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Damage and wave propagation characteristics in thin GFRP panels subjected to impact by steel balls at relatively low-velocities

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ABSTRACT

An experimental investigation was conducted to determine the damage and wave propagation characteristics in Glass Fibre Reinforced Polymer (GFRP) panels subjected to impact by steel balls at relatively low-velocities up to 91 ms^{-1}. While maintaining the same impact energy level, the influence of ball mass on panel response was studied. The effects of composite lay-up sequence and successive impacts were also investigated. The wave propagation characteristics, including wave types, wave velocities, wave attenuations, and strain rates, were extracted from dynamic strain records measured at various locations on the panels. The results showed that, for the same level of impact energy, the small ball mass produced larger deformation and delamination than the large ball mass. Additionally, the resistance to impact was influenced by the composite lay-up sequence of similar fibre weight fraction. Test panels subjected to successive impacts showed an increase in cumulative delamination areas, whereas the tests indicated that successive impacts had a little effect on the perforation limit of the test panels. The impact velocity showed a pronounced influence on the measured peak strains and strain rates. The flexural wave was the predominant wave system, propagating at different velocities in different directions. In proximity to the impact site, both flexural wave and indentation predominated over the transient response. In addition to the flexural wave, impact induced low amplitude tensile longitudinal waves of high velocity.

1. Introduction

Over the last few decades, the use of Fibre Reinforced Polymers (FRP) in many engineering applications has increased. FRP offer numerous advantages, such as high strength; high stiffness; low weight; and excellent chemical and environmental resistance. However, it is well-known that these materials are susceptible to accidental impact from foreign objects because of their brittle nature of the reinforcing fibres, the lack of through thickness reinforcement, and the relatively low inter-laminar shear strengths. The resulting impact damages can significantly reduce the strength and stability of FRP structures [1].

The impacts are often classified as low-velocity/large-mass, e.g. a dropped tool impact, and high-velocity/small-mass, e.g. runway debris impact. However, other impact scenarios may also occur, which involve large masses and relatively low (medium)/high velocities, e.g. the case of wind-borne debris impact, particularly missile impacts generated by extreme winds, such as tornados and hurricanes [19]. Wen et al. [35], Wen [36], and Wu et al. [37] carried out an extensive experimental and analytical investigations into the penetration and perforation of FRP laminates and sandwich panels. It was observed that ballistic impact on FRP can be classified into two categories: global response with local rupture and wave-dominated localized failure. Olsson [24,25] proposed a classification based on plate response as boundary-controlled and wave-controlled impact. For boundary-controlled impact, the plate motion dominates the impact response and the entire plate is deformed during the impact. On the other hand, in wave-controlled impact the plate deformation is localized to the region around the impact point. A mass-ratio based criterion governing boundary-controlled and wave-controlled impacts has been derived in detail by Olsson [25]. It was shown that wave-controlled impact occurs when the mass of the impactor is less than one-fourth of the mass of plate area affected by the impact. Unlike the case of boundary-wave impacts where the deformation energy can be distributed throughout the structure, in the impacted structures under wave-control condition the volume of energy storage is limited by the speed of the wave propagation. This would result in damages related to wave propagation characteristic in the plate, i.e., wave velocity, attenuation, and

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reflection and amplitude of the induced stress waves. With much of the work having been widely reported in the literature of investigating the damage mechanics of composite materials under impact using different experiments, including drop-weight, gas-gun, pendulum, and ballistic impact [2,8,13,27,31], the range of impact velocity in most of these works was either low or very high. Thus, there are few experimental tests that cover a range of medium impact velocities, which are important in order to fully understand the response of FRP materials under impact scenarios such as wind-borne debris impacts. In addition, many of these reported tests have been conducted on small sample coupons, most of which are unrepresentative exhibiting different behavior than large structures made of identical materials [17].

One of the most common failure modes of composite structures under impact is delamination, which is a separation that forms between adjacent plies. Depending on the stacking sequence, the plies on either side of delamination can have different fibre orientations. Therefore, a delamination can be viewed as an interface separation between two anisotropic materials. When the impactor strikes the composite panel, the material under the sticker is compressed and laterally translate in a time duration significantly less than that is needed for the overall response of the panel. The highly localized deformation gradient result in large transverse interlaminar shear and normal stresses. In addition, the impact produced a through-thickness compressive stress wave, which is reflected from the rear surface as a tension wave. Both internal stress wave and local out-of-plane deformations may initiate delamination at interfaces. The interlaminar shear strength, which is the measure of the in situ shear strength of the matrix layer that exists between plies, is the controlling factor for the delamination initiation due to impact-induced interlaminar shear stress. The amount and type of the delamination in the laminate depend upon the impact velocity/energy, the panel geometric factors (aspect ratio and thickness), and material factors (interlamianr shear strength and stacking sequence) [12].

