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An analytical model for strength prediction in multi-bolt composite joints at various loading rates

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ABSTRACT

This paper presents an enhanced analytical model to determine the complete load displacement curve of single- and multi-fastener composite joints. It is an extension of a previous spring-based method, which included the effects of bolt pre-load and clearance, but not local bearing damage. The model has advanced beyond the state-of-the-art as loading rate effects, in addition to bearing damage, are accounted for through a novel conic damage approximation function. Using the developed model, an accurate prediction of the load displacement response of single- and multi-fastener joints to complete failure can be obtained in a matter of seconds. The method is validated against experimental data and excellent correlation was observed. Further studies carried out using the model suggest that slight variations in the energy absorption characteristics at each fastener hole in a multi-fastener joint can significantly alter the bolt-load distribution in the joint.

1. Introduction

1.1. Background

The use of carbon fibre-reinforced plastic (CFRP) materials in primary aircraft structures has increased significantly in recent decades. This is evident from the latest generation of large commercial aircraft, e.g. the Boeing 787 and Airbus A350XWB, which consist of over 50% composite material by weight. Despite the lower structural efficiency when compared to adhesively bonded joints, bolted joints are still widely used in modern aircraft due to their ease of installation and disassembly, and resistance to environmental degradation. Consequently, due to the large number of mechanical fasteners in modern aircraft, significant weight savings can be realised by optimising the joint design.

There have been numerous studies carried out in literature on the quasi-static response of mechanically fastened composite joints, and as a result the mechanics of this problem are relatively well understood [1–13]. However, as a consequence of the operating environment of aircraft, many of the limit load cases for structural design are impact or crash scenarios which are characterised by high rates of loading. A number of authors have investigated joints loaded at rates comparable to those that may be experienced during a survivable crash situation [14–18].

Ger et al. [14] investigated the effects of loading rate on the structural response of mechanically fastened CFRP and carbon–Kevlar fibre reinforced plastic joints. Specimens were tested quasi-statically and dynamically (loading rates of 3–5 m/s). It was predominantly found for dynamic loading rates that energy absorption decreased and joint stiffness increased. However, inertia effects of the specimen attachment were not accounted for which might have led to unreliable or misleading conclusions. Li et al. [15] tested a number of carbon fibre joint configurations at loading rates between quasi-static and 8 m/s. The results obtained contradict those from [14]. For most specimens in [15], the stiffness and strength of the joint were found to only increase slightly with loading rate. However, a significant change in failure mode at higher rates (4–8 m/s) resulting in increased energy absorption was observed. Pearce et al. [16] tested a series of joints and structures in bearing and pull-through directions at dynamic rates between 0.1 m/s and 10 m/s. Only minor loading-rate sensitivities were observed in the pull-through and multi-bolt structural impact tests. However, specimens loaded in bearing experienced a pronounced change in failure mode when loaded at or above 1 m/s. Although the failure initiation load and ultimate load did not change with rate, the energy absorption increased significantly. This was owed to a change in residual strength of the specimens' post ultimate load. Heimbs et al. [17] also tested a series of mechanically fastened, carbon/epoxy laminate joints up to loading velocities of 10 m/s. Single-lap shear tests on single-bolt and two-bolt specimens, bolt pull-through tests and coach peel tests were

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carried out. It was found that only the two-bolt, single-lap shear specimens showed rate dependence where the final failure mode changed from net-tension to extensive bearing and pull-through. This rate-dependent change in failure mode resulted in increased energy absorption of the joint.

Single-lap shear behaviour of carbon–epoxy composite bolted aircraft fuselage joints at quasi-static and dynamic (5 m/s and 10 m/s) loading speeds were studied experimentally by Egan et al. [18]. Several composite layups were tested, and it was found that the energy absorption for all cases increased with loading rate. For thinner laminates, fastener pull-through was found to be the dominant final failure mode, but for thicker laminates the failure mode was found to vary between fastener failure and fastener pull-through. The former resulted in decreased energy absorption due to premature fastener failure. In thinner laminates it was observed that the ultimate load carried was lower in the dynamic tests.

It was apparent that any rate effects observed are dependent on a number of experimental parameters which include the parent material of the joint, its preparation and layup, and the geometry: including thickness, clearance, width and end-distance. Additionally, fastener head-type, bolt diameter, bolt pre-load, loading velocity and the loading direction (i.e. bearing or fastener pull-through) also appear to play a crucial role in the rate-sensitivity of the joint [15–18]. However, a common observation made by all authors was a change in energy absorption, with most cases showing an increase with loading rate. This appears to be a key parameter in predicting the dynamic response of composite bolted joints, and was the approach adopted herein to predict the failure response of the joints.

