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Pin Reinforcement of Delaminated Sandwich Beams under Axial Compression

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ABSTRACT: The present study is concerned with translaminar reinforcements in a sandwich beam for preventing buckling of the delaminated face sheet under edge-wise axial compression. Sandwich beams consisting of graphite/epoxy face sheets and an aramid honeycomb core were reinforced in the thickness direction using two techniques: Z-pinning using graphite/epoxy pins and a novel “C-pinning technique” developed by the authors. To evaluate the effect of reinforcement type and reinforcement spacing on the ultimate compressive strength of delaminated beams, compression tests were performed. Critical buckling loads and post-buckling behavior of sandwich beams under axial compression were evaluated by finite element analysis to provide insight into the effectiveness of translaminar reinforcement. Pin reinforcement has been shown to significantly improve the ultimate compressive load of a delaminated sandwich beam.

INTRODUCTION

RECENT ADVANCES IN core materials and adhesive bonding techniques have generated tremendous interest in sandwich structures for weight-critical structures. By combining the advantages of sandwich construction with the performance of advanced composite materials used in the aerospace industry, high-strength, high-stiffness graphite/epoxy structures can be produced. Laminated composites have long suffered from a reduction of performance due to delamination. In sandwich structures, the face sheet/core interface introduces an additional potential delamination site. Debonding of the face sheet/core interface can drastically reduce the load carrying capacity of a structure leading to failure at or below the allowable service load. The effect of debonding is particularly noticeable in the case of axial compression. Delamination in sandwich structures can oc-

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cur at the time of manufacture or in service. Foreign matter inadvertently inserted at the time of manufacture can lead to inadequate or incomplete bonding at the interface. For aerospace applications, there are many hazards during service that can lead to delaminated regions. Some of these hazards include tool drop during maintenance operations, impact events, and bird strikes. The advantages of advanced composite materials are well known: high in-plane stiffness and high strength. Their relatively poor through-the-thickness properties have limited their usefulness in certain aerospace applications. To overcome these limitations, two techniques have been developed to improve the in-plane properties of composite laminates, including sandwich structures: stitching and Z-pinning. Z-pinning derives its name from the fact that the straight pins are in the thickness (Z) direction of the laminate.

A previous study by Sharma and Sankar [8] has shown that through-the-thickness stitching can significantly increase through-the-thickness properties of composite materials. In graphite/epoxy laminates through-the-thickness stitching has been shown to increase compression after impact strength (CAI), Mode I and Mode II fracture toughness, and also impact resistance in thick laminates. While stitching has been shown to benefit laminated composites by providing continuous reinforcement in the thickness direction, there are disadvantages. Access to both sides of a composite panel is required for stitching. While this is only a mild limitation to stitching of small, flat panels, today's composite structures have both complex geometries and prohibitively large sizes. As the number of applications of sandwich composites grows, so to does the number of instances where stitching is inappropriate. As aircraft manufacturers work towards monolithic construction techniques, the difficulty in using stitching for translaminar reinforcement will increase.

The present study focuses on two types of translaminar reinforcement: Z-pinning and C-pinning. Z-pinning involves the insertion of individual pins through-the-thickness of a laminate or sandwich structure. The influence of reinforcement type and spacing on the buckling load of a debonded sandwich beam was investigated. Any technique that inserts reinforcement through the face sheet will damage fibers in the face sheet and interfere with consolidation during the curing of the sandwich panel. As a result, the reinforced face sheet will suffer reduced in-plane properties compared with a similar, laminated composite panel. An analysis must be performed to determine the allowable trade-off between reduced in-plane properties and increased through-the-thickness strength. In the case of a composite structure, the determination involves a reduction in the service load of the structure versus an increase in the damage tolerance and durability of the structure. The issues must all be considered in the design of efficient, cost-effective composite structures for weight critical applications.

