Chapter 2. Literature Review

Sandwich structural composites have experienced phenomenal advancements over the last thirty years or so. Due to improvements in manufacturing technology and applied industries that facilitate the production of high strength fiber-reinforced laminates and cellular foam core made out of polymer as well as monolithic material. Sandwich laminates, which are employed in high-performance, light-weight structures, have a low-density material as the core, sandwiched between two strong, rigid, thin face sheets. Such design schemes provide exceptional weight specific bending strength and stiffness properties. As an outcome, they substitute the requirement for conventional material in aerospace, avionics, marine, and automotive applications where weight criteria are at a premium to augment pay load capacity or to reduce energy usage without affecting the structural integrity of the system. Sandwich composites, as an illustration, not only offer strength and flexural rigidity in marine architecture, but also display outstanding buoyancy as an added attribute [8]. Sandwich composites with a foam core were drawn from nature. Natural sandwich structures like skulls, wood, and bird wings are composed of the same material as the core, while the standard man-made sandwich composites that have distinct face sheet and core materials. These primarily consist of soft and hard phases that range in size from micro to nanoscale and are organised in a complicated hierarchical structure [9-11].

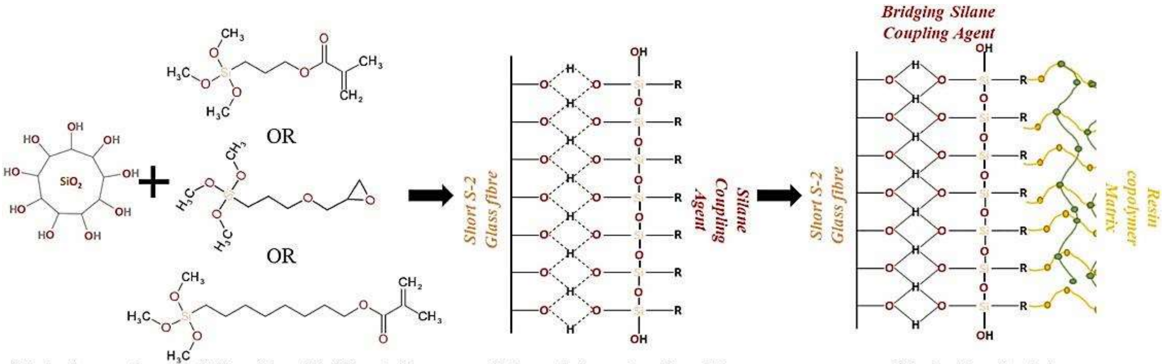
Though it is impossible to precisely imitate these characteristics of natural sandwich materials, efforts are being made to utilize its design philosophy. Similar combinations of soft and hard phases can be used to create sandwich structures, which result in a lightweight material with enhanced stiffness, strength, and toughness. Sandwich composites are used in a variety of ways, thus developing a core structure that is both cost-effective to develop and manufacture is indeed crucial.

A core and two face sheets constitute the sandwich composite structure. Sandwich composite response depends on the change in constituent's property which can improve or worsen its mechanical performance. When sandwich structures are subjected to flexural loading, the addition of a core raises the sandwich's section modulus and shifts the face sheet farther from the neutral line. Under pure bending, face sheets are often more resilient to tensile and compressive loads. The laminate's out of plane shear and compressive strength are provided by the core, which also endures shear pressures. The core is more prone to failure since it is weaker, lighter, and less rigid than the face sheets. Sandwich composites with a polyurethane foam core are an appealing choice material for weight-sensitive structural applications due to their superior stiffness and strength to weight ratios. PUF cores were investigated for potential use in the liquefied natural gas cargo containment system under static and dynamic compressive loading at both room temperature and cryogenic temperature [12]. It was seen that the strength increased with increase in strain rate, density of PUF and decrease in temperature. Inclusion of glass fiber was found to change the dynamic viscoelastic behaviour of foam. PUF with the inclusion of glass fiber when used for I section beam reinforcement was found to restrict the lateral torsional buckling of the web of I beam and the buckling resistance was observed to be almost double in comparison to same section aluminum beam [13]. The lower stiffness of some expanded polymeric foam cores compared to honeycomb cores highlights the need for more comprehensive methodological approaches. To make foam core more resilient against spherical indenter, Long et al.[14] used carbon fiber Z pin with varying inclination angles and densities. Foam core with higher Z pins density performs better against spherical indenter. Z pins were used by Nanayakkara et al.[15, 16] to enhance the performance of sandwich composites with closed-cell polymethacrylimid (PMI) foam cores under compression and impact loading.

