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Bending fatigue behavior of twill fabric E-glass/epoxy composite

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ABSTRACT

Twill E-glass/epoxy composite was considered for its bending fatigue behavior. Displacement controlled bending fatigue tests with stress ratio R of 0.1 were conducted on standard specimens and damage development in the composite was continuously monitored through the decrease of bending moment during cycling. The specimens were subjected to different fatigue loadings with the maximum loading level up to 75% of the material ultimate flexural strength. Early damage was observed after hundreds of loading cycles causing degradation of material stiffness with cycling. The amount of stiffness reduction was observed to be a function of the magnitude of the fatigue loading applied to the specimen. For some selected specimens, after 1 million cycles, fatigue tests were stopped and residual properties were measured. Different levels of reduction on material strength and elastic modulus were found to depend on the level of fatigue loading. Finally detailed discussion is made to correlate the found fatigue data and obtain general description of the material fatigue behavior useful for composite component design.

1. Introduction

Fibre-reinforced polymers (FRP) are made of reinforcing fibres embedded in a polymer matrix. FRP are used extensively in automotive, aeronautic and naval engineering. FRP offers substantial improvements over metals not only for the specific stiffness and strength, but also for their resistance to fatigue [1].

FRP are heterogeneous and anisotropic. These behaviors lead the failure of FRP under fatigue loading with a damage development that appears to be more complicated than for metals. Fong [2] explained two technical reasons why the fatigue damage modeling and prediction in general are complicated and expensive. The first reason is the several scales where damage mechanisms are present: from microlevel, through the subgrain, grain and specimen levels, to the component and structural levels. On the other hand, the second reason is the practical impossibility of producing 'identical' specimens with well-characterized microstructural features.

Generally, FRP with a polymeric matrix under a cycling loading shows a degradation of performance as a result of damage. Fatigue in FRP proceeds by accumulation of damage throughout the volume, leading to failure caused by general degradation of the material rather than a predominant single crack as in metals [3]. Though microcracks are initiated at an early stage of fatigue, FRP can withstand a very large number of load cycles before failure.

Some literatures stated that the fatigue behavior of composite materials could be well character by stiffness based S–N curve, instead of strength based S–N curves. Generally, the stiffness degradation of composite specimens can be divided into three stages [4,5]: the first stage of deterioration by fatigue is observable by the formation of "damage zones", which contain a multitude of microscopic cracks and other forms of damage, such as fibre/matrix interface failure and pull-out of fibres from the matrix [6–10]. Hence damage starts very early, after only a few or a few hundred loading cycles. A sharp initial decline of the composite stiffness can be observed. This early damage is followed by a second stage of more gradual deterioration of the material, characterized by a more gradual reduction of the stiffness. More serious types of damage appear in the third stage, such as fibre fracture and instable delamination growth, leading to an accelerated decline.

As it is well known in open literatures about the fatigue behavior of fiber reinforced composites, the generic pattern of stiffness degradation during fatigue is independent of cyclic loading level and fiber composite. Liang et al. [11] conduced an experimental investigations of tension–tension fatigue tests on flax/epoxy and glass/epoxy composites specimens with $[0/90]_{3S}$ and $[\pm45]_{3S}$ stacking sequences. The stiffness degradation of both composites exhibits similar trend despite the loading level.

On the other hand, the loading cycle frequency can have a considerable influence on the fatigue life of FRP [12,13]. Ellyin and Kujawski [12] investigated the frequency effect on the tensile fatigue performance of angle-ply glass fiber reinforced laminate and concluded that there was a considerable influence of test loading

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frequency. Especially for matrix dominated laminates and loading condition, frequency becomes important due to the general sensitivity of the matrix to the loading rate and because of the internal heating generation and associated temperature raise.

Most experiments are performed in uniaxial stress conditions, although these stress states are rather exceptional in real structures [13–15]. In [13] the behavior of unidirectional 45° angle-ply, ±45° and multidirectional $[\pm 45,0]_S$ fibre glass/epoxy laminates at room temperature under tensile and fatigue loadings have been investigated. Results for angle-ply ±45° laminates show that the rate/frequency effect is significant in both tensile and fatigue loadings. In the case of tensile loading tests, the rate effect was observed in the stress–strain response. Fatigue data indicate a considerable accumulated cyclic creep which depends on the loading conditions, i.e. applied load and frequency. The effect of frequency on the fatigue life is explained in terms of cyclic creep and its detrimental influence on the fatigue resistance is pointed out. In contrast, laminates made of ±45° unidirectional and multidirectional $[\pm 45,0]_S$ show very little frequency effects.

In a related work [14] fatigue crack growth in thin notched woven glass composites under tensile loading was investigated. Three simple stacking sequences, namely, an orthotropic laminate $[0]_2$, a biaxial laminate $[45]_2$, and a "quasi-isotropic" laminate [45,0,45] with a middle woven ply having warp fibres in the load direction were considered. Results show that the cross-over points of the woven ply are ideal places for fibre tow failure which implies that the weave pattern influences the local crack path. Moreover, the crack propagates perpendicular to yarn fibres as the global crack path remains straight. It also seems that tow fibre always fails entirely. The through-the-thickness crack extends in a discrete manner and is linked to tow width. Typical matrix damage of woven ply also surrounds the crack path. On one hand, it consists of meta-delaminations, while on the other hand, thin and long matrix cracks parallel to the fibres are located in the interstice between two consecutive tows, where their length is limited by cross-over points.

