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Impact damage reduction by structured surface geometry

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ABSTRACT

Repeated impacts can cause damage to not only a surface but also inside the material. Mechanisms include stress-wave propagation into the material, reflection of the waves at the back surface, and subsequent repeated reflections in the vicinity of the impact and the back surface. Impact damage performance was observed for polyurethane-coated fibre composites with structured geometries at the back surfaces. Repeated impacts by rubber balls on the coated side caused damage and delamination of the coating. The laminates with structured back surfaces showed longer durability than those with a flat back surface. The in-situ acoustic measurement indicates that the acoustic power within the pulse duration was 25–40% lower using the structured back surfaces. The observed effect can be attributed to scattered reflection at the back surface to reduce the high intensity duration of the acoustic waves.

1. Introduction

Composite materials are used in many engineering and structural applications [1], including automobiles, aircrafts, ballistic applications, and wind turbine blades [2]. They are often severely exposed to repeated impact loadings, affecting life of the structural materials. An example is the leading edge of a wind turbine blade exposed to raindrops, hailstones, particles, and wild life [3]. The impact load thereof may be high especially near the tip of large wind turbine blades rotating at speeds approaching to 100 m/s [3]. Therefore, even impacts of small substances can result in serious damage. It is believed that these loadings give rise to erosive damage to the wind turbine blades. Significant efforts have been made to study the rain erosion phenomena [4–6], develop damage protective coatings and assess the lives of the leading edges [3,7,8]. It is reported that polyurethane based coatings show good erosion resistant properties [8]. However, due to the future demands for still larger blades at higher tip speeds, the performances of the existing damage protection techniques will be unsatisfactory, and further efforts have to be made.

Although impact stress waves propagating through the protective coating are presented [3–7], structural design assessment to reduce leading edge erosion is not considered. Wind turbine blades are typically constituted of fibre reinforced polymer composites, called laminates. A study of repeated impacts to laminates has shown that the fracture starts inside the laminate [9], suggesting that tensile stress waves reflected at the back surface opposing the impact surface play an important role in the early internal damage. Such internal damage is difficult to detect on a component in use, and a resulting sudden failure can be serious. Hence, an improved design of structural components with high impact resistance would be advantageous.

Damping of impact stress waves can reduce the damage [10,11]. However, adding damping properties to the laminate may restrict the choice of optimal material as a structural component.

The direction of acoustic wave propagation can be controlled by carefully defining the geometry of a material surface or interface at which the acoustic wave can reflect. It is reported that traffic noises can be reduced by re-orienting the direction of the acoustic waves in air using reflection panels [12]. However, similar attempts for dissipating acoustic waves in solid materials are significantly limiting. Only one publication relevant to this issue is related to a plural layer composite armor system, in which ceramic elements with textured back surface are embedded [13]. A projectile striking at the composite armor system can penetrate into the composite and is blocked by the embedded ceramic, generating shock waves. It is indicated that in the prior art without the textured back surface of the ceramics, the complex interaction of the incident shock waves and the reflected shock waves can result in internal failure of the ceramic element [13]. It is argued that the proposed textured ceramics enables reflected shock waves at the backside of the ceramics to temporally and spatially diverge so that the interaction between the incident and reflective shock waves can be

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significantly reduced [13]. However, the technique cannot be readily applied to the structural design of the wind turbine blades. First, impact particles (rain drops) typically do not penetrate into the wind turbine blades. Second, difference in acoustic impedances between the embedded ceramic and surrounding material is low, and subsequently, acoustic reflection at the interface between the ceramic and the surrounding material is insignificant. Furthermore, there is a risk that introducing such a ceramic may induce inferior mechanical properties.

In the present work, polyurethane coated glass fibre reinforced polymer (GFRP) laminates were manufactured with special geometries of the back surfaces so as to change the stress wave reflections thereof, aiming at reducing impact damage. Repeated impacts were applied on the coated side of the laminate. Video monitoring and acoustic measurement around the impact location on the coated surface were carried out in-situ.

