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Impact properties of novel corrosion resistant hybrid structures

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ABSTRACT

The objectives of this study were to investigate the effect of impact energy and rubber thickness on the impact properties of layered steel/rubber/composite hybrid structures. Both stainless steel and mild steel based hybrid structures were investigated. The degree of damage, the failure modes, and the absorbed energy were studied.

It was found that rubber between steel and composite layers absorbs the impact energy and decreases the interfacial and internal damage in the studied hybrid structure and in its components. The amount of the absorbed energy did not change substantially when comparing structures with and without rubber. However, the area of permanent damage showed a decrease of nearly 50% with the use of rubber when comparing a structure without rubber to a structure with 1.5 mm rubber. In addition, it was observed that the area of the damage is linearly dependent on the impact energy. The main damage mechanisms found were delamination at the steel/rubber and composite/rubber interfaces and fibre/matrix debonding in the composite layer.

1. Introduction

The current demand for energy savings and competitive industrial components requires new material solutions. Hybrid structures enable the combination of the best material properties of different material groups in one structure and thus offer interesting possibilities for new applications. In addition to high specific strength and stiffness, hybrids have a potential for other advantages, such as more beneficial manufacturing methods [1] or improved damping properties [2].

In our previous studies we have investigated the potential of steel/rubber/composite hybrid structures [3–6]. In these studies, the aim was to study the possibilities to attach glass fibre reinforced epoxy composite to stainless steel with the aid of a thin rubber layer. The research questions of our previous papers concentrated on the adhesion properties in laboratory conditions and in harsh environments as well as on the vibration damping properties. Since the adhesion of these structures was observed to be at a good level [3,4] and the rubber improves the energy absorption properties of the structure [6], we anticipated that our steel/rubber/composite structure has potential to be used also in real-life applications. However, the earlier studies did not show how the structure acts under transverse loading.

Composite structures are prone to damage induced by impacts in out-of-plane directions [7,8]. The typical impact failure mechanisms of composite structures are matrix cracking and fibre fracture, fibre/matrix debonding and delamination, surface microbuckling and fibre shear out [9]. Similar to composites, laminated hybrid structures may exhibit both intra-layer and inter-layer damage under out-of-plane impacts [10]. One of the most established and studied polymer/metal hybrid structures are the Fibre Metal Laminates (FMLs). FMLs are shown to be less susceptible to impact loading than composites [11] leading to smaller damages [12]. Beyond FMLs, impact resistance of polymer/metal hybrid structures is not very widely studied. Some of the investigated structures are those combining brittle thermoplastics to aluminium or steel e.g., [10,13,14]. Typical impact damage mechanisms found for polymer/metal hybrids are denting due to the plastic deformation of metal layers, epoxy and fibre cracking in the composite layers, and delamination [10,14–17]. All in all, the knowledge of the damage mechanisms of hybrid structures under impact loading is essential for the prediction and simulation of the hybrid's behaviour in structural applications.

The impact test set-ups and test parameters used in literature vary widely. Typically, the impact tests are categorized according to the projectile velocity in low velocity (<11 m/s), high velocity (>11 m/s), and ballistic (>500 m/s) impact tests [15]. Within composite structures, the low velocity damages emerge typically during maintenance and they may be visible only on the back side of the component, whereas the high velocity damages are more likely to emerge during the actual use of the application and they are typically visible on the impacted side [15,18]. This paper concentrates on the high velocity impact loading.

In addition to standardized test geometries (e.g., ASTM D7136 or ASTM D6264), several more specific, in-house built test

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set-ups can be found in the literature. Minak and Ghelli [19] have studied the influence of specimen size and boundary conditions on the low velocity impact response of carbon fibre reinforced composites. Their rather intuitive result was that the impact behaviour of composites is dependent on both the specimen diameter and the boundary conditions through their effect on the specimen stiffness [19]. However, they also found that absorbed energy is independent on the boundary conditions and in-plane dimensions [19]. This result encourages using the absorbed energy as a test variable since it will not have any complex scaling effect.

In this study, the impact resistance of three different steel/rubber/composite hybrid structures was investigated. Two different Ethylene Propylene Diene (EPDM) based rubber grades for stainless steel based hybrids and one EPDM grade for mild steel based hybrids were used. The samples were exposed to high velocity impact loading. The failure modes and the energy absorption of the samples were compared to the impact energy and to the rubber thickness of the samples. The failure modes were studied from the cross-sectional samples with scanning electron microscopy, while the energy absorption of the samples was evaluated with the aid of a high speed video system.

