A FRACTURE DYNAMIC EQUIPMENT FOR TESTING POLYCARBONATE AND COMPOSITE MATERIALS UNDER IMPACT LOADING

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Abstract. An experimental set-up for optical evaluation of the crack propagation speed and the strain field surrounding crack growth under impact loading is described. The use of Split-Hopkinson-Pressure-Bar rig, high-speed camera, flash light and laser equipment is covered, and the specially manufactured interface, trigger and timing electronics are described.
The described set-up can be used with the optical technique of caustics to evaluate the strain field around a dynamically propagating crack. By employing a flash light rather than the laser light source, the crack propagation can be studied visually.
The test-rig is to be used for testing polymers and laminated composites under in-plane impact loads, and some preliminary results are included.

Resumen. Se describe un equipo experimental para evaluar la velocidad de propagación de grietas bajo cargas de impacto. El sistema consta de un equipo de barra partida de Hopkinson, una cámara fotográfica de alta velocidad, iluminación de flash y laser.
El sistema descrito se puede utilizar con la técnica de caustica para cuantificar el campo de deformaciones en las proximidades de una grieta propagante. Diversos ensayos se han realizado con materiales polímeros y compuestos, de las que se presentan resultados preliminares.

1. BACKGROUND

Various modes of impact damage of laminated composites exist. Low velocity impact normal to laminated panels (as when dropping a tool on an airplane wing) will cause internal resin failure and delamination [1,2]. The damage will cause loss of stiffness and is difficult to detect visually. 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 [3]. 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 [4].
In-plane impact, as birds hitting the outer guide wanes of a jet-engine or floating objects hitting the wings of a hydrofoil boat 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.
The behaviour of laminated composites is therefore important 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.

2. EQUIPMENT

Split-Hopkinson-Pressure-Bar Impact Rig

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-gauged). 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 devise. 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. The input bar of the SHPB is train gauged, so that the incident and reflected strain waves can be

measured. From this the force vs. time plots can be made.

Camera

For recording the events a Cordin high speed camera capable of recording 500 frames at a rate of up to 200.000 frames per second was employed. The camera-drum rotates half of one revolution to expose the whole film. For timing purposes etc. the camera gives 10 tacho pulses per revolution. The setup with the camera is illustrated in fig.2.
The shutter time of the camera is adjustable from 1/250 sec to 1 sec. As the maximum time was found to be too short for reliable timing of shutter open and failure event, a shutter time extender (fig.3) was made and fitted in the camera control box. When this is engaged the max. shutter time can be adjusted to a maximum of about 5 sec.

Laser and Optics

A Innova 300 laser (6 Watt) was used to provide a collimated beam of single wave length, coherent and vertical polarised light. A Bragg 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 using the laser with the Bragg-cell, the half-reflective mirror at the front of the laser was removed, and one of the mirrors in the Bragg-cell assembly put in front of the laser head to reflect the light away from the laser at an angle of about 40-45° (fig.2). This mirror, M1, has a radius of curvature (ROC) of 750 mm. Down stream from this mirror, about 375 mm. from M1, the Bragg-cell was placed, and a further 150 mm from the Bragg-cell was the next mirror placed, M2 with a ROC of 150 mm. The focal points of M1 and M2 now coincides at the position of the Bragg-cell. When correctly adjusted the light from the laser is reflected back to its rear mirror and amplified. When the Bragg-cell is activated an amount of this light is bled off, via a flat mirror M3 placed near M1. This portion of the laser beam is then expanded to provide the required light source for the illumination of the specimen. Between the collimator and the specimen, a beam splitter is situated so that the reflected light from the specimen can be directed to screen for capturing by the camera.

Flash and Laser Timers

When the high-powered flash was used, an operational amplifier with a latch up circuit (fig.4) was used to trigger the flash gun from the strain wave in the input bar. The capacitor requires a 24 volt trigger voltage, necessitating a 5-24 volt interface. The capacitor bank can be set to expose the specimen for the desired length of time, so as not to double-expose the film.