The static and dynamic indentation with spherical indenter was conducted on expanded polystyrene with varying densities. Indentation resistance is superior with higher density expanded polystyrene [17]. Vaz et al.[18] investigated the influence of the nose shape profile of indenters affecting the indentation resistance of polyurethane foam. As the indenter grows blunter, the location of the maximum breaking stresses shifts away from the axis, which controls the change from sharp to blunt. A pointed indenter with a large aperture angle behaves as a blunt indenter, but an exceedingly thin indenter with a flat end is considered to be a sharp indenter. Flores-Jhonson et al. investigated the effect of the rigid indenter's nose tip profile on the indentation properties of the polymethacrylimide (PMI) and polyetherimide (PEI) foams [19]. They concluded that nose shape and foam density govern the indentation process. The deformation mechanism of foam core being characterized by a combination of shear, tear and crushing forces were seen to vary with the indenter nose shape. Islam et al. also investigated the impact of the indenter's nose shape on an aluminium foam core [20]. Because of internal microstructure, cellular shape and structure, type of particulate reinforcement, constituent face sheet and core properties, and interface bonding characteristics define mechanism of load transfer, local stress distribution, and macroscopic mechanical properties, it is imperative that these be well illustrated.

2.1. Surface Modification of Particulate Reinforcement

Surface modification, which includes procedures like chemical modification, chemical grafting, oxygen plasma, corona discharge, and silane treatment, is one of the main problems encountered in particle reinforced polyurethane (PU) core sandwich composites [21-23]. The matrix and the reinforcement characteristics differ significantly from one another, in terms of thermal expansion, elastic modulus, density, and surface energetics [24, 25]. The interfacial adhesion between the matrix and the reinforcement is determined by the intermolecular or physical forces, while the production of the composite occurs by chemical bonding during the curing process of composites. The improved mechanical interfacial adhesion is desirable for the effective transfer of stresses from the matrix to particles, promoting the composite's overall mechanical properties. [26, 27]. The cohesive force between the organic resin matrix and inorganic reinforcement fillers is a determinant in the properties of resin composites. To boost and maintain the chemical interfacial adhesion between the interfaces of resin and fibre, silane coupling agents (SCAs) are utilised [28]. There are fewer interfacial contacts between the hydrophilic inorganic particles and the hydrophobic organic monomers when a silane coupling agent is not introduced [29]. To boost the interfacial adhesion between the fillers and resin matrix, inorganic fillers must be treated with the proper amount of silane coupling agent. Although the methods for grafting the silane coupling agent have evolved over time [30-34], the underlying principle behind polymerization and hydrolysis hasn't changed. Silane coupling agents have two functional groups: organic functional radical (RO) and three alkoxy groups. The organic functional radical (RO) copolymerize with composite resin, while three alkoxy groups when hydrolyzed reacts with hydroxyl groups of the inorganic filler. In an aqueous alcohol solution, the functional alkoxy groups hydrolyze in the presence of acidic or basic catalysts to generate intermediate acidic silanol groups (–Si-OH) [35]. Silane reaction occurs in four phases. Even if the subsequent stages are listed in order, the reactions that follow the initial step can happen at the same time. The three hydrolysable groups first undergo hydrolysis, which is followed by condensation to form oligomers. On the surface of the metal substrate, covalent linkages and Si-O-M bonds with hydroxyl groups combine to produce a three-dimensional crosslinked siloxane bond (Si-O-Si). Water is released when the hydroxyl groups on the silicon dioxide surface form a chemical connection with the silanol groups. The reaction products: alcohol (methanol, ethanol, etc.) and water are released into the reaction solution and dissipate during drying. [35-37]. The hydrolysis of methoxy silane into silanol is faster when compared to ethoxy silanes, due to the hydrolysis condensation kinetics [38-40] and was therefore chosen in this study. Fig. 2.1 describes the chemical procedure used during silane grafting [30-33] .



Silanization reaction of S-2 Glass fibre with different silane coupling agent
(a)

Optimum hydrogen bonding with monolayer silane coupling agent
(b)

Chemical bonding between organic and inorganic matrix
(c)

Figure 2.1 The hydrolysis reaction, condensation, hydrogen bonding, and covalent bond formation are the first four main steps in the silane grafting procedure. For the experimental work, various silane coupling agents (SCAs) with various molecular and structural bonds were used. (b) The glass fibre (inorganic matrix) and SCA create hydrogen bonds. (c): During the drying process used in the grafting approach, the hydrogen bond between the glass fibres is further transformed into chemical bonds.

Numerous research [23, 25, 37, 41-47] have demonstrated that silanized chemical-treated fibres produce favourable outcomes in fibre-matrix adhesion with increasing wear resistance, shear bond strength, and water resistance qualities. To get the best adhesion, a suitable silane treatment with compatible surface chemistry must be selected. Before silane treatment, the fibre etching technique is frequently recommended because it can strengthen the mechanical bond between the fibre and resin by roughening the surface of the fibres and removing any surface debris, hence increasing the surface area of the fibres [23, 48]. Silanes are believed to render ceramic glass surfaces more wettable, which lowers the structure's contact angles [44, 49].

