The influence of static normal stress on shear capacity of bonded high strength steel interfaces

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ABSTRACT. *Incorporating high strength steels in mechanical engineering structures is frequently limited by the relatively low fatigue strength of welded joints relative to the fatigue strength of the base material. Hybrid joints, which combine mechanical fasteners with bonding, provide potential joining alternatives for high strength steel structures. Not surprisingly, a wide variety of mechanical and bonded joints are used in the automotive and aircraft industries where light weight and structural integrity are primary design drivers. For thin sheet metal structures in high strength steel, structural adhesives can effectively increase the maximum service load of friction based non-slip bolted connections. For hybrid joints, mechanical fasteners provide high connection ductility and they effectively hinder peeling failures of the adhesive interface. In addition, structural adhesives are known to improve the load distribution characteristics of a joint resulting in lowered local stress concentration factors and improved fatigue strength. An extensive literature search has shown that relevant design input data are missing. An experimental and analytical research program has been initiated to assess the static and cyclic shear strength of epoxy bonded high strength steel joints subjected to various degrees of static normal pre-stress.*

INTRODUCTION

The increasing demand of light weight combined with improved endurance in structures leads to an increased use of high strength steel materials. However, the use of these materials is frequently limited by the relatively low fatigue strength of welded joints compared to fatigue strength of the base material. The problem of joining in fatigue critical applications limits the use of high strength steels, and demand for alternative joining methods has arisen. Joints that combine mechanical fasteners with adhesive bonding provide potential joining alternatives for high strength steel structures. In this context such joints are referred to as hybrid joints.

Hybrid joints are widely used in aerospace and automotive industries in joining composites and sheet metals. They have been shown to improve the strength and fatigue strength of the joint compared to simple adhesive or simple bolted joints [1-3]. The improved properties of hybrid joints result from some of the special features of hybrid joints: the adhesive equalizes the stress distribution, even though bolts create nonuniform stress distribution. It has been shown that load transfer between adhesive and bolts occurs if the adhesive modulus is sufficiently low [1]. The adhesive carries most of the load but if the adhesive fails, bolts will carry load thus providing for safer operation. In this study the combined effect of normal clamping force and adhesive strength is investigated. In real structures the normal force would be caused by the tightening of the bolts.

Some studies on joining high strength steels with hybrid joints exist, but relevant design input data and assessment methods in this field are missing. An experimental and analytical research program has been initiated to assess the static and cyclic shear strength of epoxy bonded high strength steel joints subjected to various degrees of static normal pre-stress. In the first part of the study, static and fatigue tests are being conducted under Mode II loading. Boundary conditions of the joint are designed to be as ideal as possible so that the mechanisms of static slip and fatigue damage in the adhesive can be studied. The results are reported in this paper.

ADHESIVE AND MECHANICAL COMBINED JOINTS

Very few studies of hybrid joints have been published, but the fatigue of adhesive joints has been studied quite extensively, and good summaries are available [4]. The limited studies of fatigue of hybrid joints, however, are promising [1-3, 5]. Modelling of hybrid joints in metals is mostly based on cohesive zone modelling. This is also briefly reviewed.

Fatigue of adhesive joints

The fatigue strength of adhesive joints is, in many cases better than that of welds or bolted connections. This is traditionally explained by the reduction of stress concentrations by the adhesive. Fretting fatigue is also hindered by adhesives. The mechanisms of fatigue are different between metals and polymers, and the response to cyclic loading differs due to the viscoelastic nature of polymers. The effects of environmental factors such as temperature and humidity are more severe in polymers than metals. Analysis of fatigue in adhesive joints is further complicated by the heterogeneousity of the polymer material. [4]

A standardized test method for assessing the stress-life properties of adhesive joints in fatigue is described in EN ISO 9664 [6]. The drawback of the stress-life approach in modelling of adhesive joints is that the obtained fatigue data is difficult to apply due to the strong dependence of fatigue properties on joint geometry. Methods based on fatigue crack growth are potentially more applicable to design of different joint geometries, but the difficulty of applying this method lies in defining the initial flaws, which are often located within the adhesive. [4]

Fatigue of hybrid joints

Hart-Smith [7] was among the first to publish on hybrid joints. In this study, static stress was computed and it was found that no benefit was to be gained for intact structures, but that bonded joints are useful in repair operations. Other early publications include that of Mann et. al. [5] who observed increased fatigue life in adhesively bonded bolted joints and that of Yamaguchi and Amano [8] who derived an analytical model to predict the behaviour of bonded/bolted joints.

