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Low Velocity Impact Properties of Foam Sandwich Composites: A Brief Review

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Abstract*— Composite sandwich structures have excellent properties and they are widely used in the fields of high technology such as aeronautics and astronautics, etc. Investigations of the mechanical properties of composite sandwich structures play a vital role in deciding their applicability in various engineering fields. After years of effort, along with several achievements, new difficulties have been encountered with the emergence of a lot of novel sandwich structures in recent years. The quasi-static indentation response, low-velocity impact response, residual strength after impact and high-velocity impact response of these structures has been investigated by theoretical, numerical and experimental methods. The mechanical behavior of sandwich structures is strongly dependent on the loading rate. In the case of static loading the structure have a ductile behavior, but in the case of impact loading it may behave in a brittle manner and fail catastrophically. The advances of the mechanical properties of foam sandwich composites are reviewed from several aspects, including the, low-velocity impact response, and the finite element model for low- velocity impact of composite sandwich structures.

Key words: **carbon/epoxy laminates, foam sandwiched, composites finite element method, rohacell foam.**

I. INTRODUCTION

Composites are materials consisting of two or more materials which together produce beneficial properties that cannot be attained by any of the constituents alone. Composites are composed of fibers and matrix. Fibers are the reinforcement and the main source of strength while the matrix hold all the fibers together in shape and transfers stresses between the reinforcing fibers. Sometimes, fillers or modifiers might be added to smooth manufacturing processes, impart special properties, and/or reduce product cost [1, 2].

Now a days, composite structures, such as fiber-reinforced plastic laminates and sandwich panels composites with composite face sheets are widely used in the aerospace, buses, railway constructions, marines, automobiles, locomotives, windmills and buildings, because of their preferable properties such as stiffness , low weight, thermal insulation, acoustic damping, ease of machining, and ease of forming among others. The impact peak load value and the impact damage extent of foam core sandwich composites depend on the different face sheets fabrics, core materials, and the core–facing interfaces [3-5] . These are made by sandwiching two layers of strong outer sheets, called skin, around a less dense layer part, the core. The core is usually less stiff, with lower strength. The skins can be made of fiber-reinforced composites, such as glass, or carbon fiber reinforced laminates. Some of the commonly used core materials are wood, honeycomb, truss, corrugated structures; open and closed cell foams [6]. By varying the core, the thickness and the material of the face sheet of the sandwich structures, it is possible to achieve various properties and desired performance [7]. When a composite was subjected to a low-velocity impact of sufficient energy, different damages are identified. These damages caused reduction in structural stiffness and strength, leading to growth of the damage and final fracture [8, 9]. Currently, the impact design problem is approached by two ways. The first one is experimental and requires several measurements of the impact behavior of the studied material under different loading conditions and sample geometry. 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 [10].

Historical background

In England, sandwich construction was first used in the mosquito night bomber of World War II which employed plywood sandwich construction. Feichtinger stated that during World War II, the concept of sandwich construction in the United States originated with the faces made of reinforced plastic and a low density core.

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The first research concerning sandwich construction was conducted by Marguerre in Germany in 1944 dealing with sandwich panels subjected to in-plane compressive loads. Also in the late 1940s, two young World War II veterans formed Hexcel Corporation. Starting with honeycomb cores, they are makes well over 50% of the world's honeycomb core materials.

In 1951, Bijlaard studied sandwich optimization for the case of a given ratio between core depth and face thickness, as well as for a given thickness. At that time, sandwich publications began to emanate from the U.S. Forest Products Laboratory (USFPL), which was attached to the University of Wisconsin. A Military Handbook was published which largely involved the results of the many publication issued by the USFPL. This became the definitive document for use by industry.

