LOW ENERGY IMPACT BEHAVIORS OF NONSTITCHED AND STITCHED FOAM CORED SANDWICH STRUCTURES

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SUMMARY: The objective of this study is to investigate the impact behaviors and the failure mechanisms of nonstitched and stitched sandwich structures. These sandwich structures are made of glass fabric faces with a urethane foam core. The polyester fibers as the through-the-thickness reinforcements are used to combine the upper face and the lower face through the core in stitched sandwich structures. Several impact conditions are considered, such as the drop height of the impact tup, the impactor shape, and the weight of the impact tup. Low energy impact tests are conducted on these sandwich structures using the drop weight impact tester. Various sandwich specimens, each having a different core thickness, are tested to determine the effect of the core thickness on the impact behaviors. The results show that stitched sandwich structures can sustain higher impact force than nonstitched sandwich structures and have the ability for averting delamination. Also, it is important to improve the wetting ability of the through-the-thickness reinforcements in order to utilize stitched sandwich structures effectively.

KEYWORDS: Nonstitched and stitched sandwich structures, Glass fabric faces, Polymeric foam core, Drop weight impact tester, Low velocity impact behaviors, Through-the-thickness reinforcements

INTRODUCTION

Nonstitched sandwich structures are made of two stiff and thin faces adhesively bonded to a relatively soft and thick core. In general, the faces carry the principal loads while the inner core acts to transmit the shear loads to the faces and absorbs the strain energy. These sandwich structures are widely used in many industrial fields due to a high flexural property to weight ratio, a high resistance to corrosion, and a good thermal and acoustic insulation. In particular, fiber reinforced composites have been employed for the faces and honeycomb structures are preferred as the core in the design and construction of civil and military applications. Recently, polymeric foam was also adapted as the core in certain industrial applications, where cost is of major concern, such as marine ships, refrigerating containers, and trains.

Nonstitched sandwich structures are apt to be damaged in the faces and/or the core under low energy impacts. The major modes of failure are delamination between the face and the core, the shear and compressive failures in the core, and the tensile failure in the faces. It has been recognized that these types of damage may reduce the stiffness and the residual strength of the sandwich structures during the service life. In order to overcome the shortcomings of nonstitched sandwich structures, the through-the-thickness reinforcement by a stitching process is one of the solutions for averting delamination between the face and the core, and minimizing the reduction of the stiffness and the residual strength during the impact event. One of the important concerns in the use of the sandwich structures is to identify the susceptibility to damage under low energy impacts. Although much effort has been spent to identify the impact behaviors on nonstitched sandwich structures, little literature on the study of stitched sandwich structures has been available up to now.

Lee *et. al.* conducted experimentally on the low velocity impact behavior of the sandwich beam subjected to the cylindrical impactor. The main failure pattern of the sandwich beam with the lower density core was the core shear crack, whereas the sandwich beam with the higher density core was crushed in the core and damaged in the top face underneath the impactor [1]. Caprino *et. al.* carried out the low velocity impact test on the sandwich panels and suggested the damage parameter. The experimental results showed that the damage parameter depends only on the impact energy, and the residual strength after the impact of the face can be predicted on the basis of the damage parameter [2]. Wu *et. al.* conducted a test to investigate the damage mechanisms in the sandwich beams made of graphite/epoxy faces and foam core. The major modes of failure included the local yielding in the core, the matrix cracking, and delamination in the face [3]. Hiel *et. al.* reported the inspection method for the sandwich panels with foam core and presented a procedure for the practical assessment of the post-impact damage and the residual strength [4]. Mines *et. al.* performed the static and impact tests on the polymeric composite sandwich beams in a three point bend configuration. The dominant failure modes for the sandwich beams involved the upper face failure in the vicinity of the penetrator. The impact performance of the sandwich beams showed the rate dependence effect with the failure energy reducing to a minimum at a given drop height and then increasing with the drop height [5]. Herup *et. al.* performed the low velocity impact and static indentation tests on the sandwich plates with graphite/epoxy faces and honeycomb core to characterize damage as a function of face thickness and loading rate [6].

