THERMOELASTIC INVESTIGATION OF IMPACT DAMAGED WOVEN GRP COMPOSITES

C. Santulli[†], J.M. Dulieu-Barton[‡] and W. Cantwell[*]

The feasibility of using the thermoelastic stress analysis technique to measure damage severity in woven composite materials is investigated. Controlled levels of impact damage are introduced into strip specimens manufactured from laminated woven E-glass polyester material. Thermoelastic data is obtained for the material in the damaged and undamaged state using the Deltatherm system. The readings are compared and it is demonstrated that, with knowledge of the impact location, the thermoelastic signal level increases with damage severity.

INTRODUCTION

Thermoelastic stress analysis [1] is a well-established experimental technique that has been used in a wide range of engineering applications. The technique is based on the measurement of the small temperature change that occurs in materials subjected to elastic cyclic stresses. For linear elastic, homogeneous materials it is readily shown that the stress changes in the material are directly related to the small temperature change. Until recently the standard equipment for thermoelastic stress analysis was the SPATE (Stress Pattern Analysis by the measurement of Thermal Emissions) system [1]. This system uses a single cell scanning infra-red detector to 'measure' the small temperature change. As a result of the SPATE system's scanning mode and its analogue signal processing and in order to obtain noise-free data typical scanning times can be up to three hours. Now [2], a new equipment, known as Deltatherm, is available that uses a detector focal plane array and digital processing techniques so that 'scan' times have reduced to as little as 1.2 seconds. Both systems provide a high resolution full-field digital image of the stress distribution on the surface of a test component.

Damage assessment and monitoring are topics that are receiving much current research interest; in particular the evolution and mechanisms of damage in laminated fibre reinforced plastic composites. The thermoelastic technique offers an advantage in studying these materials, in that it is non-contact and therefore does not use any specimen attachments (such as gauges) that may reinforce the material. However, as thermoelastic stress analysis requires cyclic loading, scan times of the length associated with SPATE often means that the component may damage or existing damage might grow during testing. The reduced data collection time associated with the Deltatherm system means

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[†] University of Nottingham, School of Mechanical, Materials, Manufacturing Engineering and Management, University Park, Nottingham, NG7 2RD
[‡] University of Southampton, School of Engineering Sciences (Ship Science), Highfield, Southampton, SO17 1BJ
[*] University of Liverpool, Department of Engineering, Brownlow Hill, Liverpool, L69 3GH

that the application of thermoelastic stress analysis to damage studies in composite materials has become a more realistic proposition and has introduced the possibility of 'real time' monitoring of damage growth. The underlying theory that relates the thermoelastic response or signal, S, given by the infra-red detection system to the surface stresses in an orthotropic material is identical for both systems [1] and is as follows

$$S = \frac{1}{A^*}(\alpha_{11}^{P}\sigma_{11} + \alpha_{22}^{P}\sigma_{22}) \tag{1}$$

where A^* is a calibration constant based on the detector and material properties, α_{11}^{P} and α_{22}^{P} are the coefficients of thermal expansion in the principal material directions, and σ_{11} and σ_{22} are the changes in the co-ordinate direct stresses in the principal material directions.

It is clear from equation (1) that for a general orthotropic material quantitative stress values cannot be obtained from thermoelastic data alone. The use of thermoelastic techniques for the analysis of orthotropic components should not be dismissed as the quantity $(\alpha_{11}^{P}\sigma_{11} + \alpha_{22}^{P}\sigma_{22})$ is an important stress metric and with calibration (e.g. [3]) can be used for validation purposes. Moreover, as $(\alpha_{11}^{P}\sigma_{11} + \alpha_{22}^{P}\sigma_{22})$ is directly related to the stress level in a component it can be used as the basis for a damage parameter.

In the past successful damage studies have been carried out using the SPATE system; these are described in the review given in Ref. [4]. Impact damage in sandwich construction material has been studied using the SPATE system [5] and damage evolution under fatigue load in a woven glass fibre polyester composite has been monitored using the Deltatherm system [6].

In the present paper the feasibility of using thermoelastic stress analysis to quantify the level of impact damage in woven composites is assessed. The output from the infra-red detector is related to the surface stresses and hence the orientation of the surface weave. Therefore the surface weave must be accurately related to the 'stress pattern' obtained from the Deltatherm system and the position of the impact must be located. A detailed description of the test specimens and the means of introducing the impact damage is provided, along with the application of the theory to the specimens. An analysis routine that relates the Deltatherm output from an undamaged region to that from an equivalent damaged region is developed, the results of which form the basis of the feasibility study.