In 1956, Gerard discussed sandwich plate optimization in one chapter of his landmark book, "Minimum Weight Analysis of Compression Structures." In 1966, Plantema, in the Netherlands, published the first book on sandwich structures, followed by another book on sandwich structures by H.G. Allen in England in 1969. These books remained the "bibles" for sandwich structures until the mid 1990s. Also in the mid 1960s, the U.S. Naval Air Engineering Center sponsored research with Dyna/Structures, Inc. to develop fiberglass composite sandwich constructions to compete in weight with conventional aluminum aircraft construction for aircraft. Much of this research efforts were in the development of minimizing weight methods. Many of these methods were later published by Vinson.

In 1995, a monograph by Zenkert supplemented much of the material contained earlier in the Plantema and Allen texts (which by that time were out of print). Zenkert followed this by a sandwich textbook in 1996. In 1999, another sandwich textbook was published by Vinson. Hence today there are only four texts dealing primarily with sandwich Structures: Plantema, Allen, Zenkert and Vinson. In 1999, the Journal of Sandwich Structures and Materials was initiated and it is the only journal fully devoted to sandwich structures and Materials [11, 12].

II. MATERIALS

A. Foam

Open and closed cell structured foams like polyvinyl chloride, polyurethane, polyethylene or polystyrene foams, balsa wood, syntactic foams and honeycombs are commonly used as core materials. Open and closed cell metal foam can also be used as core materials. Usually, the honeycomb cores are made out of aluminum or composite materials such as Nomex, glass thermoplastic, or glass-phenolic Figure (1a). Some of the problems in the honeycomb sandwich constructions are the low surface area of the core for bonding, and the higher cost of manufacturing and maintenance as well as it sensitivity to hot and humid environment [13, 14]. The other most commonly utilized core material is closed-cell. It is widely used as core material for sandwich constructions in the automotive and aerospace industries because of its light weight and high stiffness Figure (1b). It is also used in non-structural applications, e.g. cushioning, packaging and isolating, because of its energy absorbing properties and good capabilities in vibration and acoustic attenuations [8, 15]. Many of the advantages of foam cores are the increased support surface for bonding with the face sheets, low thermal conductivity properties, an adjustable density, and the advantage of the overall formation by the resin film infusion; (RFI)/resin transfer mold and (RTM) / vacuum assistant resin infusion (VARI) process [16, 17].

Another types of foam widely used in sandwich structures were syntactic foams, having high specific strength. The studies show that properties such as strength of syntactic foams can be increased by reducing the volume fraction of the micro balloons [18] or by using higher strength micro balloons[19, 20] . Reduction in the volume fraction of micro balloons produces higher density syntactic foams. However, the use of higher strength micro balloons was found to be more effective in increasing the compressive strength and modulus of syntactic foams without significantly increasing the density [21]. The same result was also found in syntactic foam sandwich structures [22] . The strength of syntactic foams can also be increased by reinforcing the matrix with fillers [18], nanoclay [23], and short fibers [24]. A recent study by Woldesenbet [23] show that 1% nanoclay by volume (3.59% by weight) produces the optimum concentration required to achieve high fracture toughness in syntactic foams having 60% micro balloon volume fraction.

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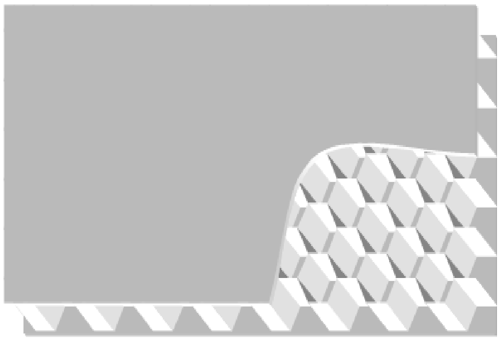
Polymethacrylimide (PMI) closed-cell rigid foams (trade name Rohacell series [25]) have been widely used in aerospace, automotive, marine and aircraft structures applications. Rohacell is a rigid closed-cell foam material. Rohacell natural color is white or pale yellow. It has good mechanical properties, with good thermal stability, chemical resistance at low temperatures and also has very low heat conductivity. At present at the same density. Rohacell foam tensile, shear modulus and strength are the highest for the polymer foam materials [26, 27].

