Smart Sandwich Structures with Impact Damage Monitoring and Repairing Capability using Optical Fiber Sensors and SMA Honeycomb Core

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ABSTRACT:

In this research, authors established a smart sandwich structure with damage detection and suppression function using a small-diameter fiber Bragg grating (FBG) sensor and a shape memory alloy (SMA) honeycomb core. Indentation damage was detected using strain change along a bend of a facesheet caused by core crushing. As for repairing the impact damage, in order to repair crushed SMA honeycomb, voltage was applied to a nichrome wire embedded in the facesheet. The core around the nichrome wire was effectively heated and the crushing in the heated area disappeared. These results were confirmed by new theoretical and numerical simulations, indicating the validity of the proposed smart technology.

INTRODUCTION

Sandwich structures consist of a light weight thick core and two thin strong facesheets bonded by thin adhesive films. Since these structures have high mechanical properties and multifunctionality, they have been utilized in many applications, such as satellites, aircrafts, ships, automobiles, rail cars, wind energy systems, and bridge construction [1].

In honeycomb sandwich structures, the facesheets primarily resist the in-plane and lateral (bending) loads, and the honeycomb core keeps the distance between two facesheets and carry transverse forces. The adhesive layer transfer shear and tensile

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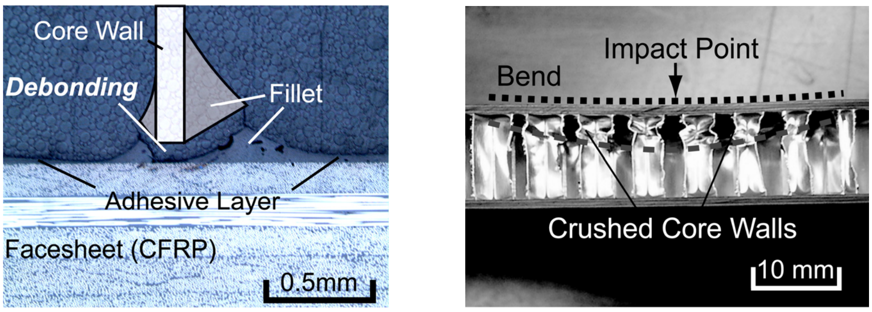


(a) Debonding. (b) Impact damage.

Figure 1: Specific damages in honeycomb sandwich structures.

stress between the facesheet and the core. These three parts in an integrated manner achieve high specific stiffness and strength [2]. However, an excessive load, repeated loading, or water absorption in the core can induce debonding between the core and the facesheet [2, 3], as presented in Fig. 1 (a). In addition, owing to low bending stiffness of thin facesheets, impact loading such as tool drops or sudden strikes by birds, stones, or hails causes localized core crushing near the impact point and a gentle bending of the facesheet [2, 4], as shown in Fig. 1 (b). Although these kinds of damage are very difficult to detect from the outside, it causes a significant reduction, nearly 50% reduction, in the in-plane compressive strength [5]. As aerospace structures require extremely high reliability, damage must be detected and repaired immediately after its occurrence. Widespread non-destructive inspection techniques and repairing methods are time-consuming, very costly, and unsuitable for large structures like satellites and airplanes. Hence, a smart technology for improving reliability of composite sandwich structures is needed [6-8]. In this research, we developed innovative techniques for detecting and repairing damage using optical fiber sensors and an SMA honeycomb.

SMART TECHNOLOGY FOR HONEYCOMB SANDWICH STRUCTURES

A schematic of damage detection techniques is depicted in Fig. 2. Small-diameter FBG sensors are embedded in the adhesive layer between the core and the facesheet in a reticular pattern with the lowest density required to detect damage whose size is unacceptable for the structure. In this technique, two patterns of debonding and barely visible impact damage (BVID) can be detected simultaneously. When debonding (a) is induced, the intensity of the transmitted light decreases by bending or breakage of the optical fiber. When debonding (b) is caused, 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. In contrast, when impact damage is introduced, the bending of the facesheet induces compressive and tensile stresses along the FBG sensor at the convex and the 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.

The basic concept of technique for self-repairing of impact damage is illustrated in Fig. 3. The honeycomb cell walls are made of very thin SMA foils. The deflection of the composite facesheet after impact loading is elastic deformation and caused by the pull down due to the crushed core beneath the impact region. Hence, the facesheet will return to a flat plate if the core crushing is repaired by heating the SMA honeycomb up to the reverse transformation temperature for shape recovery. As a result, the mechanical property reduced significantly by the impact damage can be recovered.