According to earlier studies, a silane monolayer is thought to be 10–50 nm thick, [50, 51], But, too many thick or successive silane layers might produce cohesive disintegration between the layers, which lowers the structure's mechanical strength [25, 52-54]. However, a coating of silane that is too thin may result in weak mechanical bonding and be ineffectual in enhancing the mechanical interfacial qualities. So, the optimum silane coating thickness is desired to provide superior mechanical characteristics in the fiber-reinforced composites. The silanization grafting procedure is sometimes referred to as monolayer deposition. The attachment of a surface treatment molecule to each surface atom is the most basic explanation for the monolayer deposition process. However, this kind of saturation is virtually unattainable in real life [35]. According to some research, heat treatment applied to the fibres after silanization can increase the mechanical characteristics by reducing the thickness of the silane coating [55-57]. Another study, however, failed to demonstrate the enhancement in mechanical characteristics brought about by heat treatment after the silanization procedure [58]. As a result, it is important to research the best method for using silane in the silanization process. While using particulate reinforcement in foam structure, proper adhesion, distribution and interfacial bonding should be taken care to build a defect free component. Initial surface treatment using saline coupling agent was found to increase the affinity of particles to the matrix and its interface adhesion characteristics [59-61].

2.2. Influence of Reinforcement on Cellular Morphology

For many years, polymeric foams—which are made of a polymeric matrix created by combining the solid and gas phases—have been extensively used in a variety of applications [62-64]. One significant advantage of using these materials is the reduction of raw material cost. In addition to this economic concern, the cellular structure has many other exceptional qualities, such as great damping capabilities, low dielectric coefficient, and high thermal insulation [65, 66]. However, the uses of polymeric foam have downsides, which manifest in their actual use. These drawbacks include lower mechanical strength, poor surface quality, and lower thermal and dimensional stability. The relationship between the mechanical characteristics of foam and its cell morphology has been amply shown [67]. High strength-to-weight ratio and dimensional stability are thought to be particularly achievable with small cell size, high cell density, and restricted cell distribution[68, 69]. In order to achieve this, numerous studies have looked into microcellular foams with smaller cells (<10 μm) and higher cell densities (>109 cells/cm^3).

In early 1980s, a concept of microcellular foams was developed with several advantages. To obtain polymeric microcellular foam with desirable cell size, the process typically requires higher nucleation rates and higher inert gas concentrations than the conventional processes. The additives, generally micron-sized inorganic particles, were employed as nucleating agents to induce heterogeneous nucleation for producing a large number of nucleation sites in the early efforts[70-75]. McClurg [76] outlined the qualities of ideal nucleants for polymer foaming and suggested that the large amount of uniformly dispersed particles with uniform size and nonwetting surface would be the suitable nucleating agents to produce desirable foams with high cell density and small cell size. More recent studies have focused on the production of microcellular foams with high cell density (>109 cells/cm^3) by using nano-scaled nucleating agents, of which organically modified layered silicates were the most commonly used[77-80]. Cylindrical [62, 81] and spherical [82, 83] nanoparticles were also used for microcellular foaming. The homogeneous nanoparticle dispersion, favorable surface property and particle geometry account for the significant increase in cell density and decrease in cell diameter by adding a small amount of nanoparticles [84]. Moreover, the cell size distribution is another important parameter to characterize the cell morphology in polymer foam,

which has a significant effect on the physical and mechanical properties of foams along with the cell size and cell density. It was indicated by Shafi et al.[85] that the most sensitive parameters to finalize cell size distribution were those associated with the nucleation process, such as the blowing agent concentration and Gibbs free energy. Non-uniform distribution of temperature, gas pressure, and gas concentration in polymer system, as well as a secondary nucleation process, can result in a broad cell size distribution because the cells do not generate simultaneously [86]. Therefore, shortening of the nucleation time interval is a main means to obtain narrow cell distribution in microcellular foams. An increase in cell nucleation rate obviously decreases the time interval for nucleation process, and is expected to narrow the cell size distribution of the final foam[87]. On the other hand, the heterogeneous nucleation induced by the nucleating agents, especially nano-scaled nucleating agents, decreases dramatically the energy-barrier for cell nucleation, increases the cell nucleation rate, and is expected to narrow the cell size distribution as well. However, as far as we are concerned, no experimental evidence has been reported to reveal the effect of nucleating agent with nano-scale size on the cell size distributions of microcellular foams, mostly because of the lack of suitable pure polymer system having a broad cell size distribution. Up to now, most microcellular foams of pure polymers exhibit relatively narrow cell size distribution by using supercritical fluid technology.