When the laser was used as a light source, the timing-device on the capacitor bank could not be used. A pulse counter used in conjunction with the strain gauge trigger (fig.5) was therefore designed and made. As for the flash-light case, the strain-gauges trigger the operational amplifier so that its output latches up. This high level is input to the pulse counter causing its out-put to go high and activate the laser (Bragg-cell). Since the pulse counter starts counting on the first camera pulse *after* the operational amplifier latches up, it is set to count only four pulses before de-activating the laser with a low out-put to the Bragg-cell. This is done to ensure no double exposures of the film.

Specimens

The specimen holder is designed to accommodate plate specimens with maximum dimensions of up to 225x125x25 mm.
The specimens which were used for crack speed measurements, were painted matte white for light reflection. A distance grid in a contrasting colour was also applied to the specimen in order to evaluate the crack tip position vs. time.
The specimens which are to be used for stress field evaluations, the exposed surface must be clad with a layer of vapour deposited aluminium, and the other surface matted and painted with matte black paint to avoid secondary reflections and ghost images.

3. PROCEDURE

When aligning the Bragg-cell assembly, the initial steps are done with the half reflective mirror in place. Mirror M1 is adjusted so that the laser beam hits mirror M2 just below its centre. M2 is then temporarily removed, and the Bragg-cell placed in the laser beam at the focal point. The white mark on the Bragg-cell is to face upwards, so it is at an angle of about 45° to the laser beam. There will now be light reflected up- and downwards from the Bragg-cell. The Brewster angle (rotating the Bragg-cell around and axis normal to the laser and parallel to the table plane) is adjusted till these reflections are minimised. The half reflective mirror is then reinserted and M2 replaced and adjusted so that the laser beam is amplified (becomes bright green). By activating the Bragg-cell one should now see a portion of the laser beam being bled off. By rotating the Bragg-cell around an axis normal to the table surface the Bragg-angle is adjusted till maximum amount of light is bled off. Iterative adjustment of mirror and Bragg-cell must be done to optimise the set-up.
To enable capture of an extended strain field, the laser beam must be expanded. This is obtained by passing the beam through a concave lens of short focal length, L1 to give a diverging beam. The light is then passed through a larger lens of longer focal length, L2. The distance between L1 and L2 is the sum of their focal lengths, giving an expanded and collimated beam. This expanded beam is deflected by a mirror, M4, to illuminate the specimen. Between the specimen and M4 a beam splitter is situated which will deflect the reflected light from the specimen onto the image screen. From the image screen the image is captured by the camera. Alternatively, the image may be projected directly

onto the film, without using the additional image plane. In this mode the camera (with its lens removed) must be carefully aligned with the specimen and optics. However, more light will reach the film, and higher camera speeds can be used.
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.

Experiment

After specimen, camera and flash have been set up and adjusted, the pressure reservoir is filled to the chosen level and the flash gun capacitor bank charged and the flash timer set. The balance control on the strain-gauge amplifier is adjusted so the strain gauge trigger (in compression wave mode) gives a trigger signal when the input bar is hit. The strain gauge trigger is then reset. Once the capacitor bank is fully charged the camera is started, and when the set speed is reached, the camera is 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.
When doing the experiment with the flash light source, none of the optical equipment is used, and camera and flash are pointed directly at the specimen.

The use of laser as the light source requires a nearly identical procedure to the one outlined above. The Bragg-cell driver must be switched to external repetition generator, external reference oscillator and pulse mode. (The high input on the input gate will ensure a continuous output for the duration of the high input signal). Both strain gauge amplifier and pulse counter must be reset prior to commencing the test. Also the camera must be focused on the image plane rather than the specimen.

Since the trigger electronics are sensitive to electrical noise generated from switches, motors etc., these must not be operated after the camera has been armed.