The total problem of impact involves the so-called indentation, which is the local deformation at the impact site and simultaneous wave propagation during and after impact. Theoretical analyses of impact and wave propagation in impacted composite structures have been discussed by many investigators [22,32,7,21,34]. It was shown that motion under dynamic impact is composed of five waves, two waves related to in-plane motion and three related to flexural plate deformations [21]. Experimental investigations of wave characterization of transverse wave-controlled impact on composite panels are relatively few. Daniel and Liber [9] conducted an experimental investigations to understand wave propagation characteristics on graphite/epoxy laminates impacted with silicone rubber projectiles. Flexural waves propagating at different velocities in different directions were observed in these tests. Takeda [33] tested fibreglass/epoxy unidirectional laminates under the effect of blunt-ended impactors. Both in-plane and flexural waves were observed in these tests. Fällström et al. [11] used Hologram Interferometry to detect bending waves on small glass fibre plate of 300×200 mm impacted by steel sphere (3 mm diameter). More experiments are still necessary in order to investigate the indentation/wave propagation interactions as well as the effect of impactor mass, impact velocity, and composite lay-up sequences on wave propagation characteristics.

In addition, impact induces rate-dependent stresses and deformations that differ from quasi-static problems. It is known that material exhibits higher strengths and different mechanical properties under high strain rates. Several researchers have investigated the effect of strain rate on the mechanical properties of composite materials, e.g. tensile strength, maximum strain, and toughness, caused by dynamic uniaxial tests [6, 23, 26, 29]. To account for strain rate in analysis/design of structures under transverse blast and impact loadings, Dynamic Increase Factors (DIFs), defined as the ratio of the dynamic properties to their static values, based on average strain rates, are often used [30]; however, in reality the strain rate in transversely impacted structures varies with time and locations over the structures. Thus, experimental studies on these variations of strain rates and their corresponding DIFs need to be more investigated.

The understanding of the damage and wave propagation characteristics in composite structures is essential for developing improved materials. In this paper, Glass Fibre Reinforced Polymers (GFRP) panels were impacted by three steel balls of relatively large masses (255, 535 and 1115 g) at impact velocities from 19 to 91 ms^{-1} simulating the range of impact velocities of wind-borne debris. The effects of composite lay-up sequence and successive impacts on panel responses were investigated. In order to study the transient response and capture the wave propagation, data accumulation and control system of testing machine precisely gathered the dynamic strains at different points on the composite panels. A comparison based on the peak strain response and damage characteristics of the panels for different test parameters was presented. Wave propagation characteristics including wave types, wave velocities, and attenuations were obtained and discussed. The variation of strain rates with time and location was also studied.

2. Material and experimental

Two composite lay-up sequences were used, $[0]_{9f}$ and $[45/0]_{4f}$ (in full notation as $[45/0/45/0/45/0/45/0]_f$) designated herein by GFRP-N and GFRP-B, respectively. The GFRP-N and GFRP-B had a total fibre areal density of 5292 and 5432 gm^{-2} with fibre weight fraction of 67%, and 68%, respectively. The mechanical properties of the composite panels, including the elastic moduli, shear moduli, Poisson's ratios, and tensile and shear strengths, were measured, according to ASTM D30039 [4] and ASTM D3518 [5], as listed in Table 1. GFRP-N exhibited higher elastic modulus and strength in *y*-direction (warp direction) than in *x*-direction (weft direction). This is because higher tension is typically placed on the warp fiber keeping it straighter during the weaving process [10].

High-velocity impact tests were conducted using the air cannon device shown in Fig. 1(a) and (b). The test device consisted of air compressor, chamber, and cannon barrel. Using the air compressor, air was pressurized to a given pressure in the chamber, which supplied the pressurized air to the cannon barrel where the loaded impactors were ejected at high speed. Three steel balls of masses of

Table 1
Mechanical properties of GFRP panels.

	GFRP-N	GFRP-B
Elastic modulus		
E_x (GPa)	21.5	20.0
E_y (GPa)	25	18.5
E_{45} (GPa)	12.6	19.7
Shear modulus		
$G_{xy} = G_{yx}$ (GPa)	3.8	7.4
$G_{zx} = G_{zy}$ (GPa)	3.0	4.1
Tensile strength		
σ_x (GPa)	290	230
σ_y (GPa)	350	265
σ_{45} (GPa)	110	166
Shear Strength		
τ_{xy} (MPa)	55	82
Poisson ratio		
ν_{xy}	0.19	0.33
ν_{yx}	0.16	0.33