The foam core utilized in sandwich composite is not restricted to polymers alone, metal and ceramics can also be transformed into cellular structures. These potential cellular structures are used for acoustic, thermal insulation and to absorb impact energy [88]. The influence of cell wall properties and cell geometry on the mechanical behaviour of polymeric foam structures have been well studied by Gibson and Ashby [89]. Vulnerability of core depends on the kind of reinforcement and how the reinforcement behaves in the cellular structure. Any reinforcement in the form of whiskers or particulates might not be sufficient to reinforce the parent cellular structures, rather it depends on other physical and chemical characteristics such as interface bonding, internal microstructure, reinforcement size from micro to nano scale and its affinity for the matrix[90]. Haibach et al. and Menner et al.[60, 91] synthesized highly open porous low-density polymer foams to obtain superior mechanical properties by the polymerization of the organic phase of concentrated emulsions. These open porous low density polymer foams were reinforced by nano size silica particles and increased the compressive strength and elastic moduli. Aluminium particles with 12 micrometre maximum size and reinforcement up to 50 wt % were also used to enhance the compressive strength and elastic modulus of PU foam [92]. However, those studies restrict to include the flexural and shear behaviour of foam core. After studying the filler granulometry, Saint-Michel et al.[93] concluded that reinforcement bigger than the bubble size might not be efficient. This aspect of influence of reinforcement size on cell structure was also observed by Khidas et al.[94] Typically, a normalized term λ representing the ratio of particle size to the thickness of cell struts was used to define the strength characteristics of cellular structures. When λ was below unity, particle inclusion was found to strengthen the cellular structure, in contrary as λ exceeds unity, the strengthening effect weakens abruptly while softening effect was observed for values of λ greater than 10. The strengthening mechanism not only depends on the particle size and cell morphology, but also on the uniform distribution of particle in the cell structure and the interfacial adhesion between the particles and matrix. Jiejun et al.[95] used SiC particles reinforced in aluminum foam to enhance the damping and sound absorption capability. This is ascribed to the foam structure, presence of SiC particles and SiC/Al interface.

2.3. Effect of Particulate Size and Shape

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Cherepanov [90] characterized the compressive strength of short-fiber-reinforced PU as function of foam density and fiber content. Cherepanov observed that low- density foams were almost unaffected by low glass-fiber contents; however, low glass-fiber loadings in high-density foams resulted in significant improvements. In general, these composite properties were enhanced when foams were loaded with low fiber contents, while a decrease in the reinforcement efficiency was obtained with high glass volumes. McLelland and Hepburn [96] examined the influence of glass beads and short fibers on flexible PU foams. They generally observed a marked increase in elastic modulus and a favorable decrease in the thermal expansion coefficient as a result of the addition of glass reinforcement. Chisnall and Thorpe [97] investigated the mechanism of reinforcement of PU films with glass fibers. They concluded that the use of 1.5-mm-long fibers results in superior properties compared to milled fibers. In another system, the tensile properties of fiber- glass-reinforced polyester foams were recently studied [98, 99]: their tensile modulus enhancement could be predicted by using the concept of the quasi-isotropic laminate theory and the Kerner's equation.

