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Shear fatigue of the bonded and frictional interface under constant normal pre-stress

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ABSTRACT

Fatigue damage in the idealised bonded interfaces under constant normal pre-stress is studied by scanning electron microscopy and it is found to involve several microstructurally small cracks with different lengths and orientations. Evolution of fatigue damage in the adhesive occurs as the small cracks grow, coalesce and interact with each other. The theory related to these phenomena is not yet established. Therefore, a phenomenological model of fatigue damage is proposed based on the experimentally-measured compliance of the modified napkin ring specimen. The cohesive zone law describing the quasi-static fracture of the interface is re-formulated to include the effect of fatigue damage.

1. Introduction

High-strength steels (HSS) are increasingly used to deliver light weight and improved strength in structures. However, the durability of an HSS structure depends highly on the welded joints, the fatigue strength of which does not increase proportionally with the steel strength. Hybrid joints, where the good properties of adhesives and mechanical fasteners or spot welds are combined, provide potential joining alternatives for improved fatigue endurance in high-strength steel structures. The current study focuses on hybrid joints that combine adhesives and bolts. At present, most applications involve the use of the bonded/bolted joint in the fail-safe mode, where one method takes over when the other one fails [1]. The bonded/bolted joint is also common in repair applications [2,3]. The hybrid joining technology of combining bolts and adhesive has been widely studied in the field composite structure joining, where the bolts commonly contribute to reducing the shear stress of the adhesive by transmitting a significant part of the load by the bolt pins. With the use of bonded/bolted hybrid joints in HSS structures, the load is carried by both adhesive and friction. Thus, the bolts increase the shear strength of the bonded interface by generating a compressive normal stress.

Repair and fail-safe applications do not fully exploit the potential of hybrid joints and, therefore, an in-depth understanding of the behaviour of the bonded interface under constant normal pre-stress during quasi-static as well as fatigue loading is needed. In addition, a failure assessment method needs to be developed along with an appropriate test method. The load transfer in hybrid joints is a complicated issue due to the different stiffnesses of the constituents (bolt or other mechanical fastener, adherends and adhesive). Attempts have been presented to evaluate the stresses in the different constituents using the finite element method [4–6]. Due to the long calculation times, efforts towards analytical determination of the stresses have been carried out [7,8]. However, none of these models take into account the friction which contributes to the overall interface strength in HSS joints with very high normal stress from the bolts.

The primary loading mode of the bonded/bolted hybrid joint is cyclic shear stress combined with static normal pre-stress. A test method using a modified napkin ring specimen which combines shear and normal stresses was introduced [9–12]. The method allows for the characterisation of interface properties with very well-defined boundary conditions. Thus far, the modified napkin ring specimen has been utilised in quasi-static assessment of the idealised interface [9,10] and a full-scale hybrid lap joint [13]. Fatigue assessments based on the modified napkin ring specimen have focused on identification of interface failure modes [11], estimation of the interface fatigue strength [12] and estimation of the high-cycle fatigue failure of a full-scale hybrid lap joint [14]. It was concluded that the fatigue failure of the full-scale bonded/bolted hybrid joint is a result of the combined effect of progressive damage in the adhesive and fretting fatigue. As a next step, a model

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for the progressive fatigue damage evolution is required, in order to estimate the fatigue life of a bonded/bolted hybrid joint.

In this work, the fatigue modelling of the bonded interface under static normal pre-stress is approached by the analysis of phenomena in the microscale and their effects on the mesoscale mechanical behaviour of a representative elementary volume. The microscale physical nature of damage due to fatigue loading is observed from a scanning electron microscopy (SEM) study of the adhesive layer under different degrees of fatigue damage. An equation for the evolution of damage is proposed based on the observations of the microscale study; however, the equation is determined in a phenomenological setting based on experimental observations in the mesoscale, using the modified napkin ring specimen. An increase in specimen compliance is observed during the fatigue loading history and attributed to the progressive fatigue damage in the adhesive. The cohesive zone modelling (CZM) technique has previously been used for modelling quasi-static fracture of the modified napkin ring specimen by combining the technique with the Coulomb friction model [9,10]. In this work, the effect of fatigue damage on the interface residual strength is assessed by redefining the parameters of the cohesive law to include the effect of fatigue damage. The approach is validated experimentally.

The finite element method-based CZM technique has become widely used in failure modelling of adhesive joints [15,16]. In the CZM approach, the interface between two layers is modelled using cohesive elements or contact definition, defined by the traction–separation relation. A damage parameter is employed to progressively reduce the stiffness of the cohesive element, thus simulating the growth of damage. The CZM has the advantage of being able to account for both the initiation and propagation of de-bonding, thus combining the advantages of strength-based and fracture mechanics-based approaches to failure analysis.