TEST SPECIMENS AND EXPERIMENTAL ARRANGEMENTS

The test specimen material was an E-glass reinforced polyester; the E-glass was in the form of a woven mat and the resin was an unsaturated polyester (1629 NT) with styrene as a coupling agent. The fibre mats and the resin were laminated into sheets using a resin transfer moulding process to give a fibre fraction for the laminate of 63% by volume. Ten plies of the woven mat were used which gave the sheets a nominal thickness of 3 mm. Four strips of material 200 mm long by 20 mm were cut from the sheet in a '$0^o/90^o$' orientation. To prevent any damage being introduced by the action of the gripping pressure of the loading machine glass fibre/epoxy end tabs (40 mm long by 20 mm wide by 3 mm thick) were bonded at each end and on both sides of the strips.

The impact damage was produced using a hemispherical drop-weight steel impactor mounted in a Ceast Fractovis impact tower. Each of the four specimens was pneumatically clamped on an annular support and different mass impactors (2.53 kg, 3.89 kg, 4.99 kg and 7.54 kg) were used to provide increasing levels of impact energy (5 J, 7.5 J, 10 J and 15J) and hence increasing damage in each specimen. (The impact tower was fitted with an anti-rebound device so that each specimen only received a single impact.) After impact there was no visible damage on any of the specimens, so micrographs and c-scans [7] were used to locate the damage. The micrographs provided a more detailed view of the surface damage and the c-scans revealed the location of internal damage. It was clear from both the micrograph and c-scan data that the position of impact was not in the centre of the specimen but offset towards one edge or the other.

After the impact had been introduced the thermoelastic tests were carried out. The specimens were mounted in an Instron 8501 servo hydraulic test machine and loaded to a stress level of 105 ± 35 MPa. This meant that the maximum load was approximately 50% of the tensile strength of the material. A major assumption in developing the theory that leads to equation (1) is that the temperature changes occur adiabatically [1]. It has been shown that in laminated reinforced plastic composites that this assumption may not be valid [8]. In metals a cyclic loading frequency of around 10 to 20 Hz is usually sufficient to achieve adiabatic conditions; in composites this may not be the case. Therefore the specimens were tested at six loading frequencies of 5, 10, 15, 20 25 and 30 Hz. In TSA it is standard practice to coat the test specimens with a matt black paint in order to standardise and enhance the surface emissivity [1]. It has been shown [5] that for glass reinforced polyester that this is unnecessary. As the paint coating can also influence the surface thermal conditions and cause non-adiabatic behaviour [9], the specimens used in this work were not coated. The thermoelastic data was obtained using a Deltatherm 1000 system fitted with a 25 mm lens; for each test the accumulation time was set to 1.2 seconds and to reduce noise the data was integrated over 2.5 minutes.

ANALYSIS PROCEDURE

A Deltatherm image of the specimen impacted with an energy of 10 J is shown in Figure 1. The impacted region is clearly visible to the right of the centre of the image. The regular pattern of the woven surface structure is also evident away from the damaged region. To analyse this data the surface was divided into 'structural units' that represented one complete 'cycle' of the surface weave pattern. The surface weave configuration of a structural unit is shown in Figure 2, along with the direction of the applied load. In the analysis the data from the edges of the specimen was disregarded so that the width of the structural unit was less than the width of the specimen as indicated in Figure 2.

It is clear from Figure 2 that the specimen is made-up of two weave orientations, one parallel to the applied stress, σ_{app}, and the other transverse to the applied stress. This means that for the parallel weave orientation equation (1) reduces to

$$\sigma_{11} = \sigma_{app} = A^{*}\alpha_{11}^{P}S \tag{2}$$

and for the transverse ply orientation

$$\sigma_{22} = \sigma_{app} = A^{*}\alpha_{22}^{P}S \tag{3}$$

These equations show that the signal from each weave orientation will be different and mean that there will be two distinct signals from the specimen, i.e. one from the parallel weave and the other from the transverse weave. An inspection of Figure 1 shows that approximately this is so, however there is a variation in the signal from the parallel weave. As the variations occur in a regular manner it is likely that they are caused by the manufacturing technique and by the woven nature of the surface structure resulting in an uneven distribution of fibre to resin on the surface.

To aid analysis and to quantify the variation in the readings from the parallel weave the structural unit was divided into twelve sections as shown in Figure 2. The B sections indicate the transverse weave, the C sections indicate the parallel weave either side of the transverse weave and the A and D sections indicate the parallel weave above and below the B/C sections. Readings were taken from each of the sections in the damaged and undamaged regions of each of the four specimens and processed as described in the following two sections.