In the present study the use of translaminar reinforcements in sandwich structures is investigated. Since the sandwich specimens used in the present study cor-

respond to those used by Avery [1] and Avery and Sankar [3], it is appropriate to describe the results of those studies briefly. Avery [1] conducted an experimental program to understand the effects of face sheet and core properties and their dimensions on the compressive load carrying capacity of sandwich beam-columns with debonded face sheets. They used sandwich beams consisting of graphite/epoxy face sheets and an aramid honeycomb core. The face sheet thickness, core thickness, core density, and the delamination length were varied. Sixteen types of specimens were studied, and the Graeco-Latin Square Method was used to analyze the test results and understand the effects of different variables on the ultimate compressive loads. Later Avery et al. [2], Narayanan et al. [6], and Narayanan [7] performed finite element post-buckling analyses of the specimens to explain the failure mechanisms involved. Their conclusions, in general, are that the ultimate load is very sensitive to the debond length between 0.5 and 1.0 inch and debonding of the face sheets can drastically reduce the strength of sandwich beams.

Hwu and Hu [5] have developed an analytical method to compute the buckling loads of debonded sandwich beams. Avery [1] used the method to compute the buckling loads. It is found that the buckling loads correspond to failure loads only in sandwich beams with thin face sheets and long delamination. Most of the specimens carried loads beyond the initial buckling stage. Frostig and Sokolinsky [4] used the finite difference method to study the effect of a flexible core on the buckling load and mode shapes of a delaminated sandwich structure. The effects of delamination length on buckling mode and interaction between the face sheets of a sandwich structure with a flexible core were demonstrated. Their results were able to replicate the four different types of mode shapes observed in tests by Avery [1] and Avery and Sankar [3].

While the aforementioned studies focussed on predicting the behavior and damage tolerance of sandwich beams with debonded face sheets, the present study is concerned with rectifying or avoiding those deleterious effects. The effects of translaminar reinforcements in the form of Z-pins and also a new technique called C-pinning are investigated in the present study. Unlike the Z in Z-pinning, the letter "C" in C-pinning refers to the shape of the translaminar reinforcement.

EXPERIMENTAL PROCEDURE

Specimen Fabrication

The sandwich panels tested in this study used a plain weave, graphite/epoxy pre-preg face sheet material manufactured by Cytec-Fiberite. The core material was a Nomex[®] honeycomb core material from Euro-Composites. The specimen configuration is shown in [Figure 1](#). The face sheet thickness, core thickness, and debond lengths used in this study are presented in [Table 1](#).

Translaminar pin reinforcement involves the insertion of cylindrical, graph-

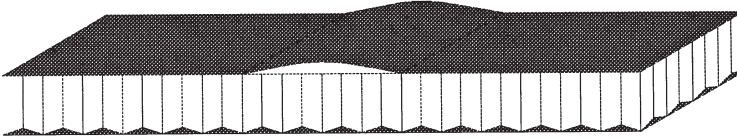


Figure 1. Specimen configuration with delaminated face sheet.

ite/epoxy pins into a composite preform. Initially, this was the technique used in this project. However, after evaluating the performance of these pins a decision was made to find a new technique of reinforcement. A technique called “C-pinning” was developed to improve reinforcement performance. “C-pinning” involves inserted strips of uni-directional graphite/epoxy pre-preg into the sandwich construction preform. These strips are then folded and cured with the sandwich panel.

Z-pins were manufactured and cured prior to being inserted into the sandwich construction. Dry 6K graphite fiber tows were used to fabricate the pins. The fibers were wetted out with a high temperature curing resin and transferred to a fixture for curing. The fixture used to cure the pins applied tension and could be rotated to twist the two 6K fiber tows to form 12K graphite/epoxy rods. After curing, the rods were approximately 0.762×10^{-3} m (0.03 inch) in diameter. The high temperature cure resin was used in the fabrication of the pins to avoid degradation of the pins while they are co-cured with the panel. Degradation of the pin material would lead to poor adhesion between the pin and face sheet. A Shell Epoxy system consisting of SU-3 resin, Curing Agent W, and 828 Resin was mixed to a ratio of 3:3:7 by weight for the graphite/epoxy pins.

Specimen fabrication was done using typical sandwich construction techniques [1] with only minor changes to accommodate reinforcement. In the case of Z-pins, the pre-pregs for each face sheet were laid up individually. The Nomex honeycomb core was cut and one of the uncured face sheets was applied. Prior to applying the second face sheet, a strip of non-porous Teflon of proper size was inserted to create a delamination. Using this sandwich preform with an interface

Table 1. Parameters used in both experimental and numerical analyses. The set number corresponds to those used by Avery [1]. Thickness of a single ply is 0.2×10^{-3} m (0.0087 inch).

