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THE LOW-VELOCITY IMPACT DAMAGE RESISTANCE OF THE COMPOSITE STRUCTURES - A REVIEW

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Abstract. A brief review of research progress in dynamic and static response of composites structures subjected to low velocity impact and quasi-static loads has been presented. This review paper focused on experimental and numerical studies done by many authors recently for the low-velocity impact damage. For simulations of drop weight low-velocity impact damage, many researchers has used software programs in order to predict the failure modes in composite structures such as ABAQUS/Explicit, LS-Dyna, and MSC. Dytran, DYNA3D, and 3DIMPACT have been commonly used. The impact response of high performance fiber composites is reviewed. An attempt is made to collect the work published in the literature and to identify the fundamental parameters determining the impact resistance of composite materials and their properties. The review concludes with detailed discussions on the damage mechanisms and failure criteria for composite structures subjected to impact loads.

1. INTRODUCTION

In a variety of engineering fields, composite materials are rapidly replacing the so-called conventional materials due to their specific properties and design flexibility. Besides mechanical properties, surface finishing of composite parts is among the most important criteria for quality control. Good surface finishing improves not only the aestheticism of the final structure, but also the quality of the part assembled after manufacturing [1-4]. The sandwich composite structure panels are increasingly being used in aircraft, automotive, and aerospace industries due to their high specific strengths and stiffness. However, sandwich composite structures are susceptible to damage and failure due to transverse contact and to impact with foreign objects. The failure mode map is found to be a good technique in designing sandwich composite structures to optimize their energy absorption properties and load carrying capacity with minimum weight to satisfy the quasi-static and impact loading requirements [5-8]. There has been a growing interest, particularly in the few last decades, in the use of composite materials in structural applications ranging from aircraft and space structures to automotive and marine applications due to their behavior under impact loading is one of the major concerns [9]. Unidirectional laminated plates are highly susceptible to the transverse impact loads resulting in significant damages such as matrix cracks, delamination, and fiber fractures. Therefore, a lot of studies have been carried out to help understand and improve the impact response of composite materials and structures [10-14]. Impact damage is a major issue in the design of laminated composite structures, as it may reduce strength and stiffness significantly without any visible damage at the surface [15]. Typical impact damage appears in the form of matrix crack-

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ing, fiber-matrix debonding, delamination, surface micro buckling, fiber shear-out, and fiber fracture. In particular, the internal delamination often occurs due to the relatively low interlaminar shear (ILS) strength, which can lead to a significant strength reduction in post-damage performance [16]. Composite laminates are expected to absorb low velocity impacts either during assembling or in use. When the laminate is subjected to even barely visible impact damage, micro-damage is incurred, which can have a significant effect on the strength, durability, and stability of the laminates [17-19]. A new characterization technique to measure and quantify surface defects in composites based on deflectrometry was used by Fotsing et al., [20]. Damaged areas can be investigated visually by optical or electron microscopy, ultrasonic B-scanning, C-scanning, and acoustic imaging [21-23]. Synchrotron radiation computed tomography (SRCT) enabled an approach for damage assessment and quantification used by Bull et al., [24]. An approach to evaluate the impact damage initiation and propagation in composite plates is investigated by Luo et al. [28]The presence of internal damage was found to cause substantial degradation in important mechanical properties, including strength and stiffness [25]. Static and low-velocity impact on mechanical behaviors of foam sandwiched composites with different ply angles face sheets was investigated by Mohmmed et al., [26]. Lightweight composites and sandwich composite structures are susceptible to impact damage, which may severely decrease the structural stiffness, stability, and load carrying capacity. However, the damage suffered internally by the panel during impact is very difficult to inspect [27-32]. A new nonlinear high order theory for sandwich beams with the analytical and experimental investigation studied by Dariushi and Sadighi. The experimental results of specimens with different arrangement support the claims which were based on analytical predictions about similarities and differences between linear and nonlinear models. In all cases the good agreement is obtained between the nonlinear analytical predictions and experimental results [33]. Most research detects impact behavior on thin laminates, typically no thicker than 2 or 3 mm. Only a few recent papers were found that analyzed or experimented with considered as a thick laminate [34]. The residual tensile, compressive, shear and bending strengths of a sandwich structure have all been shown to be reduced after low velocity impact. Perhaps the most susceptible to impact is the residual compressive strength of the structure and thus the compression after impact (CAI) test is the most important in the impact characterization process [13,35-37]. The impact design problem is approached in two ways: i) the first one is experimental and requires several measurements of the impact behavior of the studied material under different loading conditions and sample geometry; ii) the second one is mainly related to the simulation of the impact phenomena using finite element methods and requires very powerful hardware and software resources [38]. Sandwich composites are finding increasing applications in aerospace as well as commercial structures [39]. Furthermore, structural materials can be subjected to complex loading configurations, thus prototyping and experimental testing in order to evaluate the mechanical response can be expensive and time consuming process [40]. An approach to evaluate the impact damage initiation and propagation in composite plates is investigated by R. K. Luo et al. [41]. Although lightweight composites and composite sandwich structures are susceptible to impact damage, which may severely decrease the structural stiffness, stability and load carrying capacity. However, the damage suffered internally by the panel during impact is very difficult to inspect [42].

2. MATERIALS AND FABRICATION OF COMPOSITES

Many types of the materials which have been used in many research studies. However, this review focuses on performance fibers to fabricate the composite such as: [15] T700/3234 epoxy composite laminates are cured for 1 h 30 min at 130 °C and at a pressure of 0.5 MPa.

The face sheets of the sandwich panel were woven carbon fabric/epoxy laminates (AGP370–5 H/3501–6 S). The matrix is an amine-cured epoxy resin. The final sandwich panel was a square plate of 27.9 cm dimensions with an overall thickness of 2.82 cm and a mass of 0.83 kg (Fig. 1) [43]. Three E-glass fabrics, non-crimp fabric, woven fabric, and non-woven mat, were selected as reinforcements for the composite laminates for impact test was used by T. W. Shyr, Y.H. Pan [44].

