Smart Composite Sandwich Structures for Future Aerospace Application -Damage Detection and Suppression-: a Review*

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Abstract

Sandwich structures with advanced composite facesheets are attracting much attention as a solution to maximize the potential of composite materials. However, the composite sandwich structures are prone to damage, such as impact damage and debonding. Although these damages are difficult to detect using conventional nondestructive inspection method, they cause significant reduction in the mechanical properties. Hence, several researchers have attempted to detect and suppress the damages using smart sensors and actuators. In this paper recent developments on smart technologies to improve reliability of the composite sandwich structures are reviewed. First, the state-of-the-art sandwich technology in aerospace application is presented. Next, typical damages in composite sandwich structures are described, which is essential to effectively apply the smart technologies to sandwich structures. Then, smart technologies which have been applied to sandwich structures are briefly shown with focusing specific properties of sandwich structures. It includes damage detection using dynamic response, wave propagation and optical fiber sensors. Finally, a smart honeycomb sandwich concept is also presented.

Key words: Smart Material, Sandwich Structure, Composite Material, Damage Detection, Damage Suppression, Dynamic Response, Wave Propagation, Optical Fiber Sensor, Shape Memory Alloy

1. Introduction

The use of advanced composite materials represented by carbon fiber reinforced plastic (CFRP) has been increasing rapidly in wide range of industrial applications because they have excellent properties such as high specific strength, specific stiffness and fatigue characteristics. Especially in civil aviation aircraft, the weight percentage of the composite materials to the whole weight of the airplane has significantly increased for past 30 years. Recently, for Boeing 787, the composites will account for approximately 50% of the whole weight of the structure. However, almost all the composite materials in primary structures are used in a form of classical stiffened skins, in which the composites cannot maximize the realization of their potential.

Hence, composite sandwich structures are attracting much attention as a solution on behalf of the quasi metal-derived design. As presented in Fig. 1, the composite sandwich structures are integral constructions consisting of facesheets made of advanced composite
materials and core materials, such as honeycomb and foam \(^{(1, 2)}\). The facesheets primarily resist the in-plane and lateral (bending) loads, and the core keeps the distance between two facesheets and carry transverse forces. The facesheets are adhesively bonded to the core, or adhere to the core during the co-cure process, depending on the kinds of materials. Since the sandwich structures have high mechanical properties and inherent multifunctionality, they have been utilized in a huge variety of applications such as satellites, aircrafts, ships, automobiles, rail cars, wind energy system, and bridge construction. Although, in aerospace transportation, the application of composite sandwich structures are currently restricted mainly in secondly structures, they have wide range of advantages and potentials which will lead to further weight and cost saving. Hence there are many researches proposing utilization of the composite sandwich structures in primary structures in future aerospace structures \(^{(3-5)}\). However, for a more widespread application of the composite sandwich structures, several challenges to improve the performance, including damage tolerance, fail-safeness, and maintenance efficiency, must be met.

On the other hand, smart technologies to monitor and modify dynamics of the structures by distributed sensors and actuators have gained a lot of attention recently \(^{(6)}\). With smart technologies, structural safety, integrity and additional functionality, such as attenuation and adaptation of key mechanical properties, can be enhanced, resulting in considerable decreases in weight and cost of structures. In aerospace application, many kinds of sensors and actuators have been successfully integrated with the advanced composite materials for damage detection and suppression. Especially, fiber optic sensors such as fiber Bragg grating (FBG) sensor and shape memory alloy (SMA) embedded in composites have shown excellent properties as smart devices \(^{(7, 8)}\).

In this paper, the authors present a review of recent development on smart technologies to detect and suppress damages in composite sandwich structures. First, the state-of-art sandwich technology in aerospace application is presented. Next, typical damages in composite sandwich structures are described, which is essential and instructive to effectively apply smart technologies to sandwich structures. Then, smart technologies which have been applied to sandwich structures are briefly shown with focusing specific properties of sandwich structures. Smart honeycomb sandwich structure concept the authors have been proposing is also presented.

