Composites: Part B 45 (2013) 601–608

Contents lists available at SciVerse ScienceDirect

Composites: Part B

journal homepage: www.elsevier.com/locate/compositesb

Falling weight impacted glass and basalt fibre woven composites inspected using non-destructive techniques

Stefano Sfarra [a], Clemente Ibarra-Castanedo [b], Carlo Santulli [c,*], Alfonso Paoletti [a], Domenica Paoletti [a], Fabrizio Sarasini [c], Abdelhakim Bendada [b], Xavier Maldague [b]

[a] Department of Industrial and Information Engineering and Economics (DIIIE), Università dell'Aquila, Piazzale E. Pontieri 1, Monteluco di Roio, I-67100 Roio Poggio, 7 L'Aquila, AQ, Italy

[b] Department of Electrical and Computer Engineering, Computer Vision and Systems Laboratory (CVSL), Laval University, 1065 Av. de la Médecine, Quebec City, Canada G1V 0A6

[c] Department of Chemical Engineering Materials Environment (DICMA), Sapienza Università di Roma, via Eudossiana 18, I-00184 Rome, Italy

ARTICLE INFO

Article history:
Received 27 February 2012
Accepted 21 September 2012
Available online 17 October 2012

Keywords:
A. Glass fibres
B. Damage tolerance
B. Impact behaviour
D. Non-destructive testing
Basalt fibres

ABSTRACT

A limited number of comparative studies on falling weight impact properties of different composites exist, especially using non-destructive techniques (NDTs). In this work, two types of woven fabric composites, reinforced respectively with E-glass fibres and basalt fibres, were subjected to low velocity impact at different energies (7.5, 15 and 22.5 J). Comparative indications were offered by impact hysteresis cycles and the integration of data between different enhanced vision methods, namely interferometric and IR thermographic techniques. The integrated application of these techniques suggests that the increased directionality of impact damage observed in basalt fibre reinforced composites, though their impact performance appears to be slightly superior, may represent a limitation on the predictability of their behaviour.

1. Introduction

Basalt fibres are increasingly proposed as an alternative to glass fibres as reinforcement for composite materials, in that they combine ecological safety, natural longevity, and fire safety (incombustibility) [1]. In addition, basalt fibre composites have higher chemical stability, largely exceeding fibreglass as regards acid, alkali and steam resistance, which can make the former preferable over the latter e.g., in the automotive industry, where extensive use of acids is made [2]. The properties of basalt fibre composites appear to be comparable with glass fibre composites in terms of Young's modulus, compressive and bending strength, impact force and energy [3]. In practice, most studies of impact properties on basalt fibre reinforced composites still concern unidirectional impact (Charpy or Izod) [4]. For the envisaged applications, it is important to evaluate whether they offer advantages also in terms of resistance to low velocity impact damage, caused by falling weight, which is a frequent occurrence during composites service, resulting sometimes in severe internal damage being generated with no external indication. In impact damage, several damage mechanisms can be operating, viz. matrix cracking, fibre breakage, fibre pullout, fibre–matrix debonding and delamination. In addition, the composite response to falling weight impact (IFW) is affected by a number of parameters, including the mass and the geometry of the impactor, the laminate stacking sequence and the type, architecture and volume of reinforcement fibres. This complexity is one of the reasons because comparative studies between different composites, as regards IFW properties, are limited.

IFW hysteresis cycles reflect the fact that in composites the relation of the contact force with indentation responds to different laws during loading and during unloading, this difference is growing with increasing damage [5]. The study of impact hysteresis cycles from the force vs. displacement curves allows the partition of absorbed energy in different components (elastic, plastic and damping fractions) [6]. Moreover, a quasi-linear value can be obtained during loading to the maximum load, usually referred to as *linear stiffness* [7,8].

Another possibility for characterising impact damage is using non-destructive testing (NDT) methods. This can be useful in particular, whenever it is important to establish whether a composite part or structure, which has been subjected to an impact event, can continue service (after repair, if necessary). NDT methods allowing enhanced vision of the damaged area have been used already for this purpose. These include for example interferometric techniques, which allowed obtaining three-dimensional images of the impacted laminates following thermal straining [9]. Electronic speckle pattern interferometry (ESPI) proved capable of identifying the presence of impact damage, with efficiency dependent on the

* Corresponding author. Tel.: +39 06 44585408.
E-mail address: carlosantulli141@gmail.com (C. Santulli).

1359-8368/$ - see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.compositesb.2012.09.078

location of the through-thickness delaminations produced by impact [10].

Also IR thermography has already been employed for impact damage characterization, in most cases leading to additional information about the extent and criticality of degradation, in particular for damage beyond the "barely visible" level [11]. This poses the problem of the overlapping of damage information coming from different layers, information, which is merged in an "apparent damage area" obtained using IR thermography on both surfaces of the laminate. Several excitation methods have been employed to visualise damage: a possibility is using optical stimulation through the application of a thermal pulse directly on the surface to be observed or in transmission on the opposite surface [12]. Another possibility is the application of the vibration pulse, which would promote the visibility of damage, thanks to the heating produced by mutual rubbing of the delaminated layers. Here, the application of suitable signal treatment methods to IR thermography data would possibly improve the resolution and the accuracy of measurements and the possible correlation with other enhanced vision techniques, such as the interferometry-based ones [13].