Whereas on the other hand, nano-reinforced polymer foams have the opportunity to tailor mechanical properties as well as to add multi- functionality to the systems which makes them attractive for several applications from insulators in buildings to structural components for aerospace vehicles [63]. The main mechanism behind using nano-particles in foams is to trigger heterogeneous nucleation during foaming step, where cell formation and growth take place around nanoparticles as in Shish-Kebab structure due to their high surface energies [62, 63]. Cell formation and growth around nanoparticles result in a narrower cell packaging, higher cell and foam density yielding higher strength for foam structure [63, 100, 101]. Heterogonous cell nucleation is not only based on growth around nanoparticles but also on rheological effects such as viscosity variation in polymer. Foaming process in closed cell foams occurs in two steps as solid phase and gaseous phase in which the structure is formed and expanded, respectively [92, 101]. In a heterogeneous nucleation, nanoparticle inclusion increases the shear viscosity of polymer which causes less gas out for cell growth and a decrease in cell size [102]. Nanoparticles such as carbon nanofiber [103-105], carbon nanotube [105-107], nano-clay [104], titanium dioxide [104, 105], and nanosilica [100, 108] have been commonly studied by many researchers as nucleating agents in nano-reinforced polymer foams. However, carbon nanotubes (CNTs) are still the most preferred reinforcing agents due to their high strength to weight ratio [109]. Especially, multi-walled carbon nanotubes (MWCNTs) are the most common nanomaterials because of their high Young's modulus which is a combination of individual moduli of each graphite sheet plus the small influence of the van der Waals forces acting between neighboring tube layers [110]. However, high aspect ratio of MWCNTs can be a drawback since they tend to agglomerate inside the foam resulting in stress con- centration points [104, 111] and also may cause undesirable non-homogenous cell size distribution. In previous studies, the importance of proper dispersion of nanoparticles has been implied clearly through characterization and mechanical test results [101, 106, 112]. There is a variety of methods to overcome the challenge of non-homogenous nanoparticle dispersion such as shear mixing [100], ultrasound sonication [103] and functionalization of nano- particles [100, 106]. Kabir et al. [103] studied the effect of ultrasound sonication on carbon nanofiber reinforced polyurethane foam and stated that sonication provides the required energy to nanoparticles in order to eliminate the surrounding resisting force and obtain proper dispersion. Thus, sonication power and time need to be optimized to obtain the best dispersion and distribution, and maximum compressive strength [103]. Modifying nanoparticles by adding functional groups such as carboxyl groups etc. also attracts many researchers since nanoparticles adhere to polymer matrix better and disperse easier when such groups are used [113, 114]. Moreover, aspect ratio of carbon nanotubes (CNTs) is another parameter affecting load transfer between polymer matrix and CNTs [115, 116]. Additionally, Yan et al. studied graphene nanosheet and carbon nanotube reinforced polyurethane foam composites and stated that one dimensional structure of CNTs leads to an increase in viscosity of polyol and a decrease in cell size but does not hinder the foamability [117]. Based on previous studies, it is found that improved mechanical properties are directly proportional to increased foam density and thereby to cell density [117, 118]. However, in some studies such as Madaleno et al. [101], it is observed that by increasing nanoparticle concentration, foam density decreases and compressive properties still keep increasing compared to neat polymer foam. This indicates that normalized or specific compressive strengths should be used to eliminate the effect of density on reported properties.

2.4. Quasi-Static Indentation

Structural components made of fiber-reinforced polymer composites are increasingly used in several engineering applications because of their high weight-specific mechanical properties. In particular, nowadays fiber-reinforced polymer composite laminates are commonly used for aerospace[119], automotive[120], military[121], marine[122, 123], and construction[123, 124] applications. However, the higher strength-to-weight ratio of laminated composites is counterbalanced by a significant vulnerability to impact damage, due to the absence of reinforcement through the thickness and to material discontinuities at the ply interfaces. This can considerably affect the mechanical performances of the composite, and may evolve often in unpredictable ways, leading to an unexpected and sudden failure of the structural component.

In particular, for many applications the major concern regards the damage induced by low velocity impacts (LVI). LVI are likely to occur during the various stages of the life of many components, starting from the manufacturing, keeps going during the service life and the maintenance. A typical damage process originated by a LVI may lead to the development of microcracks, fiber crushing and delamination, localized in limited area. When the structural component becomes subject to subsequent loads, related to its service life, a propagation and an evolution of the original damage can occur. This evolution of the damage can totally jeopardize the mechanical properties of the component. It is important to recall that LVI damage may be sneaky, since after the impact often it is not possible to see any visible external sign of damage, although a significant internal degradation has taken place; in addition, the internal damage may spread over a wide area surrounding the impact point, leading to a considerable lowering of the mechanical properties of the composite.

For the above reasons, the study of LVI damage has become a key subject in the research on composites since the 1970s. Indeed, it is possible to find a broad literature about experimental analyses on the effects of LVI on composites. Several conditioning aspects have been analyzed like, e.g., the shape of the impactor, the number of impacts, the boundary conditions, the thickness of the composite, the velocity and the impact energy[125]. Moreover, the literature indicates that the results are strictly related to the composite type; by narrowing the landscape to fiber-reinforced polymer composite laminates, the effects of LVI damage depend on the content of the fibers and the matrix and on the arrangement of the layers [122, 126-129].

A significant fact to underline is that LVI damage tests are relatively difficult and expensive to perform, and their results are often largely scattered and of complex interpretation. Thus, a large number of studies concern the possibility of assessing LVI damage behavior of composites starting from the results of quasi-static indentation (QSI) tests [127, 130-132]. Indeed, for composite laminates the damage configuration due to quasi-static indentation is similar to that of low velocity impact[127]. Indeed, the latter is a dynamic process, whereas QSI tests are performed at such a low speed that dynamical effects are negligible. This justify the simplicity and reliability in obtaining the required results from the easily controlled QSI tests; moreover, as well as in LVI tests it is possible to consider different impact energy, in QSI tests it is possible to vary the maximum achieved displacement, in order to investigate the progression of the damage.