The objective of this study is to investigate the impact behaviors and the failure mechanisms of nonstitched and stitched sandwich structures. These sandwich structures are made of glass fabric faces with a urethane foam core. The polyester fibers as the through-the-thickness reinforcements are used to combine the upper face and the lower face through the core in the stitched sandwich structures. The low energy impact tests are conducted on these sandwich structures using the drop weight impact tester. Several impact conditions are considered, such as the drop height of the impact tup, the shape of the impactor, and the weight of the impact tup. The four types of drop heights are 100mm, 150mm, 200mm, and 250mm. The impactor shape is varied with a cylindrical type and a spherical type. The weights of the impact tup with the cylindrical impactor are 10.4N, 14.4N, 16.8N, and 19.2N being used. The weights of the impact tup with the spherical impactor are 10.1N, 14.2N, 16.6N, and 18.9N being used. Different types of the sandwich specimens, each having a different core thickness, are tested to determine the effect of the core thickness on the impact behaviors. Four types of the core thickness are varied with 23mm, 37mm, 48mm, and 61mm as the measurements.

SPECIMEN PREPARATIONS

Nonstitched and stitched sandwich specimens are made from Hankuk Fiber Glass Company according to the manufacturer's specifications. These sandwich specimens consist of glass fabric faces with a urethane foam core. The polyester fibers are used as the reinforcements to combine the upper face and the lower face through the core in the stitched sandwich specimens. For the stitching process, the diameter of the needle in the stitching machine is larger than that of the bundle of the polyester fibers to easily force the excess resins into the reinforcements during the curing process. The through-the-thickness reinforcements play a role in the reinforced column as well as the suppression of delamination between the face and the core.

Fig. 1 shows the configurations of nonstitched and stitched sandwich specimens used for this study. In the case of stitched sandwich specimen, the core is removed to visualize the reinforcements more clearly. All the sandwich specimens are 400mm in length, 75mm in width, and the face has nominally 1.72mm in thickness. The core thickness was varied with values of 23mm, 37mm, 48mm, and 61mm. This was done to observe the effect of the core thickness on the impact behavior of the sandwich structures. The stitching intervals were uniformly applied to 30mm in the longitudinal direction and in the widthwise direction, respectively.

(a) Nonstitched sandwich specimen *(b) Stitched sandwich specimen*

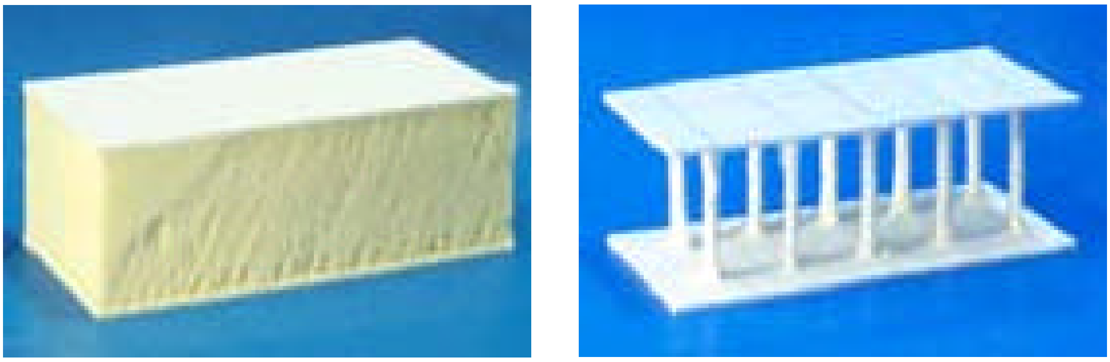


Fig. 1: Configurations of nonstitched and stitched sandwich specimens.

EXPERIMENTAL APPARATUS

Fig. 2 shows the overview of the drop weight impact tester for the relatively wide range of impact energy to the sandwich specimens. The impact tester consists of the impact tup guided by two stainless steel rods and the associated structural supports. The impact tup made of aluminum alloy has a relatively complex shape for the weight minimization. The additional weights can be added or removed to adjust the weight of the impact tup. The maximum height of the unit is 1500mm. A hydraulic system is attached at the top of the impact tester to increase the velocity of the unit. Two types of impactor shape are utilized: One is a spherical impactor with a 10mm diameter, the other is a cylindrical impactor with a 10mm diameter. A test fixture, solidly fastened to the impact tester, snugly held the sandwich specimen in the simply supported condition with a span of 340mm. The sandwich specimen was aligned on the support fixture to ensure the impactor struck at the center of the specimen.