Unidirectional E-glass fabric having a weight of 509 g/m^2 was used by M. Aktas et al., [45] as reinforcing material. An epoxy matrix based on CY225 resin and HY225 hardener was used. W.A. de Morais et al. [55] has fabricated aramid, carbon and glass fiber fabric/epoxy resin–matrix composites fabricated by vacuum bagging prepreg laminas in an autoclave. The carbon fiber/epoxy composites used were woven AGP193-PW/8552 (10 plies) and tape AS4/3051-

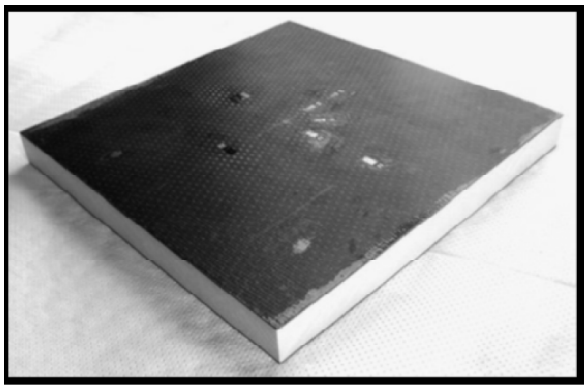

Fig. 1. Photograph of fabricated composite sandwich panel.

6 with two lay-ups: cross-ply $[0/90]_{3s}$ and quasi-isotropic $[45/0/90]_s$ [46]. Material used by P. Rahmé et al. [47] is a carbon-epoxy UD prepreg of T700/M21. Glass fiber-reinforced vinyl ester (glass/VE) panels were produced using vacuum assisted resin transfer molding (VARTM) process [48]. Woven fiber Vicotex M18-1/45%-G939 carbon epoxy prepregs with a crowfoot-type weave pattern in two thicknesses (1.62 and 3.24 mm) are used to fabricate plate specimens [49]. Recently, carbon fiber became used in an automotive application instead of steel and aluminum, especially in engine hoods due to material selection for automotive closures is influenced by different factors such as cost, weight and structural performance. Among closures, the automobile hood must fulfill the requirements of pedestrian safety [50-59].

3. TESTING METHODS

3.1. Impact test techniques for composite materials.

Actually, the impact test fixture should be designed to simulate the loading conditions to which a composite component is subjected in an operational service and then reproduce the failure modes and mechanisms, which are likely to occur. The former is generally simulated using a falling weight or a swinging pendulum and the latter using a gas gun or some other ballistic launcher. However, as stated previously, due to a lack of experimental standards a wide variety of testing techniques is presently being employed in order to assess the dynamic response of reinforced plastics making direct comparison difficult. In this section the more commonly used techniques will be presented and discussed as well as the problems associated with the ensuing data analysis [60].

3.2. Low-velocity impact test.

Impact response of composite materials includes the Charpy and Izod pendulums, the falling weight fixtures such as the Gardner and drop dart tests as well as hydraulic machines designed to perform both in-plane and out-of-plane testing at velocities up to 10 m s^{-1}.

3.3. Charpy pendulum

Many of the early impact studies on composite materials were undertaken using the Charpy test method originally developed for testing metals. The reason for this choice was the fact that the Charpy pendulum is both simple to use and can be instrumented, and therefore, in principle, can yield information on the processes of energy absorption and dissipation in composites. The test specimen is generally a thick beam, sometimes incorporating a notch at its midpoint as shown in Fig. 2. The specimen is supported in a horizontal plane and impacted by the swinging pendulum directly opposite the notch. The Charpy test is only suitable for ranking the impact performance of continuous fiber composites and as a first step in determining the dynamic toughness of these materials [61-66].

3.4. Izod test

The Izod impact test is shown schematically in Fig. 3. The test set-up and procedure are similar to those outlined above (Charpy impact test). In the Izod test specimen is clamped in the vertical plane as a cantilever beam and impacted by a swinging pendulum at the unsupported end. The test suffers similar problems to those reported above and again is best suited as a tool for ranking the impact resistance of composite materials [67-72].

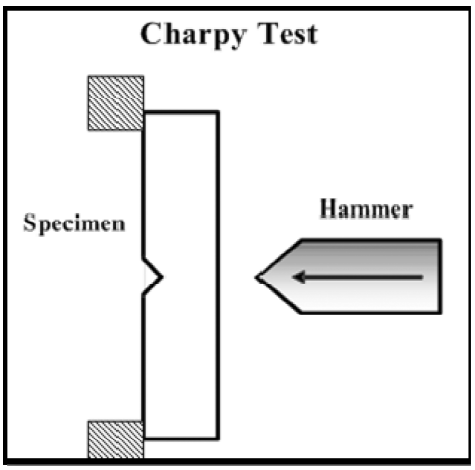

Fig. 2. Charpy impact test.

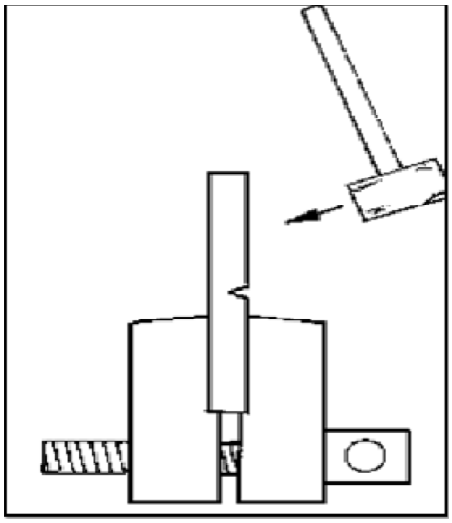

Fig. 3. Izod impact test.