In the literature, a number of studies indicates that the low-velocity impact and quasi-static indentation cause a similar response of composite laminates in terms of the induced damage and the residual strength. Anyway, the rate-dependency of the mechanical response of many composites may affect the representativity of the results of QSI tests in terms of the characterization of the low-velocity impact damage behavior[120]. Mostly, the results of QSI tests are compared to those obtained by LVI tests in terms of the comparison of the acquired force-displacement responses and in terms of the damage observed in the two different experimental procedures. For the latter, both destructive tests like microstructural analyses by SEM and compression after-impact tests or non-destructive tests like, e.g., ultrasonic C-scan tests and X-rays tests are performed. The aim is basically that of determining the extension of the damaged area and the features of the occurred damage. In general, these analyses provide an understanding of the general damage resistance response, but cannot identify the process of the development of the damage, and if there are similarities in the interaction of different damage modes. Anyway, comparison of QSI damage and LVI are performed for the same employed energy[133]. On the other hand, since LVI damage is considered very difficult to detect, there is also a broad literature about non-destructive techniques for detecting, quantifying and monitoring LVI damage on composite laminates. Among the others, ultrasonic[119, 133], ultrasonic guided waves[134], thermographic[135, 136], holographic[137] and acoustic emission techniques have been studied. A new approach for the comparison between the damage induced by LVI tests and QSI tests in glass fiber-reinforced polymer composites (GFRP) has been given. In this technique, damage resulting from low impact energy, in view of representing possible scenario where the impact generates sneaky damages, difficult to detect, but capable of evolving in a sudden failure of the composite. Since the damage of composites involves a damage induced anisotropy superimposed to the constitutive anisotropy [138-140], therefore, approach is based on the employ of ultrasonic goniometric tests, based on the analysis of change in the anisotropy of the acoustic response of the composites. Goniometric ultrasonic tests combined with ultrasonic immersion techniques and ultrasonic laser techniques have been proven to be effective tools for the characterization of the mechanical response of anisotropic materials [141, 142].

Composite sandwich panels are increasingly used in aircraft and aerospace industries due to their high specific strengths and stiffnesses. However, composite sandwich structures are susceptible to damage and failure due to transverse contact and to impact by foreign object. The failure mode map [143-149] is found to be a good technique in designing composite sandwich structures to optimize their energy absorption properties and load carrying capacity with minimum weight to satisfy the quasi-static and impact loading requirement. The introduction of a damage initiation map in this contribution would complement the failure modes map. The combination of damage and failure mode maps would be of great research interest and they will serve the needs of the structural designers.

Failure mode maps of sandwich beam have been extensively investigated since the late eighties. Investigations on the formation and implementation of the failure mode maps of sandwich structures were pioneered via three-point bend tests on sandwich beams[145, 146]. Experimental and theoretical work on three-point bend tests[144-146] and four-point bend tests[147] are readily available. Failure modes on sandwich structures subjected low-velocity impact[149], blast loading[143] and uniform pressure[148] were also proposed. Research work on sandwich panel with isotropic face sheets has been extensively investigated[150, 151]. Since the impact duration is quite short and impact damages are difficult to detect, Finite Element Analysis (FEA) has been widely used to simulate the damage evolution and failure mode of sandwich panels[152-154].

Definition of damage initiation has been defined phenomenologically according to the law of damage evolution [155]. From the extensive experimental investigations of the quasi-static indentation and impact tests[150, 156-161], damages are initiated in sandwich panels when the impact energy has exceeded a limit damage value. The contact force for damage initiation may not be the maximum load but it can be used as a valuable index to investigate the energy absorption and impact resistance of composites. To investigate the onset of damage, damage initiation modes in composite sandwich structures are classified as: (i) core buckling and core crushing, (ii) delamination in face sheet or debonding along face sheets and the core, (iii) matrix cracking in face sheet due to contact pressure, (iv) fiber breakage in the face sheet. When damage occurs in a sandwich structure, its stiffness will degrade and its load capacity decrease significantly up to the final point of failure[160]. The failure mode of wrinkling of face sheets was reported for sandwich beam structures in bending [144, 146] but there is no report of this mode for sandwich panels subjected to low velocity impact of a rigid projectile. The failure modes of sandwich structures subjected to low velocity impact load are reported to be similar to those of the sandwich structures subjected to quasistatic indentation[151, 162]. The experimental results from the quasi-static indentation tests[163, 164] and the low velocity impact tests has been combined. The damage and failure mode maps for composite sandwich panels are developed using published explicit formulae for their corresponding limit loads[165].