In the 90's the fatigue strength of riveted/bonded hybrid joints in high strength steel was studied by Imanaka et al. [3]. They found that the fatigue strength of the hybrid joint was better than that of the adhesive joint alone, but only in the case when the fatigue strength of the rivets in the hybrid joint was the same or higher than the fatigue strength of the adhesive. They also confirmed that fatigue cracks propagate more gradually in combined joints than in joints with only adhesive.

As the properties of adhesives have improved, the number of publications on hybrid joints has also increased. In spite of the increased research on hybrid joints, fatigue of hybrid joints is still a less well-studied area. Increased fatigue life in hybrid joints compared to adhesive joints has been observed recently by Kelly [1] who studied strength, failure modes and fatigue of hybrid joints in carbon fiber reinforced plastics. It was observed that the static and fatigue strength were better in hybrid joints than in adhesive joints, but the static strength was only improved by low modulus adhesives, which allow load transfer between the bolts and the adhesive. They also observed that catastrophic failure occurred when the laminate strength was lower than the adhesive strength. Hybrid joints in structural injection molded composites were studied by Fu and Mallick [2]. They observed that the static and fatigue strength of hybrid joints is better than in joints with adhesive alone. The performance of the hybrid joint greatly depends on fastener/washer design so that washers providing uniform pressure over the bonded area lead to a stronger joint while washers distributing pressure only partially over the bonded area lead to a weaker joint. They also verified their results with a finite element analysis.

In most of the research involving fatigue of hybrid joints the adherends are made of different composite materials [1,2,5,7]. Only one published study of hybrid joints in high strength steel materials was found [3].

Modeling of hybrid joints

Hybrid joints are frequently modelled assuming an adhesive layer with a constant thickness [8,9]. This is easily adapted for modelling of composite structures assembled using bolts [10]. However, during the assembly process of hybrid joints involving steel plate members, axial fastening is applied before the adhesive is cured. In this case, the high normal pressure between the plates forces the uncured adhesive out from the interface region and only small amounts of adhesive are left to fill in the surface topography induced micro-volumes on the closed contact surfaces [11]. Metal-to-metal contact will occur adjacent to these micro-volumes. Therefore, an adhesive layer with constant thickness is not a reasonable assumption for hybrid joints in steel or for other joints with significant normal clamping forces.

Decohesion finite elements have recently been developed to provide a suitable option to simulate progressive damage of adhesively bonded interfaces [12,13]. Cohesive zone models (CZM) which are implemented in FEM, are exploited to determine the critical energy release rates of bonded joints [14,15]. For a typical CZM, the magnitude of the interface traction stress increases, achieves its maximum value, and finally falls to zero due to damaging loading. In this case there is no need to define an initial crack and the damage is restricted to evolve along the predefined cohesive interface. Decohesion finite elements are placed between solid finite elements of the base material. Principles from fracture mechanics, such as the fracture energy, are adapted to control the separation of interfaces. Consequently, the fracture energy and critical interface stress govern the strength of the interface and therefore comprise the basis for material property determination for the FE model calibration. After a specified damage initiation criterion is reached, a damage evolution law begins to govern the degradation process of the interface material. A damage function derived from its corresponding damage evolution law, enables incorporation of different damage models in FEM. The most common mathematical models for damage evolution are either bi-linear [12,13] or trapezoidal [16]. More sophisticated exponential damage evolution laws have been developed by Oinonen and Marquis [17] and Valoroso and Champaney [18]. In addition, Needleman [19] has adapted a cubic polynomial damage model that was initially developed for assessing void nucleation phenomena.

EXPERIMENTAL SETUP

An experimental program has been initiated to examine the properties of bonded interface under static and fatigue loading. The effect of the normal stress on the maximum Mode II load carrying capacity was investigated. The steady frictional stress of the damaged hybrid specimens was subtracted from the corresponding total quantity to obtain the damage response as a result of the hybrid interface degradation. Four different axial clamping stress values were considered.