2. State-of-the-art sandwich technology in aerospace structures

Sandwich concept has wide range of advantages and potentials over quasi metal-derived design. Since the facesheets are continuously sustained by the core, the global and local stiffening can be achieved. Moreover, the integral simple stiffening reduces the complexity in analysis, manufacturing and maintenance, resulting in cutting the total life cycle cost of the structure. Introduction of sandwich structures in fuselage shells reduces the noise level inside the cabin, because of high damping properties of the core materials, and thus increases passengers’ comfort. In this application, an integration of thermal isolation is also possible.
Airbus initiated a CFRP fuselage project in 1999 supported by the German government \textsuperscript{(3)}. After a wide screening of technologies, this investigation led to new sandwich concepts called SoFi (Stringer outside, Frames inside) and VeSCo (Ventable Shear Core). Both of them are integrated double shell structures and use innovative core materials, i.e. carbon pin reinforced foam \textsuperscript{(9)} and folded core that looks like Origami construction \textsuperscript{(10)}, which enable the implementation of more functions into fewer parts. The future aeronautical applications of the VeSCo concept (Fig. 2) with the folded core appear to be promising, as some European aircraft manufacturers are intensively studying the possible use of these materials in primary aircraft structures. NASA/Boeing \textsuperscript{(4)} also evaluated composite sandwich fuselage concept and concluded that sandwich fuselage offered cost and weight saving of 41\% and 29\% as compared with baseline aluminum design while composite skin-stringer fuselage achieved only 23\% saving of both. Additionally, they reported that the tested composite sandwich structure with twice the original frame spacing is capable of design sustaining ultimate load conditions without damage and limit load conditions with a 1-inch long notch. Furthermore, NASA \textsuperscript{(5)} considers the composite sandwich structures as a promising structural concept for the primary structure of future space transportation vehicles.

Even though the sandwich structures have been utilized in aerospace application for a long time, the potentials of sandwich structures are not fully opened up. In order to further exploit the benefits of sandwich structures and to widely apply sandwich structures in aerospace structures, several challenges addressing damage tolerance, fail-safeness, NDT, and repair have to be overcome in the near future and mid-term future.

3. Typical damages in composite sandwich structures

Unless we know what causes damages, what kinds of damage are induced, and how these damages affect the residual mechanical properties of structures, we cannot fruitfully utilize sensors and actuators to detect and suppress damages. Hence, detailed understanding of damages in composite sandwich structures is essential to develop smart sandwich structures.

As described above, composite sandwich structures have many advantages over classical stiffened skins concept, however, they have mainly two potential problems: core materials are relatively weak compared to composite facesheets and the interfaces between two facesheets and core material may serve as sources for failure initiation and growth. Hence, in composite sandwich structures, specific damages, i.e. localized damage and damages in the adhesive layer and core, can be induced in many loading cases, in addition to composite facesheet failure such as matrix cracks, delaminations and fiber breakages. Even though these damages are invisible from the outside or difficult to be detected using traditional nondestructive inspection (NDI) method, they cause significant reduction in
mechanical properties of sandwich structures.

Honeycomb sandwich structures have long been utilized in aerospace structures, since honeycombs have excellent mechanical properties; very high stiffness perpendicular to the facesheets and highest shear stiffness and strength to weight ratio among all available core materials. Recently, however, sandwich structures with Rohacell foam core are attracting much attention, even thought the foam core is inferior to the honeycomb core in mechanical properties. That is because water does not accumulate in the closed-cell rigid foam core as in honeycombs and, further, the Rohacell core can sustain 180°C, which enable single autoclave co-curing of the foam core sandwich structures resulting in lower manufacturing cost. The modes of damages highly depend on types of core materials. Following is a brief description to typical damages in composite sandwich structures with honeycomb and foam core.