The impact tup has an impact force transducer (208B03, PCB), which is powered by a signal amplifier (482B11, PCB). The velocity of the impact tup is measured by means of the light gate when the impact tup is falling through the stainless steel rods. As shown in Fig. 3, strain gages are placed to measure the strains on the sandwich specimens subjected to the impact energy. Impact force, the velocity of the impact tup, and strain signals are each assigned a channel on an A/D converter (PCI-MIO-16E-1, National Instruments) in an IBM-PC with the data acquisition software (LabVIEW, National Instruments). The sampling frequency of 40,000 samples/sec is used.

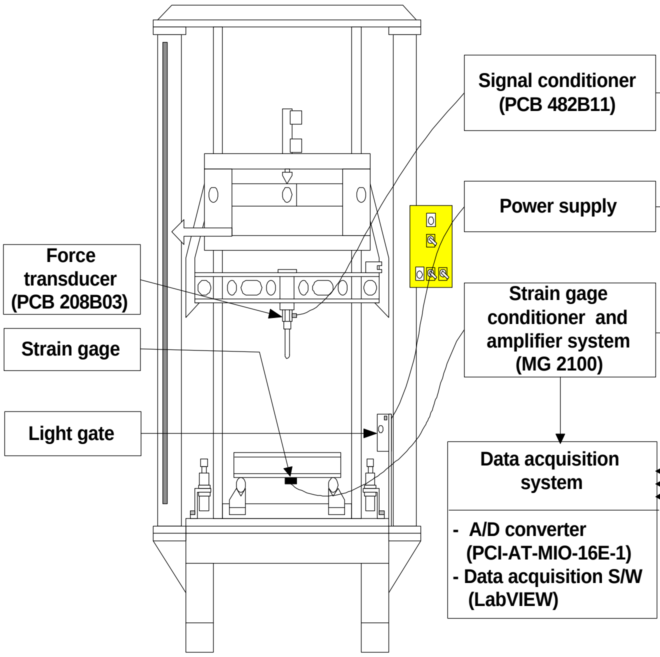


Fig. 2: Overview of the drop weight impact tester.

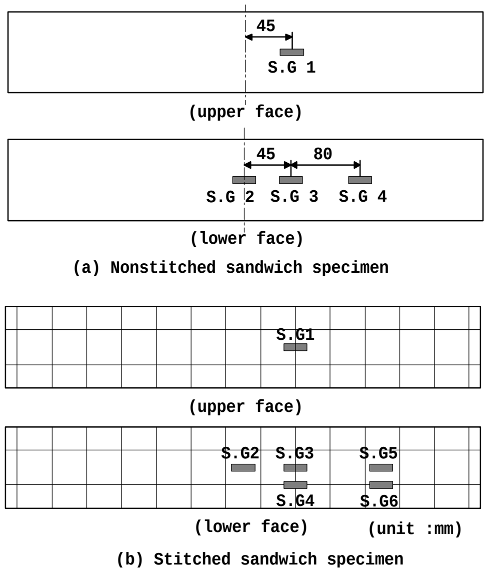


Fig. 3: Strain gage placements.

DATA REDUCTION SCHEME

In general, impact force signals from an impact force transducer consist of a signal reflecting the impact behavior for the sandwich structure and that for the impact tup. In spite that the latter is not directly related to the impact behavior of the sandwich structure itself, it will affect the impact force signals. It is necessary to understand the impact force signals from the transducer and conduct a data reduction procedure thoroughly [7].
The acceleration of the impact tup during the impact event can be obtained as Eqn 1.

$$a = \left[1 - \left(F/W\right)\right]g \tag{1}$$

where F is the impact force obtained from the impact force transducer and W is the gravitational force of the impact tup.
The velocity of the impact tup during the impact event may be determined from the previous velocity and the average acceleration as Eqn 2.

$$v_i = v_{i-1} + \frac{1}{2}(a_{i-1} + a_i)(t_i - t_{i-1}) \tag{2}$$

where v_{i-1} and a_{i-1} are the velocity and the acceleration at time t_{i-1}, respectively. a_i is the acceleration at time t_i.
The displacement of the impact tup during the impact event is obtained in a similar manner as Eqn 3.

$$s_i = s_{i-1} + \frac{1}{2}(v_{i-1} + v_i)(t_i - t_{i-1}) \tag{3}$$

where s_{i-1} and v_{i-1} are the displacement and the velocity at time t_{i-1}, respectively. v_i is the velocity at time t_i.

