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Crack sensitivity of bolted metallic and polymeric joints

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ABSTRACT

The effect of the presence of crack located at the fastener hole surface of bolted metallic (mild steel) and polymeric (Cross-ply $[0/90]_{4s}$ glass fiber reinforced epoxy composite laminate) joints on their ultimate strength and converting their mode of failure has been studied numerically and experimentally.

The present results showed that, the failure mode of bolted metallic joint is more sensitive to the presence of the crack than that of bolted composite joint. The critical crack length at which the bolted metallic joint failure mode changed from bearing failure to tensile failure has been recognized.

1. Introduction

Bolted joints are widely used in engineering structures, such as aerospace, land vehicles, petroleum pipe lines, civil engineering applications, and pressure vessels. Bolted joints exhibit three main failure modes, namely net-tension, shear-out, or bearing mode, see Fig. 1. Net-tension (mode I) and shear-out (mode II) modes are catastrophic and result from excessive tensile and shear stresses. Bearing failure mode is a progressive and non-catastrophic compressive failure mode that occurs due to contact between the bolt and the plate, and is a desired failure mode in aerospace applications due to its nature [1–6]. Cracks often exist at the joints because of stress concentration, contact interaction between the hole and the bolt, or the manufacturing process. The hole drilling operation causes geometrical discontinuities and so local stress/strain concentration under load application. In addition, surface roughness due to the machining operation will increase the likelihood of a surface fatigue crack initiating and propagating under changing load conditions [7]. Recently, strength prediction of single-lap or double-lap joints failed by net-tension have been studied using different methods such as extended finite element [8,9], cohesive zone model [10–12], and coupling techniques between the acoustic emission and digital image [13]. Most of these studies are focused on the stress/strain distribution around the fastened hole to predict the crack initiation stress. Ahmad et al. [8,9] studied the effect of different seven carbon fiber reinforced polymer (CFRP) woven fabric lay-up configurations on ultimate strength of double-lap bolted joint. They concluded that, the different lay-ups give different stress distributions along the hole boundary angle θ, see Fig. 1. They found the value of σ_{xx}, stress at X direction, see Fig. 1, has two peak values along the hole boundary angle, the first one is a tensile value at the beginning of contact regions (at about $\theta = 5°$) and the second one is a compression value at the bearing plane (at about $\theta = 90°$).

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Nomenclature

D	the hole diameter
E	modulus of elasticity
L	the specimen length
t	the specimen thickness
W	the specimen width
K_I	mode I stress intensity factor
K_{II}	mode II stress intensity factor
J	J-integral
Δm	monotonic crack tip plastic zone size
v	Poisson's ratio
CTOD	crack tip opening displacement
FEA	finite element analysis
GFRE	glass fiber reinforced epoxy
SIF	stress intensity factor
UTS	ultimate tensile stress

In general, it is necessary to determine stress around the joints in order to determine the site of crack initiation and evaluate the crack growth, which severely reduce the strength of the structure and lead to final failure [14]. Therefore, the bolted joint should be designed according to the concepts of fracture mechanics rather than the mechanics of materials. Many researchers [15–20] studied the effect of friction, clamping force, and clearance between the hole and bolt on the stress intensity factor (SIF) for the cracks at the hole-edge. Sallam et al. [2] concluded that, clamping force with rough surface has a significant effect on decreasing SIF in cracked lapped joints due to the decrease in the bearing load in addition to the resistance of the contact surface of bolt head or washer to open the surfaces of the crack beneath it. It is found that, the amount of clearance between the hole and the bolt has a significant influence on the SIF for mode I (K_I) [15]. Ju [19] illustrated the effect of edge crack at fastener hole on the normal stress distribution along the contact surface. He concluded that, the normal stress distributed as cosine shape, and was smooth. A jump occurred in cosine shape at the crack line, and this jump increased by increasing the crack length.

To the best knowledge of the authors, there has been no any published scientific research to date, which studies the effect of the presence of crack located at the fastener hole surface on converting the mode of failure of bolted joint in either metallic or composite materials. One of the main objectives of the present research is to study the effect of such crack on the bearing strength of bolted joint in mild steel and polymeric composite materials. Furthermore, the critical crack length at which the mode of failure of bolted joint converted has been investigated.

2. Numerical work

A three-dimensional finite element model was used in the present work using ABAQUS/Standard code [21]. A general static analysis with displacement control was employed in the present study. In a nonlinear analysis, the solution is found by applying the loads in increments until the final solution. It is worth to note that, in the elastic range there are two common sources of nonlinearity the behavior of frictional joints which is nonlinear mainly due to friction in the contact interfaces and composite material nonlinearity [22,23].

The steel plate and composite laminates were examined with a single-pin joint. The material of steel plate was modeled as homogeneous, isotropic and elastic–plastic with mechanical properties given in Table 1. The 0° direction in the stacking notation denotes the x-axis and the 90° direction in the stacking notation denotes the y-axis. A unidirectional fiber reinforced lamina with global and material coordinate systems is also shown in Fig. 1. The unidirectional stiffness properties are calculated theoretically and tabulated in Table 2. The material of the composite plates was modeled as a composite layup in property module in ABAQUS/Standard code by 8 ply. The orientation of each ply was defined as 0° or 90° depending on ply stacking sequence.

Figs. 1 and 2 show the geometric parameters, dimensions, and boundary conditions of bolted test specimen. Where D is the diameter of pin-hole, W is the width of plate, e is the distance of bolt-hole center to the plate edge, and t is the thickness of plate. The bolt located at the center of the hole and a load P is applied to the bolt as shown in Figs. 1 and 2. In order to evaluate the effect of the presence of crack on the joint strength and on the stress distribution around the bolt hole, crack located either perpendicular (crack A) or parallel (crack B) to the load direction is studied, as shown in Fig. 2. Different crack lengths, a, are used 0, 1, 3 and 5 mm.

Furthermore, a preliminary study has been conducted to study the effect of the presence of u-notch (radius = 0.3 mm and depth varied from 1 to 5 mm) on the stress distribution around the circumferential hole angle for either open hole or bolted joint. In the case of open hole, one end of the plate is fixed and the other is loaded.