The cohesive zone model requires the definition of several parameters, the experimental evaluation of which is not always trivial. Recently, Pascoe et al. [17] raised the issue of the lack of fundamental understanding of the physics related to the definition of the cohesive zone model in composites delamination and adhesives de-bonding analyses. Cohesive stiffness is usually chosen based on numerical reasons. Critical traction is difficult to determine experimentally and, therefore, an assumed value is used [18]. Fracture energy can be determined experimentally; however, Khoramishad et al. [18] chose to refine the value of the fracture energy obtained from experiments in an iterative manner so as to match the response of experiments on bonded joints. Another problem raised by Pascoe et al. [17] was related to the definition of fracture energy. It is assumed that the area under the traction–separation curve is equal to the fracture energy which implies that the work applied to the cohesive element is consumed entirely upon the formation of new fracture surfaces. However, in reality, at least some of the energy is dissipated by plastic or viscous deformation. In addition, the damage evolution model is described using numerous parameters, the physical nature of which is not completely understood.

In this work, the interfaces bonded with epoxy adhesive are studied. Published studies provide some experimental insights into the physical nature of damage in the epoxy adhesive material ahead of the crack tip. Chai [19] found that the mode II crack in the epoxy adhesive in the end-notched flexure (ENF) specimen propagates due to micro-cracks that form ahead of the crack tip. On the other hand, it has been found that the failure of the napkin ring specimen is a result of similar micro-cracking [20]. The stress state in the napkin ring specimen is nominally pure mode II (the stress intensity factors of the micro-cracks can be mixed-mode). Similar stress state occurs ahead of the crack tip in the ENF specimen. Thus, the damage process in the entire napkin ring specimen is equivalent to the damage process ahead of the mode II crack in the ENF specimen. Indeed, the napkin ring specimen provides an interesting opportunity to directly determine the constitutive equation for the cohesive zone model under mode II loading, which has been presented in this paper and elsewhere [9,10,14].

In terms of fatigue damage modelling, Pascoe et al. [17] pointed out that one of the main advantages of the CZM, namely, the ability to model the crack initiation phase, is rarely used in published studies, as the CZM is mostly employed to model fatigue crack growth [18,21–37]. In many of the studies, a fatigue damage parameter is introduced into the CZM, and the strength or stiffness of the cohesive law is degraded as the damage parameter evolves with cyclic loading. The onset of fatigue damage in the previous studies [24–28] usually requires the stress in the cohesive element to exceed the critical traction for static damage. This can occur at the crack tip but rarely in the un-cracked geometry. Consequently, in order to model fatigue crack initiation, the fatigue damage evolution and the resulting degradation of the cohesive stiffness and strength should occur with stresses lower than the critical traction. May and Hallett [29,30] derived a fatigue law for cohesive elements, wherein the damage evolution is divided into static, fatigue initiation and fatigue propagation damage with different calibration procedures for the different stages of damage evolution.

The work reported in this paper provides further understanding of the several parameters required by the CZM definition through the use of the modified napkin ring specimens for fatigue testing and through the related SEM analysis. The initiation of a fatigue crack as a consequence of fatigue damage could potentially be modelled using the proposed approach. Furthermore, according to the knowledge of the authors, the effect of friction on the fatigue damage evolution in the cohesive interface is assessed for the first time in this paper. The proposed model is an important step towards reliable assessment of bonded/bolted hybrid joints. The modified napkin ring experimental setup is provided in Section 2. Section 3 focuses on explaining the observations of the SEM study. In Section 4 the progressive damage model is formulated starting with discussion on the SEM results and laying out the modelling strategy. Thereafter, the cohesive zone model is re-formulated to account for the fatigue damage and, finally, the fatigue lives calculated by the model are presented. Section 5 contains the conclusions.

2. Experiments

2.1. Specimens

Test specimens were machined from HSS sheets (Ruukki Optim 960QC, nominal yield strength 960 MPa) with thickness of 6 mm. Main dimensions of the specimens are shown in Fig. 1. The eight smaller holes visible in Fig. 1 were used for fixing the specimens in the testing machine.

The 2 mm-wide circular contact surface was grit blasted with medium grit aluminium silicate. The average surface roughness R_a of the grit blasted specimens was $R_a = 3.1$ μm. Before applying

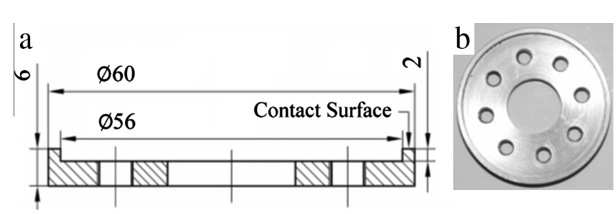

Fig. 1. (a) Main dimensions of the modified napkin ring specimen (mm). Specimens were tested in pairs with only the 2 mm-wide contact surface areas in contact. Structural adhesive was applied exclusively to the contact surfaces. (b) Photograph of the specimen.