3.5. Drop-weight impact tests.

Here a weight is allowed to fall from a pre-determined height to strike the test specimen or plate supported in the horizontal plane. In general, the impact event does not cause complete destruction of the test specimen hut rebounds, enabling a residual energy to be determined if necessary. The incident velocity of the impactor can be determined from the equations of motion or by using optical sensors located just above the target [44,73-78].

3.6. Hydraulic test machines.

Test geometries such as tensile dog bone specimens or double cantilever beam (DCB) type specimens can be tested over a wide range of strain rates. The advantage of this technique is that the test specimens permit the evaluation of basic material properties such as tensile strength, modulus and interlaminar fracture toughness without the contact effects associated with falling weight impact [79-81].

3.7. Quasi-static indentation behaviors

Quasi-static indentation had been widely used to represent and understand the impact response, because strain-rate and wave propagation effects were commonly negligible for the low velocity impacts [82]. Recently, several investigations have been carried out on sandwich panels with foam cores under quasi-static and impact loadings. A preliminary research in the quasi static indentation and low velocity impact of sandwich panels with (PMI) foam core and carbon woven fabric face sheets using a variety of impactors was performed by Flores-Johnson [83]. It was found that the resistance forces of the sandwich panels were very similar in both quasi-static indentation and low velocity impact indicating that quasi-static indentation can be used to study low velocity impact responses. Mohan et al. [84] studied sandwich panels with aluminum foam cores and various types of face-sheets under quasi-static indentation testing using both flat and spherical punches. The composite sandwich was found to fail under several failure modes, namely core indentation, core crushing, and face-sheet punching and face-sheet bending. This study shows no deformation in the bottom face-sheet. Rizov et al. [85] studied low velocity impact on sandwich panels with a PMI foam core where panels with glass fiber-reinforced polymer (GFRP) face sheets were indented quasi-statically by hemi-spherical indenter. It was observed that the load-indentation curve showed a linear behavior for low values of indentation, followed by a non-linear regime with a quick decrease in the sandwich panel stiffness caused by the extensive foam core crushing in the area under the indenter. The indenter nose shape had great influence on the indentation and impact resistance of sandwich panels which had been shown; for example, Zhou et al. [86] investigated the quasi-static indentation of sandwich panels using hemi-spherical and flat indenters; and showed that the failure mechanisms depend on the indenter nose shape. Most investigations about the effect of the nose shape on the quasi-static response of sandwich panels was limited to flat and hemi-spherical indenters. The first observation can be explained by the fact that the stiffness of the sandwich panel increased with the increase of the density of the core [87]. For Rohacell 71WF and 200WF cores, the curves were calculated using the analytical model developed by Flores-Johnson and Li [88]. It could be seen that the difference between indentation resistance of sandwich and that of the core material depends on the core density and the indenter nose shape. Baral et al. [89] observed that the increase of core density led to an increase of the flexural rigidity resulting in lower deflection of the structure, and thus, less energy absorption at first damage. Flores-Johnson and Li [90] studied the quasi-static indentation of sandwich panels. It was found that both nose shape and foam core density had a large influence on the indentation response of the sandwich panels in terms of absorbed energy, the indentation at failure and damage area. It was shown that the difference in indentation resistances between sandwich panel and its corresponding core material depended on the core density. It can also be observed that the dam-

aged area showed some preferential orientation. For indenters, the damaged area had a rhomboidal shape accompanied by fiber breakage which was commonly observed for woven laminate faces [91]. Lu and co-workers [92] conducted experimental and finite element studies on aluminum foam sandwich panels subjected to both quasi-static and impact loadings. Quasi-static tests were carried out on sandwich panels with CYMAT foam cores using a hemispherical indenter. Ruan et al [93] carried out experimental studies about the mechanical response and energy absorption of aluminum foam sandwich panels subjected to quasi-static indentation loads. It was shown that three deformation modes were observed in the sandwich panels: Global bending, localized indentation with global bending and localized indentation. Localized deformation and failure under the indenter were observed in the top face-sheet of sandwich panels in all tests. Deformation of foam core occurred before the failure of the bottom face-sheets.

4. NONDESTRUCTIVE AND DESTRUCTIVE TECHNIQUES FOR COMPOSITE SANDWICHED STRUCTURES

The non-destructive methods involve detection, measurements of the size and location of damage state based on optical microscopy, X-rays, ultrasonic, acoustic emission, laser optics, interferometry/shearography, thermal instruments, etc. There have been several excellent, comprehensive reviews [94,95] that describe a wider range of measurement techniques for destructive and nondestructive evaluation (NDE) of composite materials. The following combination of composite materials common defect types. Composite defect types generally include: cracks, resin cracking, breaking, bonding defects, voids, delamination, inclusions, excess glue, unglued, layer thick or thin, fiber breakage and curling, poor glue, thickness deviations, wear, scratches, resin accumulation ply wrinkles, pits, bumps, plot tumors. Which cracks, fracture, voids, delamination and other general aviation composite components for the main defects. The nondestructive inspection (NDI) of composites is a crucial component in the service life cycle of critical structures on airplanes, space vehicles, and boats used in transportation [96]. Various nondestructive testing (NDT) techniques are adequate for the characterization of defects like pores, delamination or debonding within the adhesive bond [97]. Two recently developed technologies, the acoustography and the ultrasound camera (acoustocam), may hold the potential for providing large area ultrasonic images in real time or near real time without the need for performing a C-scan. The acoustography employed a stress sensitive liquid crystal material that converts the ultrasonic field intensity containing flaw indications into an optical gray scale image [98]. Infrared thermography is a nondestructive testing and evaluation (NDT&E) technique allowing fast inspection of large surfaces. There are two approaches to infrared thermography: (1) passive, in which the features of interest are naturally at a higher or lower temperature than the background (e.g. surveillance, medical and biological applications); and (2) active, which requires an external energy source to produce a thermal contrast between the feature of interest and the background [99]. Many advanced NDT&E techniques such as RT real-time imaging, TOFD ultrasonic test, ultrasonic phase array, ultrasonic guided wave test, pulsed eddy current test, magnetic flux leakage test, metal magnetic memory test, acoustic emission test, infrared/thermal test is being studied, developed and applied [100]. Experimental investigation on porosity of carbon fiber-reinforced composite using ultrasonic attenuation coefficient [101]. By used guided waves inspection method for de-bond defects in aluminum skin-honeycomb core sandwich structure so guided waves based on results show that the detection of skin - honeycomb core sandwich structure de-bond is possible [102]. Aircraft manufacturers, maintenance service providers, and airline operators have recently started to use ultrasonic phased-array technology to ensure the quality of their composite parts during maintenance and manufacturing [103]. Using a capacitive imaging technique as nondestructive techniques for the inspection of composite materials, then the proof-of-concept results indicated that the capacitive imaging technique could be used to detect cracks and delamination in the glass fiber composite, defects in the aluminum core through the glass fiber face as well as surface features on the carbon fiber specimens [104]. Imaging of damage in sandwich composite structures using a scanning laser source technique. The SLS technique has several significant advantages over conventional methods, including: (i) non-contact in situ measurements, (ii) remote placement of laser equipment using fiber optics, (iii) ability to inspect surfaces with complex geometry, (iv) high spatial resolution, and (v) sensitivity high enough to detect fiber-breakage in a single ply. Example applications to image artificial and impact-induced defects in composite structures are demonstrated [105]. By using thermographic inves-