3.1 Localized damage

Since the facesheet is very thin and the core is relatively weak, composite sandwich structures are prone to damage when localized transverse load, such as impact and indentation loading, is applied \(^{(11)}\). If the loading is extreme intensive, perforation of projectile occurs \(^{(12)}\). However, when the loading is moderate, barely visible impact damage (BVID) including failure in composite facesheet and crushing of the core material is induced. It is important to say that the core damage plays an important role in the damaged sandwich structures. Though the BVID is literally difficult to find by visual inspection, it leads to significant deterioration of mechanical properties of sandwich structures. Hence, main focus of recent researches is on this kind of damage \(^{(13, 14)}\). When the localized load is applied to the composite sandwich structure, the structure is deformed globally and the upper facesheet, on which the load was applied, locally deflects against the lower facesheet, followed by transverse deformation of the core material. When the loading exceeds the elastic limit, the composite facesheets starts to break and, further, the core crushing around the loading point initiates. The crushing behavior strongly depends on types of the core. The honeycomb core shows very steep peak stress before plastic buckling while the foam core does not. During unloading process of localized load, on the other hand, the facesheet, which elastically deflects in transverse direction in loading process, starts to return to flat. Hence, the core is stretched from the crushed state. The stretching behavior of crushed core differs from core to core, and it governs the dynamics of the sandwich structure after localized damage occurrence. The metallic honeycomb represented by aluminum honeycomb is stiff even after it is transversely crushed, and relatively large dent remains around the loading point (Fig. 3 (a)). When the adhesive layer is not strong enough to adhere the facesheet and the core, debonding between the facesheet and the core occurs and slight dent remains on the facesheet (Fig. 3 (b)). On the other hand, non-metallic honeycomb represented by Nomex honeycomb is very compliant after it is crushed. Hence, almost no sign of internal damage is left on the facesheet (Fig. 3 (c)). The stretching behavior of foam core is a little different from honeycomb core. The crushed foam core is moderately stiff, and what is interesting is that the strain speed affects the stretching behavior. When the loading rate is high, fractures of the crushed core and the cavity can be observed in the core underneath loading point (Fig. 4 (a)). In contrast, the structure loaded statically tends to have larger residual dent than dynamically loaded one (Fig. 4 (b)).

The gentle dent produced by localized loading significantly changes the dynamics of the structures. The dent has both good and bad features. First, the dent acts as an impact detector. Hence the impact damage in sandwich structures can be easily detected by visual inspection during maintenance compared to stiffened composites skins, resulting in short maintenance time. Secondly, the dent significantly deteriorates the mechanical properties of sandwich structures, sometimes to 50% of the undamaged one \(^{(15)}\). Sandwich structures have
high specific bending stiffness because the core keeps two facesheets away. Hence the dent, which reduces the distance between the facesheets, makes the structures flexible and, consequently, generates stress concentration around the impact region resulting in unexpected failure. Further, under in-plane compressive loading condition, the dent changes failure mechanism and also decreases the strength \([16-18]\). Since the perturbed geometry of the facesheet alters the stress field in the facesheets, kink band initiates in the impacted specimen at lower strain compared to a specimen which has a hole in the facesheet as large as the delamination in the impacted facesheet \([17]\). Development of damage at low stress proves fatal when a structure is subjected to fatigue. Moreover, the crushed core cannot sustain the facesheet continuously and the facesheet is exposed to local instability \([16, 18]\).

### 3.2 Damages in core and adhesive layer

Since the core material and the adhesive in sandwich structures are relatively weak compared to the facesheet, accidental excessive load, like impact loading, causes several kinds of damages in them. Further, they are exposed to a complex loading situation in long term service leading to fatigue damages \([2, 19]\). Since the thin facesheet loses continuous support from the core, the facesheet may easily be buckled under normal loading condition and, moreover, damages in the core and adhesive layer also induce failure in different areas, which will lead to structural failure of the sandwich materials. These damages are invisible from the outside and difficult to detect using NDI methods because of the thickness and low density of the core. In practical use, there are too many scenarios of damage initiation and progress in the adhesive layer and the core. Following is the general description about these damages.

In honeycomb sandwich structures, the damage appears in forms of core buckling, core cracking and cohesive failure in adhesive layer, and facesheet failure, as illustrated in Fig. 5. The fracture patterns depend on both the material combination of the structures and the
loading condition, and, consequently, the weakest region in the structure fails. From the initial damage induced by over loading, fatigue, or manufacturing defects, the crack may grow without being detected deteriorating residual strength of the structures. The largest practical issue for honeycomb sandwich structures is that large amount of water accumulates inside of the honeycomb cells. Water ingression occurs at the end of the components and damaged area. The water freezes and expands during flight, and causes high stress in the interface between the core and the facesheet leading to debonding. Further, aluminum honeycomb core is also corroded by the water.

