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The effect of test parameters on the impact resistance of a stainless steel/rubber/composite hybrid structure

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ABSTRACT

In the present study, high velocity impact tests were carried out on stainless steel/rubber/composite hybrid plates. The projectile velocity, impact angle, number of impacts, sample temperature, and prior ageing were used as variables in order to investigate the effect of test parameters on the impact behaviour of the samples.

In general, the energy absorption and the damage behaviour of the studied hybrid structure were rather immune to the changes in the test parameters. Only the impact angle showed a stronger effect with increasing plastic deformation and dissipated energy with increasing impact angle. Similar but not as strong effect was found with increasing sample temperature. In addition, the effect of increasing impact angle on the damage size was found to be stronger than the effect of increasing impact energy at a constant impact angle. The repeated impact studies showed that the structure does not lose its ability to withstand dynamic loading even when there is a gradually progressive damage. The results support the potential of the studied steel/rubber/composite hybrid structure to be implemented in real life applications.

1. Introduction

When designing lighter and more economic products, hybrid structures offer great advantages because they enable tailoring the properties of a product in a way which is unattainable by any material alone [1]. In addition to lighter weight, hybrids can introduce, for example, more beneficial manufacturing methods [2] or improved damping properties [3]. However, the implementation of such new structures requires in-depth knowledge of their behaviour in different loading conditions and environments.

Layered, adhesively bonded structures are prone to damage caused by out-of-plane impacts due to their susceptibility to delamination. In addition, composite materials, which are typically used as one of the components in hybrids, are prone to damage caused by transverse loads themselves [4]. Thus, to enable the prediction of a hybrid's behaviour in an application, it is essential that the impact behaviour of the structure is known. In a previous study [5], we investigated the properties of steel/rubber/composite structures in high velocity impacts, which typically cause in-service impact voids [6]. By varying the rubber thickness and the impact energy, we found that even a thin rubber layer can decrease the impact damage area remarkably and that the dependence between the impact energy and damage area is linear at the studied energy range [5], when other test parameters are kept constant. However, in real life applications the impact conditions may vary remarkably. Examples of the possible variables in addition to the impact energy are projectile velocity, impact angle, surrounding temperature, as well as structure's prior exposure to harsh environments. In the literature, impact studies where the impact test parameters are varied can be found to a large extent for single materials, whereas the studies on hybrid structures can be found to a much lesser extent.

The impact angle determines the normal force of the projectile and thus has an effect on the deformation. If the impact angle is 90°, i.e. the projectile enters the surface at a perpendicular angle, the deformation is more compression-like in the impact area, whereas a small impact angle leads to a shear-like deformation. Thus, through different deformation modes the impact angle has an effect on the impact behaviour of materials. However, the effect of impact angle on the behaviour of materials is not widely studied, probably because the impact test set-ups rarely enable adjustment of the impact angle. For example, Walley et al. [7] have investigated polypropylene under high velocity impacts and found that increased impact angle results in more severe deformation [7].

The strain rate behaviour of materials is a widely studied area. Since steels [8], rubbers [9] and composites [10] are known to

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exhibit strain rate dependent behaviour, it can be assumed that a hybrid structure consisting of these components would do that as well. Typically the strain rate dependence is presented in a logarithmic scale. For example, Okoli [11] found linear relationship between expended energy and the logarithm of strain rate for glass fibre reinforced epoxy laminate.

Although a single impact event could leave the material rather intact, the accumulation of impact damage in a certain area may affect seriously the mechanical properties of the material. Thus it is important to study the effect of repeated impacts. In our previous study [5], we found that the primary damage mechanisms of the steel/rubber/composite hybrids were interfacial delamination and fibre/matrix debonding. Thus the possible increase in delamination and the damage accumulation in composite are at highest concern. For glass fibre reinforced epoxy composite, Hosur et al. [12] found that the amount of absorbed energy per impact does not change during repeated impacts, and the increase in damage size becomes insignificant after a number of impact events.