The impact energy absorbed by the sandwich specimen during the impact event is determined from Eqn 4.

$$T_i = T_{i-1} + \frac{1}{2} m (v_{i-1}^2 - v_i^2) \quad (4)$$

where T_{i-1} is the impact energy absorbed by the sandwich specimen at time t_{i-1} and m is the mass of the impact tup.

The deflection of the sandwich specimen and the impact force experienced by the impactor can be expressed as Eqn (5) and Eqn (6) by using the simple mass-spring model, respectively [5].

$$x = v_o \sqrt{\frac{m}{k}} \sin \sqrt{\frac{m}{k}} t \quad (5)$$

$$F = v_o \sqrt{mk} \sin \sqrt{\frac{m}{k}} t \quad (6)$$

where k is the global stiffness of the sandwich specimen, and v_o is the initial velocity at the instant of the impact event.

EXPERIMENTAL RESULTS

Fig. 4 shows the impact force signals with the variation of the core thickness in the stitched sandwich specimen. The drop height of the impact tup is 100mm, and the weight of the impact tup with the cylindrical impactor is 10.4N. The four types of the core thickness are varied with 23mm, 37mm, 48mm, and 61mm. The core thickness is closely related to the global stiffness of the sandwich specimen. The impact force increases with the core thickness, as it is proportional to the global stiffness of the sandwich specimen. The contact time during the impact event is inversely proportional to the square root of the global stiffness of the sandwich specimen. The contact time during the impact event decreases with increasing the core thickness. The sandwich specimens with thicker cores have a higher global stiffness and release the bending strain resulting from the impact event faster than those with thinner cores.

Fig. 5 shows the impact force with the variations of the drop height of the impact tup and the core thickness of stitched sandwich specimen. The weight of the impact tup with the cylindrical impactor is 10.4N. The four types of the drop height used are 100mm, 150mm, 200mm, and 250mm. The four types of the core thickness are varied with 23mm, 37mm, 48mm, and 61mm. In the case of the 23mm core thickness, the impact force is 380N at the 100mm drop height and 558N at the 250mm drop height. The impact force for the 250mm drop height is 47% higher than that of the 100mm drop height. In the case of the 61mm core thickness, the impact force is 509N at the 100mm drop height and 763N at the 250mm drop height. The impact force for the 250mm drop height is 50% higher than that of the 100mm drop height. In the case of the 100mm drop height, the impact force for the 61mm core thickness is 34% higher than that for the 23mm core thickness. Also, in the case of the 250mm drop height, the impact force for the 61mm core thickness is 37% higher than that for the 23mm core thickness.

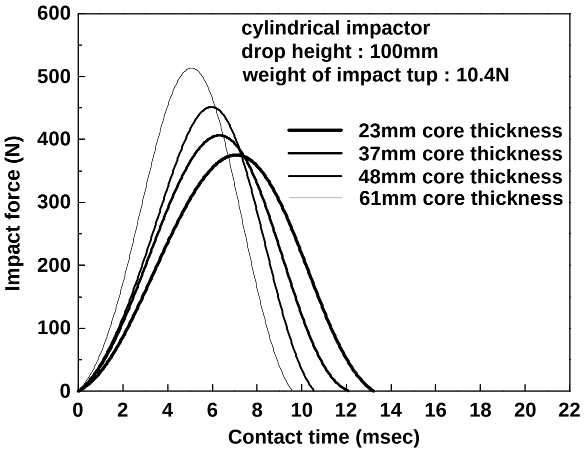


Fig. 4: Impact force signals having varied with the core thickness.

Fig. 6 shows the impact force with the variations of the weight of the impact tup and the core thickness of stitched sandwich specimen. The drop height of the impact tup is 100mm. The weights of the impact tup with the cylindrical impactor are 10.4N, 14.4N, 16.8N, and 19.2N being used. The four types of the core thickness used are 23mm, 37mm, 48mm, and 61mm. In the case of the fixed thickness of the 23mm core, the impact force is 362N at the weight of 10.4N and 554N at the weight of 19.2N. The impact force of the 19.2N weight is 53% higher than that of the 10.4N weight. In the case of the fixed thickness of the 61mm core, the impact force is 511N at the weight of 10.4N and 776N at the weight of 19.2N. The impact force of the 19.2N weight is 52% higher than that of the 10.4N weight. In the case of the fixed weight of 10.4N, the impact force for the 61mm core thickness is 41% higher than that for the 23mm core thickness. In the case of the fixed weight of 19.2N, the impact force for the 61mm core thickness is 40% higher than that for the 23mm core thickness.

