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Effect of block copolymer nano-reinforcements on the low velocity impact response of sandwich structures

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ABSTRACT

Sandwich composites with fibre reinforced plastic (FRP) facesheets have emerged as a major class of lightweight structural materials in a wide range of engineering fields including aerospace, automotive and marine structures. This is due to attractive mechanical properties such as high specific stiffness and high strength. However, sandwich structures are susceptible to damage caused by impact. The objective of this paper is to evaluate the dynamic response of sandwich composites based on Kevlar fibre reinforced epoxy and Rohacell® foam. The improvement in impact performance of these sandwich structures that can be achieved by the addition of nanoparticles in the resin matrix is investigated. Nanostrength®, an acrylate triblock copolymer that self-assembles in the nanometer scale is added to the epoxy matrix. The effect of the nano-reinforcements on flat sandwich plates under low velocity impact is investigated at different scales. An instrumented drop tower setup is used for the low velocity impact tests of the sandwich plates with neat or nano-reinforced epoxy matrix, at different energies. The macroscopic response of the sandwich structure and the microscopic phenomena involved in dissipating the impact energy are identified and compared for sandwich plates with and without nanoparticles.

1. Introduction

The sandwich structure is based on a simple construction of two thin high strength facesheets bonded to either side of a thick low density core such as foams and honeycombs. This provides a lightweight structure with high stiffness. The skins are designed to resist tensile and compressive stresses and are usually made of aluminium or fibre reinforced polymers. The core is designed to resist compression and shear stresses and is usually made of wood, polymer foams, or expanded metal or polymer honeycombs. Sandwich composites with fibre reinforced plastic (FRP) facesheets and foam cores have emerged as a major class of lightweight structural materials in a wide range of engineering fields including aerospace, automotive and marine structures. One of the main drawbacks of these high performance structures is their relatively poor resistance to impact loading [1]. Impact damage in sandwich structures can be caused by tool drops, runway debris, bird strikes, hailstorms or ballistic loading. The damage caused by low-velocity impact may result in drastic reduction of stiffness and residual strength of the sandwich composite [2]. Ballistic impacts cause localized damage which is clearly visible on inspection while low-velocity impacts involve long contact time between impactor and target which result in global structural deformation with internal damage at points far from the contact region [1]. Extensive delamination and core damage were observed in specimens with no visible surface damage [3], indicating the importance of studying the low velocity impact response of sandwich structures.

Richardson and Wisheart [4] identified low-velocity impact as impacts where the contact duration is long enough for the entire structure to respond to the impact load. The upper limit of what constitutes a low velocity impact has been defined by different researchers as either under 10 m/s or impact speeds up to 100 m/s [4]. The low-velocity impact damage of sandwich plates is typically tested using a drop tower test facility [5]. Many researchers have conducted low velocity impact tests on sandwich panels composed of different facesheets and core materials [6–10]. There has been considerable effort to improve the impact resistance of sandwich structures [11–14]. Dvorak and Suvorov [11] investigated the effect of placing a ductile interlayer between the facesheet and the foam core. The brittle nature of the epoxy matrix and its lack of resistance to crack growth is one of the limiting factors on the impact performance of the FRP sandwich structures [15]. Epoxy resins are one of the most commonly used resins because of their properties, such as thermal stability, mechanical response and low density [16]. Epoxy resins are the matrix material for glass-, Kevlar- and other fibre reinforced composites in

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many applications. Shih et al. [17] reported that the impact failure mechanism of sandwich panels containing less tough facesheets was found to change from facesheet-dominated to foam-core-dominated behaviour. Attempts to reduce matrix damage and improve the interlaminar fracture toughness of thermoset resins has involved incorporating plasticizing modifiers, or adding rubber or thermoplastic particles to the resin. Many researchers have investigated various methods to toughen the matrix with additives such as rubber [15,18]. However, the drawback of this approach is that it sacrifices the stiffness of epoxy significantly and decreases the glass transition temperature. One of the proposed solutions is the modification of the thermoset resins with nano-sized organic and inorganic particles. Carbon nanotubes (CNT), carbon nanofibres and nanoclays were identified as potential nano-scale materials for the reinforcement of epoxy [19,20,12–14]. Hosur et al. [12] studied the improvement in low velocity impact response of sandwich plates due to the addition of nanoclays both in the facesheets as well as the polyurethane foam core. They identified different failure mechanisms in the sandwich panels with nanoclay and concluded that it was possible to sustain higher loads, reduce the damage size during impact like events and lower the reduction in mechanical properties by adopting nanophased sandwich construction. Avila et al. [13] studied the effect of adding nanoclay to fibre glass/epoxy system and its use as facesheet in a sandwich structure. The authors varied the percentage of nanoclay present in the epoxy resin and studied the low velocity impact response of a GFRP/PS Foam sandwich plate. Their preliminary results however suggest that the improvement in the stiffness and impact resistance of sandwich structures due to the nanoclay is minimal.