4. PRELIMINARY TEST RESULTS

The consorted interaction of the test equipment in flash-light mode has been ascertained by preliminary testing of plexi-glass and honey-combed carbon fiber/ epoxy laminate specimens.

The plexi-glass specimen was 225x125x10 mm with a 30 mm deep 1.5 mm wide sharp notch (fig.6). The surface was painted matte white with a contrasting black grid along the expected crack path. Camera speed was set to 100 000 fps, and a low air pressure (about 50 mbar) applied. The resulting impactor speed was 10.9 m/s. The resulting pictures show with reasonable clarity the propagation of the crack, although the exact position is difficult to determine. A sequence of pictures with different time increments is shown in figure 7. By carefully measuring the tip position vs time, a crack speed of about 344 m/s was found (fig.8).

Similarly, a specimen of honey combed carbon fibre/ epoxy was tested using the same procedure. Owing to the high price and fracture energy of fibre composites, smaller dimensions were used. Compared to the plexi-glass specimens, the size is reduced by about 50% to 125x60x3 mm (fig.9). A notch length of 25 mm was needed to ensure a clean failure . The thickness is for each laminate of the honeycomb, and the lay-up is $[0_2,-45,0_2,90,0_2,45]_3$ of UD Vicotec 914/34%/G829. The air pressure was set to 1.75 bar, giving an impactor speed of 40 m/s. A sequence of pictures with different time increments is shown in figure 10. At a recording rate of 175 000 fps, a crack propagation speed of about 100 m/s was found (fig.11).

5. ACKNOWLEDGMENTS

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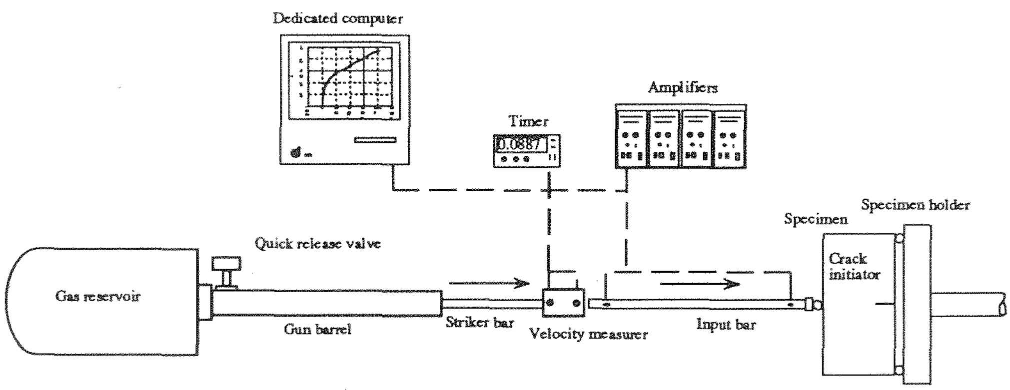