In foam core sandwich structures, the adhesive layer consists of either additionally inserted adhesive or the resin from the facesheet. Virtually, damages appear in the form of cracks inside the core, not cracks in the adhesive layer, because almost all the foam core is weaker than adhesive layer. Hence the cracks do not propagate in the adhesive layer, but in the core, and sometimes along the interface. Under fatigue loading, cracks in the core are generated in the form of accumulation of micro cracks. The cracks also propagate from the cavity induced by localized loading or a defect produced during manufacturing under bending and compressive loading. It is interesting to note that the propagation path can be determined by the stress field at the crack tip. As in the honeycomb sandwich, these damages may grow without being realized.

The above description of damages in the composite sandwich structures is not exhaustive. It is important to understand that material combination and loading condition decide damage modes and, moreover, the strength reduction due to these damages strongly depends on how the panel is designed. Hence, proper understanding of materials used and dynamics of sandwich structures are vital to understand the effects of specific damage on the structures, and essential for effectively utilizing smart technologies to detect and suppress damages in sandwich structures.

4. Smart technology for composite sandwich structures

Several researches about damage detection in composite sandwich structures have been reported, while, as far as the authors aware, no researchers have shown damage suppression techniques except for our smart honeycomb sandwich concept. Hence, in this section, we provide a brief review of the smart technologies for damage detection. Our focus is not only on techniques and results of them, but also on specific properties of sandwich structures available for damage detection, which is instructive for future researches.

4.1 Damage detection using dynamic response

Damage induces changes in global and local dynamic properties in the structures. There are many researches to detect the damage using the dynamic response of structures. Paolozzi et al. used modal analysis in order to find correlations between the variations of global modal parameters and the severity of damage in sandwich structures with CFRP
facesheets and Nomex honeycomb core. The core was debonded locally from both skins by using a sort of lancet. The debonding was always located in the center of the plate and the damaged area was progressively increased from 1 to 20% of the panel size. The experimental modal analysis tests confirmed the existence of the correlation between the natural frequency shift and the size of the debonding. Lestari et al. (22) also conducted an experimental identification of damage based on curvature mode shape. The curvature mode shapes are very sensitive to damage compared to the natural frequency, and the effect is highly localized in the region of the damage. Hence the change in the curvature mode shapes can be applied effectively to detect damage size and location in structures. Piezoelectric materials in the form of polymer film (polyvinylidenefluoride, PVDF) bonded on the facesheet were used as strain sensors. The specimens consisted of GFRP facesheets and FRP corrugated honeycomb core and artificial damage was created at the interface between core and facesheet and also in the core to simulate core-facesheet debonding and core crushing, respectively. Damage was identified from comparison of the curvature mode shapes of healthy and damaged cantilever beams. The locations of the damage for both damage configurations were identified properly using curvature damage factor and damage index method, while the magnitude of the damage was evaluated through the stiffness loss.

Meo et al. (23) showed a novel technique based on nonlinear elastic wave spectroscopy (NEWS) approach. This technique monitors the presence of harmonics and sidebands generated by the interaction between a low frequency and a high frequency harmonic excitation signal, due to the nonlinear elastic behavior of the material structure caused by the presence of damage. Two different piezoelectric transducers and three broad band acoustic emission (AE) sensors bonded on the facesheet were used to oscillate the Nomex honeycomb sandwich specimen and to acquire the plate responses, respectively. After BVID was introduced, the specimen started to behave non-linearly and sidebands and harmonics of two excited frequencies are generated, confirming the technique can be easily implemented and can be used as a first assessment of the presence of damages. In these papers, it was also mentioned that the improving performances of analyzers, accelerometers and algorithms for the retrieval of significant parameters are necessary for a future practical application in quantitative detection of small damages in complex structures.

Recently, some researchers have reported new methods to evaluate the dynamic responses of sandwich structures. Yam et al. (24) studied crack detection in the facesheet of a honeycomb sandwich structures using energy spectra of the dynamic responses decomposed by wavelet transform and an artificial neural network (ANN). Nichols et al. (25) showed a procedure for detecting impact damage in foam core sandwich utilizing concepts from the field of information theory. However these detection techniques are not based on the typical properties of the composite sandwich structures, but mainly relied on general mechanical imperfection induced in damaged structure and innovative data analysis methods. Hence, further explanations about the details of these techniques and algorithm are omitted here.