Set	Number of Face Sheet Plies	Core Thickness m (in)	Delam. Length m (in)
6	3	6.35×10^{-3} (0.25)	25.4×10^{-3} (1.0)
8	3	6.35×10^{-3} (0.5)	50.8×10^{-3} (2.0)
13	7	6.35×10^{-3} (0.5)	6.35×10^{-3} (0.5)
15	7	6.35×10^{-3} (0.25)	38.1×10^{-3} (1.5)

delamination, Z-pins were inserted through-the-thickness. The reinforced panel was then vacuum bagged. During the vacuum bagging process, the bleeder material was intentionally left out to allow the excess resin from the face sheet to flow into the structure. This excess resin helps secure the pins in the face sheet. A modified, convection oven was used to cure the sandwich panels. The oven has an electronic controller that can regulate temperature and control the vacuum pump throughout the curing cycle. Panels were cured according to manufacturers' suggested curing profile. The total cycle time was approximately 3 hours. Sandwich panels were cut into 101.6×10^{-3} m by 50.8×10^{-3} m (4 inch by 2 inch) specimens using a diamond-coated masonry saw. An environmental chamber was used to condition specimens at 23°C and 50% relative humidity in accordance with ASTM Standard C364.

As will be seen later, the Z-pins pulled out of the face sheet at high compressive loads. Hence, another technique called "C-pinning" was developed by the authors. To incorporate "C-pinning" into the sandwich structure, a single ply (inner ply) of face sheet material was applied to one side of the honeycomb core. The non-porous Teflon sheet was applied under a single ply (inner ply) of face sheet material on the opposite side of the core. Thin strips of uni-directional, graphite/epoxy pre-preg tows, approximately 1.6×10^{-3} m (0.0625 inch) in width, were inserted using a small needle. These strips protrude through the structure and were cut so that approximately 3.2×10^{-3} m (0.125 inch) was exposed on either side of the panel as shown in Figure 2. This process was repeated until the entire panel was reinforced. The spacing of the reinforcement varied in each set. After completing the reinforcement, the exposed tail of pre-preg tow was folded flat against the panel and the remaining face sheet plies (outer plies) were added. Once the additional face sheet plies are added, the pin is now integral with the face sheet. There were no signs of the reinforcement on the outer surface of the cured panel.

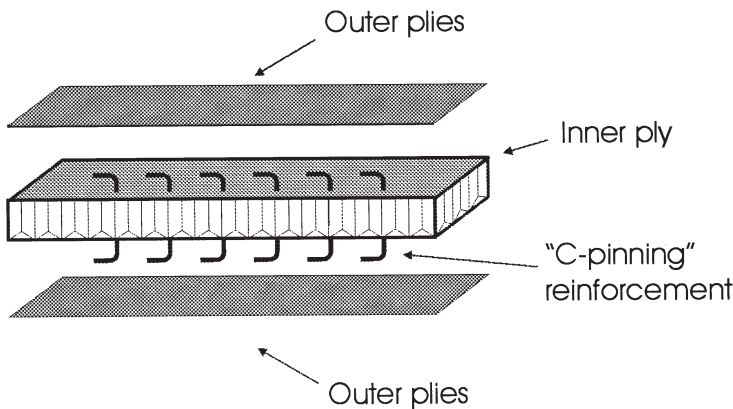


Figure 2. Insertion of reinforcement for "C-pinning" technique.

