Composite Structures 106 (2013) 446–452

Contents lists available at SciVerse ScienceDirect

Composite Structures

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

Metal to composite bolted joint behavior evaluated at impact rates of loading

Andy VanderKlok, Abhishek Dutta, Srinivasan Arjun Tekalur *

Department of Mechanical Engineering, Michigan State University, East Lansing, MI 48824, USA

ARTICLE INFO

Article history:
Available online 14 June 2013

Keywords:
Bolted joint
Split Hopkinson tension bar
Failure mode
Loading rate transfer

ABSTRACT

Metal-composite bolted joints form an integral part of a majority of structural components and finds extensive usage in aircraft and automobile industries where they could be subjected to either static or time dependent loadings. Extensive literature exists addressing bolted joint behavior under static rates of loading. However, limited studies exist which define mechanical response of metal-composite bolted joints under dynamic rates of loading. This is vital to better understand its crashworthiness characteristics when it is subjected to impact loading. In our current investigation, we have attempted to address this aspect via experimental characterization of 4142 alloy steel-E glass ply epoxy resin composite bolted joint under impact loading using a split Hopkinson tension bar. Quasi-static measurements have also been conducted simultaneously to distinguish not only the maximum bearing strength but also the operational modes of failure corresponding to different edge distance to hole diameter (e/d) ratios. Dynamic response of the metal-composite bolted joint was observed to be significantly higher than its static counterpart. Asymptotic region of failure mode alteration exists and is observed to be dependent on loading rate transfer. This study provides beneficial information in assisting subsequent design of bolted joints where behavior under impact loading is of main concern.

1. Introduction

Bolting components together is essential in the design of machine components, automobiles, aircraft, and other structures. Bolting components allows for nondestructive disassembly of components for maintenance, repair, and proves to be sufficient in strength. Considering the fact that bolted joints form an integral part of a majority of structural components, for instance in aircraft, the joint might be susceptible to loading scenarios involving impact and crash. In order to better understand the crashworthiness characteristics of bolted joints from the perspective of structural integrity of the component in which it is used, it is imperative to understand characteristics of bolted joint under impact rates of loading. Dynamic mechanical behavior of composite joints is far more complicated than its quasi-static counterpart owing to strain rate dependence and inertial effects.

A majority of literature on bolted joints have focused on its behavior under static rates of loading. Typically, the mechanical response of a bolted joint under external loading is dependent upon non-dimensional parameters namely, e/d, w/d and d/t where d denotes the diameter of the bolt, e denotes the edge distance from the center of the bolt, w and t denote the width and thickness of the jointed members respectively [1–3]. Bearing stress is representative of the maximum stress a bolted joint can sustain prior to failure. For a given type of mating adherends (for instance, a metal and a composite in our current investigation), it has been observed that the maximum bearing stress attains a constant value beyond a certain value of e/d [1–3]. This implies that under static loading conditions, bolted joint failure mode is highly dependent upon the geometry of the joint. Bearing strength and stiffness of bolted woven composite joint under quasi-static tensile load was studied by Pierron et al. [4]. Li et al. [5] investigated tensile response of composite riveted joints (made of carbon fiber-reinforced plastic: CFRP) under both quasi-static and dynamic loading conditions. The dynamic tests were performed on an ESH high-speed servo-hydraulic test machine and it was observed that energy absorption capability of the joint increases with increasing loading rate. With increasing loading rates, the failure mode changes observed were not dramatic. Icten and Sayman [6] experimentally investigated load to failure and mode of failure in pin-joined aluminum glass–epoxy sandwich composite plate under quasi-static tensile loading conditions. Investigations by Caprino et al. [7] on bearing failure characteristics of fiberglass/aluminum laminates (with varying joint geometry and clamping pressure) revealed that true bearing failure mode was achieved when sufficiently large w/d and e/d ratios were adopted (where w, e, and d denote the width, edge distance and hole diameter in the bolted joint) otherwise, the

* Corresponding author. Tel.: +1 517 884 1608; fax: +1 517 884 1601.
E-mail address: tsarjun@egr.msu.edu (S.A. Tekalur).

0263-8223/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.compstruct.2013.06.004

occurrence of net tension or cleavage failures was found respectively. Sen et al. [8] investigated bearing strength and failure mode of glass fiber reinforced epoxy laminated composite plates. Typically, bearing mode of failure is the best mode for resisting tensile load [8]. In their investigations, it was observed that for specimens with $e/d = 2$, mixed mode of failure develops which then transitions to a bearing mode of failure as the e/d ratio of specimens is increased beyond 2. Additionally, bearing strengths were seen to increase with increasing preload moment. Investigations by Pearce et al. [9] revealed increasing energy absorption capabilities of bolted joints with increasing loading rates (between 1 and 10 m/s) which was attributed to change in residual strength after ultimate load levels were reached. Recently, Yeh et al. [10] investigated the bearing performance of fiber metal laminates (GLass REinforced aluminum laminates (GLARE), non-commingled hybrid boron/glass/aluminum fiber/metal laminates (HFML) and, COmmingled Boron/glass fiber Reinforced Aluminum laminates (COBRA)) and found it to be dependent on parameters such as e/d ratio, metal volume fraction, and fiber orientation. Under longitudinal and transverse fiber orientations, failure is principally in the form of shear out and bearing mode respectively.