4.2 Damage detection using wave propagation

There are several wave propagation phenomena in solid materials. Lamb waves are two-dimensional acoustic waves that can be generated in thin solid plates with free boundaries. They are divided into symmetric $S_n$ and anti-symmetric $A_n$ modes depending on their displacement pattern. Since Lamb waves excite the whole volume of the structure between the transmitter and receiver and can propagate over long distances, they can be adapted to the inspection of large, thin plates with a small amount of sensors. Due to the significant difference of the acoustic impedance between the core and the facesheet and high thickness ratio of core to skin, several researches have studied Lamb wave propagation in sandwich structures as leaky Lamb waves (LLW).

Bourasseau et al. (26) used the LLW phenomenon to detect damage induced by
low-velocity impacts. Compared to the free plate waves problem (a facesheet without core), the phase velocity dispersion curves of the facesheet with core show that the phase velocities are approximately the same for the first modes $A_0$ and $S_0$ in low frequencies. On the opposite, significant shifts are obtained in the attenuation curves of the waves propagating along the facesheet. This attenuation is correlated to the amount of energy dissipated into the core. Further, it is important to note the following phenomenon. When the acoustic impedance of the core was vanishingly low, the wave form was almost similar with the one in a facesheet without core, i.e. only direct wavepacket. When the impedance was relatively high, however, the second wavepacket was additionally generated. To explain the difference, the following propagation mechanism was proposed. If the impedance of the core is nonnegligible compared to facesheet, waves also propagate in the core thickness. When they reach the lower facesheet, they generate new LLWs in the core and the same mechanism recurs. The reason why this propagation mechanism is not perceptible in the lower density core is that its acoustic impedance is too weak to induce an important wave leakage. According to the interpretation proposed, the amplitude of the direct wavepacket can be directly related to the global wave leakage in the core. Consequently, it could be an efficient parameter to detect debonding between the facesheets and the foam core. As for the second wavepacket, corresponding to radiation in the core from the lower facesheet, they could be sensitive to damage in the core, in addition to the debonding. Hence the separation in the temporal domain of the different wavepackets enables us to separately detect different kinds of damage. In order to evaluate the wave interactions with damages, low-velocity impact damage was induced in the specimen, which consisted of GFRP facesheets and relatively high-density foam core with respective thickness of 1 mm and 10 mm. Typical damages were delamination in the facesheets, debonding between the facesheet and the core, and core failure. The experimental results confirmed the feasibility of debonding and foam damage detection using the second wavepacket. On the contrary, the direct wavepacket seemed to provide a poor interaction with this particular type of defects. However, its amplitude was likely to be correlated to facesheet damage.

Diamanti et al. \cite{27} also showed a cost and time effective inspection strategy using the low frequency LLW phenomenon. The sandwich beams consisted of quasi-isotropic CFRP facesheets $[+45/-45/0/90]_2S$ and three different types of approximately 10 mm thick core. The core types used were aluminum honeycomb, and two types of Rohacell foam R51 and R71. Small piezoceramic patches were selected for the generation and reception of low-frequency $A_0$ waves, because their low weight and volume makes them suitable for incorporation into smart structures, which is beneficial, if the technique is to be implemented for the continuous monitoring of aircrafts. The transmitter was placed on one upper facesheet and the signal was captured from two receivers bonded on both facesheets of the beam at the same edge as the transmitter. From the measure pulse, it was confirmed that there was LLW propagation in the specimens with two different types of foam core. Although the attenuation was greater, the reflection from the far edge of the beam could still be detected, after it traveled approximately 1 m. Therefore, the $A_0$ mode at low frequencies could therefore be used for the long-range inspection of sandwich structures. With the aluminum honeycomb core, however, these observations were not very clear and the more modes and reflections were evident from the response of the beam. In the presence of damage, part of the propagating wave is reflected back to the receiver in addition to the pulse reflected from the far side. The time of the maximum peak of the two signals can be used for the location of damage. Damage was introduced in the form of debonding between the lower facesheet and the core by inserting a thin blade. The debonding was approximately 25 mm long and across the whole width for all beams. The location of the debonding was successfully detected and it was concluded that, even though the resolution of the technique is poor and closely spaced damage areas cannot be separately identified,
the low frequency Lamb wave technique could be used in the first stage for global detection and location of damage in combination with a more sensitive technique, such as conventional ultrasonic C-scan or radiography, which would accurately characterize and size damage where necessary. They also successfully detected impact damage in foam sandwich using the same technique (28). The impact area, in general, consisted of debonding of the facesheet from the foam core, crushed core and delamination in the facesheet. Additionally, an asymmetric sandwich specimen with aluminum honeycomb core was inspected.

