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In-Plane Impact Loading of Composites: Optical Evaluation and Crack Severity Assessment for Graphite-Epoxy

F.G. Benitez and L. Andrades

Department of Mechanical Engineering, University of Seville, Av. Reina Mercedes, Sevilla 41012, Spain

Abstract. This paper describes the test performed for the optical evaluation of propagating cracks, which assess the severity of through cracks in composite laminates. The paper begins with the description of the experimental rig designed for dynamically loading the specimens. In particular a modified split-Hopkinson pressure bar for impacts at medium range (10 to 30 m/s) is covered. The specimens are prepared in order to have a mirror reflective surface, by depositing aluminium, which is used to reflect a laser collimated beam in order to visualize optically the dynamic event in the crack neighborhood.

Résumé : Ce papier décrit le test réalisé pour l'observation optique de la propagation de fissures dans les composites. La configuration expérimentale est décrite, en particulier, une barre de Hopkinson modifiée pour obtenir des impacts dans le domaine de 10 à 30 m/s. Les échantillons sont préparés afin de disposer d'une surface de réflexion de type miroir, en déposant de l'aluminium. Une méthode utilisant un faisceau laser collimaté est utilisée pour observer optiquement les phénomènes dynamiques dans le voisinage de la fissure.

1 INTRODUCTION

Two of the most noteworthy characteristics that qualifies carbon-fiber-epoxy resin composite materials for being used in engineering applications are the high strength and stiffness per unit of weight. These two attributes make this material particularly attractive for its use in mobile structures. On the other hand, this application reveals one of the greatest disadvantages of this material: its low strength to impact loadings and, in particular, the difficulties in detecting the damages produced by this type of loadings.

Various modes of impact damage on laminated composites exist. Low velocity impact normal to laminated panels will cause internal resin failure and delamination. The damage will cause loss of stiffness and is difficult to detect. Tougher matrix material will improve the resistance. High velocity impact normal to the laminate will cause tear-out, with damage to a smaller part of the surrounding material. The damage resistance can be improved through use of woven fabric rather than UD material, and choosing tougher fibres such as Kevlar, where large amounts of micro failures around each filament and energy demanding fibre pull-out will absorb the impact energy, and prevent penetration. In-plane impact, as birds hitting the outer guide vanes of a jet-engine, floating objects hitting the wings of a hydrofoil boat, small pieces of pavement fired by tires during the landing or taking off of aircrafts, etc., can also cause matrix and/or fibre failure. Low velocity impact can be prevented from initiating damage by ensuring a resin rich leading edge. Damage caused by high velocity impact can be reduced by carefully choosing the fibre type and architecture (use of woven laminae versus unidirectional or interleaved fibers to avoid delamination, above others). The behaviour of laminated composites is therefore desirable to characterise, and the impact resistance of these materials is important to find. This report describes a test-rig which can be used for that purpose, and how the individual parts of the apparatus are interfaced to consort. The preliminary results for in-plane impact loaded carbon/epoxy composite plates, and the efforts to make optical techniques applicable to composites by the careful preparation of the surfaces necessary to get images of sufficiently low noise level, are also included.

Along this paper an experimental set-up for visualizing cracks propagating under impact loads is presented. The objective is to determine crack length versus time and, from it, to obtain the propagating speed. In addition to this we also use the set-up for monitoring strain gradients versus time by using the optical method of caustics during the dynamic process.

