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Experimental investigation of composite laminates subject to low-velocity edge-on impact and compression after impact

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ABSTRACT

In this paper, the experimental response of polymer matrix composite laminates subject to low-velocity edge-on impact and compression after impact is studied. An experimental method for coupon level edge-on impact is introduced. Experiments at different impact energies were conducted to establish the edge-on barely visible impact damage (BVID) limit for a specific laminate. Two different impact angles were investigated, 0° and 45° with respect to the impacted edge. Non-destructive and destructive post impact inspection was conducted. Surface damage measurements by visual inspection were compared against ultrasound scanning methods for validation. Fractography using optical microscopy was performed on chosen impact energies for further visualization of the impact damage mechanisms. Industry standard for compression after face-on (transverse) impact was found to be insensitive to the impact damage. An adjusted version of the Combined Loading Compression (CLC) method was introduced for capturing the compressive strength after edge-on impact. A reduction in compressive strength after impact was seen for the impact energy range studied.

1. Introduction

Foreign object impact on composite materials is an ongoing research activity with high interest from industry and academics. An increase in the use of composite laminates in applications is mainly due to their attractive strength to weight ratio and the ability to tailor the response of the structure according to the exposed loading environment. In service, a composite structure is likely to be subjected to impact from many different sources, at different impact angles and energies. These impacts can range from bird impact, collision with another vehicle, hail, and tool drops, to name a few. Impacts are typically categorized depending on the impact velocity, energy, impactor mass, non-penetrating or penetrating, and damage visibility. Low-velocity/energy impacts often fall in the category of barely visible impact damage (BVID) impacts. BVID impacts can cause significant internal damage while showing minimal surface damage. The residual strength of a structure subject to face-on BVID impact has been shown to be significantly lower than that of the pristine structure [1–3]. A quite significant amount of work has been conducted on the face-on impact of laminated composites where the research has been mainly focused on the response, damage mechanisms and the extent of damage due to impact and the effect it has on the compressive strength of the structure. Work in the field up until the year 2004 was reviewed by Abrate [1,2] and Davies and Olsson [3]. A more recent summary is provided in Thorsson and Waas [4].

While face-on impact on composite laminates has been widely investigated [5–19] with industry standards being established (ASTM D7136 and D7137 etc.). Studies on edge-on impact have been relatively scarce in comparison to face-on impact. Edge-on impact is most commonly related to impact on the edge of a stringer on a stiffened panel. Numerous studies have been conducted on skin (face-on) impacts and compression after impact of skin-stringer (or stiffened) composite panels [20–27]. The most typical impact locations that have been studied are on the skin side at the middle of the stringer flange and at the flange root connections. Detailed ultrasound and fractography inspection for skin impacts conducted at different panel locations have been presented by Greenhalgh et al. [20].

Edge-on impact on a skin-stringer panel and compression after impact was studied by Li and Chen [28]. Two different types of stiffener geometries were studied, T shaped and I shaped stiffener webs. The

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compressive strength after impact was reported to be sensitive to the impact damaged stiffeners.

The impact damage due to near-edge and edge-on impact on glass fiber reinforced epoxy laminates using a spherical indenter was investigated and found to show a significant amount of damage [29]. The effect of BVID edge-on impact on a composite laminate stringer using a spherical indenter as well as the compressive strength after impact was reported by Rhead et al. [30], where a cylindrical indenter was recommended for further research.

The edge-on impact research presented in this paper is a more complete and in-depth investigation of experimental work previously published by the authors [31], where the coupon level edge-on impact method was introduced.

Similar work by Ostré et al. [32,33] has since been published, where a similar coupon level edge-on impact fixture was used. The study used a spherical impactor, impact energies tested were beyond the BVID limit. Ostré et al. introduced an adjusted CAI experimental procedure. The method utilized knife edge supports to restrain the panels from buckling, knife edge supports were induced at the non-impacted side of the specimen and the center. Ostré et al. found the CAI method to be sensitive to the impact damage induced in their study.

Due to the high demand from industry to quantify and accurately predict impact damage and the resulting compressive strength after impact (CSAI) of the structure, which has been shown to be highly sensitive to the face-on impact damage state and shape [34]. That being said, it is therefore necessary to also understand the edge-on impact failure modes correctly, and develop models to assess the structural integrity after edge-on impact. Furthermore, due to high cost of manufacturing skin-stringer (or stiffened) panels for testing, it is clear that a standardized coupon-level experimental method would be highly beneficial.

In this paper, the response of a 20 ply polymer matrix composite (PMC) laminate subjected to low-velocity edge-on impact is studied at impact energies in the BVID regime. The specific values of the impact energies can not be disclosed due to the proprietary nature of the material. Impacts are performed with a cylindrical impactor, and specimens are impacted at two different angles, 0° and 45° with respect to the impacted edge. Post-impact damage inspection was done by visual inspection of the specimen surfaces as well as ultrasound C-scanning being used to acquire the full damage extent of the impact. Optical microscopy was performed on chosen damage sections for a few of the impact energies. The industry standard for compression after impact (CAI) proved to be insensitive to the impact damage. Therefore a new approach for conducting CAI was introduced using an adjusted version of the Combined Loading Compression (CLC) standard for compressive testing.