tigation of sandwich structure made of composite material by V. Dattoma el al. [106]. The A_0 Lamb wave propagation in sandwich structure has been studied at low-frequencies (10–50 kHz). At least 10% of the amplitude of the excited signal was monitored after 1 m of propagation distance, which shows that the technique is applicable to the inspection of relatively long sandwich structures. Changes in the response of the propagated pulses have been used to detect and locate impact damage. The technique could be used to inspect the damage that is located in any position, though the thickness even if only one side is accessible for testing [29]. Ultrasonic C-Scan and shearography NDI techniques, evaluation of impact defects identification, investigation of Roman et al. [107]. Table 1 below summarizes results obtained by non-destructive and destructive techniques [108].

5. FAILURE CRITERIA METHODS

Wang et al. [7] used Hashin and Yeh failure criteria to predict and evaluate the impact damage. Maximum stress and quadratic stress failure criteria were employed in three failure modes [41]. The dominant failure mechanisms taking place in composite laminates when subjected to impact loading are a very complex combination of energy absorption mechanisms such as delamination predominantly caused by mode II shear, matrix cracking caused by transverse shear, and trans laminar fracture in terms of fiber fracture and kinking [75]. Hashin criteria were used to predict the failure of the face sheets by R. Mohmmed et al. [38]. The Chang-Chang failure criteria [109] and DYNA3D are widely used for the prediction of impact damage in composites [110-113]. Damage evolution in composite sandwich panels under quasi-static impact is investigated by using a progressive failure analysis methodology. Several failure criteria, e.g. Hashin's and Besant's criteria, are used for different failure mechanisms such as fiber breakage, matrix or core cracking, and interfacial delamination in the impacted face sheet [21].

6. ANALYSIS METHODS OF IMPACT DAMAGE

An alternative method is an energy profiling method (EPM) which was used by M. Aktas et al. [38], based on variation of the excessive energy (E_e) versus impact energy (E_i), is presented to determine penetration threshold (*Pn*). A quadratic equation was shown to provide a best fit to the experimental points, and the coefficient of the quadratic term was shown to reflect the increase of the impact resistance with laminate thickness [114]. An energy profiling method, showing the relationship between impact energy and absorbed energy, as shown in Fig. 4 was used together with load-deflection curves to determine the penetration and perforation thresholds of hybrid composites [115]. The energy profiling method (EPM) is a diagram that shows the relationship between impact energy and corresponding absorbed energy [116]. A number of analytical approaches have been proposed for the prediction of CAI strength [117-120]. A numerical model has been developed and implemented in the commercial explicit finite element code, LSDYNA, to predict the impact behavior of fabric panels. The model is shown to be effective in capturing the impact response of two types of Kevlar

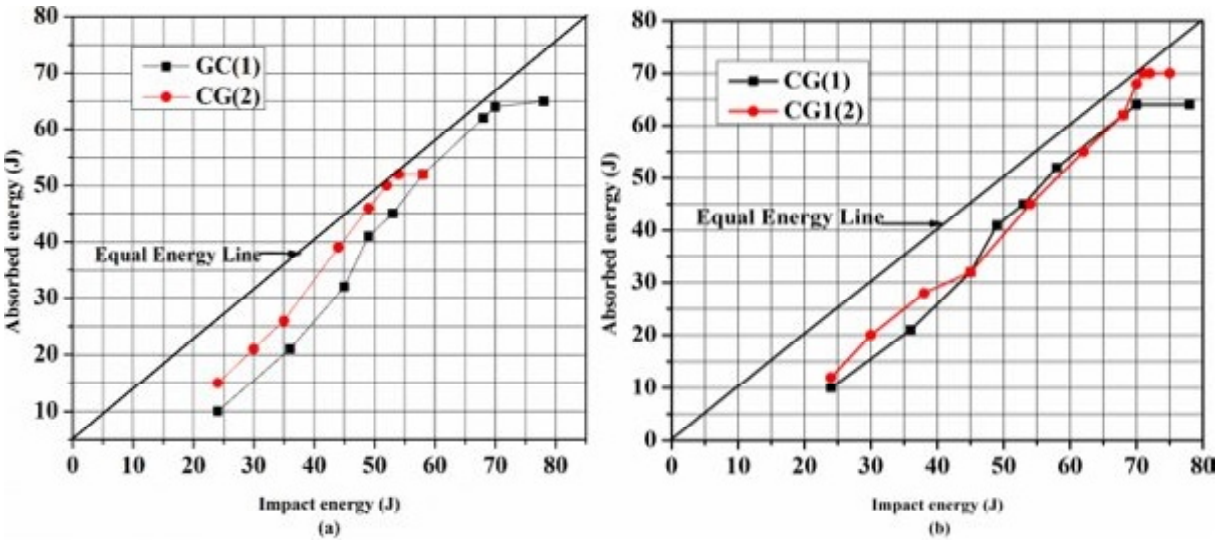

Fig. 4. Energy profile diagrams, data from 115.