2 EXPERIMENTAL TECHNIQUES

2.1 Test Equipment

The test rig is based on a standard Split-Hopkinson-Pressure-Bar (SHPB) setup, where the output bar is replaced by a specimen holder (which is not strain-gaged). The rig comprises striker bar, input bar, specimen and specimen holder (fig.1). In addition there is a compressed air reservoir for accelerating the striker bar towards the input bar, and measuring equipment for capturing the output variables such as striker bar speed and strain waves in the input bar. By opening the quick release valve on the reservoir, the striker bar is accelerated down the barrel of the air gun. Immediately before the striker bar hits the input bar it passes through a velocity measuring device. The velocity is calculated by measuring the time between breaking two light beams of known distance. The specimen holder and the input bar form a three point bending rig, where the strain wave traveling through the input bar causes an impact action-force on the specimen, and the specimen holder the two reaction-forces. The specimen is held so that the impact load causes a crack to grow from the notch towards the point of impact, and provisions are made so the specimen can be accurately aligned with the striker bar and input bar, to avoid compression-bending coupling and flexural waves in the input bar. Two sets of gages are set on the input bar of the SHPB, so that the incident and reflected strain waves can be measured. From this, force vs. time plots can be made. As the specimen holder replaces the output bar, no transmitted strain wave can be measured. The duration of the striking pulse is function of bars length (500 mm each one).

The events were recorded using a Cordin high speed film-camera capable of capturing 500 frames at up to 200,000 pictures per second, and a high speed video-camera with a speed of up to 40,500 pictures per second. Both systems can be used indistinct and independently for monitoring crack and caustic propagation. For illuminating the whole event a laser beam is used as light source, which is expanded up to a collimated beam of 10 cm diameter. The film-camera is provided with a mechanical shutter which opens early enough previous to the time-window the event takes place and closes far after the period of interest, this forces the experiment to be carried out in darkness.

An operational amplifier with a latch up circuit is used for triggering the illumination in from the signal given by one of the photodiode used by the bar-speed measurer. The illumination is extinguished when a tacho signal from the film-camera is received corresponding to the instant the whole film has been fully exposed. This procedure precludes a multiple exposition of the film. The same signal that triggers the illumination in is used for triggering the video-camera, which runs till it reaches a fixed number of images (16,384 pictures).

An Ion laser of 6 Watts in continuous wave was used to provide a collimated beam of single wave length (514 nm, 2 w.), coherent vertical polarised light. An acousto-optical cell was used to provide a means of rapid on-off switching of the laser beam, in order to expose the camera-film the correct amount of time. When this modulator is activated an amount (95 %) of this light (1st order beam) is bled off, through an iris which is lined-up with the beam-expander optics. This portion of the laser beam is then expanded to provide the required light source for the illumination of the specimen.

After illuminating the specimen by the collimated light, this is directed to a lens which focusses an imaginary plane distant z_0 from behind the specimen plane, in order to visualize a caustic created during the process of testing. This technique is used due to the specimen opacity, which forces to work under reflexion. The created image is sent to both cameras, the film-camera and the video-camera, by using a beam splitter situated so that the reflected light from the specimen can be directed to both of them simultaneously for capturing purpose.

The test rig is designed to accommodate plate specimens with maximum dimensions of up to 300x200x30 mm. The specimens are opaque. In order to have a flat reflector, needed for the application of the method of caustics by reflexion, a half-a-wavelength flatness surface has to be created. Owing to the inevitable imperfections of woven composites in and near the surface, this had to be covered. The coating needs to be thin, so it does not affect the behaviour of the composite and elastic so it follows the deflections without cracking. This was achieved by grinding the surface to be observed, coating it with a thin gel-coat film cured under pressure over a flat glass panel to give a plane and perfectly smooth surface and claded with a layer of vapour deposited aluminium, to obtain a reflective surface (fig.2). A distance grid in a contrasting colour was also applied to the specimen in order to evaluate the crack tip position vs. time.

2.2 Optical Technique

A schematic of the optical arrangement is depicted in figure 3. To enable capture of an extended field, the laser beam must be expanded. This is obtained by passing the beam through a bi-concave lens, L1, to give a diverging beam. The light is then passed through a bi-convex lens, L2, with a focal length function of the required light beam diameter. This expanded beam is deflected by a mirror, M1, to illuminate the specimen. The reflected beam is converged by a bi-convex lens of a large focal distance (3.5 m) and sent by mirror M2 to the optical recording system. After mirror M2 a beam splitter is situated which will deflect the reflected light from the specimen onto the film-camera and an image screen from which a video-camera captures the event. By positioning lens L3 with respect to specimen-plane the shadow optical technique of caustics is utilized for monitoring the crack-tip caustics from which the stress-intensity factor as a function of time can be determined [1].