RESULTS FROM UNDAMAGED REGION

For each specimen and loading frequency readings were taken from a structural unit approximately 30mm away from the impacted region. The average of the readings for each section group (e.g. A1, A2 and A3) was obtained and in each case gave a variation of around 5%. For the A and the D sections the values were virtually identical and the combined coefficient of variation of the average of the A and D sections was less than 5%.

Figure 3 shows uncalibrated signal readings plotted against frequency for the specimen impacted with an energy of 5 J; the A and D weaves are shown as combined values. From 10 to 25 Hz there is a clear decrease in the signal for the A, C and D weaves from around 7100 U to 6500 U indicating there may be some non-adiabatic behaviour at these frequencies; between 25 and 30 Hz there is practically no change in the signal. For weave B there is a slight reduction in the signal although not as marked as in the parallel weaves. It is noteworthy that the readings from weave C is almost the same as those for weaves A and D, which confirms that only small variations arise in the signal as a result of manufacturing.

A similar procedure was carried out on the other three specimens. The specimens with the 7.5 J and 10 J impacts yielded much the same results. However the specimen with the 15 J impact gave slightly increased results of the order of 10 %; this may be due to matrix cracking remote from the impact region caused by a greater specimen deflection at the higher impact energy.

RESULTS FROM DAMAGED REGION

The purpose of this section of work is to quantify the effects of damage on the thermoelastic signal from the material at the point of impact and on the signal from the area surrounding the impact. To avoid any possible discrepancies due to non-adiabatic behaviour it was decided that only the readings taken at 30 Hz should be used (see above). The signal from each section of the structural unit in the damaged region was normalised by dividing it by the appropriate average reading taken from the undamaged region, e.g.

$$S_{NA1} = \frac{S_{DA1}}{S_{UA1}} = \frac{(\sum_{1}^{n_{A1}} S_{DA1})/n_{A1}}{(\sum_{1}^{n_{A1}} S_{UA1} + \sum_{1}^{n_{A2}} S_{UA2} + \sum_{1}^{n_{A3}} S_{UA3} + \sum_{1}^{n_{D1}} S_{UD1} + \sum_{1}^{n_{D2}} S_{UD2} + \sum_{1}^{n_{D3}} S_{UD3})/N} \qquad (4)$$

where the subscripts U and D denote undamaged and damaged readings and n is the number of signal readings from each section and N is the total number of readings from the six sections (or three for B and C) used in the averaging process.

The normalised results for each impact energy are plotted as histograms in Figure 4, 5, 6, and 7 for 5, 7.5, 10 and 15 J respectively. For this type of presentation an S_D/S_U value of unity means that the damage has had no effect and that the material is in its 'normal' condition. Because of signal noise the normal condition should be regarded as somewhere between 1.10 and 0.90. Values of outside this range indicate that a change in the stress state and/or material properties has occurred and that the damage is influencing the signal. In assessing the results in Figures 4 to 7 it is important to locate the position of the impact; the Deltatherm images were used to identify an approximate position, along with the c-scan and micrograph data. The approximate positions of the impacts within the structural unit is given in Table 1.

TABLE 1 Approximate position of impact

Impact energy (J)	Section
5	A1
7.5	C2
10	B2
15	A3/B3

Figure 4 shows the results for the 5 J impact energy. From examination of the Deltatherm image and the micrographs it appeared that for this specimen the impact occurred in section A1, this is confirmed by the fact that the largest normalised reading is given by section A1. This means that sections B1, B3, C1, C3 and D3 were adjacent to the impact; these regions have S_D/S_U readings of greater than one indicating that these regions were also affected by the impact.

Figure 5 shows the results for the 7.5 J impact. Here the impact took place in section C2, which gives a normalised reading of 1.2. Sections A2, A3, B3, D2 and D3 were adjacent to the impact region and the impact appears to have little effect on the A and D sections. (This indicates that it is likely that the 5 J impact (see Figure 4) occurred at the interface between A1 and D3 as the D3 reading is comparatively large.) Although only section B3 is adjacent to the impact all of the B readings are in excess of 1.2. This points to the possibility that the transverse weave signal response is more sensitive to damage than the parallel weave.

In Figure 6 the impact took place in section B2, which gave a S_U/S_D value of 1.6, i.e. 30% greater than all the other values obtained from this specimen. The adjacent sections are A2, A3, C3 D2 and D1, with the exception of A2 these appear not to have been affected by the impact. As with the 7.5 J test the readings from the non-adjacent B sections are large, once again indicating that the transverse fibre signal response is more susceptible to damage.