Table 1. Rating of major inspection techniques with respect to impact damage sensitivity.

Factor or consideration Damage type sensitivity	De-ply technique	Fractography	Visual inspection	Scanning acoustic microscopy	X-ray tomographic microscopy	Thermal imaging	Acoustic emission	Laser holography
Delamination	Good	Very good	Good	Good	Fair	Fair	Poor	Fair
Fiber breakage	Fair	Good	Fair	Very poor	Good	Poor	Poor	Poor
Matrix cracks	Fair	Fair	Fair	Very poor	Good	Poor	Poor	Poor
Surface defects	Good	Good	Very good	Poor	None	Poor	Very poor	Poor
Damage size sensitivity	Good	Good	Fair	Good	Good	Fair	Very poor	Poor
Damage location sensitivity, distance from surface	Good	Very good	Fair	Good	Good	Poor	Very poor	Very poor

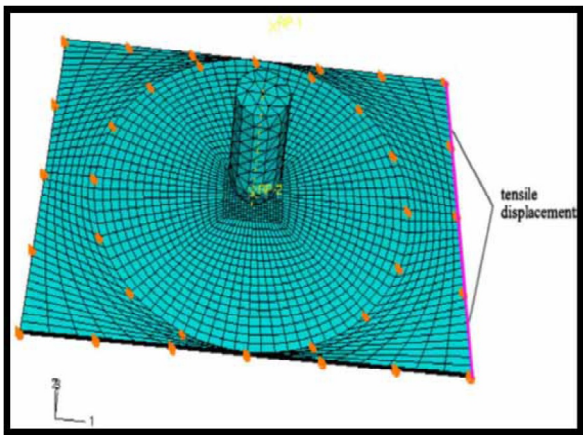

Fig. 5. FE model of carbon fiber composite laminates with rigid impactor.

129 plain weave fabric panels considered in this study [121]. In recent years, the majority of research into the impact analysis of sandwich structures has focused on Nomex honeycomb core structures with carbon fiber face sheets [122]. This is because accurate damage prediction of these structures is difficult to achieve due to the complex damage mechanisms of the face sheet and core materials. Also, due to the increasing application of these materials, there is a need to accurately predict the impact performance to reduce the required amount of impact testing. This can then reduce design cycle times and certification costs. Two separated constitutive models are formulated at the meso-scale using a rigorous thermodynamic framework: one for the description of the debonding between the plies of the laminate (i.e. Delamination) [123], and another for the description of the damage mechanisms that can occur in each ply (i.e. Intralaminar damage mechanisms: matrix cracking, fiber– matrix interface debonding, and fiber breakage) [124-127]. Some researchers have chosen to use existing, commercially available, FE codes. When modelling panel impact, researchers have variously used 3D continuum solid [73,128-130].

7. THE FINITE ELEMENT (FE) OF THE LOW-VELOCITY IMPACT DAMAGE

The finite element (FE) software, ABAQUS/Explicit is employed to simulate low-velocity impact characteristics and predict the residual tensile strength of carbon fiber composites laminates. These numerical investigations create a user-defined material subroutine (VUMAT) to enhance the damage simulation [15]. The composite laminate is modeled as a rectangular plate, and clamped on the circumferential edge to simulate the clamped condition in the test machine, as shown in Fig. 5. M. Q. Nguyen et al. [131] they used three commercial explicit FE analysis packages program software such as LS-Dyna, MSC.Dytran, and Pam-Shock, to determine their capabilities in predicting barely visible impact damage (BVID) in composite structures. The explicit finite element (FE) software codes of LS-Dyna (Version 950e), MSC. Dytran (Version 2000) and Pam-Shock (Version 2000) are commercial tools employed within various engineering industries. The FE computer program FE77 has been used to model some impact tests where significant damage does not become dominant, so that the overall material behavior can be treated as linear elastic with reasonable accuracy. The modeling results of impact response obtained by using FE77 was compared with that obtained by using DYNA3D with a reasonably good agreement [16].

Finite element analyses were carried out by Aymerich et al. [132]. With the parallel explicit solver of the commercial code Abaqus 6.5, and a user defined subroutine (VUMAT) was developed for implementation of the cohesive behavior of interface elements. In his model two rows of vertical cohesive elements, sharing the nodes of adjacent solid elements, were also placed on the symmetry plane of the laminates (i.e. On the boundary of the quarter model) parallel to the 0^0 directions for $[0_3/90_3]_s$ samples (as visible in Fig. 6) and to the 90^0 directions for $[90_3/0_3]_s$ laminates.

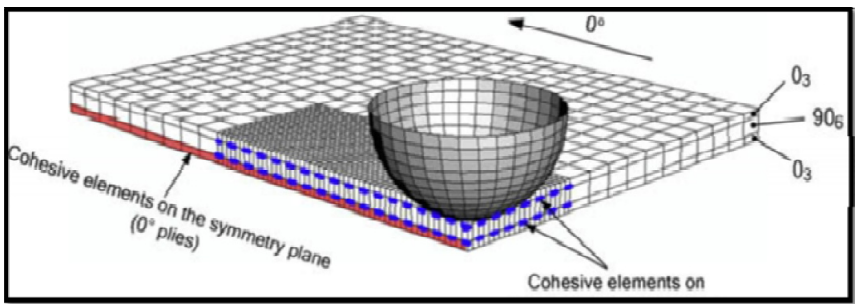

Fig. 6. FE model of a $[0_3/90_3]_s$ laminated plate.