2.3 Loading Technique

When aligning the specimen in the Hopkinson-bar rig, care must be taken to ensure that the line described by the intersection of the specimen neutral plane and the crack plane is parallel and coincides with the axis of the input bar. This is to ensure a pure mode I crack growth without any flexural loading neither in the specimen nor the input bar.

After specimen, camera and optics have been set up and adjusted, cameras are started, and when the set speed is reached in the rotating drum (for film-camera), both cameras are armed. When executing the test, the camera shutter is opened immediately before the quick release valve is opened and the shutter timer set to close it shortly after. This is to minimize any unwanted stray light exposing the film.

The use of laser as the light source requires a similar procedure to the one outlined above. The acousto-optical cell is driven by a modulator which must be switched on just before the impactor hits the specimen and off just before the film-camera begins a second exposition of the film. The camera writing time is large enough to capture the time-window through which the crack propagates. One or both cameras must be focused on the image plane rather than the specimen in order to visualize the generated caustics.

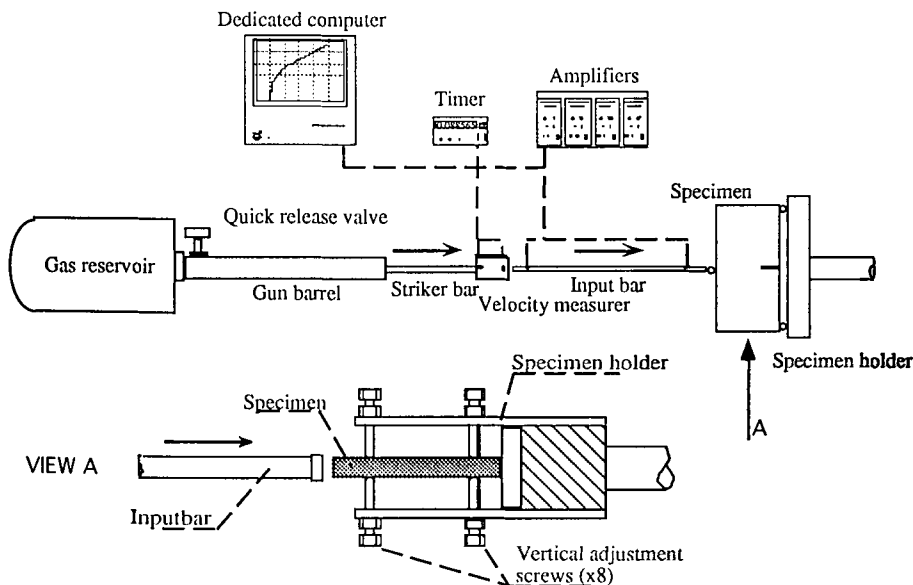


Figure 1: Schematical view of the test rig.

2.4 Specimens

The specimens tested are coupons of size 125x60x2.5 mm (fig.2) from a sandwich panel, utilized for building the structure of space satellites, made of honey-combed carbon fiber-epoxy laminates. A notch length of 20 mm was needed to ensure a clean failure. For shorter crack-length the failure mechanism is just a penetration of the impactor without any crack propagation (fig.4) . The thickness is for each laminate of the honeycomb, and the lay-up is [02,-45,02,90,02,45]₃ of UD Vicotec 914/34%/G829.