Kessler et al. (29) and Yang et al. (30) also utilized Lamb wave for damage detection in sandwich materials. After several mathematical trade studies, the first anti-symmetric $A_0$ and symmetric $S_0$ mode was excited, respectively. The locations of damages were successfully estimated using the time of flight (TOF) of reflected wave from damaged area. Meanwhile, Blaze and Chang (31) proposed an innovative technique to detect debonding in composite honeycomb sandwich structures using an array of piezo-ceramic sensors embedded in the honeycomb core by efficiently using the space available inside the honeycomb cell. Compared to surface mounted piezo-ceramics, these sensors could produce a signal that is over five times as powerful, since the connecting rod constrains the sensor between the two skins. Wiring for the sensors was done through a flexible circuit technique with a wire layer whose thickness was less than 0.003in. Further, installing the sensors in the core did not modify the manufacturing process of the sandwich panel, since only one additional step of inserting sensor assembly consisting of the sensor, the rod and the wire layer is included before installing the facesheet.

There are a few researches based on other wave propagation phenomenon, i.e. AE. Meo et al. (32) employed the stress wave generated by impact loading to locate a potentially damaging (elastic) impact on an orthotropic sandwich plate with CFRP facesheets and Nomex honeycomb core with the aid of an impact detection algorithm. Piezoelectric films (PVDF films) were bonded on the facesheet. The algorithm used the differences in TOF of the stress wave propagation to the sensors and trigonometric identities. The arrival time of stress waves at the sensor locations were determined by analyzing the recorded signals using the wavelet transforms. First, the stress wave propagation phenomenon was characterized by the measuring the propagation speeds along different directions. Then, elastic impact load was generated by an impact hammer. The impact location was precisely calculated from a system of non-linear equations: maximum error in estimation of the co-ordinates of the impact location was less than 9% for all different type of loading. It was also mentioned that one of the main advantages of the proposed methodology is that it does not require an exact knowledge of the material properties, but only the characterization of the material group velocities as a function of the frequency. While, Burman and Battley (33) conducted an AE based investigation of fatigue damage initiation and progression in GFRP sandwich structures with nominal density foam core (Divinycell H100). Under fatigue four-point bending condition, the high shear stresses along the midpoint of the core cause the initiation of small individual micro cracks which eventually grow in number and interact with each other forming a horizontal crack. Once these cracks form and start growing together, the stress intensification increases rapidly which drives them even faster, foaming a visible horizontal crack. This macro crack is subjected to an almost pure Mode II field, leading to the crack kinking away diagonally out towards the faces, resulting in a final crack. This final stage phase occurs very quickly. Since the propagation of the crack through a cellular foam material involves successive fracture of individual cell walls, an AE system should be able to detect such damage. In the case of an existing crack, emissions are likely to be generated due to friction between fractured cell walls. The four-point bending test was used to conduct fatigue testing of the sandwich beam. The tests were continuously
monitored using four AE transducers, mounted directly on the GFRP facesheets. Though the progression of damage was slow and neither visible cracks nor change of stiffness of the beam could be observed until the last 10% of the fatigue life, there was a gradual linear increase in the hits. Additionally, using the intermediate averaged velocity beforehand determined in the static attenuation tests, the location of the AE hits were mainly found in the center part of the beam where final crack is observed. The final stage of the failure was characterized by a dramatic increase in activity: approximately 90% of total AE. This phase trend was independent of the load level and loading ratios, although the total number of hits and rate of increase varied over the majority of the test significantly. Attempts were also made to correlate transient data from the fatigue tests with the static test results. Approximately 90% of the FFT plots from the fatigue transient data were of a general form, suggesting that one fracture mode dominates the fatigue failures. This was mostly closely related to the type of FFT from a static Mode II type test, which is reasonable since the crack development in the fatigue test is predominantly Mode II.