Figure 7 shows the results for the 15 J impact that took place at the interface of section A3 and B3. Although, A3 and B3 give large S_D/S_U readings the most noticeable trend is that all of the readings are greater than unity indicating that the impact damage is provided by the higher energy level is spreading to influence the thermoelastic readings from the entire structural unit.

DISCUSSION

This work is not intended to provide an in-depth study of the effect of impact damage on woven composites, but to show that thermoelastic data obtained from impact damaged specimen can be interpreted in a meaningful way in respect to the level of impact damage. The results given in the previous section have demonstrated that despite the complex surface structure of the material this can be done. It is clear that without prior knowledge of the point of impact the interpretation of the results would not be straight-forward. However, the Deltatherm images provided an indication of the impact position, which was confirmed by other non-destructive techniques.

A notable feature of this work was that the damage was mainly sub-surface and it was detected and quantified using the thermoelastic technique. The impact damage clearly disrupted the regular pattern of the data obtained from the undamaged regions and gave a good indication of the damage location. The technique of taking the signal readings from small sections of the specimens and normalising them with respect to equivalent undamaged signal proved successful as the point of impact was identified as that with the greatest S_U/S_D value for each specimen. Most notable is the general increase in the thermoelastic response of the transverse sections as the impact energy increases (see Figure 8) regardless of the location of the impact. This indicates that the thermoelastic response of the transverse orientation is more sensitive to low levels of damage in comparison to the parallel orientation. This result may only be valid for the tensile loading mode, as the transverse weave will be weak in comparison to the parallel weave and any minor damage will be exaggerated. Another possibility is that the resin material properties dominate the response from this mode (see equation (3)) and comparatively small matrix cracks may serve to change the thermoelastic properties of the material. The change in the signal from the transverse weave as damage increases is certainly an important finding of the work and clearly warrants further investigation.

A cautionary note is the change in the thermoelastic response in the undamaged material over the frequency range. A similar variation was noted in the damaged region and hence the decision to use the highest frequency achievable with the loading machine. Non-adiabatic behaviour is clearly a topic that requires further detailed examination, in particular the changes in the thermal conditions that occur as the damage progresses.

CLOSURE

The thermoelastic stress analysis technique has been used to study damage in woven glass polyester composites. The work has clearly shown that the thermoelastic technique has great potential in this area and that it is feasible to use the thermoelastic signal as a damage indicator.

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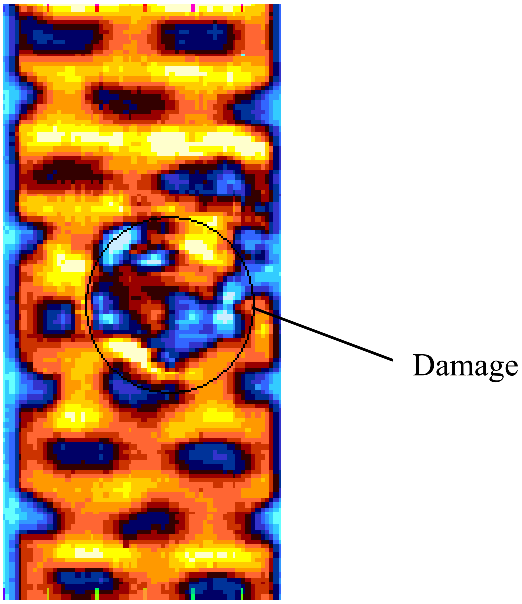