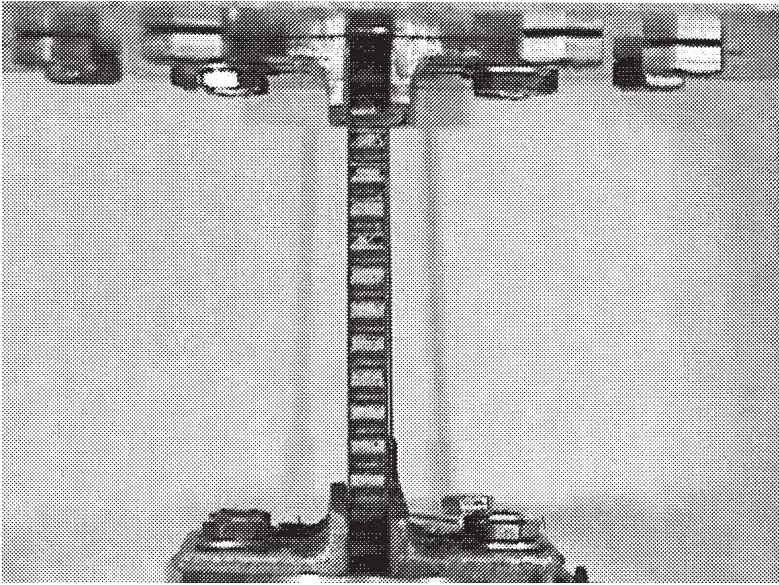


Figure 3. Compression specimen in loading fixture.

Experimental Setup

All tests were performed on an MTI Pheonix 30,000 lb, screw-driven, testing machine. [Figure 3](#) shows a specimen in the compressive loading fixture. Load and displacement information was collected using a standard PC-based data acquisition system. Applied load was measured using a Revere 12,000 lb capacity load cell. Displacement measurements were made using a Schaevitz, 2000 HR LVDT and conditioner. Tests were run in displacement control using the ASTM recommended crosshead velocity of 0.51×10^{-3} m/min (0.02 in/min). The measurements taken included the load and end-shortening up to failure.

EXPERIMENTAL RESULTS

The experimental work involved specimens reinforced at 12.7×10^{-3} m and 6.35×10^{-3} m (0.5 inch and 0.25 inch) pin spacing. A comparison of results for both reinforcement techniques are presented in [Table 2](#). [Figure 4](#) shows representative curves for both the non-reinforced, delaminated specimen and the specimen with Z-pin reinforcement. Similar results for “C-pinning” reinforcement are shown in [Figure 5](#). From [Table 2](#), one can note that specimens reinforced at $12.7 \times$

Table 2. Comparison of experimental results for Z-pins and “C-pinning.” The percent increase is with respect to corresponding non-reinforced specimens.

Reinforcement Type	Spacing	% Load Increase
Graphite Z-pinning	1/2" spacing	34%
“C-pinning”	1/2" spacing	68%
	1/4" spacing	248%

10⁻³ m (0.5 inch) pin spacing with Z-pins showed an average increase of 34% in the ultimate load compared to that without pins. During the tests, local buckling of the face sheet occurred between adjacent pins prior to the pins pulling out of the face sheet. A “pin cushion” effect could be observed where the pins would reinforce the structure locally. Pin pullout occurred when the pin force reached a critical value. This was the dominant failure mode for these specimens.

In order for pin reinforcement to be effective, the load must be transferred from the face sheet to the pin. In the case of Z-pins, the only available mechanism is shear transfer. The critical value of allowable pin force depends on pin diameter and face sheet thickness. In order to improve the performance of structures with translaminar reinforcement, this failure mechanism needed to be addressed. To increase resistance to pin pullout, either the critical pin pullout force must be in-

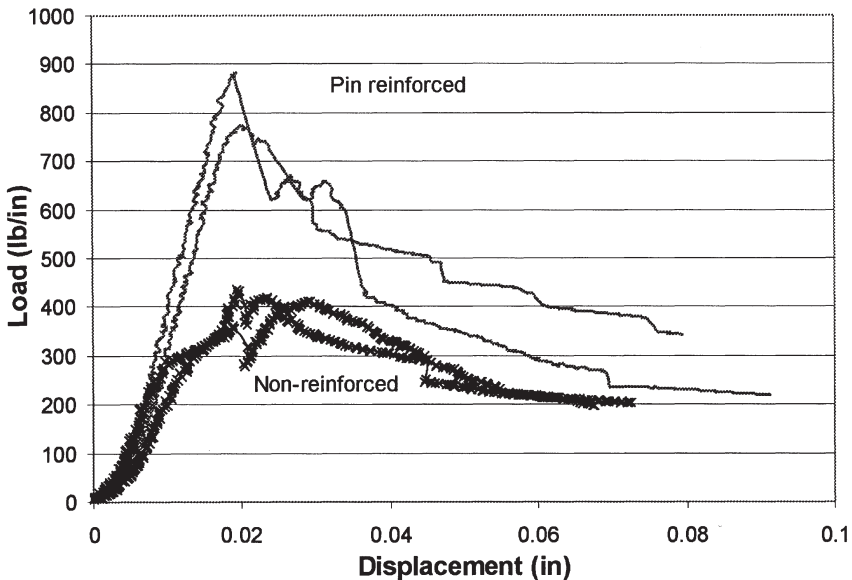


Figure 4. Comparison of experimental results with and without translaminar reinforcement.

