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Prediction of load threshold of fibre-reinforced laminated composite panels subjected to low velocity drop-weight impact using efficient data filtering techniques

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ABSTRACT

This work is concerned with physical testing of carbon fibrous laminated composite panels with low velocity drop-weight impacts from flat and round nose impactors. Eight, sixteen, and twenty-four ply panels were considered. Non-destructive damage inspections of tested specimens were conducted to approximate impact-induced damage. Recorded data were correlated to load–time, load–deflection, and energy–time history plots to interpret impact induced damage. Data filtering techniques were also applied to the noisy data that unavoidably generate due to limitations of testing and logging systems. Built-in, statistical, and numerical filters effectively predicted load thresholds for eight and sixteen ply laminates. However, flat nose impact of twenty-four ply laminates produced clipped data that can only be de-noised involving oscillatory algorithms. Data filtering and extrapolation of such data have received rare attention in the literature that needs to be investigated. The present work demonstrated filtering and extrapolation of the clipped data using Fast Fourier Convolution algorithm to predict load thresholds. Selected results were compared to the damage zones identified with C-scan and acceptable agreements have been observed. Based on the results it is proposed that use of advanced data filtering and analysis methods to data collected by the available resources has effectively enhanced data interpretations without resorting to additional resources. The methodology could be useful for efficient and reliable data analysis and impact-induced damage prediction of similar cases' data.

1. Introduction

Carbon fibre thin laminates are being widely used as building blocks of aircraft and modern light-weight structures due to their high elastic modulus and high strength. However, their behaviour under the flat nose low velocity tool (tool box) drop impacts during part assembly, manufacturing, normal service, and maintenance operations is a major concern. Such impacts could cause barely visible internal damage. The invisible damage could severely reduce compressive strength of the impacted sub-component during future operations and might result in un-expected catastrophic failure. Extensive investigations are being carried out on various aspects of the topic in order to maintain level of quality and safety required to avoid failure. Selected and most relevant studies are referred below for further details.

Widely used drop-weight impact testing and damage measuring procedures of laminated plates are documented in (ASTM: D7136). Impact damage resistance and damage tolerance of fibre reinforced laminated composites using different approaches to assess impact induced damage are reported in [1,2]. Effect of impactor shapes and geometries were investigated in [3–5]. The damage response on multilayer plates and stacking sequences is reported in [6,7]. Mainly utilised non-destructive techniques in aircraft industry consisting of: visual inspection, ultra-sonic C-scans and Eddy-current are reported in [8,9]. The techniques produce a planar indication of the type and extent of damage to detect certain kinds of damage distribution and progression without causing any major damage to the laminate that can be re-used or further tested. Main disadvantages and limitations of using the techniques are: whole structure has to be inspected, inspection process causes interruptions in normal operations and delays, and produces two-dimensional scan plots where multi-plane delaminations are projected on a single plane [10–12]. Hence, the techniques need to be supplemented with the data analysis for impact induced damage interpretations and analyses.

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Common difficulty in measuring data, analysis, and damage detection is the contamination of noise due to vibration of impactor, target, rig, and other apparatus at different frequencies [13].

Damage detections in impacted composite laminates using de-noising and frequency response methods are described in [14]. De-noising the impact produced data and damage detection by means of electrical potential techniques are reported in [15,16]. The studies report that the impact produced noise could amplify and distort data interpretation and analysis [17]. It has been reported that three-dimensional elasticity theory based finite element analysis combined with the low velocity impact tests could reduce the noise in [18]. Another study to reduce the difficulty with data analysis based on coupled finite element and Kalman filter is proposed in [19]. A new sigma-point (linear regression based) Kalman filter was proposed in [20] to address nonlinearities induced by inter-laminar lay-ups. The filter uses the first order Taylor series expansion and accordingly updates statistics of the structural state. Improved estimates on delamination state and parameter identification via joint Kalman linear statistical filters are reported in [21].

In addition to the traditional data filtering and time signal averaging techniques, the Fast Fourier Transforms are also being applied to filter and analyse data in material damage detection for many years [22,23]. Filtered curves were used in conjunction with the unfiltered curves to predict the threshold load [24]. Laminates of three types of lay-ups: eight, sixteen and twenty-four were tested using round and flat round nose impact profiles. Components of higher frequencies were filtered so that only harmonics of fundamental frequency level responses could be seen as reported in [25]. Experimental results have shown significant improvement in accuracy with using the FFT-Convolution techniques as signal analysis tool greatly aid in interpretation of the data [23].