A secondary paper which introduces a shell based finite element model for capturing the edge-on impact and CAI results presented in this paper, is to appear in literature shortly [35,36].

2. Experimental procedure

A fixture for coupon level edge-on impact that would resemble a stringer impact was designed, Fig. 1. Edge-on impacts at 0° and 45° with respect to the edge of the specimen were desired for this study. The fixture was designed to accommodate specimen dimensions in accordance to the industry standard for face-on impact and CAI, ASTM D7136 and D7137, respectfully. Therefore the specimen dimensions were chosen to be 150 mm by 100 mm where the impact would be conducted on the longitudinal edge of the specimen.

The specimen is inserted into a channel along with a steel bar. Depth of the channel is 19 mm and extends the entire length of the fixture. Bolts are then inserted into threaded holes on the side of the fixture, these bolts exit perpendicular to the steel bar (and specimen surface, located behind the steel bar). By applying a torque to the bolts a uniform pressure can be applied to the specimen, resulting in the specimen to be clamped between the steel fixture and the steel bar, effectively resulting in a clamped boundary condition. Brackets are used to suppress out-of-plane displacements away from the impacted area. These lateral supports act as a method of resembling the length of the actual stiffener. Vise grips are applied to the top of the brackets to ensure full contact between the brackets and specimen during the impact event. For the 45° edge-on impact, the fixture was mounted on 45° angle blocks, Fig. 2. The fixture was then mounted on to a heavy steel base plate to ensure that no unwanted motion would be incurred due to the 45° tilt of the fixture.

Edge-on impact experiments were carried out on the composite laminates at different impact energies, 5 replicates for each impact energy. The laminate investigated has a traditional stacking sequence consisting of 0°,90° and ± 45° ply angles. The composite layup of the specimens is [45/90/−45/0/0/−45/0/45/0/**45**/−**45**/0/45/0/−45/0/0/−45/90/45], which is symmetric except for the midplane plies. This results in a [40/50/10] laminate, meaning that there are 40% 0° plies, 50% ± 45° plies and 10% 90° plies. This stacking sequence, when subject to impact, was expected to show an interesting and rich set of failure mechanisms. This material system would give rich insight into the failure mechanisms of composite laminates subject to edge-on impact while not simplifying the problem away from industry standardized stacking sequences and laminate thicknesses. Specimen thickness is 3.84 mm. Impacts were performed on an in-house built drop tower, and the impact load was captured using a Kistler 9104A piezo-electric load washer (load capacity of 140 kN) inserted between the impact sled and the impactor. A cylindrical steel impactor with a diameter of 12.7 mm was used for all impacts, a mass of 25 kg was used to produce low velocity impacts. The impactor was positioned so that the impact location was centered between the lateral support brackets. Subsequently, CAI of the specimens were studied.

For digital image correlation (DIC) purposes, the specimen surface was speckled with matte black and white spray paint, giving an even distribution of black and white on the surface. Two Photron SA-X high speed cameras were utilized in a stereo setup to record the speckled surface of the specimen during the impact event. A recording rate of 50,000 frames per second was used. The resolution of the cameras was set to 640 × 336 pixels and 512 × 368 pixels for the 0° and 45° impacts, respectively. The commercially available DIC software, ARAMIS, was used for camera stereo calibrations and post-processing of the images. The DIC post-processing allows for the full field in-plane strain and displacement fields to be acquired as well as the out-of-plane displacement of the specimen being acquired through the 3D correlation of the stereo setup cameras.

Due to the nature of the impact, the energy required for inducing BVID is significantly lower than the 7.6 J per mm of thickness as recommended by ASTM D7136 for face-on impact. Preliminary studies with a coarser impact energy interval were conducted to acquire the energy range desired for the BVID impact study presented in this paper. Once a relevant impact energy level which induced damage in the BVID range was achieved, multiple impacts in the vicinity of that energy level were conducted. Impacts at 0° and 45° angles were carried out at even energy level integrals which will be referred to as E1-E5.

Compression after impact testing was initially performed in accordance to the ASTM D7137 standard for measuring compressive strength after face-on impact. Minor adjustments were made to the experimental procedure, which will be described in Section 4.1. The method proved to be insensitive to the impact damage induced by the edge-on impact and therefore a different approach for CAI was required. An adjusted Combined Loading Compression (CLC) experimental procedure is suggested. The CLC method would result in a smaller specimen dimension which would, as a result, be more sensitive to the edge-on impact damage. The method will be further described in Section 4.2.

The CAI testing was performed on an MTS 809 axial/torsional load frame with a 444.8 kN load capacity. Loading rate was chosen to be