1. Factors effecting velocity impact test of the foam

The effect of the nose shape on the responses of polymeric foams under low velocity impact is shown in figure (2). A study of the penetration behavior of PMI foams under a range of low velocity impacts from 4 to 8 m/s with conical, truncated-conical, flat and spherical nose impactors had been carried out. An analytical model was developed to predict the penetration behavior of PMI foams under low velocity impact [28]. E. A. Flores-Johnson and Q. M. Li [29] studied the effect of the impactor nose shape on the penetration behavior of polymethacrylimide (PMI) foams in the velocity range of 4-8 m/s. It was observed from velocity impact tests that penetration force depended on the geometry of the impactor and the density of the foam. Rizov *et al* [30] found that the impact force increased with the increase of the impact velocity/energy. It was also reported that the maximum force for a given impact energy was higher for specimens with high density. These foams show a special behavior in uniaxial compression as illustrated in Fig.3. The foam properties were obtained from uniaxial compression tests according to that given in ASTM D5308 standard [31]. Loading velocities were selected in two cases of 2mm/min and 100 mm/min. Finite element analysis was performed using the FE code ABAQUS with the model of crushable foam material. The results obtained were found to be in good agreement with the model [32].



(a)

(b)

Fig. 1 Sandwich panels with (a) honeycomb core and (b) foam core [13]

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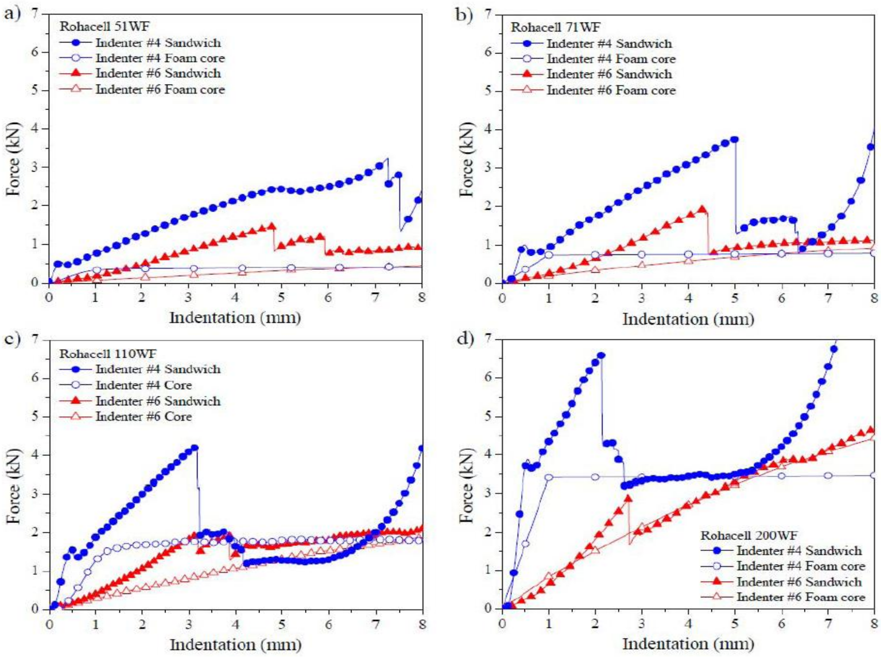

Fig. 2 Force-indentation curves using indenters for sandwich panels and their corresponding core materials: a) Rohacell 51WF, b) Rohacell 71WF, c) Rohacell 110WF and d) Rohacell 200WF [33].