2. Experimental methods

A flat GFRP laminate was manufactured by vacuum infusion of a symmetric glass fibre layup (Biax/4xUD/Biax/4xUD/Biax/Biax/4xUD/Biax/4xUD/Biax) using Ahlstrom UD1150+Biax100 and Biax600 glass fibre fabric combined with a Huntsmann epoxy resin Araldite® LY1564/Aradur® 3487. The laminate was cured at 40°C for 19 h and post-cured at 80°C for 5 h, and cut into 15 mm thick laminates with a shape of 150 mm × 150 mm. Three different designs of the back surfaces were employed. The first laminate, referred to as a flat laminate, has a flat back surface and the thickness was reduced to approximately 13 mm so that the mass of the laminate would be close to those of two other structured laminates. The second laminate, referred to as a striped laminate, has a linearly striped pattern. The cross-section perpendicular to the linear stripe shows a regular zigzag structure with approximately 45° slopes relative to the back surface. The adjacent peaks and the adjacent valleys have a pitch of approximately 1.0 cm. The pattern was milled from the original 15 mm thick laminate. The third laminate, referred to as a pyramidal laminate, was a further modification of the second laminate by rotating it by 90° and performing the same milling for manufacturing the second laminate. As a result, each convex has a pyramidal shape. The images of these laminates are shown in Fig. 1. The measured mass of the flat, striped and pyramidal laminates, are 556.3 g, 566.9 g, and 527.9 g, respectively. Each of the laminates was further cut into 9 pieces, sized 47 mm × 47 mm to fit the device for impact testing. Side photographic views of the cut laminates are added as insets.

The foreside of each laminate opposite to the back surface was cleaned with acetone and ethanol. Transparent polyurethane coating was applied by spraying (Polyurethane KLAR LAK, plasti-kote). The thickness and hardness of the dried and cured coating were estimated to be approximately 1 μm and at least 0.2 GPa, respectively. A home-made impact tester was used to apply repeated impacts on the coating side of the laminates.

Fig. 2 shows a schematic diagram of the setup. A 6-mm diameter rubber ball was fed to an end of a barrel one by one by a ball feeder. Compressed air was released with a predetermined interval to accelerate the ball through the barrel. The ball hit substantially at a same location on the coating at a speed of 165 m/s with a frequency of 1 Hz. During testing the impact area and its vicinity were monitored using a digital microscope camera. More detailed description can be found in [14].

An acoustic emission (AE) sensor (miniature Nano30 sensor, Mistras Group inc.) was mounted within 20 mm from the impact location on the coated surface to detect elastic stress waves caused by the impacts. The detected signals were amplified and the resulting waveform was delivered to the AE system which processes the information. An amplitude, an average frequency of the reflected

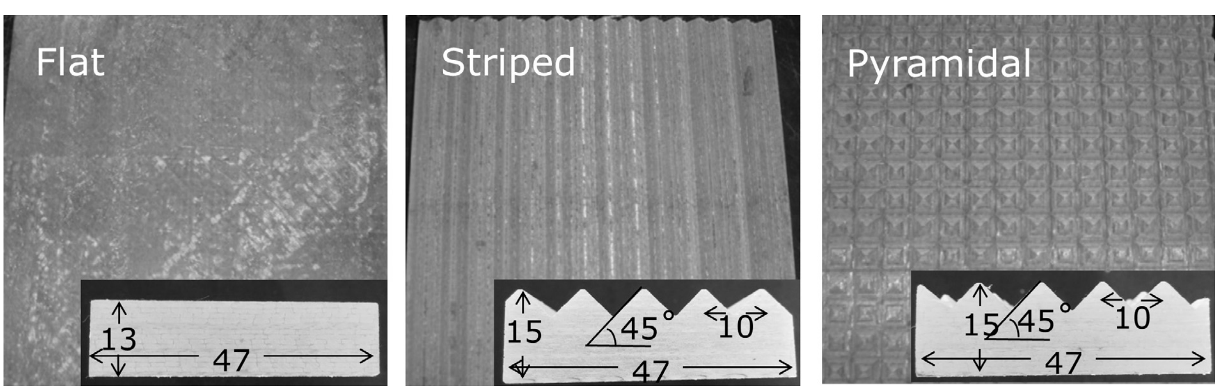

Fig. 1. Images of the back surfaces of the flat, striped and pyramidal laminates (150 mm × 150 mm). Side views of the cut specimens as insets (unit of length in mm).

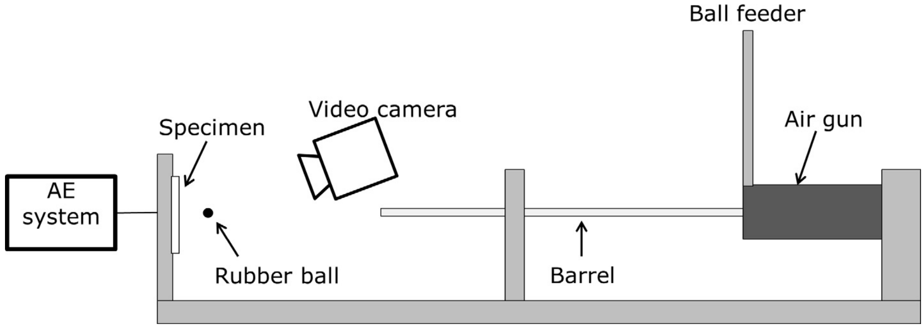

Fig. 2. A schematic diagram of the impact tester.