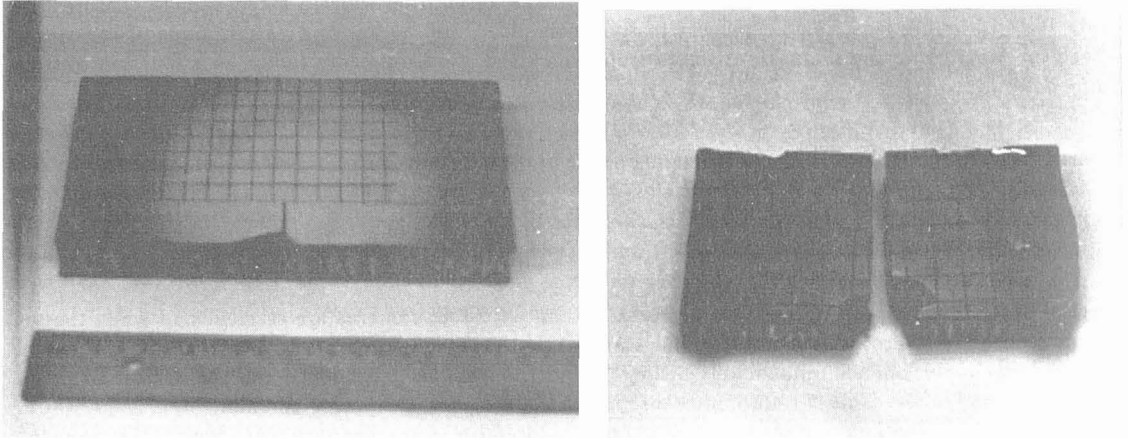


Figure 2: Honey-combed carbon fiber-epoxy laminate specimen, before and after tested.

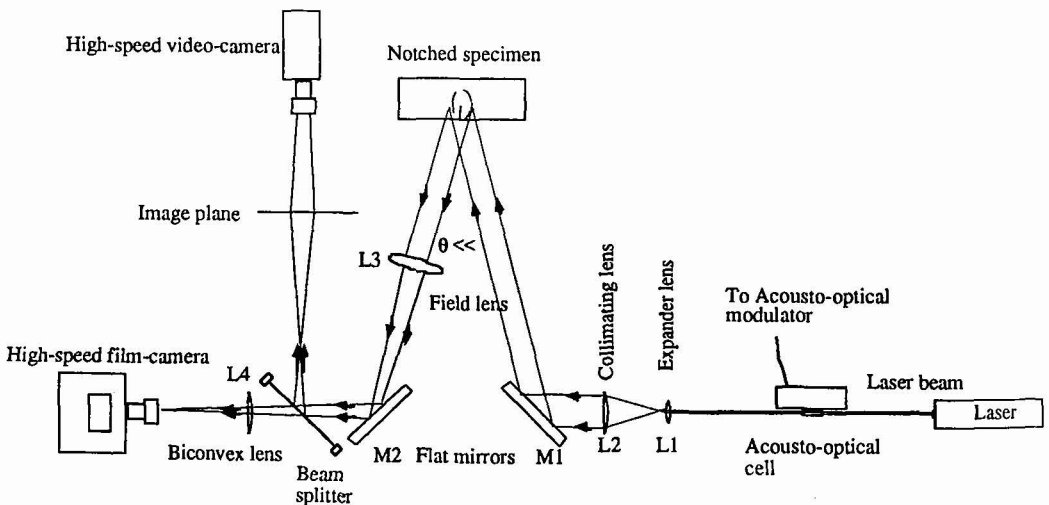


Figure 3: Schematics of the optical set-up.

3 RESULTS

For tests under an impactor velocity of 30 m/s, a sequence of pictures with different time increments is shown in figure 5. At a recording rate of 175,000 fps, a crack propagation running with medium speed of the order of 100 m/s was found (fig.6), with peaks of 250 m/s and 400 m/s.