FIGURE 1 Deltatherm image of specimen impacted with an energy of 10 J

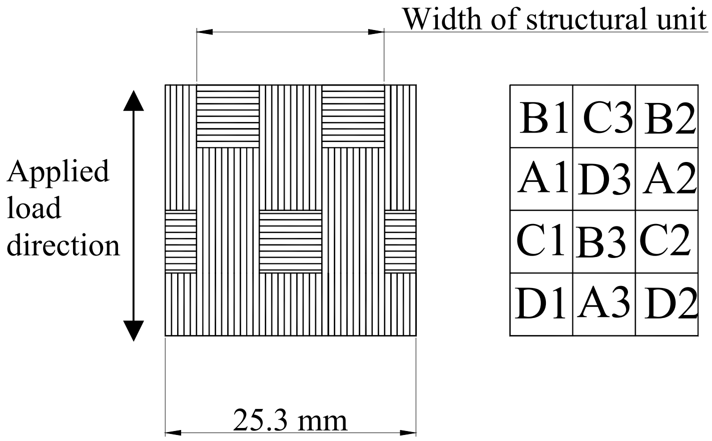

FIGURE 2 A structural unit of surface ply

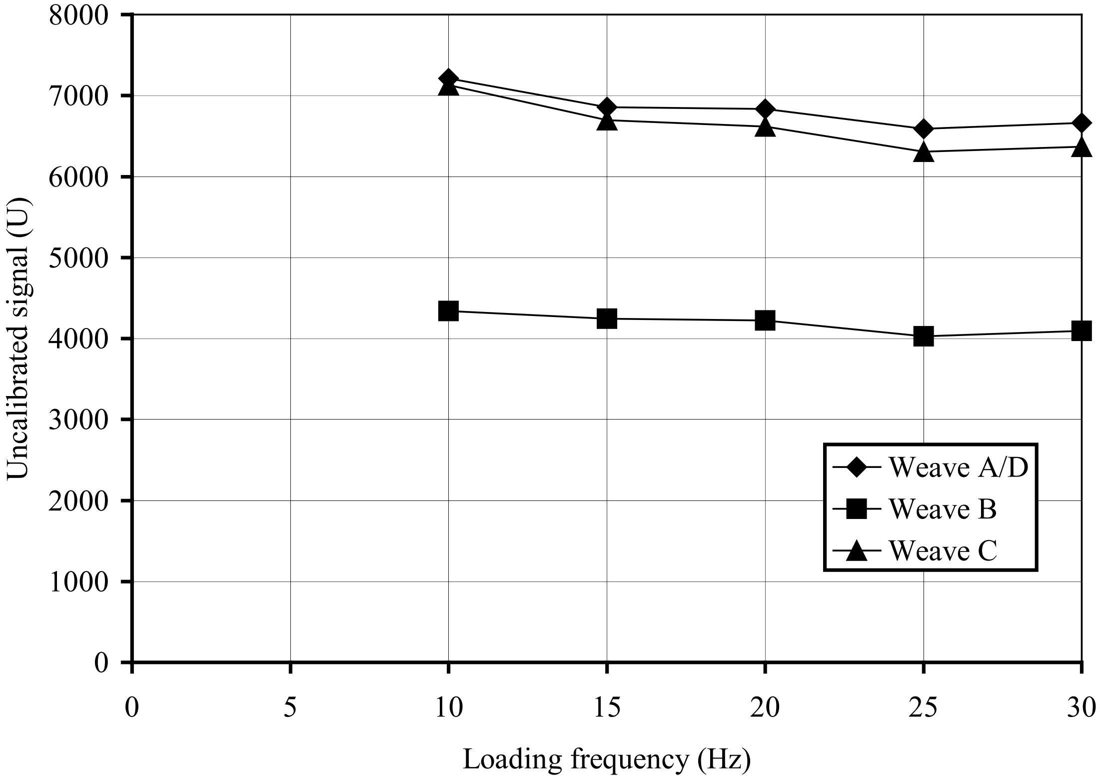

FIGURE 3 Thermoelastic signal against loading frequency for undamaged material

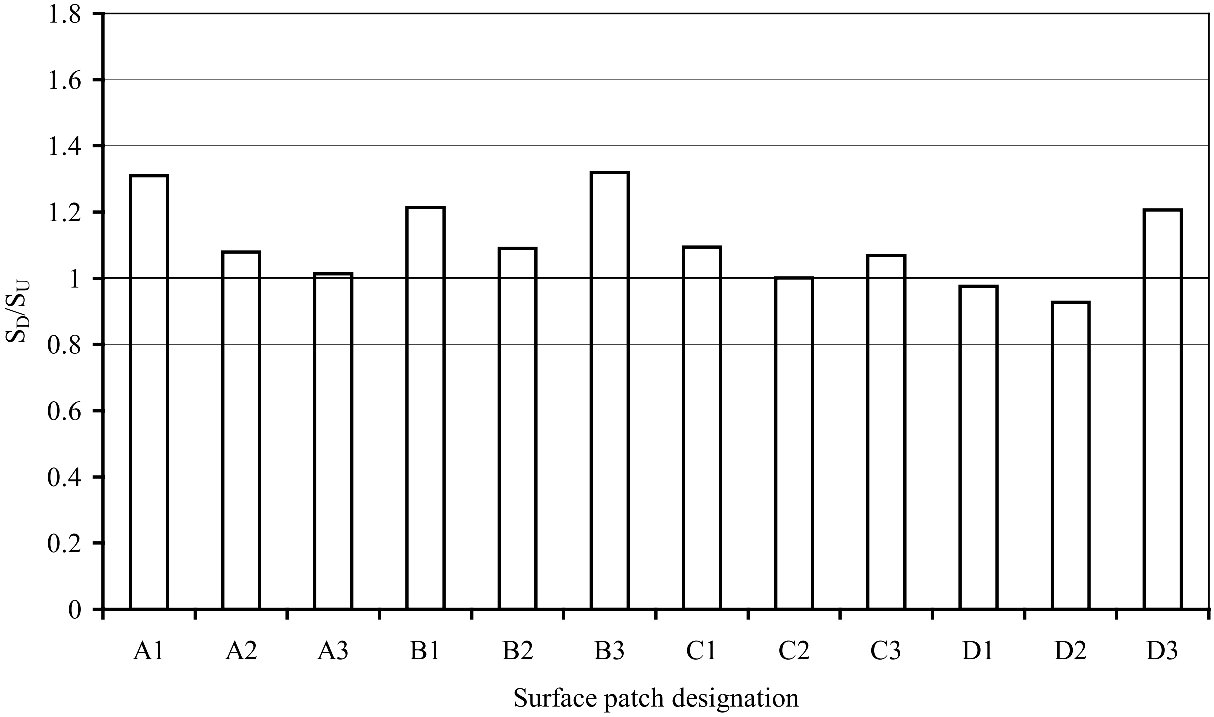