Dynamic loading events are representative of high loading rates, high kinetic energy and possibly loads well in excess of the static design strengths [9]. Consequently, under dynamic rates of loading, the frictional interaction between surfaces changes. This leads to a significant likelihood of change in behavior of bolted composite joints with varied loading rates. The demand for use of composite materials such as fiber glass yields hybrid designs consisting of both metallic and composite materials alike. In our following investigation, we attempt to address the following questions with respect to bolted joints subjected to impact rates of loading: (a) dependence of dynamic bearing strength with varying e/d ratio (b) how do the values under dynamic regime compare with its static counterpart? (c) does there exist an asymptotic region with varying e/d as has been observed previously for static tests? (d) what are the failure modes present under impact rates of loading? (e) is there a dependence of failure mode on e/d ratio? The current investigation attempts to address all the aforementioned aspects for bolted joints subjected to impact rates of loading via carefully designed experiments and correlation with high speed camera images.

2. Materials and methods

The metallic member in the joint corresponds to 4142 alloy steel, obtained from McMaster Carr, and has a Young's modulus of elasticity of 205 GPa, and a tensile yield strength of 689 MPa. Choice of this steel specimen was made in order to resist compliance during measurements. The composite member in the joint corresponds G-10 FR-4 composite commercially obtained from ACP composites. It represents a fiber glass composite laminate consisting of a woven glass cloth material with an epoxy resin binder and has the following properties: Young's modulus of elasticity of 18.65 GPa, tensile strength of 275.79 MPa, compressive strength of 413 MPa, flexural strength of 379.21 MPa, and a shear strength of 131.00 MPa. Quasi-static loading of the metal-composite bolted joints was accomplished with a multipurpose MTS machine (10 kN load cell) at a crosshead speed of 0.5 mm/min. Pinned and threaded grips were utilized to hold the specimen in position, and 3 specimens of 3 varying geometries (total of 9 tests) were tested corresponding to configuration as outlined in Table 1. For dynamic tensile measurements of the metal-composite bolted joints, the geometric configuration was kept the same and the tests were conducted using a Split Hopkinson tensile bar (SHTB) at an average loading rate of approximately 100 MN/s.

Table 1
Tested specimen non-dimensional parameters.

Specimen type	e/d	w/d	d/t	l/d	Bolt preload (N)
1	1.00	5.00	0.36	9.60	2669
2	2.00	5.00	0.36	8.60	2669
3	3.00	5.00	0.36	7.60	2669
4	4.00	5.00	0.36	6.60	2669

To achieve the aforementioned loading rate associated with impact rates of loading (as are experienced in car crashes or ballistic impact), the SHTB was utilized as shown in Fig. 1. The setup uses pressurized helium to accelerate a 5.0 in. striker (2 in. in diameter) to impact the anvil at the end of the incident bar. This induces a tensile wave, as well as pulse elongation due to a paper pulse shaper used at the interface of the anvil and striker. A thin anvil was used to achieve high strain amplitude to ensure specimen failure. The incident bar (5/8 in. diameter and 10 foot in length) is made of 6061-T6 aluminum and outfitted with two diametrically opposing EA-13-250-BG electro-resistive strain gages outfitted to an Ectron 835 amplifier configured in a half bridge configuration to eliminate bending and amplify axial strain. The end of the incident bar was tapped with 1/2-20 threads to accept a steel grip for the metallic specimens to be pinned and glued. The 1045 steel transmission bar (5 feet in length) is equipped with similar tapped 1/2-20 threads that accepts a grip shown in Fig. 1 (bottom) where the composite half of the specimen is gripped onto the transmission bar. The metallic half of the specimen is reverse dog bone in shape and is bolted to the composite half with a preload moment of 30 in-lbs as shown in Fig. 1 at the incident side of the setup. Levels of this torque were selected as it provided pretension of the bolt that does not exceed the compressive strength and the interlaminar shear strength of the glass composite [11]. This value of applied preload moment is equivalent of a preload of about 2669 N. This has been calculated using the formula [12], $T = Fp*k*d$, where T, Fp, k and d denote the applied preload moment, equivalent preload, nut factor (=0.2) and the diameter of the bolt respectively. The strain gage cluster was adhered 15 in. from the specimen end of the transmission bar and configured into a full bridge configuration for amplified sensitivity of strain in the axial direction and cancellation of bending strains.

3. Results and discussion

3.1. Static load bearing characteristics

Quasi-static mechanical response of the bolted joints were obtained for the specimens corresponding to geometries as tabulated

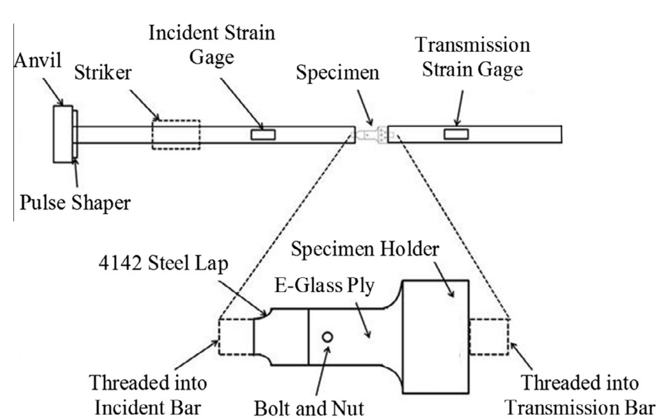

Fig. 1. Split Hokinson tension bar (SHTB) apparatus setup (shown at the top) and the specimen setup with holding fixtures (shown at the bottom).