Fig. 1. Schematic View of Lateral Three Point Bending Impact Rig

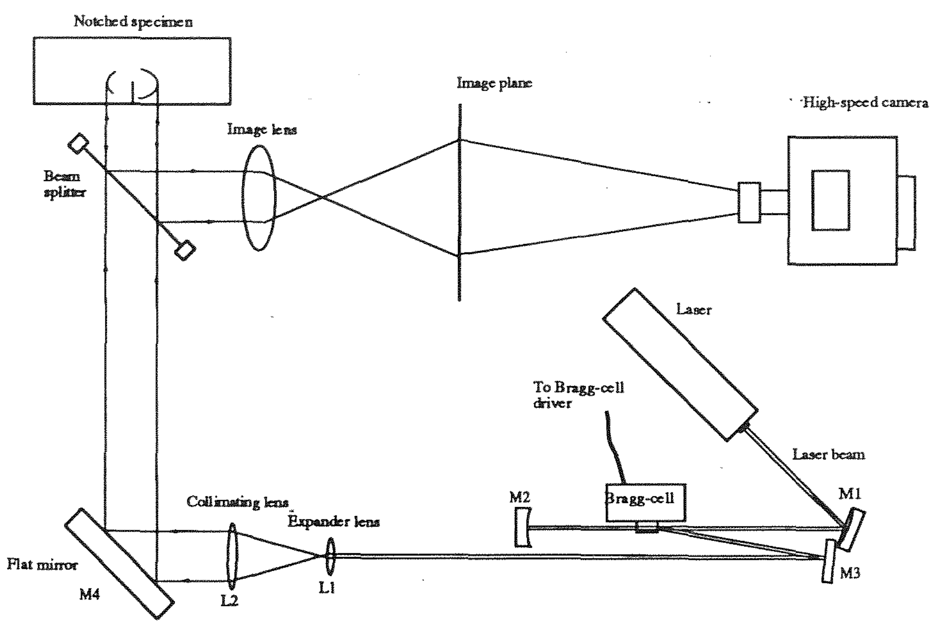
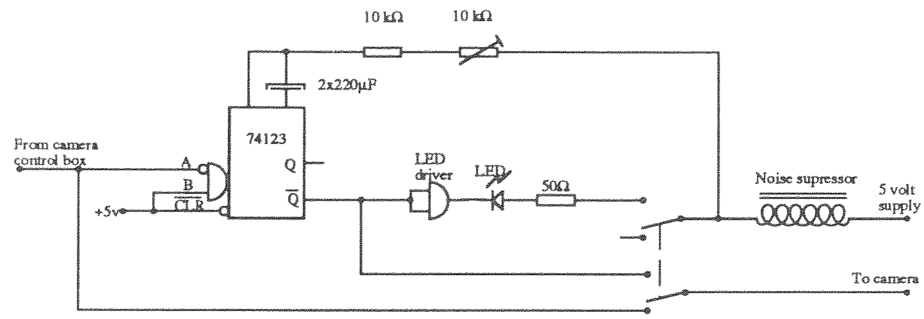
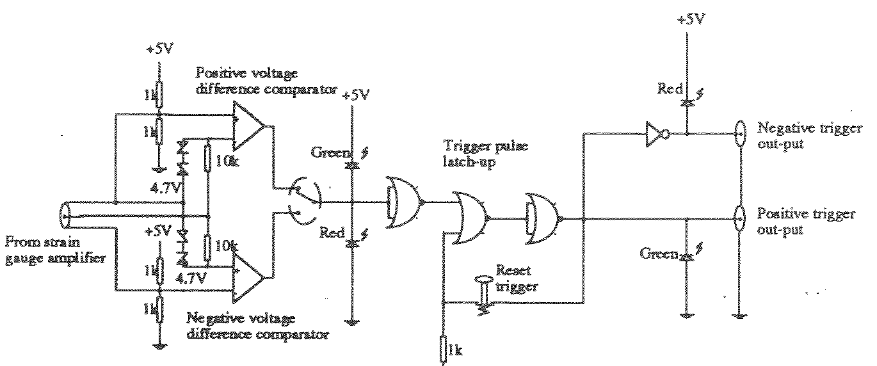


Fig. 2. Schematic View of Optical Set-Up



The lower change over switch directs the shutter opening signal either directly through to the camera (lower position), or through the circuit.
The circuit is connected to power permanently, but the LED is disconnected when in by-pass mode. This to minimise electric noise while switching from one position to the other.
Noise absorbing capacitors are not shown.

Fig.3 Shutter Time Extender



Zener diodes works as input protections, by short circuiting the signals above 5 volts, through the 10k resitors.

The LED's after the op-amps shows the polarity of the input signals, relative to the trigging polarity.
Red LED- no trigger action and green LED - trigger action.
Both LEDs on, no or very small input voltage difference.