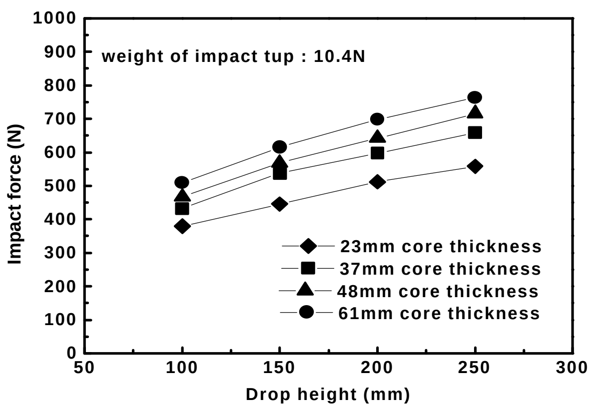


Fig. 5: Impact force versus contact time varying with the drop height.

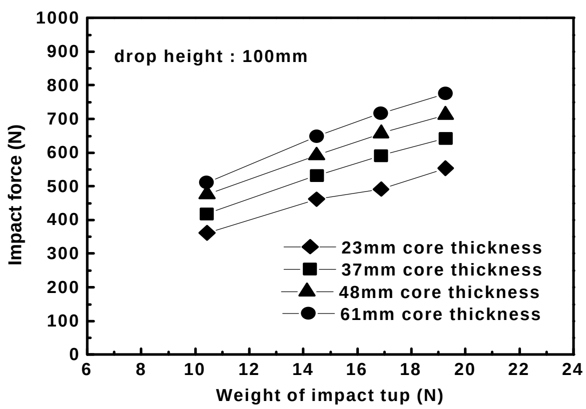
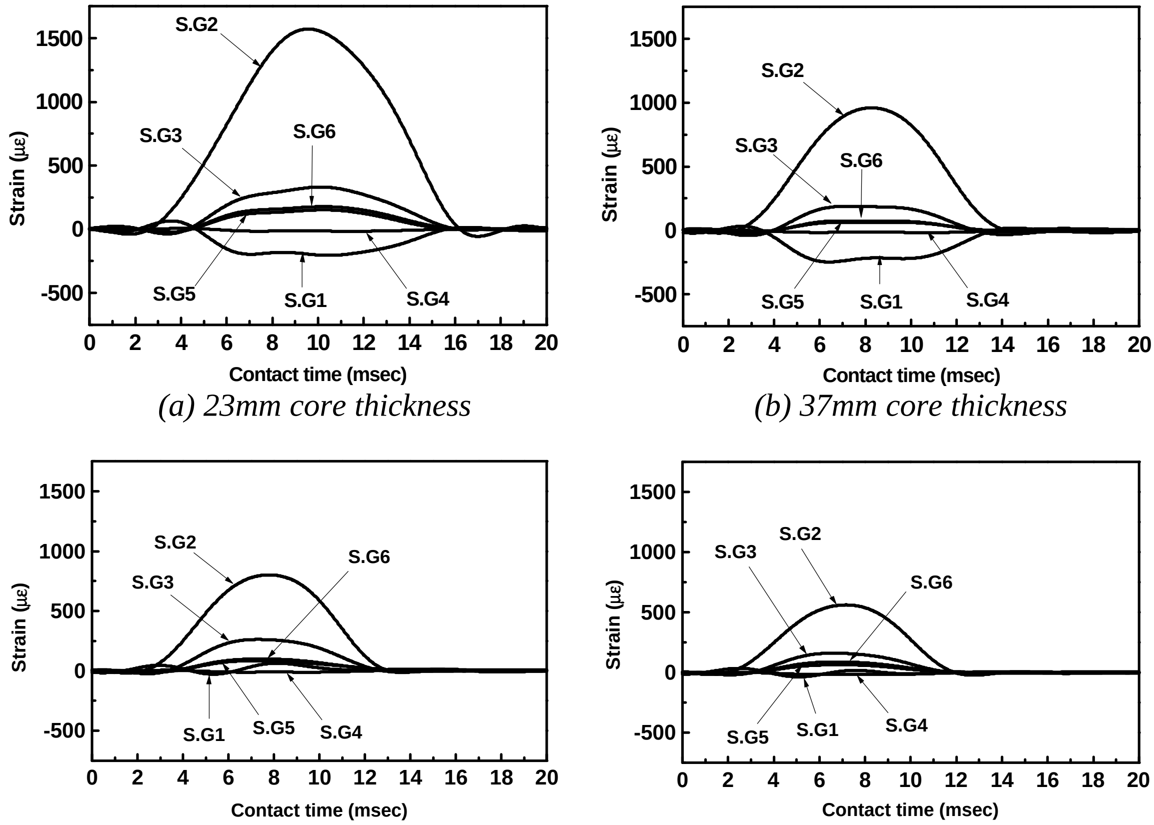