While most of the research has been focussed on carbon nanotubes (CNT) or nanoclay and silicate nanocomposites, a new method to synthesize block copolymers which self-assemble in the nanoscale was reported by Barsotti [21]. This would appreciably reduce the problems associated with dispersion of the nanoparticles. Nanostructuration is induced by the strong repulsions between the side and middle block. The thermodynamic miscibility of the block copolymer leads to a homogeneous and reproducible dispersion on a nanometer scale. The author claimed that using triblock polymers consisting of polymethylmethacrylate–polybutylacrylate– polymethylmethacrylate (MAM) and styrene-b-butadiene-b-polymethylmethacrylate (SBM) families enhanced the fracture toughness and impact performance with minimal sacrifice of thermal properties [21]. A systematic study on the effect of these nano reinforcements on the mechanical performance of FRPs made with these nano-modified resins, especially to impact loading, is lacking. Denneulin et al. [16,22] identified the dearth of literature on composites with nano-elastomers of block copolymer and studied the influence of Nanostrength embedded in the matrix, on the low velocity impact response of Kevlar fibre reinforced composite structures. Denneulin [22] reported that while the carbon nanotubes did not have significant effect, the addition of the nanoparticles of block copolymer to the resin improved the impact resistance of the Kevlar FRP and prevented catastrophic failure due to fibre breakage and perforation seen in the sample without the nanoparticles.

The paper aims to compare the low velocity impact response of sandwich structures with and without Nanostrength in the epoxy matrix. The sandwich structures chosen for the study have facesheets made of Kevlar fibre reinforced epoxy laminates and a core made of closed cell PMI foam. A series of low velocity impact tests are performed using an instrumented drop tower. The force–displacement curves of the sandwich panels, the energy absorbed during impact and post-mortem observations are employed to compare the impact resistance of sandwich structures.

2. Manufacturing of samples

2.1. Material

The sandwich panels with the Kevlar fibre reinforced epoxy skins were manufactured using a wet layup process. Kevlar129 (Saatilar Style 802; Taffeta 190 g/m^2; thickness: 260 μm) was chosen for this study because of its very high tensile toughness (σ_r = 3.4 GPa, ϵ_r = 3.5%). Sandwich composites with Kevlar fabric facesheets were shown to possess the best impact resistance and the least extent of damage compared to glass, carbon and carbon/Kevlar hybrid facesheets [10]. Three layers of plain woven fabric with the ply orientation [0/90] were used. Closed cell Rohacell® PolyMethacryImide (PMI) foam with a density of 51 g/cm^3 was chosen as the core material for the sandwich panels.

The DGEBA thermoset epoxy resin Epolam and hardener supplied by Axson Technologies was used. The hardener was used in the ratio 0.345 (w/w) (34.5 g of hardener for 100 g of resin) as recommended by supplier. For the resin with nano-reinforcements, 10 g of triblocks copolymer M52N Nanostrength® supplied by Arkema was added to 100 g of Epolam resin. Denneulin et al. have shown from tests on Kevlar composites with three different formulations of block copolymer (M22, M42, and M52N) that 10% M52N Nanostrength® in the epoxy resin system provided the best performance with regard to perforation resistance [16]. Nanostrength® which is in powder form is added to the resin by mixing, using a mechanical stirrer at 290 rpm at 110 °C for a duration of 2 h. Transmission Electronic Microscopy (TEM) was used by Denneulin et al. [16] to check the self-assembling process of the block copolymer nanoparticles.

2.2. Method of fabrication

The sandwich samples were manufactured using a wet lay-up process. The different steps involved in the fabrication of the sandwich plate are shown in the Fig. 1. The manufacturing process was similar to the method explained in [16]. In the first step, each layer of Kevlar fabric cut to desired dimensions was impregnated with the resin-hardener mix manually (with a brush). The three impregnated layers of fabrics were placed between two sheets of baking paper and compressed in the press for 5 min at room temperature and a pressure of 1.5 bars. This step ensures that excess resin is ejected from the facesheet. The step was repeated for both the top and bottom facesheet of the sandwich. The two facesheet layers of $[0/90]_3$ Kevlar fibre were then bonded on each side of the core material and the sandwich panel was co-cured in a hot press at 90° for 90 min. No additional adhesive was introduced between the face sheets and the core. Co-curing the facesheets ensured good adhesion with the core. Finally, the sandwich composites were post-cured in an oven at 80 °C for 2 h. Square plates of length 200 mm were fabricated using this method. The nominal thickness of the cured sandwich plates was 20 mm.

3. Experimental setup

Low velocity impact testing was accomplished using a drop tower. The drop tower setup consists of an instrumented impactor that is secured to a carriage that falls along guideposts and collides with the plate. An electromagnet holds the carriage lifted to a predetermined height and the impact event is initiated by switching off the electromagnet and letting the carriage fall freely under the action of gravity. The impactor head transfers the impact energy to the test specimen. The drop height is varied to give a range of impact energies while the mass of the impactor is kept constant. The maximum impact energy that can be obtained is limited by the