Fig. 4. Strain Gauge Flash/Laser Trigger

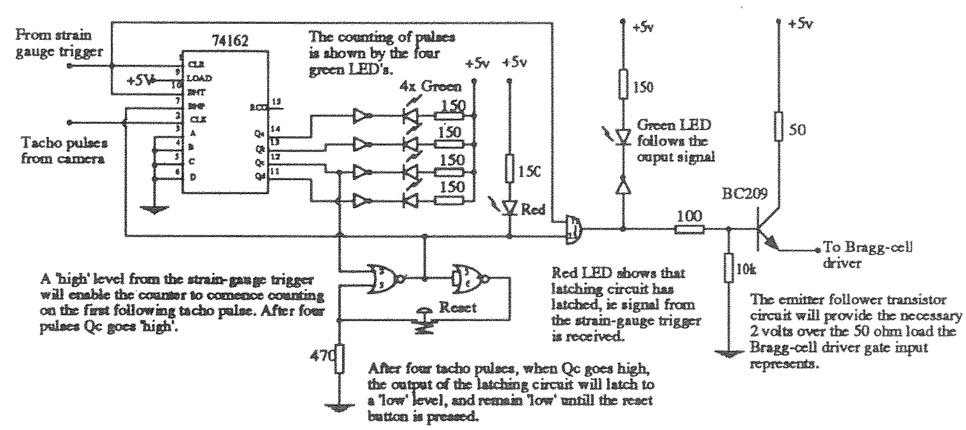


Fig. 5. Pulse Counter

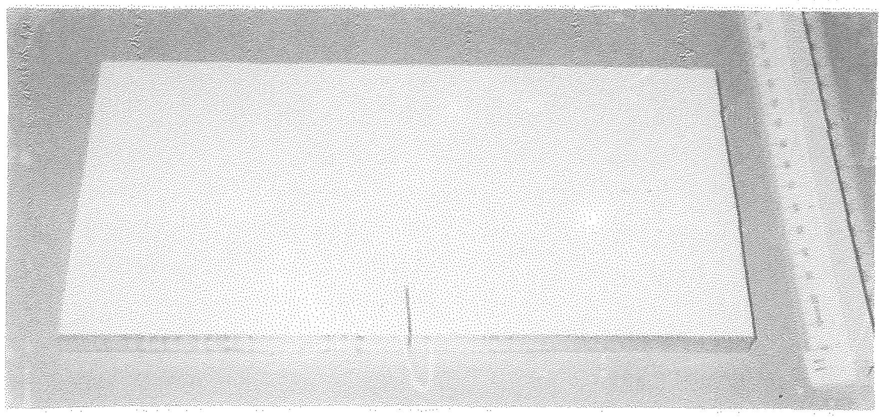


Fig. 6. Plexy Glass Specimen

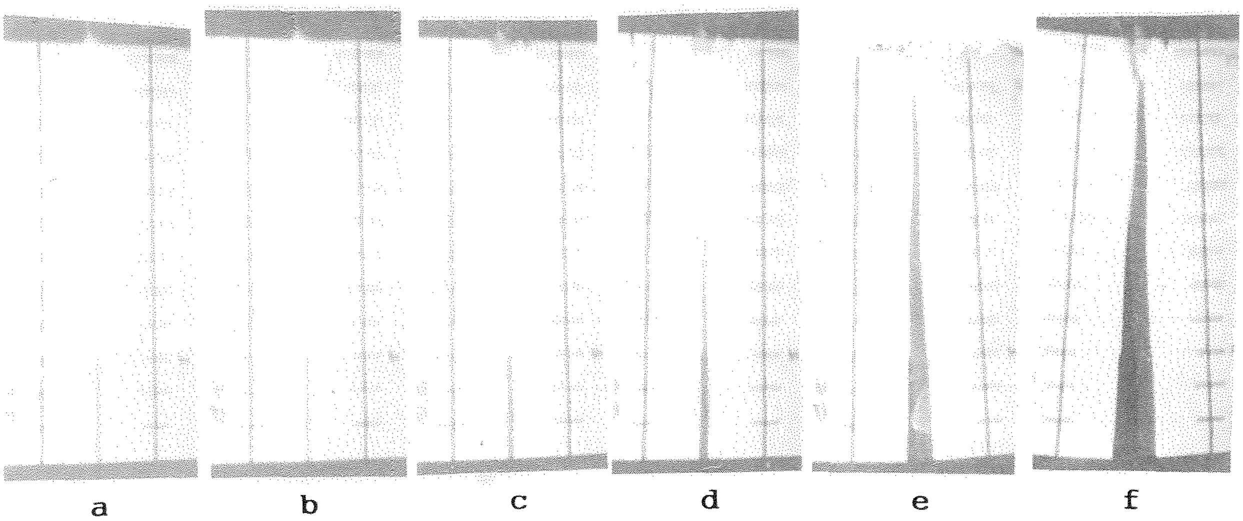


Fig. 7. Crack Propagation in Plexy Glass. The time increments between pictures is 160 micro-seconds for a-b-c-d and 400 micro-seconds for d-e-f.