Specimens

In practically all of the previous experimental studies, the lap joint has been used for the test samples. This is also the sample geometry described in the standard EN-ISO 9664 [6]. The lap joint geometry is simple to prepare and very suitable for laminates but the true stress distributions in the adhesive layer is quite complex. In this study the samples are designed so that the applied shear stress will be nearly uniform. This allows for more reliable assessment of static and fatigue mechanisms in the adhesive.

Test specimens were machined from high strength steel sheets (nominal yield strength 960 MPa) with thickness of 6 mm. Main dimensions of the specimens are shown in Fig. 1. There are eight smaller holes, which were used for fixing the specimens in the testing machine. The 2 mm wide circular contact area was not machined but was in the as-rolled condition from the steel mill. For all specimens, the contacting surfaces were blasted using medium grit aluminium oxide sand and cleaned with acetone to ensure proper adhesion. The machined surfaces inside of the Ø = 56 mm contact area were protected using a plastic annular seal to prevent adhesion inside the desired contact areas. A two component structural epoxy adhesive DP760 produced by

3M [20] was used for bonding the connections. The standard curing time of the adhesive at room temperature was one week [20]. Specimens were tested in pairs with the circular contact surface of one specimen opposing the contact surface of an identical specimen. During the assembly process, adhesive was applied to the contact surfaces of the specimens and clamping to the desired pre-stress was immediately applied. The pre-defined normal pre-stress was constant during the curing process and was the same stress as used during subsequent testing.

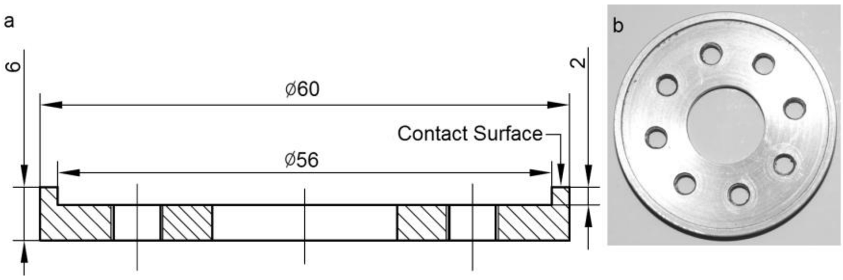

Figure 1. a) Hybrid specimen with the main dimensions [mm]. Specimens were tested in pairs with only the 2 mm wide areas in contact. Structural adhesive was exclusively applied onto the sandblasted contact surface. b) Photograph of the specimen.

Laboratory Testing Procedure

Experiments were performed using a servo-hydraulic test machine which applied pure torsion load across the circular glued interfaces. During testing, normal stress on the interfaces was maintained via a threaded rod equipped with an axial load cell. An eddy current extensometer was fixed to each side of the specimen pairs in order to measure displacement (slippage) between the contact surfaces. In the static tests torsion displacement was applied at the rate of 0.027 mm/s at the mean diameter of the contact interfaces. Two identical static tests were performed for each normal clamping load value. The fatigue tests were conducted under force control with a loading frequency of 3Hz and normal clamping stress of 100 MPa. Different levels of loading in R=0.1 were tested.

RESULTS OF THE TESTS

Figure 2 shows the static combined slip and decohesion response of the hybrid specimens in the range $0 \leq \Delta \leq 1$mm.