2.5. Utilization of FA as a Reinforcement

Advanced sandwich composites comprising the face sheets and core harness the coupled effect of the high strength of face sheet and low density core demonstrating enhanced higher bending stiffness, strength, impact resistance and damping accompanied with lighter structural properties [166]. However, for large scale application of sandwich composites replacing traditional monolithic materials, there has always been a trade-off between cost and property enhancement apart from weight considerations. Enthusiastically, this has laid the authors to seek low cost and light weight industrial by-product fly ash as reinforcement inclusion in foam core structure. It is not that fly ash was never used earlier, rather it finds its application in resin, plastic, rubber and cement industries successfully to reduce the density of product. Some relevant published works and the research findings are listed here. Fly ash cenosphere with 40 wt. % was used with high density polyethylene and synthetic foam to reduce porosity due to lack of penetration of resin between particles [167]. FA inclusion increased the specific modulus of elasticity up to 2.6 times for the 3D printed filament although fracture strain was decreased by 40%. Garcia et al. [168] compared the performance of fly ash reinforced epoxy synthetic foam at room and arctic environment. It was seen that fly ash inclusion resulted not only weight saving but also provide higher elastic modulus. The specific strength of the fly ash filled synthetic foam was found to be higher at arctic condition than room temperate condition.

Another advantage might be cited that while using fly ash, indirectly we are reducing the industrial waste and its hazardous effect on environment. Fly ash is usually disposed either by landfills or in built up settling ponds. Either of the disposal systems later impacts the terrestrial ecosystems. The adverse effect is ascribed to the leaching of potentially toxic substances from fly ash into the soil and groundwater, thereby affecting the nearby habitats. Degraded quality of water and soil leads to reduced vegetation and more importantly its composition. These hazardous elements also enter into the food chain and can severely impact humanity with incurable diseases [169]. Basically, fly ash (FA), is the solid waste resulting from combustion of coal in thermal power plants is a by-product produced in massive quantities across the world. It is considered as an environmental pollutant. Owing to its bad effects on the environment, research is being conducted all over the world for the utilisation of FA. The demand for energy is increasing day by day. Due to the shortage of natural gas and crude oil, it is becoming very difficult to fulfil even the primary energy requirements. So, coal-based energy production methods have gained attention in mass energy producing units. For rapid combustion of coal and to extract maximum energy, pulverized coal is used in power plants. Rapid combustion of coal produces FA. The FA production depends on the quality of coal used; for instance, Indian coal has high ash content (35–45%) and is of lower quality [170]. The major portion of FA produced is disposed of in ash pond and landfill and a very small fraction of it is being utilised [171]. Due to its toxic contents and high salinity, disposal in landfill leads to soil pollution [172]. FA production and utilisation in India from 2011 to first half year of 2016–17 has been shown in Fig. 1, Fig. 2 respectively.

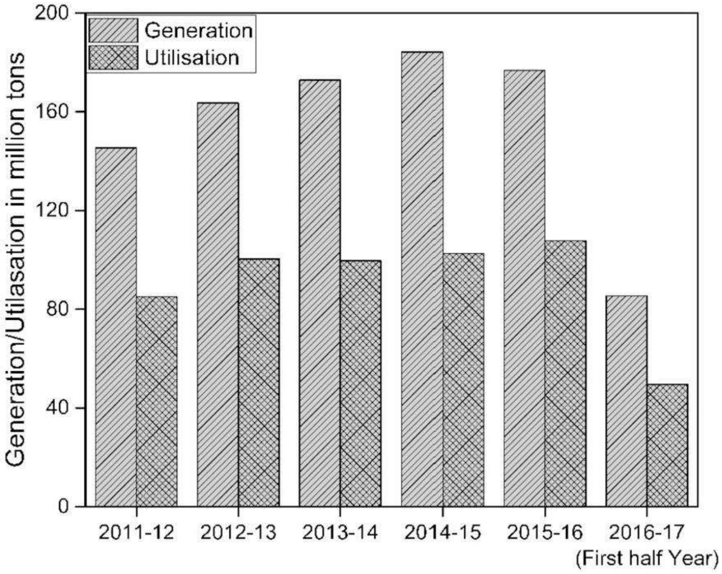

Figure 2.2 Fly ash production/utilisation (millions tons per year) in India during 2011 to 2016–17 (first half year) (plots present data from the source: http://cbrienvis.nic.in).