FIGURE 4 Histogram for 5 J impact

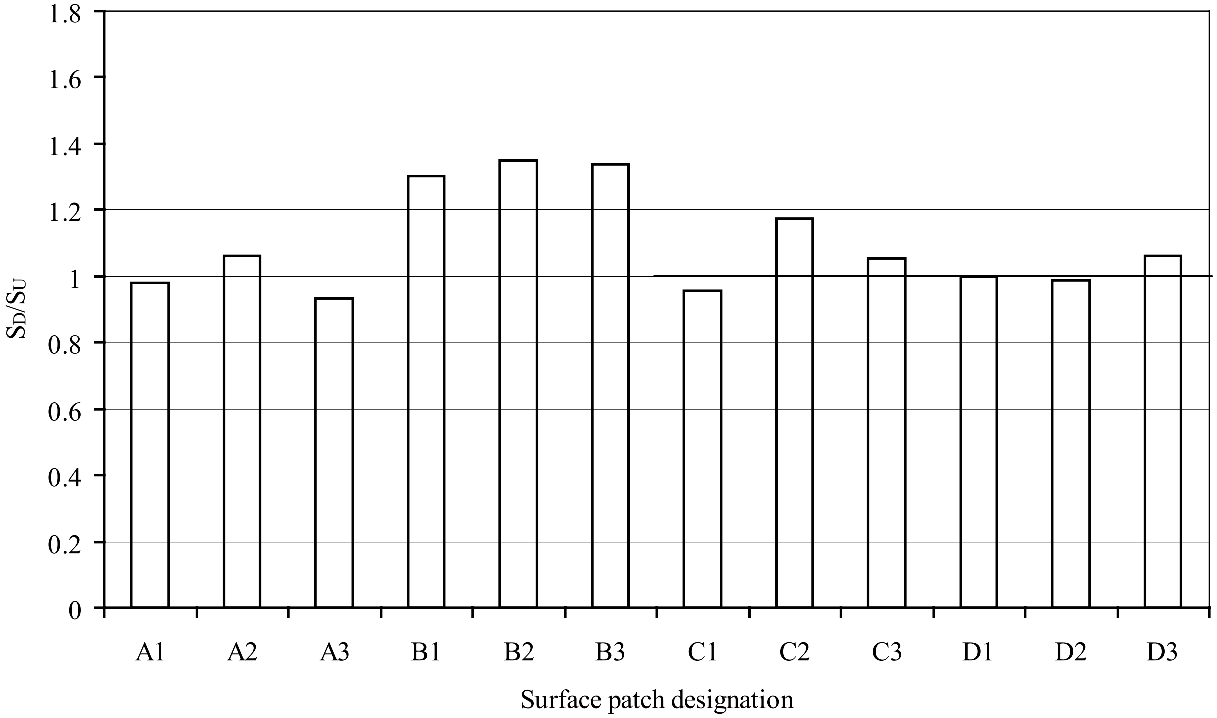

FIGURE 5 Histogram for 7.5 J impact

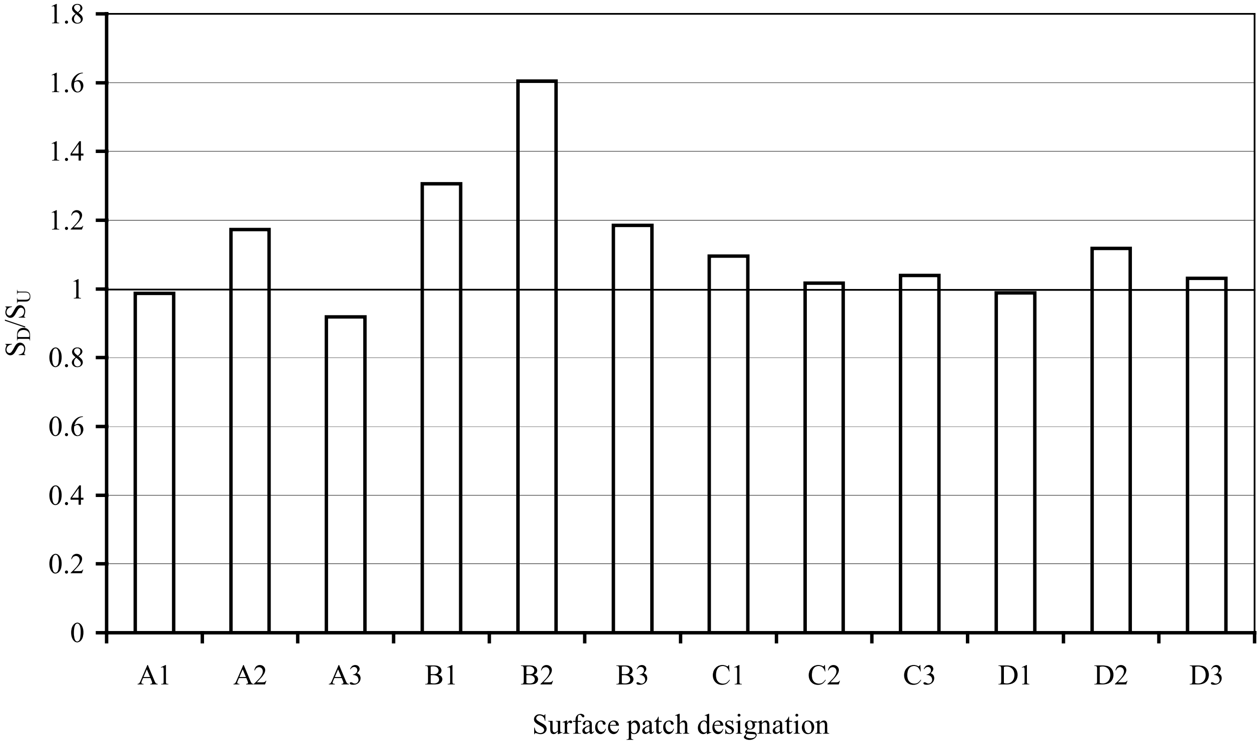

FIGURE 6 Histogram for 10 J impact