The authors have shown that the damage in the sandwich materials can be detected quantitatively from the response of the optical fiber sensors [9, 10] and the impact damage can be repaired by heating the specimen [11]. However, we couldn't quantify the impact damage size and location automatically, because there are no accurate methods to calculate the strain distribution along the facesheet during and after the impact loading. In contrast, when we repair the localized core crushing, we needed to heat the whole structures, wasting considerable amount of thermal energy on warming un-damaged area.

In this article, for the fundamental investigation, we detect quasi-static indentation damage in a sandwich beam with CFRP facesheets and aluminum honeycomb core using the small-diameter FBG sensor bonded on the facesheet. The change in the reflection spectrum is reproduced by a new analytical model to simulate the mechanical response of the sandwich beam. Furthermore, we show an innovative system to heat the SMA honeycomb effectively by energizing nichrome wires embedded in the facesheet.

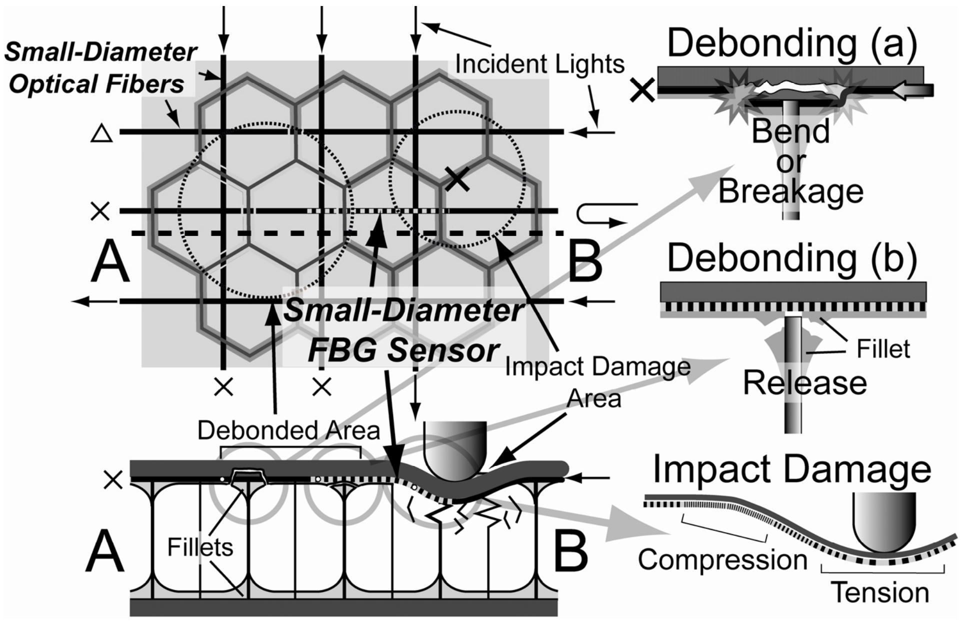
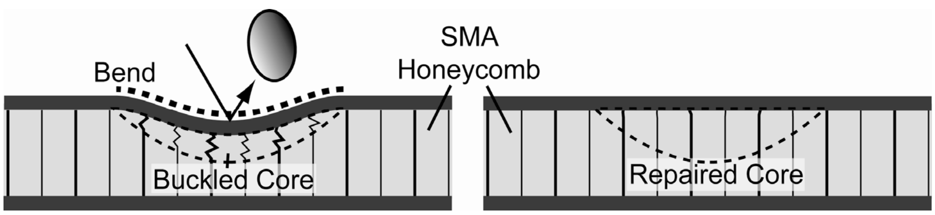


Figure 2: Schematic of novel damage detection techniques for honeycomb sandwich structures.



(a) After impact loading. (b) After heating.

Figure 3: Basic concept of technique for self-repairing of impact damage.