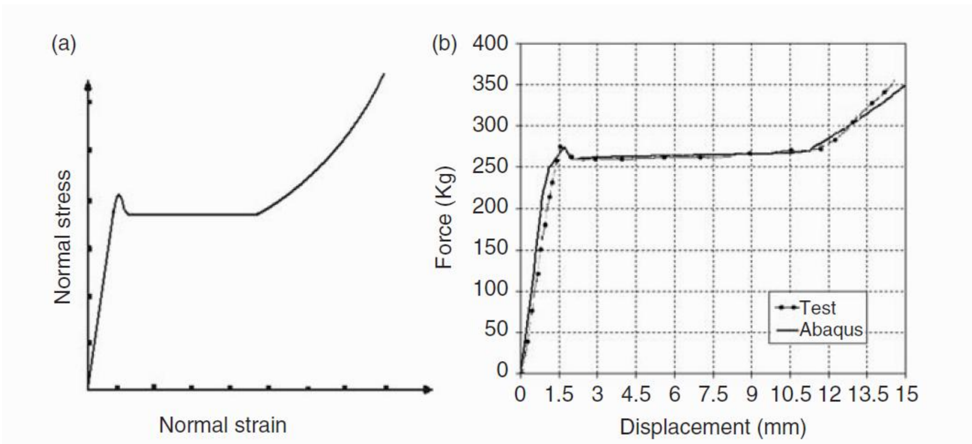

Fig. 3(a) Foam behavior in uniaxial compression; (b) foam loading in uniaxial with velocity of 2 mm/min [32].

B. Skin

The skins were directly laminated over the slices of core material to ensure good bonding between skins and core. Hand lay-up followed by vacuum bagging was employed as the fabrication method. Application of vacuum ensures uniform distribution of resin in the material and ensures a good bonding between skin and core. Laminates of glass or carbon fiber reinforced thermoplastics or mainly thermoset polymers (unsaturated polyesters, epoxies...) are widely used as skin materials. Sheet metal is also used as skin material in some cases. The strength of the composite material is largely dependent on two factors:

a) The outer skins: If the sandwich is supported on both sides, then stressed by means of a force in the middle of the beam, then the bending moment will introduce shear forces in the material. The shear forces result in the bottom skin being in tension and the top skin being in compression. The core material spaces these two skins apart, the thicker core material, the stronger composite. This principle works in much the same way as an I-beam does.

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b) The interface between the core and the skin: Because the shear stresses in the composite material changes rapidly between the core and the skin, the adhesive layer also shows some degree of shear force. If the adhesive bond between the two layers was too weak, the most probable result will be delamination.

1. Carbon/epoxy laminates

Fiber Reinforced Plastic (FRP) composites exhibit high specific strength and stiffness as compared to conventional metallic components. Different types of FRP composites, carbon/epoxy laminates are most used in the weight sensitive aerospace industry as they offer highest specific strength and stiffness. However, the increased use of carbon/epoxy (CFRP) composites in many applications has been hindered due to concerns of the complex failure modes intrinsic to composite materials. The primary concern with the current conventional CFRP materials is premature failure due to delamination under transverse loading [34]. Conventional composite materials, which consist of laminated layers of unidirectional fibers embedded in matrix, are very strong in the direction of fibers, but much weaker in the direction perpendicular to the fibers. Out-of-plane properties of a unidirectional composite laminate are matrix dominated [35]. Delaminations are usually initiated in one of three ways: by means of mechanical defects in the composite, damage due to impact, and out-of-plane loads. In all the cases development of through-the thickness stress is the primary cause of delamination. When subjected to impact loading, inelastic energy in composites is absorbed in the form of creation of new surfaces. The failure mechanisms include matrix cracking, delamination and ply splitting, playing an important role in reducing the residual mechanical properties of composite material [36-38]. Only a limited amount of work has concentrated on the effect of stacking sequence on impact resistance. Three parameters were studied: interface angle, ply orientation relative to a fixed axis, and ply grouping. Each parameter was found to affect the damage resistance differently [39-41] Figure 4. Dorey [42] showed that laminates containing ±45o surface ply offered superior impact resistance and improved residual strength compared with those having 0o surface layers. This was attributed to the increased flexibility of the composite increasing its ability to absorb energy elastically.

