Abstract
Use of composite armours is gaining importance in defence applications due to their high strength and stiffness to weight ratio. In the present research immersion type ultrasonic C-scan is performed on ballistically impacted Kevlar epoxy composite armours of different thicknesses and extent of damages of different severity are identified through C-scan imaging. A methodology based on segmentation of ultrasonic data into different clusters is implemented for automated generation of the C-scan image of the scanned domain. The core-damage areas for different impact cases are evaluated from the representative C-scan images and their dependence on the different impact parameters are noted. In general, the areas of core damage zones are found to be sensitive to the loss of energy of the shot. However it increases rapidly in case of shot-lodging. The present methodology implements imaging effectively requiring less intervention of the skilled personnel.

Keywords: Ultrasonic C-scan, Data clustering, Composite Armours and Shot Lodging.

1. Introduction

Non-Destructive Testing (NDT) has been practised for many decades with initial rapid developments in instrumentation spurred by the technological advances that occurred during the World War II and subsequent defence effort. During the earlier days, the primary purpose was the detection of defects, mostly in the medical sense. Gradually NDT was applied in detection of defects in engineering structure. Of a variety of NDE techniques, ultrasonic methods are versatile and relatively inexpensive for such tasks. Application of composite materials also presents several specific challenges to non-destructive testing and evaluation as these materials tend to develop different types of defects during service. Apart from overt defects like delaminations and impact damage, inspections should also reveal defect states such as high void content, fibre bunching, resin richness, matrix cracking, fibre breakage and poor quality fibre/matrix bonding etc.

In recent years, with the advent of high speed Analog to Digital (A-D) converter cards, attention has been focused on the automated C-scan technique through interfacing and control by computers. The available literature suggests that only a limited number of research works has been conducted in relation to automated C-scan image generation. T.S.Jones [1] developed a computer controlled ultrasonic scanning and data collection system using a mini-computer which allowed a part to be inspected in a single scan without need for stopping or modifying the sensitivity of the setting. Datta et al. [2] performed ultrasonic C-scan in normal beam pulse echo and through transmission on laminates with impact and inclusion type damages. Frequency domain features were used, individually or in combination, for generation of C-scan images. Hierarchical clustering using Ward’s algorithm was implemented for classification of dataset. Bhatt et al. [3] has performed an experimental investigation, where low velocity impact damage has been inducted in CFRP laminates at specific energy levels. This damage and its distribution through the thickness have been studied and the area at different depths has been computed.
Ultrasonic imaging has been utilized extensively and innovatively to detect, locate, measure and quantify the impact induced image. Datta et al. [4] performed immersion type C-scans on impacted composite specimens. The impact was created by repeated dropping of weights on the GFRP panels. For automated image generation, grouping of signal amplitude data set was done by UPGMA linkage method, but based on a pre-selected number of clusters.

In the present investigation, a methodology for nearly real time evaluation of impact damage in Kevlar epoxy composite is proposed. The experimental set up and different steps of data grouping methodology are discussed in the following sections.

2. Experimental Set-Up

In this work, the experimental set-up comprises of (i) Ballistic testing set-up and (ii) C-scan set-up.

2.1. Ballistic Testing Set-Up

The composite laminates were mounted on specially designed holders where two sides were clamped for rigid holding and placed in the line of fire of a 7.62mm caliber military rifle. The impact energy was varied by adjusting the propellant mass in the ammunition. The impact and the exit (residual) velocities were measured by the foil and counter method. Each frame consisted of two thin aluminium foil separated by a thin insulating paper board and were connected to a timer. Two frames were separated by a distance of 3m and placed as close to the impacted panel and the velocity was calculated from the time taken by the projectile to travel between two frames at a measured distance apart. A similar set up was used behind the laminate panel to record the exit velocity in case of perforations.

2.2. C-scan Set-Up

The C-scan setup is developed in-house for automated immersion scanning of composite laminates. It consists of an immersion tank of acrylic glass and a mounting frame furnished with two lead screws in mutually perpendicular directions. Two stepper motors drive the lead screw and a common nut, moving linearly due to their rotation, holds the probe holding device. The transducers fitted in the probe holding device, can move along two mutually perpendicular directions in precise steps and are capable of scanning any predefined two-dimensional region. The transducers are connected to an Ultrasonic board that acts as the pulser, receiver and digitizer of the ultrasonic waveform. The present Ultrasonic board is PCUS11 [5], which can digitize signals with a sampling rate of upto 80MHz. The board seamlessly interacts with manufacturer supplied software [6] that has the capacity to condition, gate and zooming of the digitized signal. The composite laminate is kept immersed in water (coupling agent) and is held strictly parallel to the plane of the movement of the transducer(s). The minimum linear movement possible for the transducer is 0.025 mm. Necessary settings to the effect may be used as input to the stepper motor controller via a wired remote control.