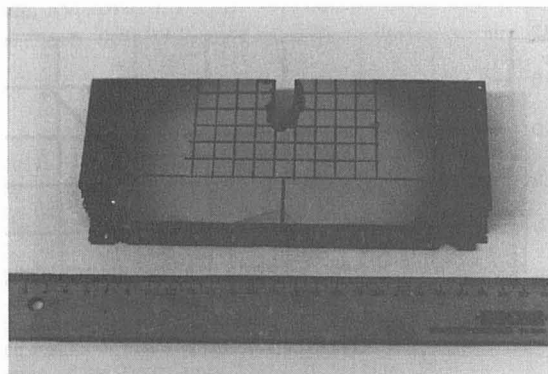


Figure 4: Failure mechanism for specimens with short cracks.

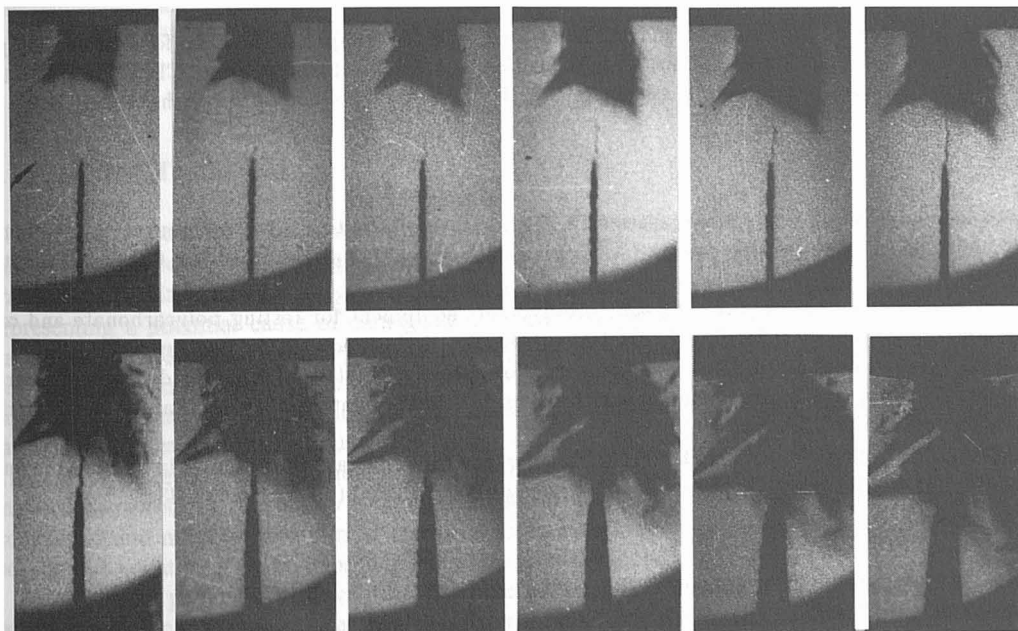


Figure 5: A propagating crack in honey-combed carbon fiber-epoxy laminate specimen. Photographs are shown in intervals of 28.5 μ s (upper row) and 57 μ s (lower row).

4 CONCLUSIONS

Taking into account that cracks propagate in steel at speed of the order of 1000 m/s and in PMMA of the order of 300 m/s, as average values [2,3,4], we could bear in mind that for this type of structural material the mechanism of through-crack propagation is not very severe even when the crack-length is large enough. For shorter cracks (less than 30% of the specimen width) the failure mechanism precludes the propagation of any through-crack at all.

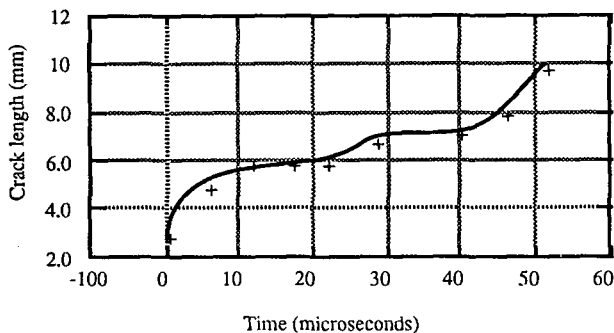


Figure 6: Crack growth in honey-combed carbon fiber-epoxy laminates.

5 ACKNOWLEDGMENTS

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