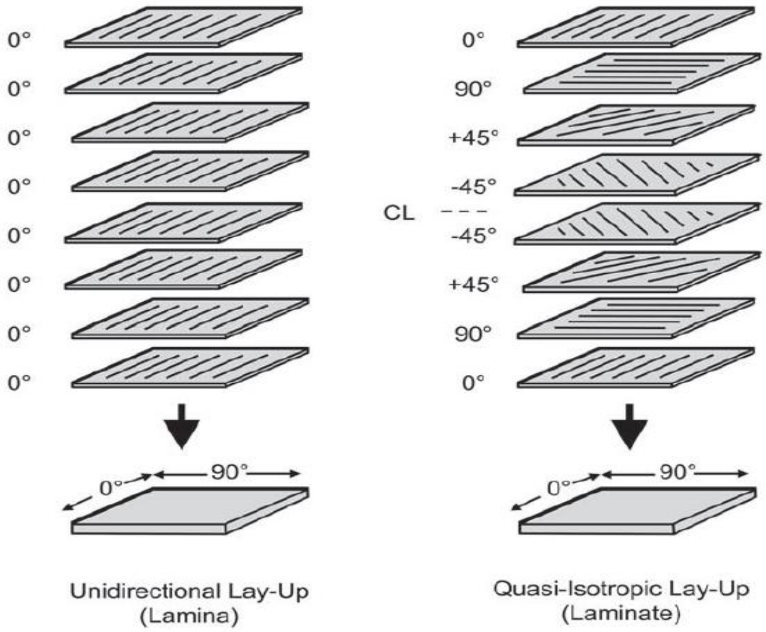

Fig. 4 Lamina and laminate lay-ups [39]

III. DYNAMIC BEHAVIORS OF SANDWICH COMPOSITE

The dynamic behaviors of sandwich structures, especially low-velocity impact behavior, have been widely investigated. Kim and Jun [43] investigated the effects of face lay-up sequence (graphite/epoxy) and core density (Nomex honeycomb) of a sandwich plate on the impact delamination area of the laminated facesheets. It has been shown that the higher density core and laminates of small relative angular orientation between adjacent plies tend to be more damage resistant than those of relatively larger angular orientation and small density core. Sun and Wu

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[14, 44] and Anderson *et al*. [45] presented experimental results for low-velocity indentation of sandwich panels and sandwich beams in related studies. Several failures modes (matrix cracking of the face sheets, skin/core debonding and core crushing) have been identified and the monitoring factors of these failures were found to be the density of the core and facings structures. Rizov *et al*. [46] studied the effect of indentation values by using low velocity impact on sandwich panels. Cantwell *et al*. [47] studied the impact properties of polymeric foam sandwich structures and had shown that their dynamic response depended on the elastic properties of the core material. Lendze *et al*. [48] studied the impact resistance of sandwich structures with skin-core bonding efficiency using two types of adhesives and bonding with "wet" resin and air-coupled ultrasonic C-scan technique. It has been shown that in all sample types, top skin suffered some damage (delamination) due to the impact. Hosur *et al*. [49] developed foam core sandwich panels filled with neat and nanophase clay. Damage analysis showed that nanoclay infused foams had a smaller damage area than their neat counterparts. Assessment of the residual mechanical properties of a sandwich structure had a crucial effect on impact properties. The damage tolerance of a composite sandwich structure composed of woven carbon/epoxy facesheets and a PVC foam core was investigated by Schubel *et al*. [50, 51]. Xia and Wu [52, 53] proposed that the damage extent of foam core sandwich composites with various facings may be characterized by the average damage angle, penetration depth, and maximal cracking width. The susceptibility of sandwich structures to localized (impact) damage was one of the main reasons of its non-applicability in large primary aircraft structures of airliners. Investigation of the damage tolerance of representative composite sandwich panels has shown that the foam core material had a considerable influence on the amount of damage detected by ultrasonic TTU C-scan [54].