Although bending fatigue tests are not widely accepted as a standard, they are used a lot for research purposes [16–20]. They do have some important advantages as well: (i) bending loads often occur in in-service loading conditions, (ii) there are no problems with buckling, compared to tension/compression fatigue, and (iii) the required forces are much smaller. To evaluate the stiffness degradation and damage growth in the fibre-reinforced laminate, the hysteresis loop of one loading cycle can be measured. In case of three-point bending fatigue, the history of bending force versus midspan displacement is recorded.

Sakin et al. [21] investigated bending fatigue behavior of glass-fiber reinforced polyester composite materials, namely, 800 g/m^2, 500 g/m^2, 300 g/m^2, and 200 g/m^2 glass-fiber woven and 225 g/m^2, 450 g/m^2, and 600 g/m^2 randomly distributed glass-fiber mat samples with polyester resin. According to the test results, the highest fatigue life has been obtained from 800 g/m^2 fiber glass woven specimens with 0/90 lay-up. The property of anisotropy of the GFRP (Glass Fiber Reinforced Plastic) material is dominant on the fatigue strength which has been clearly observed from the experiments. In the test results, the effective parameters were density of fiber distribution on the area, fiber angle, resin permeability of woven fiber, full infiltration (wetting) or without infiltration of fibers.

Van Paepegem and Degrieck [22–24] performed a displacement controlled bending fatigue on plain woven glass fabric/epoxy laminates. Two sets of specimens were considered having the warp direction of each layer aligned with the loading direction $[\#0°]_8$ and at a 45° angle to the loading direction $[\#45°]_8$. The symbol '#' refers to the fabric reinforcement type. When the maximum displacement is the same, the stiffness degradation path is quite different for the two specimens [2]. In particular, the rate of reduction of the stiffness is much higher for the $[\#0°]_8$ specimens so that after nearly 300,000 cycles, the remaining stiffness of the $[\#45°]_8$ has become larger than that of the $[\#0°]_8$ specimens.

In related work [1], a hybrid glass–carbon fiber reinforced epoxy matrix composite, characterized by the presence of intraply biaxial glass–carbon laminate as well as biaxial glass laminate and biaxial carbon laminate, were considered for its bending fatigue behavior. It was concluded that early damage was observed after a few hundred loading cycles causing degradation of material stiffness with cycling. The amount of stiffness reduction was observed to be a function of the magnitude of applied fatigue loading on the specimen. Residual tests revealed that reduction in material strength and elastic modulus was found to depend on the level of fatigue loading. However, the reduction in stiffness does not exactly correlate with the reduction in strength. Kar et al. [25] also investigated the flexural fatigue behavior of hybrid composite rods made of unidirectional carbon and glass fibers. Results show that bending fatigue damage only initiated when the hybrid composite was exposed to a deflection in excess of 42% of its static flexural strength, which does not occur in actual conductor field use. Damage reached a saturation point along the GF/CF interface because of the stress concentration that existed between the two material systems, resulting in asymptotic behavior of the stiffness loss. Because damage did not extend into the CF core, static mechanical properties were retained to 85% or more.

Although detailed discussion on glass FRC have been done by [1,20–25], as per authors' knowledge, no systematic work was found in the open literature focused on investigating the stiffness and strength reduction of twill E-glass/epoxy composite subjected to cycling bending loading under different stress levels. Hence the main objective this work is to investigate the bending fatigue behavior of twill E-glass/epoxy composite under displacement controlled bending fatigue test. The paper presents essential data that characterizes the fatigue behavior and post-fatigue residual stiffness and strength of twill E-glass/epoxy composite.

2. Manufacturing process of specimens

The material used for the experiment was a prepreg (twill 2×2 type) E-glass/epoxy composite with a mass of 250 g/m^2 and resin mass content of 36.5%. The resin matrix type was epoxy and developed for transport sectors. It is characterized by good impact resistance properties, quality surface finish and in particular adapted for high speed cold stamping. Prepreg layers were stacked together in order to obtain the laminates with lay-up of $(\#0°)_{20}$ and $(\#0°)_{14}$ for bending fatigue tests and ASTM uniaxial tests, respectively.

During mold preparation, special attention was given to select appropriate mould material that can be reused. Dimensional stability at high temperature and chemical compatibility with specimen materials were some of the main factors to choose epoxy resin block as a mold. To achieve high grade surface finish, the moulds were cleaned with Chem Cleaner after machining process in order to remove all traces of solvent-soluble contaminants such as waxes, silicones, and oils. Then after, Chemlease® MPP 712 EZ which acts as a sealant was used to coat the surface of moulds and cured for about 3 h at room temperature. After the mould was cured, Chemlease® mold release was applied to assist easy removal of the finished laminate from the mould. At this stage, plies were cut from prepreg E-glass/epoxy fabric and assigned in inside the mold according to desired stacking sequence, $(\#0°)_{20}$ and $(\#0°)_{14}$.

To avoid voids and entrapped air inside wet prepreg, the mould was covered with vacuum plastic bag and subjected to vacuum pressure of 0.98 bar (see Fig. 1a). Then the specimens were