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Response of hygrothermally aged GLARE 4A laminates under static and cyclic loadings

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ABSTRACT

An experimental investigation focusing on the hygrothermal aging-structural degradation–mechanical property relationship of GLARE 4A laminates was conducted. Water immersion conditioning at 80 °C for up to 4 months was carried out on GLARE 4A laminates. It was found that although the outer aluminum layers effectively protected the glass/epoxy composite layers from hygrothermal attack, the composite layers absorbed moisture through the edges. Consequently, significant decrease in both, the tensile strength and fatigue life of the GLARE 4A laminates, was observed although no structural defects were apparently identifiable in the microstructures of the conditioned laminates. Detailed experimental investigation was conducted to study the mechanism of mechanical property decay due to hygrothermal aging. It is proposed that the strength of the S2-glass fibers was not fully realized due to the weakening of the fiber/matrix interface and the deterioration of the sizing, which consequently led to the reduction in the tensile strength and fatigue life of the GLARE 4A laminates. The stiffness degradation characteristics of GLARE 4A laminates under cyclic loading were also investigated.

1. Introduction

GLARE (Glass Laminate Aluminum Reinforced Epoxy) is a type of fiber metal laminates (FMLs) based on high-strength glass fibers. It typically consists of several layers of thin aluminum alloy sheets interspersed with layers of glass fiber reinforced epoxy composite materials. GLARE was initially developed at Delft University of Technology as an improvement of ARALL (Aramid fiber Reinforced Aluminum Laminate) for aeronautical applications [1]. GLARE laminates were produced and commercialized since 1990s [2]. It takes advantages of both metals and fiber-reinforced composites, providing superior mechanical properties that cannot be achieved by either of its constituents [3,4]. Major advantages of GLARE include low density, high fracture toughness and strength [5,6], high impact [7] and fatigue resistance [8], excellent moisture and corrosion resistance [9], etc. Due to the advantages listed above, GLARE is being sought after for more applications in the aerospace industry. For instance, GLARE is selected for the fabrication of the Boeing 777 impact-resistant bulk cargo floor [10] and the upper fuselage panels of Airbus A380 [11].

Plenty of research effort has been dedicated to the investigation of the potential effects of hygrothermal exposure on the various mechanical properties of polymer matrix composites (PMCs) [12,13]. However, to the best of the author's knowledge, only limited experimental results about the durability of GLARE laminates or FMLs under hygrothermal environments are reported in the literature. Borgonje and Ypma [14] reviewed long term behavior of GLARE, including the environmental effects on different components of GLARE and the experimental work already performed on GLARE. The influence of moisture on GLARE is reported to be relatively minor when compared to conventional composites. However, some GLARE properties still showed significant degradation after the hygrothermal exposure [14]. Botelho et al. [15] studied the elastic properties of hygrothermally conditioned GLARE laminates. It was reported that while the tensile and compressive values of glass fiber/epoxy composites reduced after hygrothermal conditioning, no changes in mechanical properties (tensile and compression strength) were observed for GLARE laminates, regardless the hygrothermal conditioning conducted. In FMLs, only the outer aluminum layers are exposed as a result of its unique lay-up configuration. The prepreg layers are only exposed through the edges of the laminate and holes, if any [16]. Therefore, the moisture absorption in GLARE laminates is slower when compared with polymer composites due to the barrier of the outer aluminum layers.

Moisture and chemicals, however, can penetrate the composite layers through the edges after long-term exposure. Thus, moisture and hygrothermal exposure can still be a threat to GLARE laminates. In addition, the hybrid nature of GLARE laminates may make the environmental degradation process much more complicated than the case for PMCs since epoxy resins generally absorb moisture when exposed to humid environments and metals are prone to surface corrosion. For instance, how moisture and harsh environmental conditions affect the metal/

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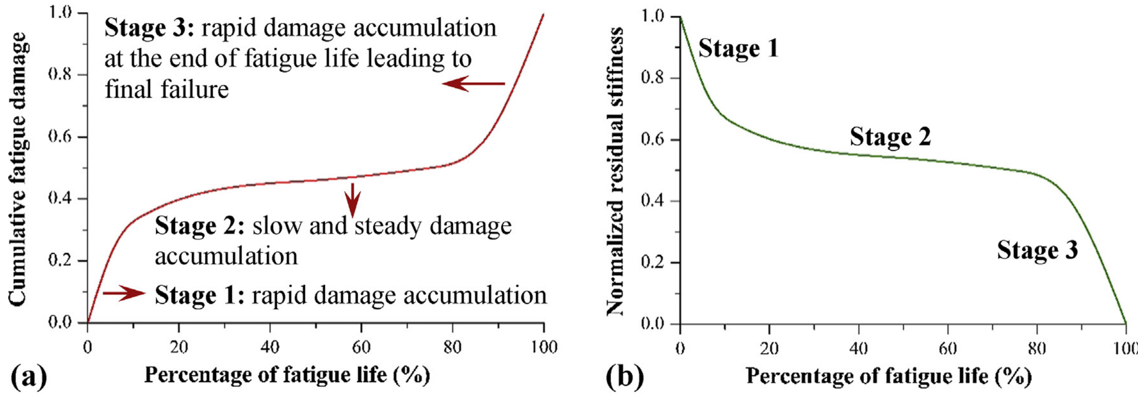

Fig. 1. Typical (a) fatigue damage accumulation curve and (b) stiffness degradation curve for a wide range of laminated composites under tension–tension cyclic loading. The normalized residual stiffness is defined as $\frac{\text{Residual stiffness}}{\text{Original stiffness}}$.

prepreg layer interface is unknown. Potential degradation of both the microstructures and mechanical properties of GLARE laminates due to hygrothermal attack is still to be identified. Therefore, further investigation is crucial for the understanding of the durability of GLARE laminates under combined hygrothermal environments.