IV. FAILURE MODE OF SANDWICH COMPOSITE

It is very important to identify the mode of failure because this will yield information not only about the impact event, but also regarding the structure's residual strength. Interaction between failure modes is also very important in understanding damage mode initiation and propagation. The heterogeneous and anisotropic nature of fiber reinforced plastic (FRP) laminates gives rise to four major modes of failure (although others could be cited) [55, 56]:

1) ***Matrix:*** Mode-cracking occurs parallel to the fibers due to tension, compression or shear.
2) ***Delamination:*** Mode-produced by inter laminar stresses.
3) ***Fiber:*** Mode-in-tension fiber breakage and in compression fiber buckling.
4) ***Penetration:*** The impactor completely perforates the impacted surface.

The damage in sandwich composites subjected to low velocity impacts can be broken up into three distinct classifications: facesheets damage, facesheets-core interface damage, and core damage, as shown in Fig. 5 Damage to the impacted facesheets is through matrix cracking and delamination, with fiber breakage occurring at higher impact energies[57]. Significant indentation of the facesheets can often occur at the impact location as a result of the fiber breakage. The exact order and relative size of these failure modes depends upon the face sheet configuration.

The damage at the core of foam core sandwich composite structures can be classified as either core cracking or core crushing. As a result of impact loading, a shear crack appears in the core originating at the impact site on the top face sheet, and propagates through the core to the lower face sheet. This crack is due to shear failure of the foam. The crack propagates through the foam core and then branches into face sheet-core delaminations [45, 58]. Core crushing is caused by the collapse of foam cells due to cell wall buckling or breakage, creating a cavity within the core[17, 59]. Torre and Kenny [10] , and Lee *et al.* [60] have shown that the cavity in the foam greatly diminishes performance of the structure.

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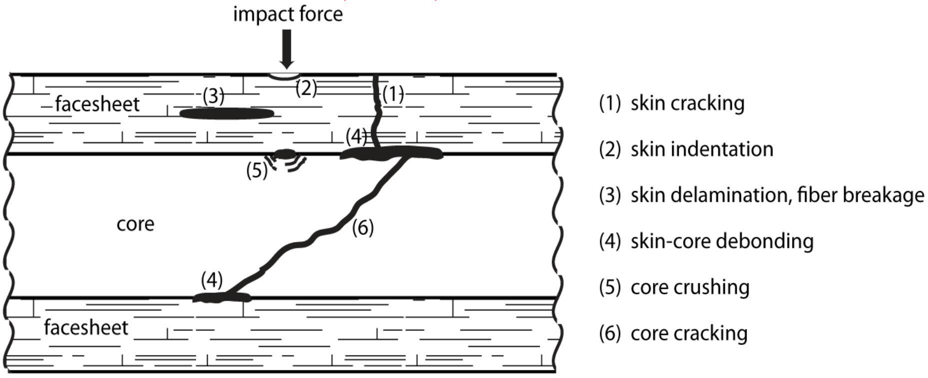

Fig. 5 experimentally observed damage modes in a sandwich composite under low-velocity impact.

The skin-core interface often plays a critical role in the form of reduced bending stiffness and strength [61]. Face sheet-core delamination is typically induced by intra-matrix cracking in the foam core on each side of the impact. Further degrading the integrity of the face sheet to core bond and the core material itself. To further complicate matters, face sheet cracking can sometimes appear prior to interface delamination [62]. The results of the experiments performed by Caprino and Teti [57] show that the impact damage, defined as the maximum width of the zone with fractured fibers, is essentially independent of the (PVC) foam core density and thickness.