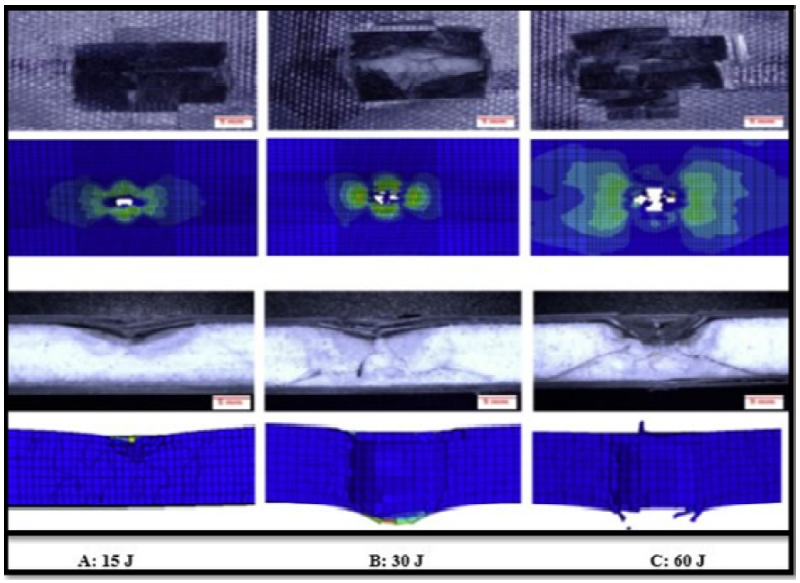

Fig. 7. Comparison of impact damage between experimental and FEM simulation of foam sandwich composite with cross-ply face sheet.

Numerical model has been created with the finite element commercial code ANSYS/LS DYNA to simulate impact response of composite laminate [40]. Therefore more often simulation codes are applied by industry to optimize the performance of the composite material response during in service load. Most common commercial simulation codes used to predict impact properties are LS-DYNA, ABAQUS, PAM-CRASH, 3DIMPACT, etc. [15,133-136]. General purpose finite element code LS-DYNA is one of the most frequently used commercial codes in crash test simulations by the automotive industry, as well as in aerospace, metal forming, material processing, sport, biomedical and other industries [133,135-137].

R. Mohmmed et al. [38]. In his validity of FEM is shown in Fig. 7. That the existence of a good agreement between the experimental and FEM results. The finite element (FE) software Ansys coupled with the explicit FE software code LS-Dyna (Version 970) is commercial tools employed within various engineering industries. Both the aerospace and automotive industries have accepted simulation as part of the design process to minimize design costs and to create more efficient structures [138].

8. COMPARISON BETWEEN EXPERIMENTAL AND NUMERICAL RESULTS

The simulation projects need to evaluated and be sure about the simulation for the modeling results to be agreement with experimental results especially for impact damage modes, can evaluate and validation model of composite by several variables are selected to validate the numerical models, peak load, maximum deflection for all laminates, load history for our specimen , Peak loads, time at failure and the trend of the curves (force-time , displacement- time) obtained in the numerical simulations agree with the experimental results for all the samples that according to suitable condition to experiments [26].

In Fig. 8, C. Santiuste et al. [91] shown comparison between experimental and numerical load history for UN1 test (UN1 means unidirectional structure) they used two criteria failure to validate their model; these were: Hou and Hashin criteria. As a

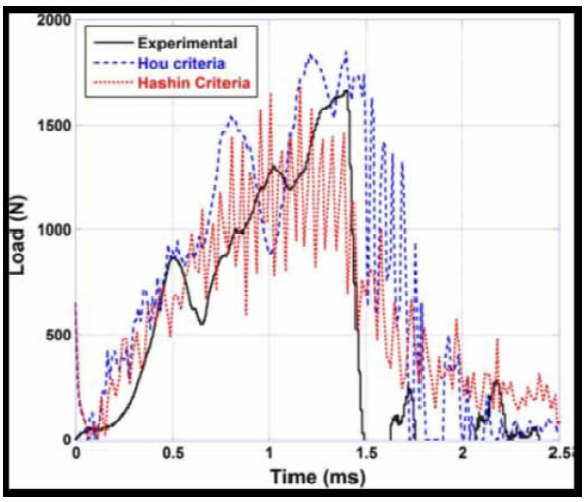

Fig. 8. Comparison between experimental and numerical load history for UN1 test.

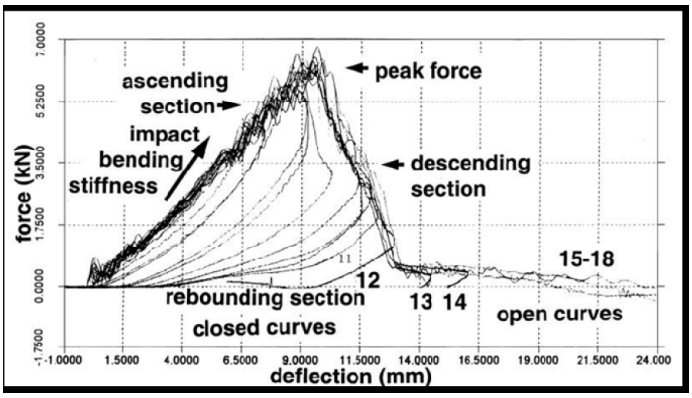

Fig. 9. Force-deflection curves of composite plates.

result, good agreement has been found between experimental and numerical results.