Fig. 6: Impact force versus contact time varying with the weight of impact tup.

Fig. 7 and Fig. 8 show the strain outputs versus contact time for stitched sandwich specimen subjected to the impact energy with the spherical impactor and the cylindrical impactor, respectively. The weight of the impact tup with the spherical impactor is 10.1N and that of the impact tup with the cylindrical impactor is 10.4N. The drop height of the impact tup is 100mm. The four types of the core thickness are 23mm, 37mm, 48mm, and 61mm being used. The relatively smooth trace of the strains indicates that no damage occurred in the sandwich specimen. No specimens displayed any visual signs of damage at any impact energy below the level that causes catastrophic failure. For the sandwich specimen with the thin core thickness, the absolute strains on the upper face are nearly similar to those on the lower face at the same distance from the center of the specimen, due to the dominant flexural behaviors. However, the local deformation occurs near the impacted region of the sandwich specimen, as the core becomes thicker. When the sandwich specimen is impacted with the cylindrical impactor, the impact energy is uniformly distributed along the width of the specimen. The local deformation in the case with the spherical impactor is more severe than that in the case with the cylindrical impactor.

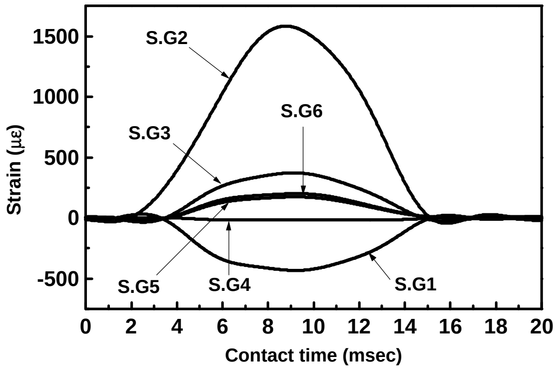


(a) 23mm core thickness *(b) 37mm core thickness*

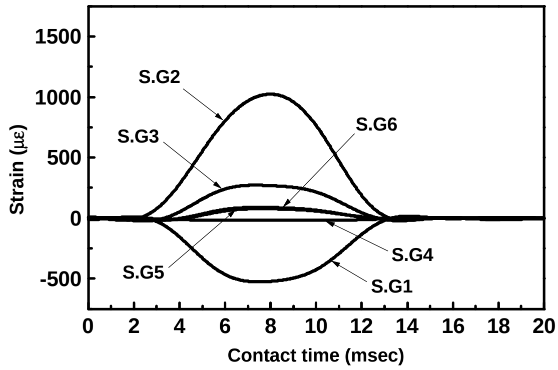
(c) 48mm core thickness *(d) 61mm core thickness*

Fig.7: Strains versus contact time in the case with the spherical impactor.