Table 1 Developments of low velocity impact studies of different sandwich structures

Foam	Skins	Fabrication method	Test method	Ref.
PVC,PEI,PVC/PUR	A woven glass/ phenolic resin.	A cold stamping procedure	Impact tests (falling-weight impact tower) indentation tests	[47]
Aluminium	A unidirectional glass reinforced polypropylene and a woven glass reinforced-polypropylene	A cold stamping procedure	Impact tests (falling-weight impact tower.) indentation tests	[47]
Closed cell PVC	Glass fiber/polyester	Traditional wet (hand) lay-up technique	Impact tests	[48]
Polyurethane PU	Woven carbon/epoxy	Co-injection resin transfer molding (CIRTM)	Low-velocity impact testing.	[49]
Closed cell polymethacrylimide (PMI)	A bidirectional carbon/epoxy	Vacuum infusion process	Low-velocity impact tests	[54]
Closed-cell PVC	Woven carbon fabric/epoxy laminates	Hysol 9430 adhesive with vacuum	Low-velocity impact tests, CAI test	[50, 51]
RPU	Glass fabrics , carbon fabrics , carbon/Kevlar hybrid fabrics , Kevlar fabrics with vinyl ester resin	RTM process.	Impact test	[52]
RPU	Glass fabrics, carbon fabrics , carbon/Kevlar hybrid fabrics , Kevlar fabrics with vinyl ester resin	RTM process	Impact Test	[53]

V. FINITE ELEMENT MODEL

The explicit finite element software, ABAQUS/Explicit, is employed for impact simulation [63]. The performance of FEM simulations of sandwich beams descriptions of the damage induced by the contact area required the modeling of both the face sheets as well as the core. With respect to the composite laminate face sheets, specialized

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criteria which described the occurrence of various failure modes and material degradation models that reduced stiffness properties were used [9, 64]. The sandwich plate was modeled as a rectangular plate, and clamped at its top and bottom circumferential edges to simulate the clamped condition in the test machine, as shown in Fig. 6 [65]. The rectangular specimen was chosen for the test of residual tensile strength [66-69]. Since the integrative forming method was employed to manufacture this new sandwich structure [68, 70] , interfaces between facesheets and core were undamaged under impact and tension process. However, there was a lack of knowledge about the interaction between the failure of the core and the failure of the composite facesheets. This interaction was important because sandwich beam subjected to low velocity impact presents high stress levels in the core due to the contact force and, consequently, there was collapse of the foam located in the contact zone [71].

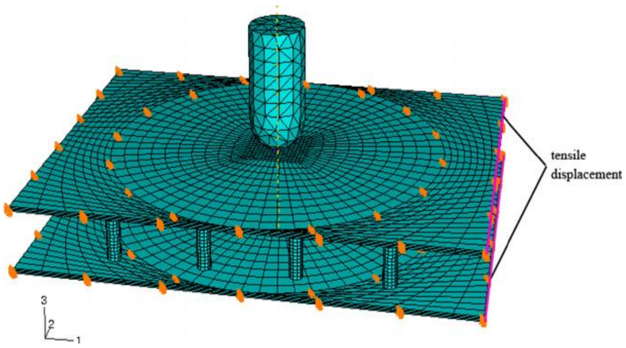

Fig. 6 FE model of carbon fiber columns truss core sandwich panel with rigid impactor [65].

Numerical Study

A numerical model was developed to analyze the dynamic flexural behavior of composite foam core sandwich structures, using ABAQUS/Explicit code. Many of these works involve experimental studies on the behavior of polymer foam core sandwich structures [72-74]. And A number of workers have attempted to model the impact response of sandwich structures [75-77].

