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Experimental investigation and modeling of mean load effect on fatigue behavior of adhesively-bonded pultruded GFRP joints

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ABSTRACT

The effect of mean load on the fatigue behavior of adhesively-bonded pultruded GFRP double-lap joints under constant amplitude loading was experimentally investigated. The joints were examined under nine different stress ratios (R) representing pure tension, compression, and combined tension–compression fatigue loading. A transition of the failure mode, from tensile to compressive, was observed as the mean load decreased from positive to negative values. The slope of the S–N curves derived for R-ratios with positive or negative mean load consistently decreased with increasing mean load. The highest load amplitude corresponded to the R-ratio where the transition of the fatigue failure mode occurred ($R = -2$). The characteristics of the constant life diagram developed for the examined bonded joints are thoroughly discussed. A phenomenological formulation was proposed and its accuracy evaluated by comparisons with the derived experimental data. The comparison of the new formulation with models commonly used for composite materials proved its higher accuracy that is achieved with less implementation effort.

1. Introduction

Engineering structures comprise parts that are subjected to cyclic loading patterns. In fact, most structural failures occur due to mechanisms driven by fatigue loading, whereas purely static failure is rarely observed in open-air applications [1]. Fatigue mainly affects the weak links of structures, usually laminates and joints that serve to transfer loads from one part of the structure to another. The structural integrity of these components is therefore of great importance for the viability of the entire system.

The effect of several critical parameters on the fatigue life of a material under a certain loading condition can be examined when experimental work is performed under this condition. Although the result is useful for the analysis of the examined loading scenario, the experimental effort should be repeated for any other applied loading spectrum. This practice is costly and cannot be followed in practice where numerous different loading patterns are applied on a structural element. Therefore experimental databases are derived for basic loading conditions (e.g. constant amplitude fatigue loading) and appropriate modeling is performed for extrapolation of the experimental evidence to predict the life under other, more complicated, loading conditions.

The stress ratio, the ratio of the minimum to maximum applied cyclic stress ($R = \sigma_{min}/\sigma_{max}$), is used to specify the loading type; $0 < R < 1$ expresses tension–tension (T–T) fatigue, $1 < R < +\infty$ represents compression–compression (C–C) fatigue, while $-\infty < R < 0$ denotes mixed tension–compression (T–C) fatigue loading that can be tension- or compression-dominated. It is well documented that for a given maximum stress in a tension–tension case, the fatigue life of the composite increases with increasing magnitude of R. In compression-compression loading, increasing the magnitude of R reduces the fatigue life of the examined composite [2–6].

The influence of the R-ratio on the fatigue behavior of composite materials has been the subject of numerous investigations in the past, e.g. [2–8]. This effect is assessed by using constant life diagrams (CLD). Constant life diagrams reflect the combined effect of mean stress and material anisotropy on fatigue life, and can be used for estimation of the fatigue life of the material under loading patterns for which no experimental data exist. The main parameters that define a CLD are the cyclic mean stress, stress amplitude and number of fatigue cycles. The CLDs for composite materials are usually shifted towards the tension- or compression-dominated domain, reflecting the degree of anisotropy of the examined material [8–14]. For laminates exhibiting significantly higher tensile strength than compressive strength, e.g. unidirectional carbon/epoxy laminates [8], the CLD is shifted towards the right, tension-dominated domain. For materials exhibiting higher compressive than tensile fatigue properties, e.g. short-fiber composites [14], the diagram is shifted towards the compression-dominated domain. It has also been reported that this tendency towards one side of the diagram can alter with the number of cycles. Fernando et al. [11] revealed a similar form of constant life curves concerning

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four different material systems for a fatigue life of 10^5 cycles. However, a change in the form of the iso-life curves was reported in [8,10]. The shape of the curves gradually alters from linear to non-linear form with increasing fatigue life.

The classic CLD formulations require that the constant life lines converge to the ultimate tensile stress (UTS) and the ultimate compressive stress (UCS), regardless of the number of loading cycles [15–17]. However, this is an arbitrary simplification originating from the lack of information about the fatigue behavior of the material when no amplitude is applied. In fact, this type of loading cannot be considered as fatigue loading, but rather as creep of the material (constant static load over a short or long period), see e.g. [5,7]. Although modifications to take the time-dependent material strength into account have been introduced, their integration into CLD formulations requires the adoption of additional assumptions, see e.g. [5,18], and yet none of these modifications can provide a general model to characterize the fatigue–creep interaction in composite materials.

Although a considerable amount of information exists regarding the R-ratio effect on the fatigue life of composite laminates, there is little literature regarding similar investigations for adhesively-bonded structural joints. Experimental studies on joints are based on tensile fatigue loads because they focus on joints exhibiting a cohesive or an adhesive failure. Nevertheless, as shown from several studies, e.g. [19,20], different failure modes can be observed depending on the adherend materials and the joint geometry. Moreover, significant R-ratio effects were reported, e.g. [21], especially for pultruded FRP joints in which cracks in the adherend lead the failure process and also different failure modes are observed under tension and compression fatigue [22].