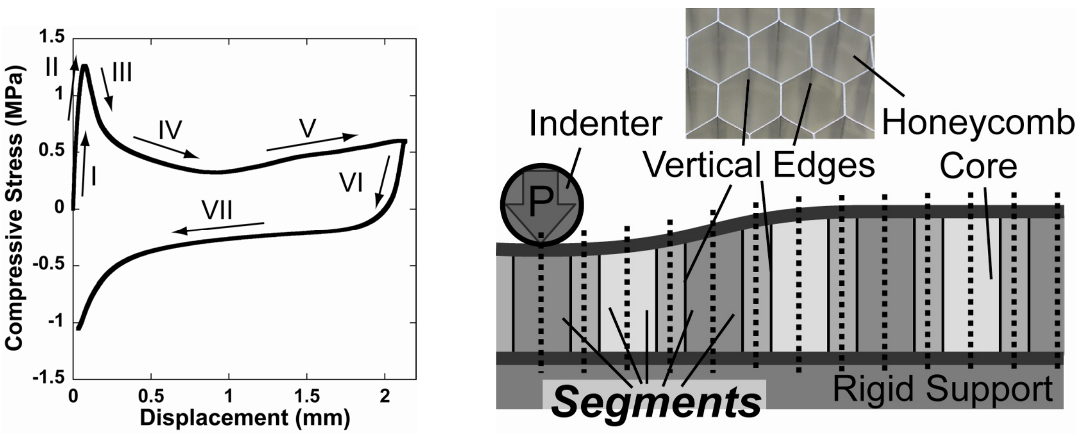
INDENTATION DAMAGE DETECTION

Materials and methods

A specimen (140 × 25.5 × 23 mm^3) consisted of carbon fiber reinforced plastic (CFRP) facesheets (T700S/2500, Toray Industries, Inc., $[0_8]$), an aluminum honeycomb core (AL 1/4-5052-.001, Showa Aircraft Industry Co., Ltd., thickness: 20 mm) and an adhesive film (REDUX312UL, HEXCEL Co.). The specimen was bonded to a flat steel plate with a thermoplastic adhesive film (AF-163-2K, 3M Co.) and the overall bending was eliminated. A steel cylinder, whose diameter was 10 mm, was attached to a material testing system (AG-I, Shimazu Co.) and a concentrated line-load was applied to the center of the specimen. After maximum indentation displacement of 1 mm was reached, the specimen was unloaded and a constant crosshead displacement rate of 0.5 mm/min was used. A small-diameter FBG sensor (Hitachi Cable Ltd.) [9, 10], whose gage length was 14 mm, was glued on the surface of the facesheeet 11 mm away along the axial direction from one end of the FBG sensor. The optical fiber was illuminated by an amplified spontaneous emission (ASE) light source (AQ4310 (155), Ando Electric Co., Ltd.) and the power spectrum of the reflected light from the FBG was measured by an optical spectrum analyzer (AQ6317, Ando Electric Co., Ltd).

New theoretical model for indentation damage in honeycomb sandwich

First of all, transverse property of the aluminum honeycomb core was measured by modified flatwise compression tests, in which a tensile force can also be applied to the crushed core. The example of a stress-displacement curve obtained by the test is shown in Fig. 4 (a), for illustrative purposes. There were five specific sections during compressive loading process: (I) an elastic deformation section, (II) an elastic buckling section, (III) a plastic buckling starting section, where the elastic buckling finally generated the plastic buckling and the compressive stress rapidly decreased, (IV) a plastic hinge growing section, where the plastic hinge developed in the section (III) stably grew and the compressive stress slowly decreased, and (V) a new hinge emerging section, where the plastic hinge which grew in the section (IV) were fully crushed and a new plastic hinge started to emerge, and, consequently, the compressive stress stably



(a) Transverse property of core. (b) Segmentation of sandwich beam.

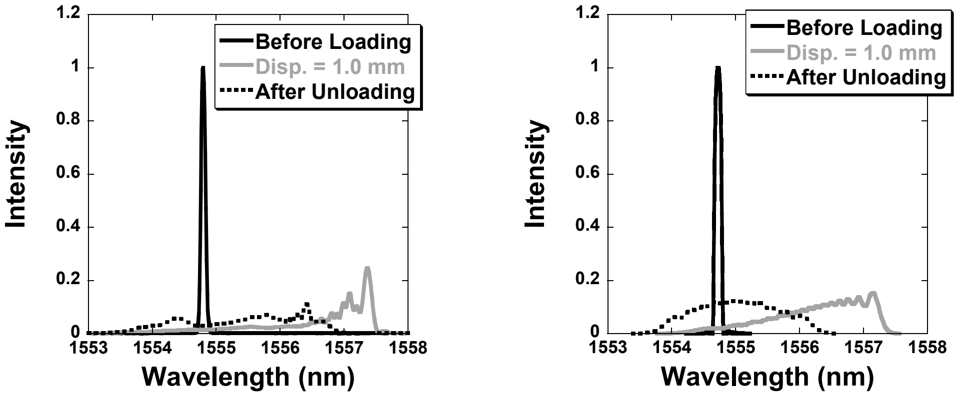
Figure 4: New theoretical model for simulation of indentation damage.