For experimental analysis of the influence of these variables, numerous tests were required. In order to achieve more accurate results and to minimize the number of experimental tests and hence reduce design costs and time of such tests, it is essential to use numerical simulation models. These models should be accessed through experimental testing. Two of the few analytical models that have been used are mass spring model [73, 78] and an energy balance model [79, 80] they have been used to predict the peak load , the load history and to study the impact response of composite sandwich structures due to the complex interaction between the composite face sheet and core during deformation and failure. For more detailed analysis, most researchers used finite element simulations. Mines and Alias [81] used the Hashin criterion and the Lee extended Hashin's arguments to consider the modes of laminate failure (fiber breakage, matrix cracking, and delamination). They used a foam model based on critical state theory with adjustments to take into account volumetric effects and a non-associative flow rule. Icardi and Ferrero [82] used the latest 3D version of the Hashin's criterion with *in situ* strengths to predict the failure of fibers and the matrix, Choi Chang's criterion and a Heuristic criterion for delamination. Von Mises yield criterion has been used for considering the foam core to be a homogeneous isotropic material. Sadighi and Pouriayevali [83] used a model of a crushable foam material which was validated by uniaxial compression test. The results described the response of sandwiched composites, impactor displacements in terms of core and face thicknesses, core material, impactor energies for static and impact results. The experimental results were in good agreement with the analytical and FE analysis. Foo et al. [84] developed a three-dimensional finite element model to analyze low-velocity impact response and damage in honeycomb sandwich composites (the FE results compared well with experimental results).

Ivañez [72] showed the accuracy of the finite element model, determined by comparing experimental results with numerical predictions at several impact energies in terms of contact force histories, peak force, maximum displacements of upper and lower face sheets, and absorbed energy. Agreement with the experimental results was satisfactory. The flexural behavior and failure mechanisms of composite sandwich beams in flatwise and edgewise positions had been studied experimentally, analytically and numerically by Manalo *et al*. [85]. The experimental

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investigation showed that under flexural loading, the composite sandwich in the flatwise position failed with sudden brittle type failure. In the edgewise position, the presence of fiber composite skins increased the ultimate strength of the composites. The theoretical prediction of failure was found to be in good agreement with the experimental results. Low-velocity impact properties and residual tensile strength of carbon fiber composite lattice core sandwich structures were investigated by Wang *et al*. [86]. It has been shown that according to FE analysis results, degradation of residual tensile strength in sandwich structures could be divided into three stages: lower impact energy degradation stage; plateau stage; higher impact energy degradation stage. In monolithic laminates, one of the most commonly used criteria to predict the failure of laminates under dynamic conditions was the model developed by G. Castillo [87], which considered three damage mechanisms: fiber breakage, and tensile as well as compressive matrix cracking. Modifying the equations, which described each mechanism and adding delamination criterion. Considering the foam core to be a homogeneous isotropic material used the Von Mises yield criterion. Schubel *et al*. [50] also indicated that the load pulse for low impact energies is sinusoidal and the sinusoidal nature of the pulse is preserved with some fluctuations.

VI. CONCLUSION AND FUTURE PROSPECTS

Sandwich structures are one of the most rapidly emerging classes in the construction of various composite materials. Composite sandwich construction provided a unique opportunity to incorporate optical and other materials for sensing, monitoring and advising regarding the "health" of the structure during manufacture and use. Impact tests are used to study dynamic deformation and failure modes of materials. Impact tests on composite plates could be performed by using drop-weight machine and also by ABAQUS/Explicit. Different impact energies, impact locations, peak loading and simulation of complicated damage problem and residual tensile strengths could be predicted by this testing. Another testing which is being used to evaluate the structural features of sandwich structures is the quasi-static testing.

It has been observed that cracks initiate from the tensile side and propagate to the compressive side within the core in all sandwich structure specimens. Final failure only occurs when the bottom skin fails. The future for sandwich construction looks bright indeed. Sandwich construction will continue to be the primary structure for satellites. In aircraft, sandwich construction will be increasingly used particularly for large aircraft. Several countries are now using composite sandwich constructions for their navy's ship hulls. However one of the largest uses will be for bridge constructions. Not only will it be used in those states whose departments of transportation (DOT) are or become knowledgeable, but there is a large international market in developing countries who may welcome the advantages. Finally, with the growing need for alternative sources of energy, wind energy mill systems are being developed all of which rely heavily on composite sandwich constructions.

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