2. Experimental

2.1. Materials

In this study, the impact properties of steel/rubber/composite hybrid structures were investigated. Three different specimen types were used: two based on stainless steel and one based on mild steel. The steel grades used were stainless steel AISI 304 (provided by Outokumpu Stainless Oy, Finland) and passivation treated cold rolled mild steel EN 10130 DC01 (provided by Rautaruukki Oyj, Finland). The thickness of the steel sheets was 0.5 mm. The surface finish of the stainless steel was industrial 2D (cold rolled, heat treated, pickled), while the mild steel surface was cold rolled and passivation treated. Prior to rubber bonding, the steel sheets were rinsed with acetone and ethanol. Other pre-treatments, such as grit blasting, were not used.

The glass fibre reinforced epoxy composite sheets were manufactured in-house by vacuum infusion from stitched 0/90 E-glass fibre fabrics (682 g/m^2, from Ahlstrom Oyj, Finland) and Sicomin SR 1660/SD 7820 epoxy (from Sicomin Composites, UK). The nominal thickness of the composite sheets was 3.5 mm consisting of 6 layers of fabrics. The fibre content of the composite was about 46 vol.%. The heat resistant epoxy was chosen to provide the good resistance of the GFRP sheet to the vulcanizing temperature used for the rubbers. From the adhered composite surface, a HexForce® T470 (Hexcel Co., USA) peel ply was removed prior to rubber attachment. The peel ply creates a rough composite surface.

Three different Ethylene Propylene Diene (EPDM) based rubber grades, grade A manufactured by Teknikum Oy, Finland and grades B and C manufactured by Kraiburg GmbH, Germany, were used to adhere the steel and the composite sheets together. The hybrid structures were manufactured by vulcanizing the rubber between the metal and the composite layers under heat and pressure (at 1.2 MPa and 130–160 °C depending on the rubber grade). Three nominal rubber thicknesses, 0.5 mm, 1.0 mm and 1.5 mm, were used. Thin metal plates between the steel and the composite sheets ensured uniform rubber thicknesses during the vulcanization. In addition, as a reference a commercial epoxy adhesive 3M™ Scotch-Weld™ Epoxy Adhesive DP190 Gray was used to produce steel/composite samples with no rubber between (i.e., zero rubber thickness). This adhesive exhibits good peel, shear and environmental aging properties. The studied samples and the test parameters are summarized in Table 1. Three samples were tested with each test parameter combination.

2.2. Methods

The impact test equipment was an in-house developed High Velocity Particle Impactor (HVPI). In this device, compressed air is used to fire a 9 mm diameter projectile towards the sample. The velocity of the projectile is determined by a computer controlled pressure reservoir and the projectile velocity is recorded with a commercial ballistic chronograph placed in front of the target assembly. The test setup allows a wide range of impact angles to be studied, approximately from 10° to 90°. The impact event is recorded with a high speed camera (NAC Memrecam fx K5, NAC Image Technology, USA). The high speed video images were recorded at a constant frame rate of 40,000 fps. The HVPI equipment is fully computer controlled.

In this study, through hardened steel balls (2.98 g in weight) were used as projectiles. The specimen angle was set to 45 ± 1° as a compromise between the two extremes. The pressure was varied between 1 and 14 bar, leading to the velocities for the steel balls between 44 and 142 m/s and the corresponding energies of

Table 1
Studied sample components with nominal thicknesses and applied impact energies.

To study the effect of rubber thickness			
Steel	Adhesive	Composite	Impact energy (J)
Stainless steel AISI 304 0.5 mm	Rubber A 0.5 mm Rubber A 1.0 mm Rubber A 1.5 mm Rubber B 0.5 mm Rubber B 1.0 mm Rubber B 1.5 mm Epoxy adhesive	GFRP 3.5 mm	15
Mild steel EN10130 DC01 0.5 mm	Rubber C 0.5 mm Rubber C 1.0 mm Rubber C 1.5 mm Epoxy adhesive		
To study the effect of impact energy			
Steel	Adhesive	Composite	Impact energy (J)
Stainless steel AISI 304 0.5 mm	Rubber A 1.0 mm	GFRP 3.5 mm	3 15 30