1.2. Previous work

Present joint design practices involve analytical approaches [1–4], three-dimensional finite element (3D-FE) analyses [5–10] and experimental testing [11–13]. Detailed 3D-FE models require each component of the joint to be modelled separately, while contact models with tight tolerances model the interaction between each component. This approach allows the effects of clearance, bolt-torque and detailed contact stresses, friction between discrete regions of the joint and material damage propagation to be captured [5–7]. Although this technique yields accurate solutions for smaller joint specimens, the computational time required for large joint assemblies is penalising, generally making further numerical optimisation studies unfeasible using this approach.

In relation to the penalising issues of 3D-FE techniques, the issue of efficient joint design practices has been addressed by a number of authors. Tate and Rosenfeld [3] empirically derived an expression for the equivalent spring stiffness term of a double-lap isotropic bolted joint. This formula was later modified by Nelson et al. [4] allowing it to be applied to single-lap composite joints. McCarthy et al. [2] quite accurately modelled the effects of bolt-hole clearance on load distribution in multi-bolt composite joints using the spring stiffness terms developed by Tate and Rosenfeld [3], Nelson et al. [4] in an equivalent spring-mass model. McCarthy and Gray [1] modified the model developed by McCarthy et al. [2] to include the effects of bolt torque and friction forces. It should be noted, however, that [1–4] did not account for damage in the joint.

In addition to mass-spring models, a number of authors investigated methods to improve the efficiency of finite element analyses of bolted joints [19–21]. Ech and Schön [19] used linear beam elements to model the bolts and laminates in multi-fastener joints, while connector elements accounted for bolt clearance and pre-load effects. Although highly efficient, this approach was limited to modelling single-column joints. Gray and McCarthy [20] used the analytical model developed by McCarthy and Gray [1] to control the response of user-defined beam elements, representing the joint region. As laminates were modelled using shell elements, this technique was not limited to single-column joints. Furthermore, damage in the joint was accounted for through the use of a cubic spline interpolation. Pierce et al. [21] used PLINK (point link) connector elements, to efficiently model the joint response at various loading rates. These elements assumed a linear response up to a defined failure load, followed by a region of constant load extension and linear softening to final failure. The method presented in this paper predicts the damaged response of the joint based on the energy absorption. This is unlike previous methods where the entire load displacement curve from a control case is required [20], or where the non-linear effects in the joint damage curve are simply omitted [21].

2. Problem description

The objective of this work is to develop an analytical model to determine the bearing response of multi-bolt composite joints at various loading rates. A single-bolt, single-lap joint was used as the basis for the model, as extensive experimental and numerical studies had been carried out on this configuration. In addition, several analytical models have been developed for this joint previously, as outlined in Section 1.2. In order to access its accuracy in predicting the load–displacement response of multi-bolt joints, a comparison was made with experimental data obtained from three-bolt, single-lap joint tests at a number of loading rates.

A phenomenological approach was taken to the development of the model, whereby a series of piecewise continuous functions were employed to represent the response of the joint throughout the various stages of loading. These loading stages were based on the results of experimental and numerical studies and appropriate functions were determined to characterise the single-bolt response in terms of suitable independent variables. The multi-bolt model is simply an extension of this, as the governing functions of an equivalent single-bolt joint are superimposed locally. A full description of the model is provided in Section 4 of this paper. The response of the joint has been approximated into five stages of loading and these are: friction, transition, load take-up, non-linear damage and quasi-linear softening, as illustrated in Fig. 1(a) and (b). The latter two stages correspond to the propagation of damage and ultimate failure of the joint, and for the remainder of this paper, this will be collectively referred to as the “damaged response”.

The undamaged response of the joint has been idealised into three linear regions to model the effects of friction, clearance and load take-up. The initial loading phase was assumed to be governed by the classical Coulomb friction law. However, during this stage any displacement observed can be attributed to the shearing of the composite material in the plane that is parallel to the direction of loading and through the thickness of the joint, giving rise to the stiffness value K_S. This stage of loading continues until the maximum friction load (P_{FRIC}), which is dependent on bolt pre-load [5,22]. Once the maximum coulomb friction load has been exceeded, the joint undergoes a transition region where the applied load is now partially reacted by the mechanical fastener and partially through the effects of friction between the laminates. This effect has been simplified somewhat by assuming a constant-load slip condition during which the laminates experience a relative displacement c. It was found that a suitable value of c is the clearance between the fastener and hole [1]. The stiffness associated with the load take-up region, K_E, was determined based on the mechanical properties of the fastener and the surrounding composite materials [1–4]. Once the failure initiation load (P_i) is reached, a non-linear force–displacement relationship is assumed where the load monotonically increases with increased joint displacement until the maximum load (P_F) is carried. At this point, any increase in joint displacement will result in quasi-linear