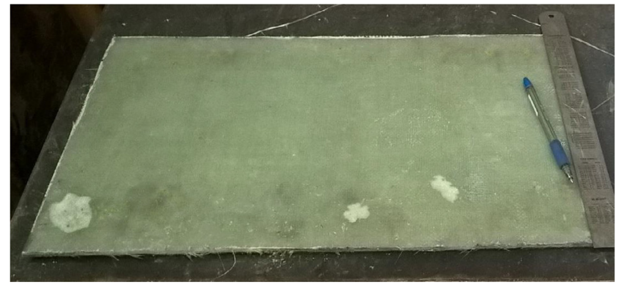

Fig. 1. Laminate used for the study.

After finishing the hand layup, laminate has been let to harden for a week. Then margins have been cut by 2 cm from each side using hacksaw. Fig. 1 shows the built laminate with the size of 600 × 300 × 4 mm. The volume fraction of fiber calculated 40%.

Flat rectangular cross-section test specimens with a centerline hole located near the end of the specimen, as shown in Fig. 2, extracted from the built laminate according to ASTM D 5961/D 5961M standard [14]. After cutting specimens from original laminate parallel to its fiber orientation, they have been drilled by a 6.5 mm diameter drill using a Heller SB32 machine. The reason for using 6.5 mm diameter drill instead of 6 is shrinkage of the hole due to elastic deformation. Fig. 3a and b are showing the drilling condition and a drilled specimen respectively. To conduct this experiment, 20 specimens are needed for testing at four different speeds in the batches of five.

The specimens have been loaded at the hole in bearing through a fastener or pin that is reacted in double shear by a fixture as shown in Fig. 4. The bearing load is created by pulling the assembly in tension in an SANTAM STM-50 testing machine. The tensile tests have been conducted in the environmental condition of 24 °C and 40% relative humidity. The loading speeds were 2, 8, 16 and 32 mm/min. These speeds where chosen in order to scrutiny the gradual transition of load speed from quasi-static to dynamic. The upper bond was limited due to limited rate of data collection of test machine which leads to data loss in high speeds and inaccurate force-extension plots. Load speeds of 2 and 8 mm/min could be example of loading speed and 16 and 32 mm/min can represent high ones with different behavior than the low ones.

3. Weibull distribution

The Weibull distribution is one of the most widely used lifetime distributions in reliability engineering. It is a versatile distribution that can take on the characteristics of other types of distributions, based on the value of the shape parameter, β [15]. Equation (1) shows the 3-parameter Weibull Probability Density Function (*pdf*):

$$f(t) = \frac{\beta}{\eta}\left(\frac{t-\gamma}{\eta}\right)^{\beta-1} e^{-\left(\frac{t-\gamma}{\eta}\right)^{\beta}} \quad (1)$$

Where η is scale parameter or characteristic life, β is shape parameter and γ is location parameter (failure free life) as:

$f(t) \geqslant 0,$

$(t-\gamma) > 0$

$\beta > 0$

$\eta > 0$

$-\infty < \gamma < +\infty$

The 2-parameter Weibull *pdf* is obtained by setting $\gamma = 0$. In other words, it means that there is a failure probability in any time (or other