In addition to the dimensions of the sample and the parameters of the projectile, the environmental conditions, such as exposure to low/high temperatures or to humidity before or during the impact event, are important variables as well. For composite structures, some impact test studies can be found in the literature that concentrate on the effect of the environment. Sayer et al. [4] studied carbon–glass fibre reinforced epoxy composites and found that the energy absorption capability of the composite is highest at room temperature and decreases towards colder and hotter temperatures. The effect of prior cold–dry and cold–moist environments on the carbon fibre reinforced epoxy composite has been studied by Hosur et al. [13]. They found that the exposure to cold–dry environment improves the impact response of the structure until the duration of the exposure exceeded a certain limit and the damage size increased again [13]. For the cold–moist environment Hosur et al. [13] found that the plasticization of the matrix improved the impact response properties but the extent of damage was similar to the cold–dry results.

In this study, the effect of impact test parameters on the damage mechanisms and dimensions as well as on the amount of absorbed energy was investigated under high speed impact loading. The effect of varying strain rate with fixed impact energy was studied by using different mass/velocity combinations for the projectiles. In addition, the effect of sample damage on the energy absorption properties was studied by repeated impacts. Other variables used were the impact angle, temperature of the samples, as well as ageing of the samples in harsh environments prior to impact loading. The failure modes of the impacted samples were studied from the cross-sectional samples with scanning electron microscopy.

2. Experimental

2.1. Materials

In this study, the influence of test parameters on the impact behaviour of a steel/rubber/composite hybrid structure was investigated. The steel grade of the structure was stainless steel AISI 304 (provided by Outokumpu Stainless Oy, Finland). Thickness of the steel sheets was 0.5 mm. The surface finish was industrial 2D (cold rolled, heat treated, pickled). Prior to rubber bonding, the steel sheets were rinsed with acetone and ethanol. Other pretreatments, 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 glass transition temperature of the matrix is 150 °C. The nominal thickness of the composite sheets was 3.5 mm consisting of 6 layers of fabrics, and the fibre content was approximately 46 vol%. A heat resistant epoxy was chosen to provide resistance for the composite sheet to the vulcanizing temperature of the rubber. From the adhered composite surface, a HexForce® T470 (Hexcel Co., USA) peel ply was removed prior to rubber attachment.

The EPDM based rubber was manufactured by Teknikum Oy, Finland. The trade name of the rubber grade is Teknikum TRA10. The Shore D hardness of the rubber was 41 [14] and the glass transition temperature −38 °C. The hybrid structures were manufactured by vulcanizing the rubber between the metal and the composite layers under heat and pressure (1.2 MPa at 160 °C). The nominal rubber thickness was 1.0 mm, which is the intermediate one used in the previous study [5]. Thin metal plates between the steel and the composite sheets ensured uniform rubber thicknesses during the vulcanization.

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). The high speed video images were recorded at a constant frame rate of 40,000 fps. The HVPI equipment is fully computer controlled. A schematic presentation of the test set-up is illustrated in Fig. 1.

In this study three different balls were used as projectiles: steel (2.98 g in weight), tungsten carbide (WC, 5.73 g in weight) and silicon nitride balls (Si_3N_4, 1.25 g in weight). Specimen angle was either 30° ± 1°, 45° ± 1° or 60° ± 1°. Impact angles higher than 60° were not used since high energetic projectiles after impact in an angle close to 90° would have caused damage for the test equipment after rebound. The used pressure range was 1–14 bar, and it was adjusted to provide a suitable kinetic energy for the projectiles. Some of the samples were heated in an oven or cooled in an ethanol/liquid nitrogen bath together with the sample holder just before testing to investigate the influence of different temperatures. Heating the samples over the ageing temperature of 85 °C was avoided, which set the upper limit of the temperature range. The lower limit was chosen to be above the glass transition temperature of the rubber. The impact temperatures of the samples were recorded by type K thermocouples welded to the sample surface and a Fluke 52 II Thermometer. The temperatures shown in Table 1 are temperatures before the projectile was launched. The launch switches strong halogen lights on, which may have raised the specimen temperatures slightly. Other tests were done in room temperature (RT). To study the effect of ageing, some samples were exposed to a hot/moist environment (85 °C and 85 %RH) for 20 days prior to impact testing. In our previous study [14], it was observed that the adhesion properties of this structure do not change during the ageing process. Three samples were tested per each test parameter combination. Summary of the test conditions is shown in Table 1.

The 50 × 50 mm size samples were fixed with the steel side upwards in a 130 × 130 mm aluminium clamp. The clamp had a circular opening of 40 mm in the centre. The geometry enables the sample to bend during the impact. A schematic presentation of the clamp and the sample geometry is shown in Fig. 2.