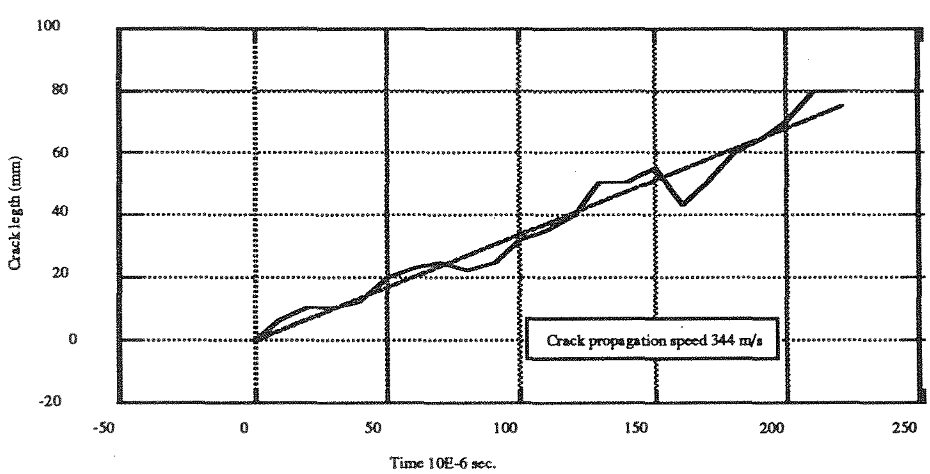


Fig. 8. Crack Growth in Plexy Glass

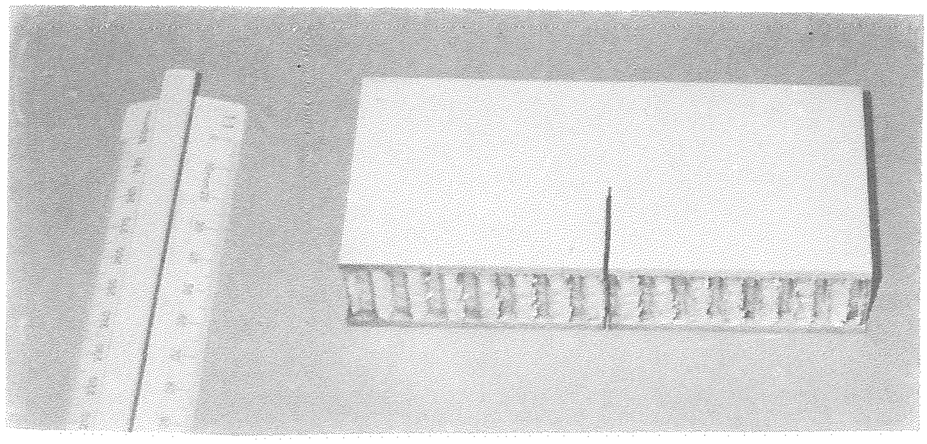


Fig. 9. Composite Specimen

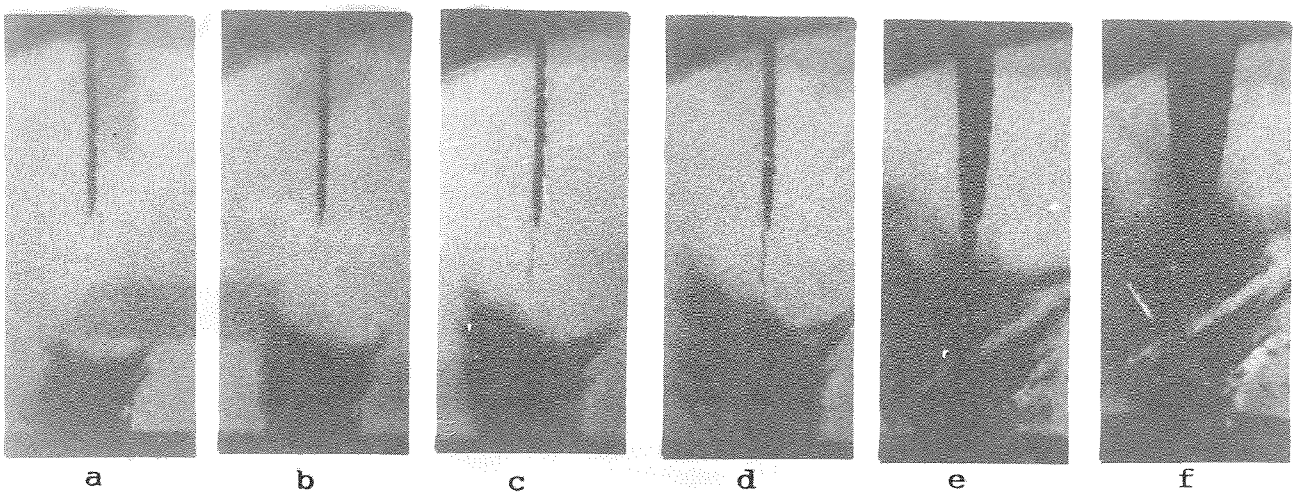