increased again. During unloading, on the other hand, there were two sections: (VI) an elastic unloading section, (VII) a plastic stretching section, where the plastic hinges formed under compressive loading were smoothed out.

Next, an innovative theory to model the complicated property of the honeycomb core is derived. We modified the theory by Abrate [4], which assume an elastic Winkler foundation for the elastic core, and a perfectly plastic foundation for the part of the core that undergoes crushing. During the crushing of the honeycomb core, the compressive load is mainly taken by the vertical edges, since the buckled core wall cannot sustain large stress any more [12]. The vertical edges are defined as intersections between the flat honeycomb cell walls. Hence, we divided the structures into segments centered around the vertical edges and modeled the upper facesheet as a series of beams as presented in Fig. 4 (b). The honeycomb core in the each segment was assumed to have the complicated transverse property with the aid of linearization. Then, using this theoretical model, damage growth simulation of the honeycomb sandwich was conducted.

Comparison between experiment and analysis

The reflection spectra from the experiment and the analysis are shown in the Fig. 5. The reflection spectra were simulated by solving couple-mode theory using the transfer matrix method [13] from the distribution of optical properties along the sensor obtained from the strain distribution. The intensity of the reflection spectra were normalized by the intensity of the highest component in the initial spectrum. The reflection spectrum measured before loading had only one sharp narrow peak, however, as the indentation displacement increased, the reflection spectrum was obviously distorted. At the indentation displacement of 1 mm, the spectrum shifted to the longer wavelength side and wide shorter-wavelength component beside the maximum peak appeared. After unloading, the reflection spectrum almost evenly spread between 1554 nm and 1557 nm. These distortions of the reflection spectra were expected to be generated from the non-uniform strain distribution along the FBG sensor depending on the size and the location of the indentation damage. Hence, conversely, we can detect the indentation damage quantitatively from the shape of the spectra during and after



(a) Experiment. (b) Analysis.

Figure 5: Obtained reflection spectra during indentation test.

indentation test. The simulated reflection spectra reproduced these changes in the form of the reflection spectra, confirming the validity of the developed analytical method. In near future, the indentation damage will be evaluated automatically by fitting simulated spectra to measured spectra using a suitable inverse analysis method.

NEW SYSTEM TO HEAT SMA HONEYCOMB FOR SELF-REPARING OF IMPACT DAMAGE

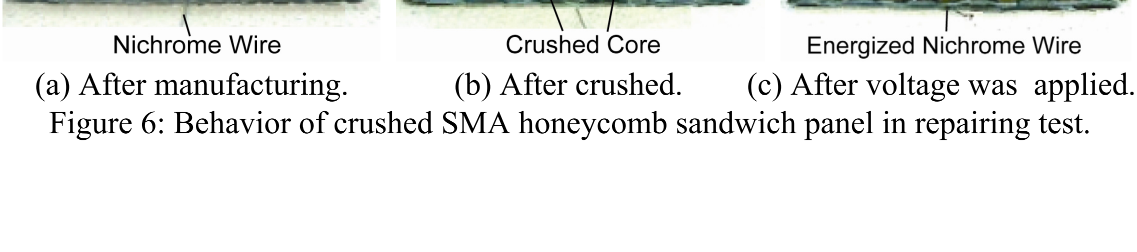
In order to repair impact damage in the SMA honeycomb sandwich structures, one must heat the crushed region of the SMA honeycomb core up to the reverse transformation temperature for shape recovery [11]. In this research, we propose to embed very thin nichrome wires in the CFRP facesheet laminate. By using this system, only damaged area can be heated by selective energization of the nichrome wire near impact damage. Furthermore, since this system is integrated inside the structures, we can make in-situ repair of in-service impact damage. As a result, this system achieves effective and real-time self-repairing of impact damage.