The load experienced by composite structures in service frequently involves cyclic loading. The fatigue life of structural materials is always among the most important concerns during the material selection and structure design stage. What essentially occurs under cyclic loading of certain magnitude in a material includes the initiation and propagation of fatigue failure (e.g., micro-cracks in metals, matrix cracking in laminated composites) and the resulted mechanical property degradation (e.g., stiffness, strength). When the residual strength is lower than the applied stress, final failure of the material occurs. It is now commonly accepted that for many fiber reinforced composite materials the fatigue damage accumulation and the resulted decrease in residual stiffness as well as strength can be divided into three stages as illustrated in Fig. 1 [17–20]. Rapid damage accumulation usually occurs at the early stage of fatigue life (i.e., Stage 1 in Fig. 1a). Possible damage mechanisms at this stage include initiation of micro-cracks in multiple locations in the matrix (e.g., near pre-existed defects), debonding at the weak interfaces between fibers and matrix, fracture of low-strength fibers, etc. [18]. Correspondingly, a rapid reduction in stiffness is expected (i.e., Stage 1 in Fig. 1b) [20]. Stage 2 represents the majority of the total fatigue life. At this stage, damage accumulation exhibits a slow and steady manner. During the last stage (Stage 3), the damage again grows rapidly in the laminate until the final fracture. The dominant failure modes generally include delamination and fiber breakage. In the meantime, the residual stiffness also decreases abruptly with respect to fatigue cycles as illustrated in Fig. 1b.

However, the fatigue phenomenon of GLARE is much more complicated owing to its lay-up design. The fatigue damage accumulation takes place in both the aluminum layers and the fiber/epoxy composite layers, making the interpretation of the possible stiffness reduction more difficult. While preliminary experimental studies on the fatigue behavior of GLARE laminates can be found in the literature [21,22], results concerning the effects of hygrothermal conditioning on the fatigue life of GLARE laminates are limited. During the fatigue testing on GLARE laminates, fatigue crack initiation generally occurs in the aluminum layer first. Fatigue life to the detection of the first crack at the aluminum layers is defined as the fatigue initiation life. Homan [23] investigated the effect of exposure to a combination of moisture and elevated temperature (85% humidity, 70 °C, 3000 h) on the fatigue initiation life of GLARE laminates. It turned out that the exposure did not affect the initiation behavior of fiber metal laminates. However, whether hygrothermal exposure would affect the fatigue life of GLARE laminates was not considered in their investigation. Research work by Da Silva et al. [24], however, did take into account this phenomenon. Aluminum alloy 2024-T3 sheets and prepreg materials based on glass fiber in plain weave fabric form and epoxy resin were used to fabricate the GLARE laminates. As fabricated GLARE samples were placed into an environmental conditioning chamber in which a hygrothermal environment with a temperature of 80 °C and a relative humidity of 90% was maintained. Prior to tension–tension fatigue testing, 0.3% increase in weight because of moisture uptake in GLARE laminates was achieved. The phenomenon observed was that the fatigue life of

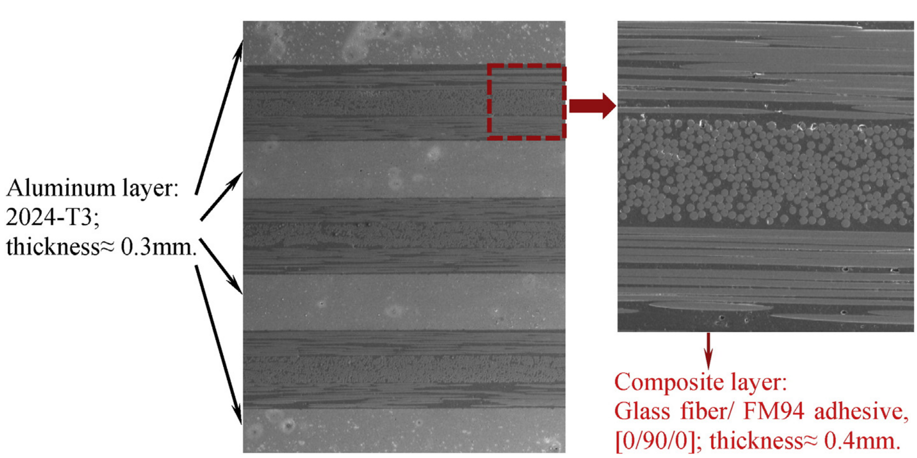

Fig. 2. Cross-section of the GLARE 4A laminate.