Liu et al. [116] they studied impact perforation resistance of laminated and assembled composite plates. Fig. 9 shown force-deflection curves of composite plates, the slope of the ascending section of each force-deflection curve was termed the impact bending stiffness due to its representation of the stiffness of composite laminates under impact-induced bending in the beginning of impact process. All the force-deflection curves seemed to ascend similarly, indicating similar impact bending stiffness. They then reached individual maximum levels. According to Fig. 9, the maximum forces increased as the levels of impact energy increased. When the impact energy was high enough, the maximum forces seemed to have a similar value. This value was termed the peak force of the composite laminates under the specific central impact. In each sub-perforation impact, the force-deflection curve rises, reached a maximum level and returned back to the origin. It formed a close curve representing the impactor's impacting onto the composite laminate and rebounding from the composite laminate. The area enveloped by the closed curve was the absorbed energy of the composite laminate under the specific impact. Apparently, as the impact energy increased, the enveloped area increased, so did the absorbed energy. If the impact energy continued to increase, perforation then took place. Once perforation occurred, the force-deflection curve would no longer be a closed curve. The area bounded by the open force-deflection curve and the deflection axis was then the energy absorbed by the perforated composite laminate. It was also interesting to point out that the impact events which had sufficiently high impact energy to reach the peak force seemed to share partial descending sections together. As a result, regardless of the rebounding sections, all the impact events seemed to form a master force-deflection curve.

Aktas et al. [45] the impact response of unidirectional glass/epoxy laminates has been investigated by considering energy profile diagrams and

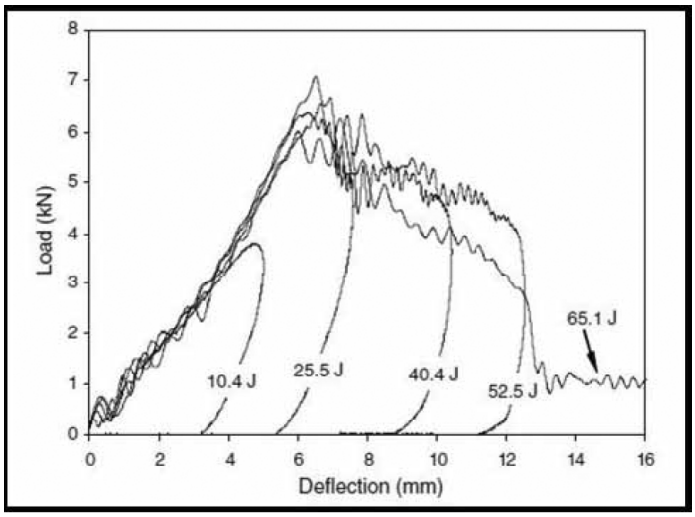

Fig. 10. Typical load–deflection curves of $[0/90/0/90]_s$.

Table 2. Characterization of the impact damage in composite structures

Materials	Structures	Testing methods	NDT	Failure criteria and damage modes	FEM	Objectives	Results	Ref.
CFRP	Composite laminate	Impact test	Pulsed eddy current	-	-	Characterization of CFRP using PEC thermography under transmission mode	1-the detection mechanisms for impact and delamination in CFRP are totally different 2-The delamination will lead to a dark area, while impact will lead to a hot area under transmission mode	[3]
CFRP	Composite laminate	Ultrasonic measurement and transducer positioning system	Ultrasonic guided wave	Multiple delaminations	3D numerical simulations	NDT technique based on application of ultrasonic guided waves and intended for CFRP rods used for aerospace applications	By numerical modelling and experiments, it was demonstrated that guided waves can be applied for inspection of small diameter carbon fiber reinforced plastic rods	[4]
E-glass face sheets+ foam	Sandwich composite structures	Quasi-static load and dynamic blast load	-	Single degree-of-freedom	-	Air blast loading of a lightweight foam core sandwich panel with composite face sheets.	A comparison with some quasi-static test results were performed and it was found that the experimental data were consistent with the analysis.	[5]
Eglass/Epoxy and PVC foam	Sandwich composite structures	Quasi-static and impact loads	-	Transition equations between the failure modes	impact test simulation by Abaqus/explicit	Static failure modes and load capabilities of foam core composite sandwich beams	1- The static load capabilities and failure modes predicted by simple equations showed good agreements with the test results 2- the impact energy absorption capability was related to the failure mode strongly	[6]

CFRP	Carbon fiber composite laminates	Impact test and residual tensile strength	-	Hashin and Yeh failure criteria	Impact test simulation by Abaqus/explicit with VUMAT	Low-velocity impact characteristics and residual tensile strength experimentally and numerically	The impact contact force and the tensile strength are accurately estimated using the present method. Two different tensile damage modes after different impact energies are observed.	[15]
CFRP	Carbon fiber composite laminates	Impact test	C-scan	Matrix crack, delamination and fiber breakage	Impact test simulation	Comparison of damage predicted by numerical with the damage obtained experimentally	Delaminated area due to impact loading depends on the number of interfaces between plies. Two failure mechanisms were influenced by stacking sequence and the thickness of panels	[18]
CFRP	Carbon fiber/ epoxy composite	Impact test and CAI	C-scan and X-radiography	Delamination, splitting and fiber fracture	-	Effect of stacking sequence on impact damage and compression in a carbon fiber/ toughened epoxy composite.	Stacking sequence influences both the pre- and post-impact compression strengths and affects the impact damage in carbon fiber/toughened epoxy laminate.	[19]
Carbon/epoxy prepregs + aramid honey comb core	Composite sandwich parts	Quantitative measurements on real defects	deflectometry	Surface porosities and resin shrinkage	-	Characterization method for different surface defects encountered in the composite materials industry	This paper presents a new alternative for surface finish characterization of fiber reinforced composites	[20]
NOMEX honey comb core + face sheet	Composite sandwich panels	Quasi-static tests	C-scan	Hashin's and Besant's criteria + fiber breakage, matrix or core cracking, and interfacial delamination	3D of honey comb sandwich panels are analyzed by Abaqus	Failure analysis subjected to quasi- static loading condition, to predict the damage initiation, growth, and propagation to fracture	An efficient, progressive failure analysis method for sandwich composites has been implemented into the commercial finite element software ABAQUS through the use of a user subroutine UMAT	[21]