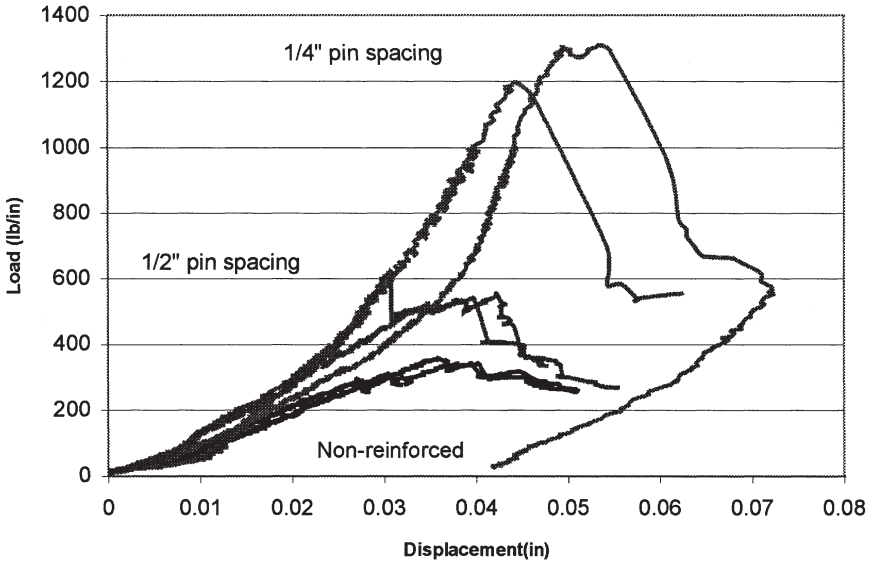


Figure 5. Representative curves for both the delaminated specimen and the specimen with “C-pinning” reinforcement at 1/4” and 1/2” pin spacing.

creased or the applied pin force has to be reduced. A reduction in pin force under identical loading conditions would require an increase in pin density. This would, however, increase the weight of the structure. Increasing the performance of reinforced sandwich without increasing weight would then require that the allowable pin force be increased without changing the existing structure. “C-pinning” accomplishes this by integrating the reinforcement into the face sheet. Using reinforcement that is integral with the face sheet does not rely on shear transfer to carry the loads. By increasing the allowable pin force, failure of the structure is delayed and higher post-buckling loads can be obtained. Test results show that specimens reinforced with the “C-pinning” technique show a significant increase in ultimate load. Reinforcement spacing of 12.7×10^{-3} m (0.5 inch) yielded a load increase of 68% compared to a non-reinforced specimen. Using high-density pin spacing of 6.35×10^{-3} m (0.25 inch), a 248% load increase was observed.

NUMERICAL MODELING

A preliminary finite element study was performed in order to understand the effects of translaminar pins in sandwich beams. The purpose of the finite element analysis is to identify the range of pin spacing that will be effective in suppressing

the buckling of the debonded face sheets, and thus increase the compressive load carrying capacity of the sandwich structure.

The material system for the present analytical study is the same as used by Avery et al. [2] and Narayanan et al. [6]. Finite element models developed in this study are based on those by Narayanan et al. [6] and Narayanan [7]. These models were extended to include translaminar reinforcements. Plane solid elements were used in this study. These models used eight-node biquadratic, plane strain elements for both the core and face sheet. Both linear bifurcation and non-linear post-buckling analyses were performed. The first three eigenmodes were calculated in the linear buckling analysis. The non-linear analysis used the Riks algorithm.