3. Data Clustering Methodology

Clustering is an important technique used in discovering the inherent structure present in any given data set. The task involves grouping or segmenting a set of data (obtained from
measurements, observations) into subsets, such that those within each subset are more closely related to one another than objects assigned to other subsets. There are numerous techniques in this category such as Hierarchical, Non-Hierarchical and Fuzzy. The performance of these algorithms is greatly influenced by the choice of number of cluster. This is a sensitive task and may require enough pre-idea regarding nature of distribution of objects in the set. In order to improve these drawbacks an algorithm was proposed by Wong et al. [7]. This method is based on regulating a similarity measure and replacing movable vectors so that the appropriate number of clusters is determined by the calculation of the best performance index. At initial stage a data point is chosen as a reference vector and those vectors that have high similarity with the reference vector has to be found. Then reference vector will be replaced with the average of those vectors with high similarity with the reference vector. In this way one time will reach when all the replaced vectors will tend toward their cluster centres. In the iterative process of the algorithm, the width of the similarity measure function can be changed. The value of this width plays an important role in determining how large or small range of data can be grouped in the same cluster. Each different width value may result in different number of clusters and their centres. In the iterative process, the width (σ) is increased by the increment (dσ), calculated on the basis of similarity measure, and for each (σ) the classification process is evaluated through calculation of a performance index. In this way the optimum numbers of clusters along with the classification results are obtained that correspond to the highest performance index.

4. Results and Discussions

C-scan images of several impacted regions from Kevlar epoxy composite laminates of thicknesses 20mm, 15mm and 10mm are presented and discussed. The extents of the core damage zones as obtained from the images are then compared with the respective impact and residual velocities of the projectile. For striking velocities higher than the ballistic limit, the bullets perforate the laminates and come out with a residual velocity. In some cases, however, shot lodging takes place, i.e., the bullet does not perforate the laminate and remains within it. Such phenomena are expected to happen when the striking velocity is close to the ballistic limit or if the bullet gets diverted from its striking direction while perforating the plate.

4.1. Dependence of core damage areas of impacted regions in the 20 mm thick Kevlar epoxy Composite Plate on impact parameters

To find the dependence of core damage area on impact parameters, three impacted regions in the Kevlar epoxy composite plate has been chosen for ultrasonic C-scan. Out of the three, two are square regions (zone-1, zone 3) of sizes 72mm x 72mm and 50mm x 50mm. Rest one is rectangular (zone-2) in shape, of size 72mm x 60mm. The scanned zone 2 had to be made rectangular to avoid overlapping with neighboring impact zones. In Figures 1 to 3, the C-scan images of the above regions generated by Wong algorithm are shown. During generation of each of the images, area of the core damage region was estimated. The correlation between the damage areas and the impact velocities is discussed in Table 1 where variations of the core damage areas for zone-1, zone-2 and zone-3 with the striking velocity, residual velocity and energy absorbed are shown. It is observed that in general, the core damage area increases with the increase in absorbed energy.
Table 1. C-scan result of Kevlar Epoxy composite plate based on peak amplitude

<table>
<thead>
<tr>
<th>Scanned zone</th>
<th>Striking Velocity ($V_s$) (m/s)</th>
<th>Residual Velocity ($V_r$) (m/s)</th>
<th>Energy absorbed (J)</th>
<th>Core Damage Area (mm$^2$) by Wong algorithm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zone-1</td>
<td>427</td>
<td>159.1</td>
<td>785.08</td>
<td>190.77</td>
</tr>
<tr>
<td>Zone-2</td>
<td>514.7</td>
<td>278.5</td>
<td>936.77</td>
<td>246.86</td>
</tr>
<tr>
<td>Zone-3</td>
<td>581.9</td>
<td>348.5</td>
<td>1085.78</td>
<td>251.48</td>
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</tbody>
</table>
4.2. Dependence of Core Damage Areas of Impacted Regions in the 15 mm Thick Kevlar epoxy Composite Plate on Impact Parameters

For assessment of the core damage area and its dependency with other impact parameter, another Kevlar-epoxy composite plate of 15mm thickness is ballistically impacted at four different locations with a varying striking velocity. C-scan images of these impacted zones are shown in Figures 4 through 7. The size of the each of the domains is 72mm in both the directions. Feature used in generating the image is the peak amplitude of digitized waveform.