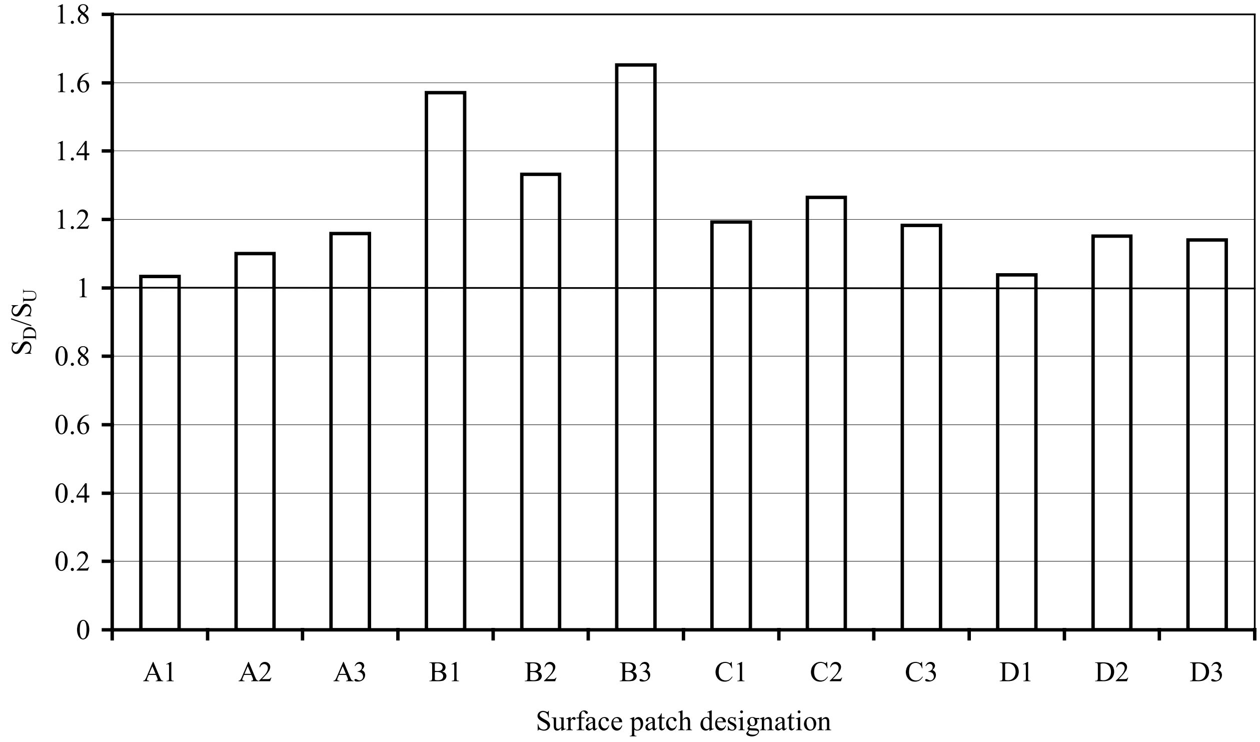

FIGURE 7 Histogram for 15 J impact

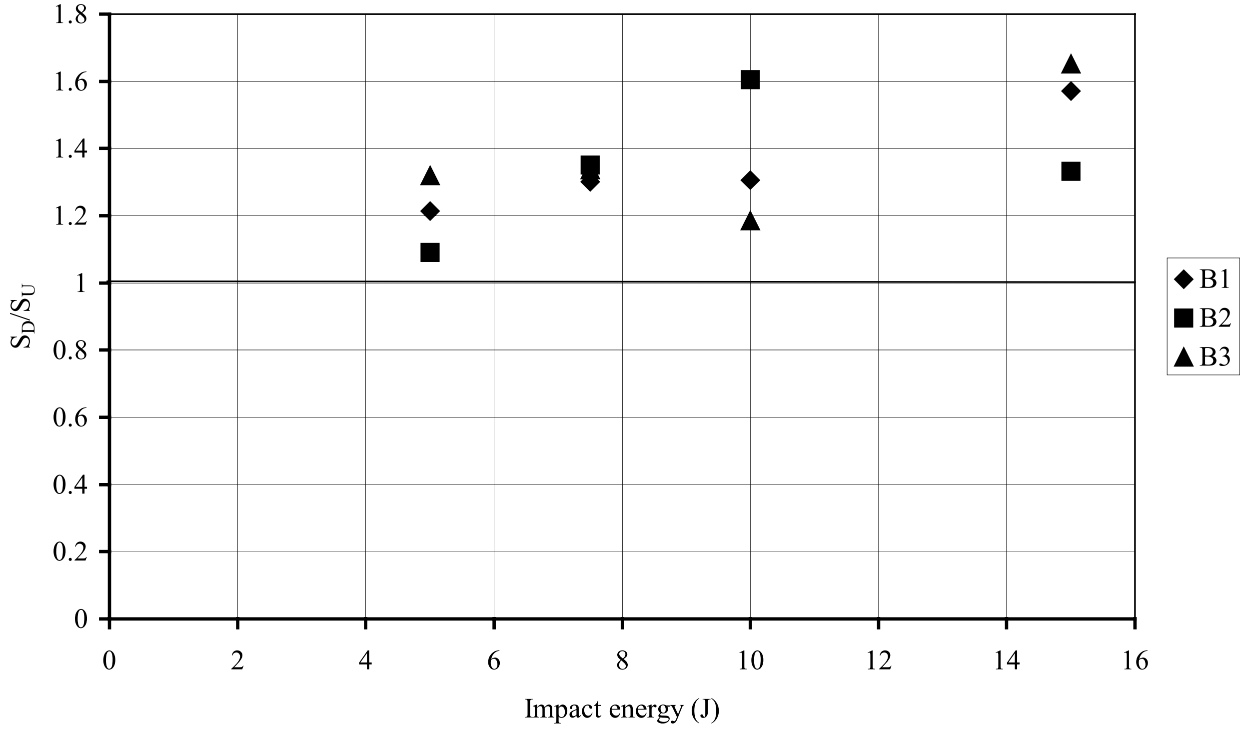

FIGURE 8 S_D/S_U for weave B