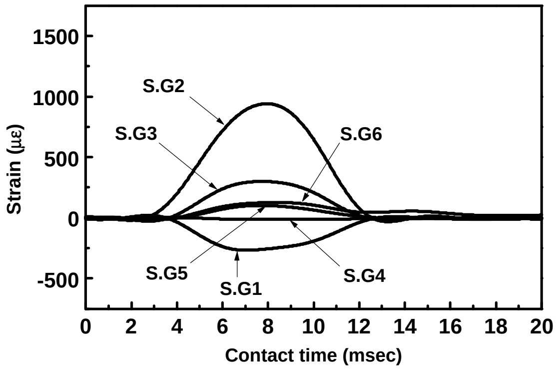
Fig. 9 shows the impact force versus contact time for nonstitched and stitched sandwich specimens with the 37mm core thickness. The drop height of the impact tup is 1200mm and the weight of the unit with the cylindrical impactor is 21.6N. The given level of the impact energy is sufficient to damage the sandwich specimen. When nonstitched sandwich specimen is subjected to the impact energy, the impact force increases linearly up to maximum value (O-A). The maximum value of the impact force, which does not result in an increase in load, is considered as the onset of failure. It related to the appearance of the visual damage such as the shear failure in the core. Once the visual damage occurs, the sandwich specimen rapidly loses the load carrying ability and delamination initiates in the interface between the face and the core (A-B). Finally delamination propagates completely along the longitudinal direction and nonstitched sandwich specimen no longer has the structural integrity (B-C). When stitched sandwich specimen is subjected to the same impact energy, the impact force increases linearly up to maximum value, which is higher than that in nonstitched sandwich specimen. When the shear failure occurs in the core, stitched sandwich specimen can withstand the applied force and is able to avert delamination due to the presence of the through-the-thickness reinforcements. Even though delamination propagates along the longitudinal direction, stitched sandwich specimen maintains its structural integrity.



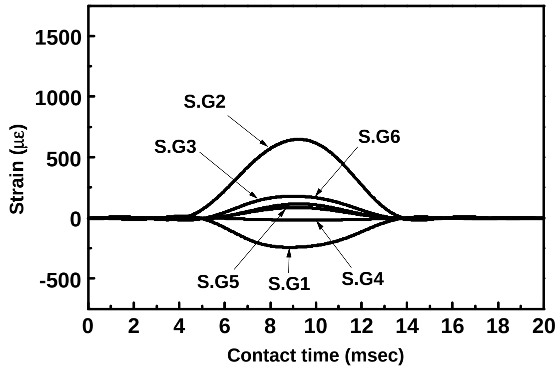
(a) 23mm core thickness



(b) 37mm core thickness



(c) 48mm core thickness



(d) 61mm core thickness

Fig. 8: Strains versus contact time in the case with the cylindrical impactor.

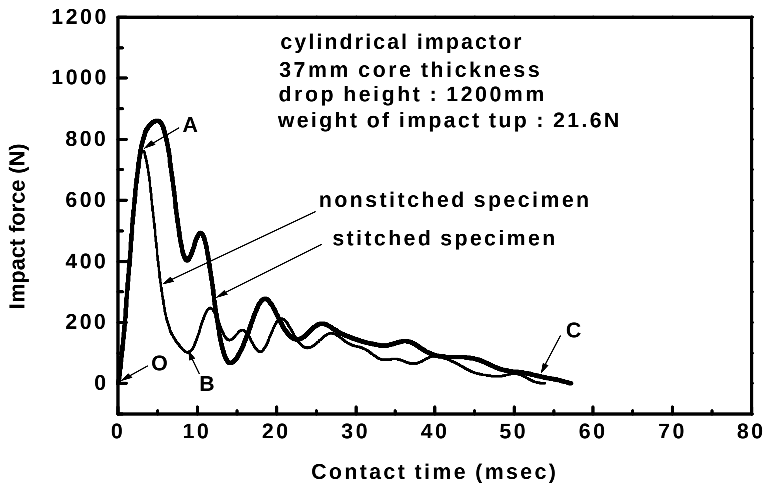
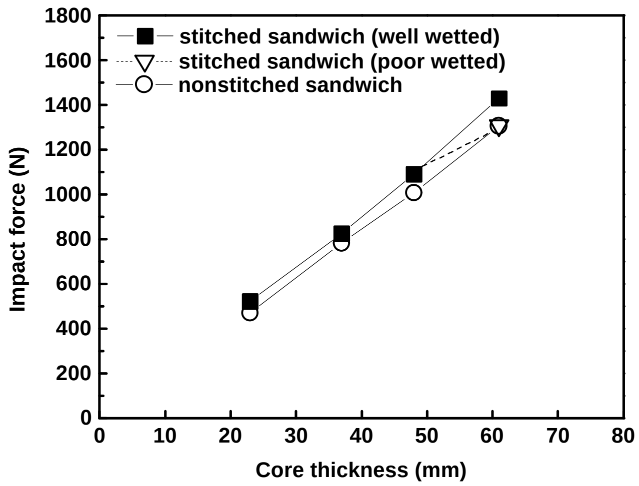


Fig. 9: Impact force versus contact time curves for nonstitched and stitched sandwich specimens.