4.3 Damage detection using optical fiber sensors

When the optical fiber sensors are embedded in the materials, they can act as "nerves" and monitor the condition of the materials from the manufacturing process till the destruction of the structure. There have long been few researches to apply optical fiber sensors to sandwich structures compared to advanced composite laminates (34). Recently, however, several researchers have attempted to utilize optical fiber sensors for monitoring manufacturing process and damage development. Two damage detection systems have been integrated in structures; one based on optical time domain reflectometry (OTDR) and the other on fiber Bragg grating (FBG) sensors. The OTDR uses backscattering of light launched into a optical fiber. When the bending of the fiber is induced, the OTDR signal shows a stepped decrease at the bended position. Further, when the bending is critical (small radius of curvature), a reflection phenomenon adds to the loss phenomenon (Fresnel reflection), which means that a reflection peak appears in the OTDR signal. If there is just a loss, the defect is located at the beginning of the decreasing step. If there is a reflection phenomenon, the defect is located at the top of the peak. On the other hand, the FBG has been used for strain measurement. The FBG sensors have a periodic variation in the refractive index along the short length of a single-mode optical fiber. When broadband light is launched into the sensor, a narrow band of light is reflected. The wavelength of the reflected light, $\lambda$, is given by $\lambda = 2n\Lambda$, where $n$ and $\Lambda$ are the effective refractive index and the grating period. The wavelength $\lambda$ is known to change linearly depending on the strain and temperature applied to the sensor. This wavelength shifts can be used for measuring strain and temperature.

Bocherens et al. (35) utilized these two systems to detect impact damages in radome sandwich structures with GFRP facesheets and foam core. The impact damage detection by OTDR was based upon the hypothesis that an impact is able to induce a permanent local bend into the structure and thus on the optical fiber embedded between the upper facesheet and the core with the help of grooves formed in the core. After impact loading was applied to the center of the specimen, the loss and reflection phenomena were observed. The detected defects together roughly outlined the 'border' of a damaged area, which agreed with the results given by the conventional NDI methods. In order to realize more accurate detection, the FBG sensors were used. The permanent deformation of the facesheet induced by impact damage was monitored using strain change measured by FBG sensors. However, relationship between the size and mode of the impact damages and the responses of the optical fiber sensors was not fully explained. Hence the sensitivity of the detection technique is not clear.

Kuang et al. (36) utilized the FBG sensors in aluminum-foam sandwich structures based
on thermoplastic fiber-metal laminates (FMLs) for monitoring fabrication cycle. FML consisted of alternating layers of a glass fiber reinforced polypropylene (GFPP) and an aluminum alloy. The FBG sensors were embedded between two plies of GFPP to monitor the melting and solidification processes in these hybrid systems from the shift of the Bragg wavelength. Differential scanning calorimetry (DSC) was also carried out, confirming the FBG sensor has a potential to monitor key transition points in the process cycles of thermoplastic-based sandwich structures. Further, they reported the use of the embedded FBG sensor for monitoring damage initiation and subsequent damage development \(^{(37)}\). They used the FBGs as strain sensors to measure the reduction in the flexural stiffness of the structure. The shift in the Bragg wavelength was recorded during the test cycle to monitor the strain response of the sandwich beam. Damage was introduced into the sandwich beams by cycling the samples whilst subjecting them to increasing forces as the test progressed. Beyond the elastic threshold, the stress-strain curve became progressively non-linear indicating the onset of some form of damage within the sandwich structure. It was observed that local indentation had occurred in the top FML skin near the center of the beam. The degree of damage within a sample was quantified by monitoring the reduction in the specimen stiffness during the cyclic test. However, the technique of monitoring damage development is based on the change in the flexural stiffness of a simple sandwich beam under three point bending test, hence the availability of this technique to quantitatively evaluate damage state in the actual sandwich plate, which has complicated geometry and is exposed to random loading, is unclear.

Recently, Dawood et al. \(^{(38)}\) applied the FBG sensor to GFRP sandwich composite materials with foam core (Core-Cell A500) manufactured using vacuum infusion method. They mainly focused not on the damage detection in the foam sandwich structure but on the embedding the sensor between the facesheet-core interface, since currently there are no standard procedures available in the public domain to advise on how to embed optical FBG strain sensors within foam core GFRP sandwich composite materials manufactured using the vacuum infusion process. In many papers, the actual embedding process is covered up and the practical problems encountered or solutions developed to overcome them are not explained. Practical issues relating to sensor placement, fiber alignment, specimen lay-up and resin infusion were discussed in detail. Among them the alignment of the optical fibers is particularly notable. First, the optical fiber was aligned and temporarily held in position of the foam core using ordinary white tack. Then, an epoxy resin similar to the one prepared for infusion process was used to permanently bond the fiber to the core at selected locations. The effectiveness of the modified manufacturing procedure was validated by conducting comparative static and dynamic load analysis tests. It is important to note that the resin-rich area randomly interrupted accurate strain measurement, hence the improvement of the procedures seems to be needed to locate the optical fiber sensor in discrete points with minimum epoxy resin to permanently bond the optical fiber to the core.