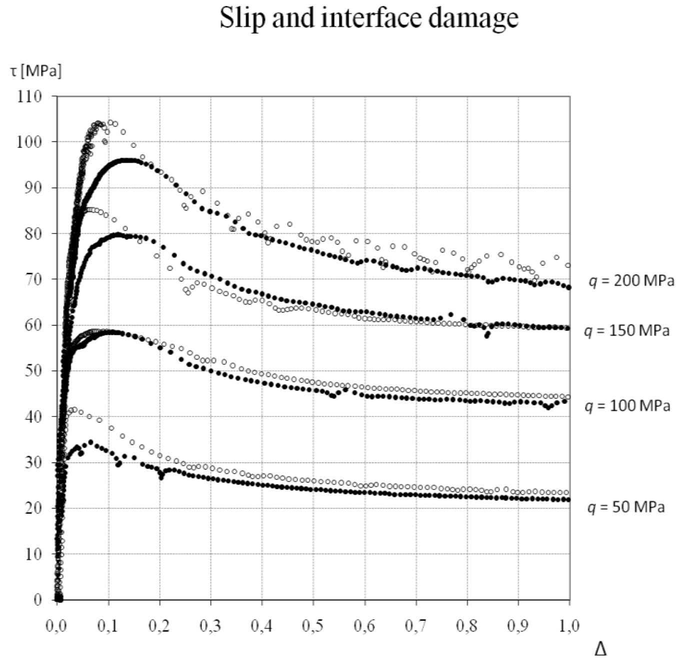

Figure 2. Combined slip and interface damage responses of static test samples. The results for four different preload cases are shown. At $\Delta \approx 1.0$ mm, the mode II load carrying capacities approach steady state corresponding to full interface damage.

The computed shear energy release rate G_{II} vs. Δ, i.e. *R*-curves of the hybrid interfaces, are shown in Fig. 3. At $\Delta \approx 1.0$ mm, G_{II} has approximately reached G_{II}^{c}. The clamping stress is indicated by *q*.

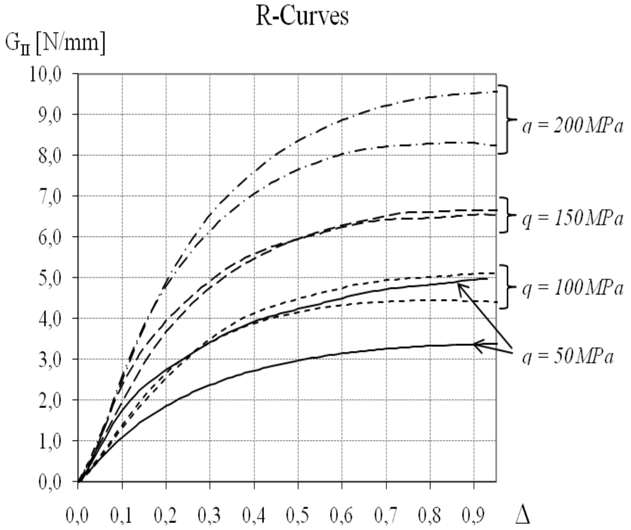

Figure 3. R-curves from the static tests.

The fatigue tests conducted so far are preliminary tests that provide directions for designing future tests. All fatigue tests were conducted under clamping stress of q = 100 MPa and loading conditions of R=0.1. The first three tests with intact sandblasted surfaces did not result in fatigue failure and the test was halted after $2x10^6$ cycles. After tests 2 and 3, the samples were tested for static strength. The results along with fatigue test conditions are shown in Table 1.

Table 1. Stress ranges of the preliminary fatigue tests and fracture strength measured after the discontinued fatigue test.

τ_{max} [MPa]	**τ_{min} [MPa]**	**N_f**	**τ_f [MPa]**	
47	4.7	-	-	
53	5.3	-	77	
60	6.0	-	79	
60	6.0	500	-	grooved sample

A sample with four grooves machined on the contact surface was tested with the same loading conditions as the intact samples. In this case a failure occurred after 500 cycles. The grooves were added to provide exit paths for potential fretting debris that may form between the two contact surfaces.

DISCUSSION & CONCLUSIONS

Annular specimens made of high strength steel and joined together by a structural adhesive combined with normal clamping force were tested for both static fracture strength and fatigue behaviour. The static tests indicate that the applied clamping force influences the strength of the joint not only by increasing friction but also by increasing the adhesive strength (Fig. 3). In fatigue, even though the maximum shear stress across the interface was nearly equal to the static shear strength of the interface, no fatigue failure was observed and tests were halted after $2x10^6$ cycles. For future tests, the test fixture is being modified to permit R=-1 loading. All that can be deduced from the fatigue tests at this point is that the adhesive significantly increases the fatigue capacity of the joint. The maximum shear stress in fatigue is clearly greater than the friction strength of the joint without adhesive. The objective of future research is to determine the mechanism of fatigue failure in the bonded interface.

Two static tests for each clamping load were conducted, and as can be seen from Figs 2 and 3 the measured data varies between specimens. The same kind of variation is also observed in the fatigue test results. The fatigue loaded samples had larger fracture strength than the statically loaded samples tested at 100 MPa. In future experiments special attention is given to the treatment of the samples, especially the sandblasting phase. More tests for all levels of clamping load will also be conducted.

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