Fig. 10. Crack Propagation in Composite Specimen. The time increment between pictures is 57 micro-seconds for a-b-c-d and 229 micro-seconds for d-e-f.

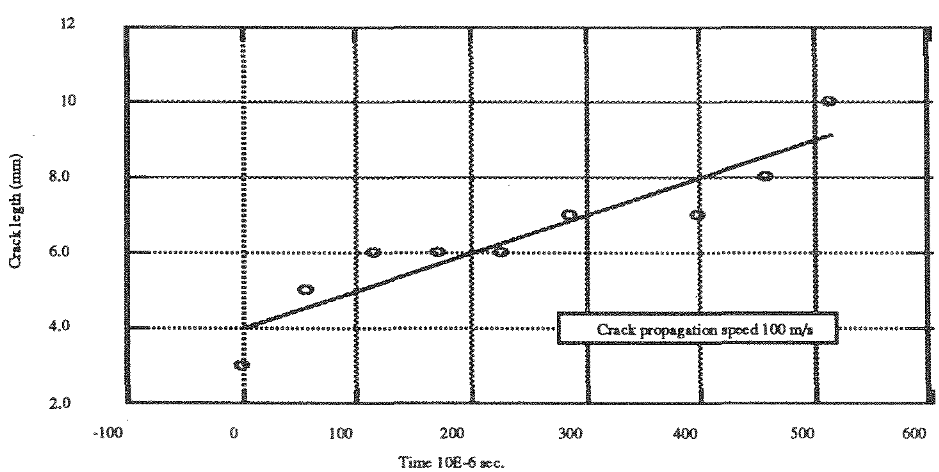


Fig. 11. Crack Growth in Composite