5. Smart honeycomb sandwich concept the authors have been proposing

The authors have been proposing original smart honeycomb sandwich structure concept by taking advantage of the unique changes in dynamics of the structure generated by the occurrence of damages. The techniques use small-diameter optical fiber sensors and SMA to detect and repair typical damages in sandwich structures. These concepts are illustrated in Figs. 6 and 7.

The small-diameter optical fibers \(^{(7, 39)}\) including FBG sensors are embedded in the adhesive layer between the honeycomb core and the facesheet in a reticular pattern with the lowest density required to quantitatively detect damage whose size is unacceptable for the
Fig. 6 Schematic of novel damage detection techniques

Fig. 7 Basic concept of technique for self-repairing of impact damage

structure. Since there is no space for optical fibers to go through between the core and the facesheet, small slits are formed on the bottom of the core walls by a wire discharge cutter. The small-diameter optical fiber (40 µm in clad diameter and 52 µm in polyimide coating diameter) can be embedded in the adhesive layer without deteriorating bonding strength of the adhesive layer. As shown in Fig. 6, facesheet failure, cohesive failure in adhesive layer, and BVID can be detected simultaneously with the embedded optical fiber sensors (40). When the facesheet failure is induced, the intensity of the transmitted light decreases by the bending or breakage of the optical fiber. We can detect the occurrence of the debonding from the decrease in the transmitted optical power and furthermore identify the size and the location of the debonding from the positions of damaged optical fibers. The other two techniques use the sensitivity of the FBG sensor to non-uniform strain distribution. When the non-uniform strain is applied to the grating, \( n \) and \( \Lambda \), which were defined above, also become non-uniform. Hence the form of the reflection spectrum is distorted owing to the reflected light at various wavelengths. This distortion of the reflected spectrum has been used to detect various kinds of damage in CFRP laminates (7, 41). When the cohesive failure of the adhesive layer is occurred, the reflection spectrum from the FBG sensor recovers its original shape by the release of non-uniform thermal residual strain along the sensor induced by the fillet, which is defined as an adhesive rich region formed at the root of the core wall (39). Further, we focused on the dent remained on the facesheet to detect BVID. When the impact damage is introduced, the dent of the facesheet induces tensile and compressive stresses along the FBG sensor at the convex and concave parts. Consequently, the reflection spectrum is deformed corresponding to the impact damage size. These techniques have the potential to be applied to honeycomb sandwich structures with any
combination of materials.

On the other hand, in order to repair the BVID, the honeycomb cell walls are made of SMA foils (thickness: 45 µm) and thin nichrome wires (Ø 100 µm) are embedded in the facesheet. When impact damage is introduced in honeycomb sandwich structures, as we described above, the core materials around impact loading point is crushed and the dent of the facesheet remains. Since, the deflection of the facesheet is elastic deformation and caused by the pull down due to the crushed core, the facesheet returns to a flat, if the core crushing is repaired by heating the SMA honeycomb up to the reverse transformation temperature for shape recovery. For heating only the crushed core, we selectively energize the nichrome wires near the impact damage, which achieves effective and real-time repairing of impact damage. As a result, the mechanical property reduced significantly by impact damage can be recovered. It has been confirmed that, using the SMA honeycomb, we can repair the shape and, further, recover the bending stiffness of damaged specimen (42).

In near future, the damage detection techniques using the optical fiber sensors and the self-repairing technique utilizing the SMA honeycomb will be combined in the smart sandwich structures for highly reliable future aerospace structures.

6. Conclusions

In this paper recent developments on smart technologies to improve reliability of the sandwich structures with advanced composite facesheets were briefly reviewed. First, the state-of-the-art sandwich technology in aerospace field was shown. Next, typical damages in the composite sandwich structures were described, which is essential and instructive for future researches. Then, damage detection technique using dynamic response, wave propagation and optical fibers were explained. Finally, smart honeycomb sandwich concept the authors have been proposing was also presented.

References

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