Glass/polyester face sheets/PVC foam	Sandwich structures	Impact test	C-scan	delamination	-	To investigate impact damage on sandwich composites	The air-coupled C-scan testing with respect to sandwich structures is recent technique and further tests need to be performed.	[25]
CFRP	Composite laminate	Impact test, quasi-static test and CAI	C-scan	Based on quantification of SRCT	-	Role particles play towards improving impact damage resistance and post-impact residual compressive strength	Particle toughening is an important area of development for composite material systems	[24]
Carbon-fiber/ epoxy prepreg of TR 50S12L	Sandwich structures	Impact test and quasi-static	-	Delamination, matrix crack and fiber failure	-	Impact damage and failure modes of composite sandwich structure with different face sheets.	Unidirectional has the highest peak load. While unidirectional face sheet have lowest peak load, lowest displacement at peak load and minimum energy absorption	[26]
Glass/ epoxy face sheets + core	Sandwich structures	Three points bending tests	-	-	-	Analytical approach which considers large strains of face sheets and core.	Good agreement is obtained between the nonlinear analytical predictions and experimental results.	[33]
Carbon-fiber/ epoxy prepreg of TR 50S12L	Sandwich structures	Impact test and quasi-static	-	Hashin criteria	Abaqus was used to simulate low-velocity impact properties	Experimental and numerical investigation of impact damage and failure mode composite with different ply angle face sheets	The results shown that there are good agreements between the experimental and the FEM models	[38]
UD-nylon 6,6 fiber-polyester resin	Composite laminates structure	Impact test	-	-	-	Effects of test span and fiber volume fraction on Charpy impact characteristics	The mechanisms considered responsible for VPPMCs improving impact toughness by performing Charpy impact tests on unidirectional Nylon 6,6 fiber–polyester resin	[61]
Carbon/epoxy and carbon/ BMI	Woven fabric composites	Quasi-static and high strain-rate dynamic tests.	-	-	-	Experimental investigation of high strain-rate behavior of fabric composites	Undamaged tension and shear modulus are observed in dynamic tests compared to quasi-static ones.	[62]

Rayon twill weave	ACC laminates	Flexural and impact tests	-	-	-	Impact and flexural properties of ACC laminates based on regenerated fibers using 3-point bending, puncture impact and Charpy impact testing	The unique combination of high flexural and impact strength of ACC laminates demonstrates the potential of ACC laminates as a new class of bio composite.	[63]
E-glass and polyester	Multi-axial warp knitted composites	Impact tests at room and liquid nitrogen temperatures	-	-	-	The impact properties of 3D MWK composites with different fiber architecture are examined by Charpy impact test	Impact properties decrease significantly with the increase of the fiber ply angle at both room and liquid nitrogen temperatures	[64]
CFRP/ ABS/ CFRP	Sandwich Structural	Impact test	-	-	-	To investigate the effects of HLEBI before lamination assembly on impact value of CFRP/ ABS/ CFRP	Homogeneous 100keV-class low voltage electron beam irradiation (HLEBI) prior to lamination assembly often improved the Charpy impact values	[66]
PU	PU Matrix Composite	Pendulum Impact Test, Izod Impact Test and Charpy Impact Test	-	-	FEA software by used Ansys to create The square rod model	To predict the damage development under specific load and pressure.	Modelling and analysis of impact properties on Polyurethane composites using FEA were investigated	[67]

associated load–deflection curves Fig. 10. Absorbed energy in an impact event can be calculated from load–deflection curves. Characteristic of load–deflection curves also includes some useful tips on assessing the damage process of composite structures. Therefore, several load–deflection curves of samples, in this study, for varied impact energies are given in Fig. 10.

Two types of the curves can be observed in Fig. 10, closed curve and open curve since 10.4 J to 52.5 J the impactor doesn't penetrate the samples and rebounding back due to stiffness of composite and have good resistance to impact damage, but in case 65J observed the curve from closed curve changed to open curve that means increase the impact energy led to the impactor penetrated the samples. Table 2 explains last methods techniques that were used to characterize the impact damage in composite materials.

9. CONCLUSION

In this contribution, models using numerical, mathematical and experimental investigation of composite structures subjected to quasi-static and impact loads were reviewed. This review paper has been carried out as part of a research on characteristics of the impact damage modes on the properties of the composite materials. The impact responses are classified according to the various key parameters, and different methodologies are listed for different classes of impact. The characteristics of each class of impact responses were also classified and discussed. Different kinds of impact response could be solved using different methods. The term damage resistance refers to the amount of impact damage which is induced in a composite system. Clearly, the vast majority of impacts on a composite plate will be in the transverse direction, but due to the lack of through-thickness reinforcement, transverse damage resistance is particularly poor. Interlaminar stresses-shear and tension-are often the stresses that cause first failure due to the correspondingly low interlaminar strengths. Damaged areas can be investigated visually or by using optical or electron microscopy, ultrasonic C-scanning, and acoustic imaging. Impact damage in composite plates is a combination of major failure modes: delamination, matrix cracking, and fiber breakage. The first two types of failure are dependent on the properties of the resin matrix, whereas fiber breakage is more responsive to the fiber specifications and characteristics and is usually caused by higher energy impacts. Many types of the materials which have been used in many studies were found to be focused on carbon fiber with epoxy to fabricate the composite, glass with polyester and graphite with epoxy that means the type of the reinforcements has big effect to impact resistance of composite materials. Delamination causes catastrophic failure of composite materials in compression by causing instability in the structure through kink band formation. Furthermore studies need to detect and predict the delamination in composite structures to control the strength and stiffness of the composites. The two main programs, software which used to simulate low-velocity impact damage is: ABAQUS/Explicit and LS-Dyna. These two programs have always been used as an analytical tool.

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