Impact generated data were filtered, threshold loads were predicted, compared and correlated to the relevant C-scan identified damage zones and were found within acceptable (±12%) deviations. The results proposed that use of advanced data filters can enhance interpretation of the data recorded with the available resources and make the investigation more efficient and reliable.

2. Materials of laminated composite panels

Carbon fibre composites were developed by combining two or more engineering materials reinforced with strong material fibres to obtain a useful third material that exhibits better mechanical properties and economic values. Most of the composite materials are made by stacking several distinct layers of unidirectional lamina/ply made of the same constituent materials: matrix and fibres. The laminates used in this study were donated by industry, made of aerospace grade carbon fibre reinforced toughened epoxy infused Fibre dux 914C-833-40 embedded with satin weave fibre horn technique of every fifth ply. Stacking sequence code is $[0/45/\text{-}45/90]_{ns}$ for the symmetrical laminates where the subscript 's' stands for symmetric and '*n*' varies from 1, 2, and 3 for repetition of the lay-ups. In-plane dimensions of the laminates consist of plane dimensions of 150 mm × 120 mm. Panels have average variable thickness: 2.4 (±0.02), 4.8 (±0.023), and 7.2 (±0.026) mm respectively as shown in schematic view Fig. 1.

The uniform material properties of individual layer in the laminates were assumed as given in Table 1.

3. Outline of the study

An outline of the investigation is depicted in flowchart Fig. 2. Physical tests were conducted of the panels shown in Fig. 1. Non-destructive examinations of the impacted specimens were performed. Impact produced data were analysed using built-in, statistical, numerical and fast Fourier filters. Data analysis assisted using filters to remove the low frequency impact response so that they could not dominate the high frequency signals.

4. Impact tester and drop-weight impact testing

The tests were performed analogous to the actual impact event of real materials using an instrumented drop-weight testing system, INSTRON™ Pneumatic Dynatup System 9250HV (Products, 2011) shown in Fig. 3. The drop-weight machine represents situations such as accidentally falling of drop hammer, tool (box) during fabrication or maintenance, kitchen van etc. The test system is suitable for a wide variety of applications requiring low to high impact energies using an instrumented falling weight with no energy storage device. The maximum impact energy is limited by the adjustable falling height. The target clamping fixture sandwiches laminate between two rectangular steel plates that had circular central holes for 50 mm diameters test area. Flat and round nose shape steel impactors were used in the study. The flat type impact is regarded as common danger in aerospace industry hence the nose shape was fabricated in the university workshop. Selected specifications of the machine requiring power 240 V are given below. Force transducer type: strain gauge/piezoelectric, measurement of drop mass (maximum load = 80.5 kg): electrical with strain gauge load cell. Position transducer (max energy = 1603 J; min pressure = 0.414 MPa): optical encoder. Position accuracy: equal of less than ±0.2 mm or ±0.05% of displayed reading. Position repeatability: ±0.015 mm; speed accuracy: ±0.1% steady value. Velocity (max velocity = 20 m/s) detector display accuracy: ±0.25%; and velocity accuracy: ±2% of set value.

The laminates were tested mostly following the accepted American standard testing method for measuring damage resistance of a fibre-reinforced polymer matrix composite to a drop weight impact event (ASTM: D7136). The design of the testing was restricted to the analysis of low velocity below 5 m/s to avoid penetration. Prior to impacting, the laminate was tightly clamped around edges. As it is expected, these stable structures provided more logical experimental results. All tests were performed at room temperature. During each test, initial height was adjusted from the drop-weight height release levels to hit the laminate with a selected velocity at the centre of the laminate under the impactor head. To calibrate the brake system, the impactor was lowered to touch the surface of the laminate. Once the machine was set to its correct configuration and all data acquisition software running, the impactor was released to impact the laminate. Experiments start from minimal damage to the laminate under varied impact velocities ranging from approximately 1.6 to 4.3 m/s. Three different experiments were performed at the same impact velocity and the same conditions because there may be loose connection, defected samples or errors in sensors. Histories of impact loading were recorded using a PC-controlled high-speed A/D converter during every test.

5. Non-destructive damage inspection

Specimens were impacted at constant weight and different impact velocities to examine step by step damage. Results from relatively thin panel (8-Ply laminate) are well documented and are not being reported [1,8,10,15,18,26]. Similarly, Visual inspections and Eddy-current diagnosis methods provide quick and in-expensive general assessment but low velocity impact damage is internal and invisible. The C-scan maps of impacted laminates provide information on the damage mechanisms more particularly