The rationale for this work comes from a previous study concentrating on post-impact flexural data of these composites impacted at the same impact energies i.e., 7.5, 15 and 22.5 J. In that case, it was suggested that both laminates show some properties degradation for growing impact energies: more specifically, the maximum impact energy applied, 22.5 J, does result in a degradation of flexural strength and modulus not exceeding 15% [14]. However, basalt retains some superiority, as was already the case for the flexural properties of non-impacted laminate [15]. It was suggested nevertheless that a substantial amount of damage was present in both cases, especially for the highest impact energy applied, which recommended further characterisation.

In this respect, the integrated use of a number of enhanced vision techniques on impact-damaged composites, with data provided by the analysis of IFW hysteresis cycles, may be able to offer a global picture of the post-impact situation of a laminate. In this work, Digital Speckle Photography (DSP), Holographic Interferometry (HI) and Square Pulse Thermography (SPT) are used to compare glass fibre and basalt fibre reinforced laminates subjected to IFW.

2. Materials and methods

The basalt (BAS 220.1270.P) and E-glass fabrics (RE 220P) were plain weave fabrics supplied by Basaltex-Flocart NV (Belgium) and Mugnaini Group srl (Italy), respectively. Both fabrics had the same specific surface weight (220 g/m^2). The matrix used was a Bisphenol-A epoxy based vinylester resin (DION 9102) produced by Reichhold, Inc (USA). The hardener and accelerator were Butanox LPT (MEKP, 2 wt.%) and NL-51P (Cobalt 2-ethylhexanoate, 1 wt.%), respectively.

The laminates were manufactured by the laboratory Resin Transfer Moulding (RTM) system [16]. The fibre volume fraction for both composites was equal to 0.38 ± 0.02 and their thickness was approximately equal in both cases to 3 ± 0.1 mm. From the laminates 100 mm-side square plates were removed for falling weight impact damage characterization. Low velocity impact tests were conducted using a drop-weight impact tower fitted with an anti-rebound device. The impactor, with a 12.7 mm diameter, consists of a piezoelectric load cell to record the force and a high-speed video camera to record the impactor displacement during the impact test. Prior to undergoing impact loading, the samples were clamped to a square frame with a 73 mm square window. The mass of the bare impact carriage was 2.5 kg. Further masses were added to obtain the required impact energy. In particular, three different impact energies were used in this study, being equal to 7.5, 15 and 22.5 J respectively. These were obtained by setting the impact height at 300 mm and varying the weight, which was equal to 2.5, 5 and 7.5 kg respectively. Five laminates were tested for each impact energy.

2.1. Holographic Interferometry (HI) – Double-Exposure technique (DE)

Holographic interferometry (HI) is defined as the interferometric comparison of two or more waves, one of which is holographically reconstructed, to acquire spatial information about the shape and the deformation of the object with no dependence on the surface roughness or texture [17]. During holographic testing, a highly coherent light is required, while the specimen does not need any prior object preparation.

In the present research work one variation of the holographic interferometry technique was assessed, double-exposure HI [18]. In double exposure HI, two holograms are recovered on the same plate, with each one capturing the object in a different state separated by a fixed time interval (Fig. 1).

This technique can be used to gain meaningful information as regards the structural characteristics of a component, by observing the surface deformation produced when the component is subjected to a mild stressing force. Double-exposure method has potential for inspection problems wherein the feature of interest can be visualised as an anomaly in an otherwise regular interferometric fringe pattern. Stress application technique must be devised in such a way that the anomalies induce detectable perturbations in the surface deformation.

During reconstruction the two waves, scattered from the object in its two states, will be reconstructed simultaneously and interfere, producing onto three dimensional virtual image of the object an interference pattern that in general represents a contour map of the object changes. The double-exposure hologram can be stored and later reconstructed for analysis.

Distortions of the photographic emulsion affect both images equally and no special care needs to be taken in illuminating the hologram during the reconstruction.

In addition, since the two diffracted wavefronts are similarly polarized and have almost the same amplitude, the fringes have a very good contrast.

During the interferometric inspection, the interferograms were acquired using a laser product by CRISEL INSTRUMENTS S.r.l. with a fundamental wavelength of 532 nm, vertical polarization and a specified power of 250 mW. Double-exposure measurements were made in transmission mode using a welder (P_{max} = 400 W) as thermal source (distance welder-specimen: 3 mm) [19,20].

2.2. Digital Speckle Photography (DSP)

A diffuse scattering surface, illuminated by laser light, appears covered by a pattern of bright and dark spots or speckles randomly distributed in space, due to an interference phenomenon [21,22].

Digital Speckle Photography (DSP) is based on the calculation of the geometrical displacement of a speckle pattern [23,24].

In modern DSP, the classical point-by-point interrogation can be digitally simulated by segmenting the digital specklegram into a series of small sub-images and Fourier transforming each sub-image. Then, a second fast Fourier transform is applied to the fringe pattern and two symmetrical peaks are generated in the spectral domain. An automated measure of the magnitude and orientation of displacement can be made from the FFT spectrum. Separation of each pair of side peaks gives a direct measure of the translocation of the speckles in the respective interrogation region, while its direction is given by the line connecting the peaks. Repeating the