The effect of a combination of tensile and compressive loads on the fatigue behavior of adhesively-bonded pultruded GFRP joints has been studied in the present work by generating load-life data for a range of R-ratios covering all CLD domains. A phenomenological CLD formulation is developed for modeling the R-ratio effect taking into account the creep damage with little data required. Although the new formulation is based on a limited number of input data it is very accurate, as proved by comparisons with experimental data.

2. Experimental investigation

2.1. Experimental program

Symmetric adhesively-bonded double-lap joints composed of pultruded GFRP laminates bonded by an epoxy adhesive system were examined under axial, tensile, compressive and reversed fatigue loads. The pultruded GFRP laminates, supplied by Fiberline A/S, Denmark, consisted of E-glass fibers and isophthalic polyester resin. The laminates comprised two mat layers on each side and a roving layer in the middle with a thin layer of polyester veil on the outer surfaces. Each mat layer comprised of 0/90 woven fabric stitched to a chopped strand mat (CSM). A two-component epoxy adhesive system was used (Sikadur 330, Sika AG, Switzerland) as the bonding material [22].

Two different joint configurations were prepared; one with a total length of 410 mm, see Fig. 1, and used only for tensile loading, and another with a reduced total length of 350 mm, which was used when compressive loads were applied to avoid any buckling of the joints. To achieve the latter configuration, the free length of the "inner laminate" was reduced from 100 mm to 40 mm without changing the bonding and gripping length. These dimensions were selected after preliminary testing and modal analysis using finite element modeling, which indicated that this length reduction sufficed to prevent buckling of the laminates. Furthermore, the finite element stress analysis showed that this change of the laminate length did not result in significant changes in all stress components, through the inner laminate and the bonding area thickness, and also in the interface along the bond line. The gripping part (shown on the right side of Fig. 1) was designed to adapt the thickness of the specimen to the jaw faces of the machine. A bolted connection was used to prevent any failure in the gripping part that may have affected joint behavior. All fatigue experiments were carried out on an INSTRON 8800 servohydraulic machine under laboratory conditions (23 ± 5 °C and 50 ± 10% RH) under load control, using a constant amplitude sinusoidal waveform, and a frequency of 10 Hz. Six R-ratios (denoting the ratio of the minimum to the maximum applied cyclic load) were selected to cover as many CLD domains as possible; $R = 0.5$ and $R = 0.9$ for the T–T domain, $R = 2$ and $R = 1.1$ for the C–C domain, $R = -0.5$ for the T–C domain, and $R = -2$ for the C–T domain. At least six specimens were examined under each R-ratio in order to cover the entire lifetime between low and high cycle fatigue. The experimental results of this work complement a previously derived database containing fatigue data from experiments on the same joint type under $R = 0.1$, 10, and -1, [22].

2.2. Experimental results

2.2.1. Failure modes

Under T–T ($R = 0.5$ and $R = 0.9$) and T–C ($R = -0.5$) fatigue, the failure mode was similar to that observed under T–T ($R = 0.1$). A fiber-tear failure was observed with a dominant crack that initiated from the joint corner of one of the bond lines, between the adhesive and the inner GFRP laminate, and then shifted deeper, between the first and the second mat layers of the inner laminate, and propagated along this path up to failure. Under C–C loading ($R = 2$ and $R = 1.1$), as under $R = 10$, failure occurred within the roving layer of the inner laminate. Under C–T loading ($R = -2$), the failure mode was similar to $R = -1$, as reported in [22]. Under this loading condition, in addition to the dominant crack along one of the bond lines related to the tensile component of loading, a smaller crack was observed in the middle of the inner laminate at a similar location as for compression fatigue. However, during the fatigue life the dominant crack was propagating and leading the failure process, while the crack created by the compressive component of the applied cyclic load reached a maximum length of 5 mm

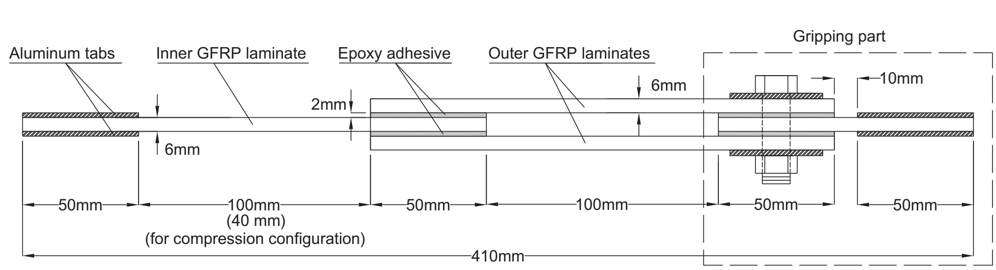

Fig. 1. Double-lap joint geometry.