Figure 4. Peak amplitude based C-scan images of zone-1

Figure 5. Peak amplitude based C-scan images of zone-2

Figure 6. Peak amplitude based C-scan images of zone-3
During generation of each of the images, area of the core damage region was estimated. Details of the impact information in terms of striking velocity, residual velocity, and energy absorbed with the corresponding areas of the core damage regions for all the zones are summarized in the Table 2.

<table>
<thead>
<tr>
<th>Scanned zone</th>
<th>Striking Velocity ($V_s$) (m/s)</th>
<th>Residual Velocity ($V_r$) (m/s)</th>
<th>Energy absorbed (J)</th>
<th>Core Damage Area (mm$^2$) by Wong. algorithm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zone-1</td>
<td>618.9</td>
<td>560.4</td>
<td>344.95</td>
<td>622.08</td>
</tr>
<tr>
<td>Zone-2</td>
<td>350.1</td>
<td>261.4</td>
<td>271.2</td>
<td>323.48</td>
</tr>
<tr>
<td>Zone-3</td>
<td>225.1</td>
<td>0</td>
<td>253.35</td>
<td>522.54</td>
</tr>
<tr>
<td>Zone-4</td>
<td>466.2</td>
<td>408</td>
<td>254.39</td>
<td>199.06</td>
</tr>
</tbody>
</table>

The results presented in Table 2, show that the core damage area increases with the increase in loss of energy of the bullet. However the shot lodging case (zone-3) can be taken as a special case where there is an abrupt increase in core damage without corresponding increase in absorbed energy. This can be attributed to the embedding of a bullet of diameter 7.62mm and length 39mm. This is expected to create a damage that covers a large part of the scanned region of 72mm x 72mm.

4.3. Dependence of Core Damage Areas of Impacted Regions in the 10 mm Thick Kevlar-epoxy Composite Plate on Impact Parameters

The images and the corresponding core damage areas are considered for the 10 mm thick Kevlar-epoxy composite plate are presented in this section. The composite plate is ballistically impacted at four regions with different striking velocities. C-scan has been performed in an area 72mm by 72mm in size around the zone of each impact. With this C-scan data, peak amplitude based image is generated for each zone. Figures 8 through 11 show the C-scan images of the impacted zones generated by Wong algorithm. The images clearly bring out the damage region marked with white shade, and these are in consistent with those in the actual specimen. In Table 3, the
core damage areas for zone-1, zone-2, zone-3 and zone-4 with the corresponding striking velocity, residual velocity and energy absorbed are shown. It is observed that in general, the core damage area increases with the increase in absorbed energy.

Figure 8. Peak amplitude based C-scan images of zone-1

Figure 9. Peak amplitude based C-scan images of zone-2

Figure 10. Peak amplitude based C-scan images of zone-3
Figure 11. Peak amplitude based C-scan images of zone-4

Table 3: C-scan result of Kevlar-epoxy composite plate based on peak amplitude

<table>
<thead>
<tr>
<th>Scanned zone</th>
<th>Striking Velocity ($V_s$) (m/s)</th>
<th>Residual Velocity ($V_r$) (m/s)</th>
<th>Energy absorbed (J)</th>
<th>Core Damage Area (mm$^2$) by Wong algorithm</th>
<th>Core Damage Area (mm$^2$) by UPGMAA algorithm</th>
</tr>
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<tbody>
<tr>
<td>Zone-1</td>
<td>360.8</td>
<td>315.5</td>
<td>153.18</td>
<td>149.3</td>
<td>165.8</td>
</tr>
<tr>
<td>Zone-2</td>
<td>507.7</td>
<td>471.1</td>
<td>179.12</td>
<td>157.59</td>
<td>279.6</td>
</tr>
<tr>
<td>Zone-3</td>
<td>253.7</td>
<td>168.3</td>
<td>180.19</td>
<td>215.65</td>
<td>309.89</td>
</tr>
<tr>
<td>Zone-4</td>
<td>550.1</td>
<td>525</td>
<td>134.93</td>
<td>124.42</td>
<td>149.22</td>
</tr>
</tbody>
</table>

5. Conclusions

Based on the above results and discussions following conclusions are made:

- Clustering technique is found to be an effective tool for systematic classification of acquired data pertaining to a single ultrasonic feature or feature set and thus paves the way for automated C-scan image generation.

- From the generated images, it has been observed that the performance of the Wong’s algorithm is consistent to detect the target flaw and its spread. This algorithm is implemented and is shown to fully automate the image generation procedure as it generates optimum number of clusters on the basis of a performance index.

- The automated imaging technique has been employed for assessment of damage due to ballistic impact on several Kevlar-epoxy composite panels. C-scan images generated are able to extract relevant information of the damage state in the impacted Kevlar epoxy composite panels. The areas of the core damage zones are sensitive to the absorbed energy and it increases rapidly in case of shot lodging.
References