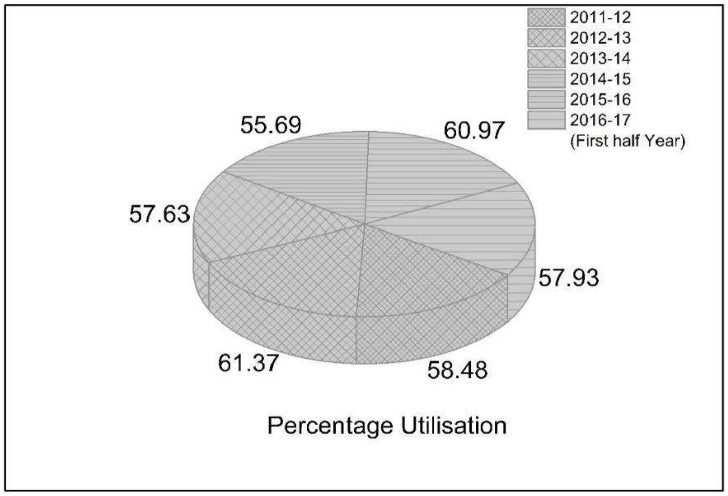

Figure 2.3 Utilisation (%) of Fly ash in India during 2011 to 2016–17 (first half year) (plots present data from the source: http://cbrienvis.nic.in).

The ministry of environment and forest (MoEF) in India issued solid waste management (SWM) rules 2000 to ensure proper waste management and new updated draft rule has been published recently (MoEF, 2015) [173]. Because of negative impact on the environment and enormous generation all over the world, research is being conducted to utilise FA rather than dumping. Till now, it has been used for making ceramics [174], cement and concrete additives [175-181], water treatment [182], agriculture application [183], Building materials [184], CO_2 sequestration [185], metal matrix composites [186], Polymer matrix composites [187-189] etc.

2.6. Motivation and Research Gaps

After extensive literature review, it has been observed that none or very less literature is available which utilises fly ash to reinforce the cellular foam structure. Although, several literature state that the micro size particles can effectively be utilised to reinforce the cellular foam for its improved mechanical performance. This work aims to use fly ash a viable particulate reinforcement. As already discussed in previous section, fly ash which is the by-product of thermal power plants, hazardous to the environment. Usually, fly ash waste kept on collected in ash pond, sometimes resulted into the fly ash floods if not handled properly.

Therefore, this work aims to convert fly ash into asset which is generally considered as nuisance.

The synergetic effect of fly ash and cellular foam structure are hardly investigated for its mechanical properties. The effect of fly ash concentration to the foam core needs to be investigated. This type of investigation will provide perspective while optimizing the FA concentration to cellular structure.

It was also observed that the sandwich composites sustain high flexural loading but, prone to localised stress concentration or low velocity impact loading acting out of the plane. Several literatures are available which accounts, the effect of indenter's nose tip geometry on quasi static indentation response of foam core. But literature does not include, the effect of FA reinforcement and FA concentration on the quasi-static indentation response with different nose tip profile.

Eventually, the sandwich composites were extensively investigated in previous studies under flexural loading and quasi-static indentation. But again, the effect of fly ash reinforced PUF core sandwich composites were hardly studied.

2.7. Research Objectives of the present work

In the view of the above, the present work foremost aim is to convert the fly ash waste into viable asset. In this regard, fly ash has been investigated for its viability as reinforcement to PUF core. Then clubbed together with different face sheets and investigated further for the flexural and quasi static indentation loading conditions. The investigations provide better understanding of load transfer and deformation mechanism of FA reinforced PUF core and its sandwich composites under compression, flexural and quasi-static indentation.

The objectives of the present work are outlined as follows:

(i) The surface treatment of the FA with GPTS for better interfacial adhesion to cellular PUF matrix.

(ii) Fabrication of GFRP and CFRP face sheets of sandwich composites by hand lay-up method.

(iii) Fabrication of neat and FA-PUF core with varying FA weight parentage (5, 10, 15 and 20 %) of PU matrix.

(iv) Fabrication of neat and FA-PUF GFRP and CFRP sandwich composites.

(v) Investigation of effect of varying FA wt. % added to PUF core under compression and shear for enhance mechanical performance.

(vi) Neat and FA-PUF GFRP and CFRP sandwich composites are investigated to understand the effect of FA on stiffness and load bearing capacity of sandwich composites under flexural loading condition.

(vii) Effect of different indenter's nose tip profile (flat-circular, hemispherical and conical) on the deformation and indentation resistance of neat PUF core

(viii) Effect of varying FA wt. percentage on Neat and reinforced PUF core is investigated under quasi-static indentation for deformation mechanism and indentation resistance capability for different nose profile geometry (flat-circular, hemispherical and conical).

(ix) GFRP and CFRP sandwich composite were investigated for variation in indentation resistance and deformation mechanism for different (flat-circular, hemispherical and conical indenter) nose tip geometry of indenter accounting the effect of face sheet material.

(x) Effect of varying FA to PUF core GFRP and CFRP sandwich composite on the indentation resistance response and deformation mechanism under quasi-static indentation.

(xi) Scanning electron microscopy has been utilised to investigate the variation in PUF cell size and cell density with FA inclusions.

(xii) The deformed neat PUF and FA-PUF core under different indenter nose profile geometry were cut and investigated under SEM for the deformation mechanism.

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