Three different modeling techniques were used in understanding the effects of reinforcement. In the first model the pins were modeled as uniaxial bar elements and located between the inner surfaces of the face sheets. These pins were normal to the face sheet plane. In the second model the pins were modeled as shear deformable beam elements, thus providing flexural as well as transverse shear stiffness. The pins penetrated both face sheets thus connecting the outer surfaces of the face sheets. This model is close to the test specimens. Further, the interaction between the pins and the face sheets can be predicted in this model. In the third model the pins were positioned at 45° to the normal to the face sheets. This arrangement created a truss type structure within the sandwich beam. In all models the graphite/epoxy pins were inserted spaced at either 6.35×10^{-3} m (0.25 inch) or 12.7×10^{-3} m (0.5 inch) in a rectangular array.

The present numerical study considered 4 of the 16 test specimens used by Avery (Sets 6, 8, 13 and 15). The variables in the four specimens are given in Table 1. These four sets are representative combinations of thick/thin face sheet and thick/thin core. The results of the numerical study are presented in Table 3. Representative load vs. end-shortening curves for Set 6 and Set 15 are shown in Figures 6 and 7, respectively.

Initially, the pins were thought to provide the necessary reinforcement because of their axial stiffness as in the truss element model. This configuration would allow transverse forces to be transferred between the face sheets. Local buckling of

Table 3. Effects of pins on the compressive strength in finite element models. Loads are in kN/m, English units are in parentheses. Specimen set numbers correspond to Avery [1].

Set	6	8	13	15
No pins	156.6 (894)	69.7 (398)	1490.6 (8512)	282.5 (1613)
1/2 inch pin spacing	165.1 (943)	118.7 (678)	1515.1 (8652)	343.9 (1964)
1/4 inch pin spacing	377.6 (2156)	219.9 (1256)	1704 (9734)	553.5 (3161)
45 degree pins	330.4 (1887)	—	—	—

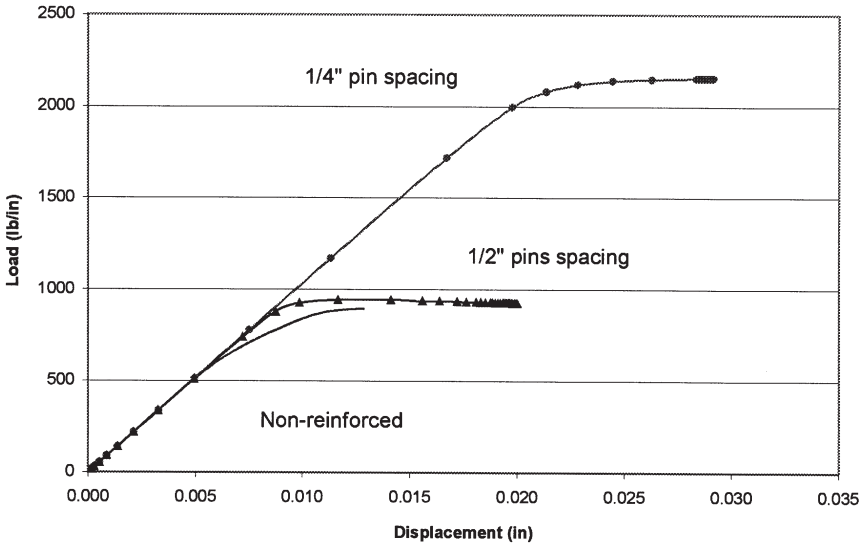


Figure 6. Load-deflection diagrams of Set 6 with and without pins predicted by the nonlinear finite element analysis.

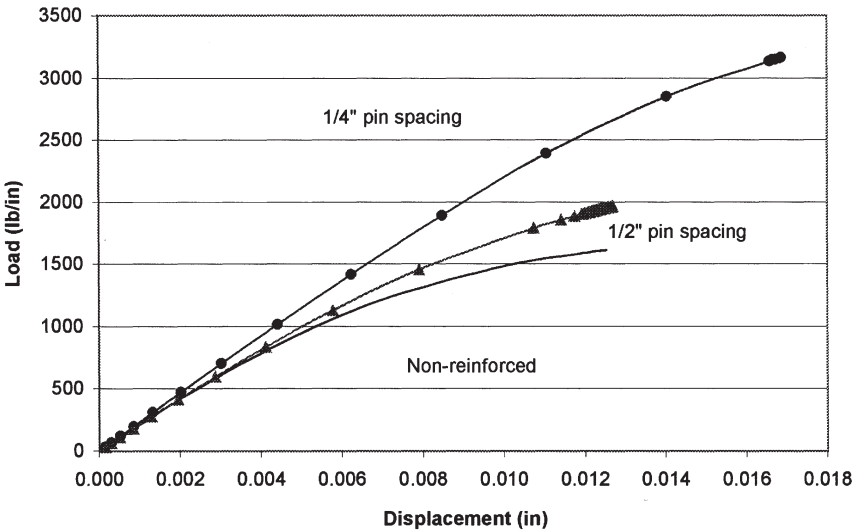


Figure 7. Load-deflection diagrams of Specimen 15 with and without pins predicted by the nonlinear finite element analysis.