Experiment of repairing crushed SMA honeycomb core

We conducted a repairing test using an SMA honeycomb sandwich structure. The specimen consisted of CFRP facesheets (T700S/2500, Toray Industries, Inc., $[0/90_2/0]$), an adhesive film (REDUX312UL, HEXCEL Co.) and an SMA honeycomb [16] (cell size: 4 mm, cell wall thickness: 45 μm, thickness of core: 10 mm). A nichrome wire was embedded between the 90˚ direction layers parallel to the fiber orientation. This embedment position was decided by considering the amount of electric leakage to the carbon fibers, which may degrade the functionality of the heating system. The cross-sectional observation of the facesheets revealed that the carbon fibers distributed evenly around the nichrome wire embedded between the 90˚ plys, confirming little electric leakage to carbon fibers, which have high electric conductivity. The specimen before test is shown in Fig 6 (a). First, uniform downward displacement of 1 mm was applied to the specimen by standard flatwise compression test. The SMA honeycomb core was evenly crushed, as presented in Fig. 6 (b). Then the specimen was heated by applying electric energy of 0.024 Wmm^{-1} to the nichrome wire. The specimen after 300 sec is shown in Fig. 6 (c). The four cells of crushed core around the energized nichrome wire recovered its original shape.

Simulation of temperature change in SMA honeycomb core

In order to confirm above experimental result, we simulated the temperature change in the SMA honeycomb core using ABAQUS code. The CFRP cross-ply



(a) After manufacturing. (b) After crushed. (c) After voltage was applied.

Figure 6: Behavior of crushed SMA honeycomb sandwich panel in repairing test.

facesheet, the nichrome wire and the SMA honeycomb core were modeled for 3D finite element analysis (FEA). When reverse transformation of an SMA occurs as temperature increases, the SMA absorbs some amount of latent heat. The effect of the latent heat was introduced into this analysis by increasing the apparent specific heat between reverse transformation start temperature, A_s, and reverse transformation finish temperature, A_f, which are 48˚C and 60˚C respectively [14]. The amount of latent heat was assumed to be 1548 $Jmol^{-1}$. Coupled thermal-electric analysis with time increment of 0.5 sec was conducted by applying electric energy of 0.024 Wmm^{-1} to the nichrome wire, which is the same as the experiment.

The comparison between the experiment and the analysis at t = 300 sec is shown in Fig. 7. The core in the area where the temperature was above the 60˚C in the simulation was repaired, and the core in the area where the temperature was between 48˚C and 60˚C, seemed to be starting to recover, confirming the validity of the numerical simulation.

In near future, embedment density of nichrome wires sufficient for real-time self-repairing of impact damage will be determined, and the repairing system using the SMA honeycomb and the damage detection system using optical fiber sensors will be combined in the smart sandwich structure.

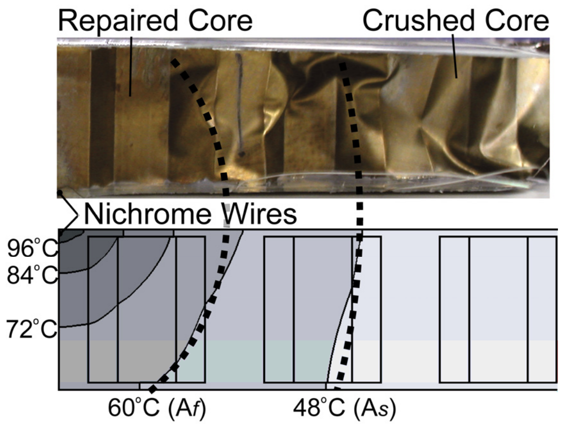


Figure 7: Comparison between experimental result and simulation result at t = 300 sec.

CONCLUSIONS

The authors conducted fundamental researches for a smart sandwich structure with damage detection and suppression function using a small-diameter FBG sensor and an SMA honeycomb core. As for damage detection, a new theoretical model for barely visible indentation damage in honeycomb sandwich structures was established by taking account the complicated transverse property of the core. The analysis using this new model reproduced the distortions of the reflection spectrum from the FBG sensors during indentation test, confirming the possibility of automatic detection of impact damage. As to repairing the damage, we proposed an effective heating method using nichrome wires embedded in a facesheet. The validity of this method was confirmed through an experiment and a numerical simulation.

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