Fig. 10 shows maximum impact forces having varied with the core thickness in nonstitched and stitched sandwich specimens. The drop height of the impact tup is 1200mm, and the weight of the impact tup with the cylindrical impactor is 21.6N. The impact energy is 25.90 joules, which is sufficient to cause the failure events. For nonstitched sandwich specimen, the maximum values of the impact force are 471N at the 23mm core thickness, 784N at the 37mm core thickness, 1008N at the 48mm core thickness, and 1307N at the 61mm core thickness. For stitched sandwich specimen, the maximum values of the impact force are 523N at the 23mm core thickness, 902N at the 37mm core thickness, 1002N at the 48mm core thickness, and 1309N at the 61mm core thickness. The results reveal that stitched sandwich specimens have 8~15% higher maximum values of the impact force than nonstitched sandwich specimens except for the 61mm core thickness. As the core becomes thicker, it is not easy for the excess resins to penetrate into the through-the-thickness reinforcements during the curing process. The relatively lower value for the 61mm core thickness is due to the poor wetting ability as shown in Fig. 11. However, in stitched sandwich specimen having with the well-wetted reinforcements, the maximum value of the impact force is 1430N at the 61mm core thickness. This is 9% higher than that in nonstitched sandwich specimen with the same core thickness. Therefore, it is important to improve the wetting ability of the through-the-thickness reinforcements in order to utilize stitched sandwich structures effectively.



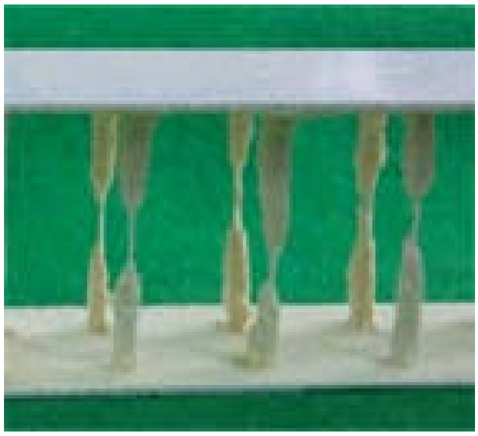


Fig. 10: Maximum impact force versus core thickness. *Fig. 11: Poor wetted reinforcements.*

CONCLUSIONS

Low energy impact tests are conducted to investigate the impact behaviors and the failure mechanisms of nonstitched and stitched sandwich structures. These sandwich structures are made of glass fabric faces with a urethane foam core. The polyester fibers as the through-the-thickness reinforcements are used to combine the upper face and the lower face through the core in stitched sandwich structures. The drop weight impact tester is used and various impact conditions are considered. The four types of drop heights are 100mm, 150mm, 200mm, and 250mm being used. The impactor shape is varied with a cylindrical type and a spherical type. The weights of the impact tup with the cylindrical impactor are 10.4N, 14.4N, 16.8N, and 19.2N. The weights of the impact tup with the spherical impactor are 10.1N, 14.2N, 16.6N, and 18.9N. Different types of the sandwich specimens, each having a different core thickness, are tested to determine the effect of the core thickness on the impact behaviors. Four types of the core thickness are 23mm, 37mm, 48mm, and 61mm as the measurements.

The impact force increases with the core thickness, as it is proportional to the global stiffness of the sandwich specimen. The contact time during the impact event is inversely proportional to the square root of the global stiffness of the sandwich specimen. The sandwich specimens with thicker cores have a higher global stiffness and release the bending strain resulting from the impact event faster than those with thinner cores. When stitched sandwich specimen is subjected to the impact energy, the impact force increases linearly up to maximum value, which is higher than that in nonstitched sandwich specimen. When the core shear failure occurs, stitched sandwich specimen can withstand the applied force and is able to avert damage such as delamination due to the presence of the through-the-thickness reinforcements. Even though delamination propagates along the longitudinal direction, stitched sandwich specimen maintains its structural integrity. However, as the core becomes thicker, it is not easy for the excess resins to force into the through-the-thickness reinforcements during the curing process. This may result in the relatively lower value of the impact force, due to the poor wetting ability. Therefore, it is important to improve the wetting ability of the through-the-thickness reinforcements in order to utilize stitched sandwich structures effectively.

ACKNOWLEDGEMENTS

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