Figure 8. Pins inserted at an angle through-the-thickness of the sandwich beam.

the delaminated face sheet would create an axial force in the graphite/epoxy pin, which is then transferred into the undamaged face sheet. With this understanding, pins were modeled as uniaxial bar elements. The results for uniaxial bar elements were not encouraging. There seemed to be only a minor increase in load carrying capacity, regardless of pin size or spacing.

The following observations can be made from the results presented in [Table 3](#). Set 6 was modeled with pins at 1/2" spacing with only a 5% increase in compressive strength. However, when pins were placed in the model at 1/4" spacing there was a 141% increase in capacity. The buckling load increased from 3976 N (894 lbs.) to 9589 N (2156 lbs.).

The case of 12.7×10^{-3} m (0.5 inch) pin spacing in Set 6 models turned out to be an anomaly. The delamination length in specimen Set 6 is 1 inch. Since the delamination is centered in the model, three pins would fall within the delamination when using a 12.7×10^{-3} m (0.5 inch) spacing. One pin would fall at each crack tip while the third pin would fall at the centerline of the delamination. The mode shape for Set 6 was locally symmetric. In this particular case, the pins were located only at nodal points. These points have only transverse deflection, not axial displacement. This result reinforces the belief that the restriction of axial displacement of the face sheet is key in increasing the load carrying capacity of the beam. Load-deflection results for Set 6 are shown in [Figure 6](#). Although the loads predicted for Set 6 shown in [Figure 6](#) are not consistent with experimental data, the behavior of the model and the experiments match qualitatively.

Results from the other three sets were consistent with Set 6. The models with 12.7×10^{-3} m (0.5 inch) pin spacing all showed little or no increase in compressive strength depending on the delamination length. Short delamination lengths showed almost no increase in compressive strength, while longer delamination lengths showed mild increases. These increases are likely attributed to the contribution of the axial stiffness of the pin. Models with 6.35×10^{-3} m (0.25 inch) pin spacing consistently showed large increases in strength. Increases varied from 14% to 215%.

Pins inserted at an angle to the face sheet ([Figure 8](#)) could not be realized in practice, because damage done to the core material would far outweigh any advantage the pins might provide. However, this model did show a significant increase in load carrying capacity. The ultimate load increased from 156.6 kN/m (894 lb/in.) in non-reinforced beams to 330.4 kN/m (1887 lb/in.). The finite element model yielded tremendous insight into the behavior of the sandwich structure with transverse reinforcements.

CONCLUSIONS

Debonding of face sheet and the core can reduce the in-plane compressive strength of a sandwich beam significantly. However incorporation of translaminar reinforcement can reduce the loss of strength. In this study translaminar reinforcements in the form of Z-pins increased the compressive strength of delaminated beams by 34%. The failure mode in pin reinforced sandwich beams was pin pull-out from the face sheet when the debonded face sheet tends to buckle. To avoid the pullout an alternative technique called C-pinning was developed. In this method the translaminar reinforcements are folded in the form of “[”. The C-pinning technique improved the ultimate load by 68% for 0.5 inch spacing and by 248% for 0.25 inch spacing. A finite element simulation was carried out to understand the reinforcing mechanisms. The models also indicated that the increase in compressive load carrying capacity depends on the pin spacing, and they demonstrated up to a 215% increase in the compressive strength. The models were used to study the effects of reinforcements at an angle to the normal to the face sheets, i.e., at an angle to the z -axis. The inclined pins were also found to be effective in suppressing the delamination and improving the compressive load carrying capacity of debonded sandwich beams. Future research in this area should focus on practical and efficient methods of inserting translaminar reinforcements in sandwich structures.

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