Investigation of composite materials and structures for marine applications

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Investigation of Composite Materials and Structures for Marine Applications

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Abstract

Several topics in the area of marine composites were addressed. The first two papers address the effectiveness of a peel stopper device at arresting dynamic peeling. The first paper addresses experimental design issues and preliminary tests surrounding the test setup to be used to create dynamic peeling in full-scale ship panels. The second paper deals with the testing and construction of full-scale panels. The second paper also describes several smaller tests that were performed to investigate possible scenarios that could defeat the peel stopper. All test results supported the effectiveness of the peel stopper. The third paper is a comparison of the mechanical properties of glass fiber composite to carbon fiber composite. The two materials were compared in tension, compression, open hole tension, open hole compression, transverse tension, and slow impact. The same vinyl ester matrix was used for all specimens of both composites. Glass fiber was found to be stronger in compression and transverse tension. The two materials were equal in open hole compression. Carbon fiber composite was stronger in the other tests. The two composites represent materials choices that are employed for structural components of ships. The forth paper addresses the effect on transverse tensile strength of carbon fiber / vinyl ester composites when the dry fibers are exposed to different environments prior to infusion. It was found that when the fibers were exposed to heat and vacuum for the 240 hours before the infusion, the composite had the highest transverse strength.
Thesis

This thesis is comprised of an introduction and the following four papers.

Paper A.

Paper B.

Paper C.
Wonderly C. and Grenested, J.L, “Comparison of mechanical properties of vacuum infused glass and carbon fibers in a vinyl ester matrix.” *To be submitted*.

Paper D.
Wonderly C. and Grenestedt, J.L, “Dry Fiber Environmental Conditions that increase carbon fiber / vinyl ester interfacial strength.” *To be submitted*.
Introduction and Summary

The present work deals with several topics that are important to marine composite structures. One important topic deals with debonding of skins from composite sandwich structures. The hulls of large composite navy ships such as the corvette class Visby are made with two skins vacuum infused to a structural PVC foam core. This offers a significant increase in stiffness and decrease in weight over using a single thick skin.

One disadvantage to using a sandwich structure is that small damage to the outer skin can initiate peeling of this skin from the core. This peeling has been known to cause catastrophic damage to ships. This is illustrated in the case of the Swedish Jet Rider ship. After a harbor touch caused small initial damage, the ship got underway where upon a large fraction of the outer skin dynamically peeled from the ship. To address this issue several peel stopping devises have been proposed [1,2,3]. Grenestedt’s peel stopper has proven effective in static tests, and its presence does not weaken the hull if the primary loading is bending [4]. The chief advantages over other proposed peel stoppers is that it is easy to fabricate and that does not connect the inner and outer skins. The latter could be advantageous for UNDEX performance. The relatively soft foam may compress from the explosion. If there is composite attaching the two skins then this compression is impeded and there is a risk that the composite could break through both the inner and outer skin. If the two skins are not connected, however, this could be a potential disadvantage because if the growing crack of the debonding skin kinks down into the foam core, there is a risk that it could go under the peel stopper and continue growing.
Another topic addressed in this thesis is a comparison of glass fiber composite to carbon fiber composite. Carbon fiber / vinyl ester was selected for use in the Visby ship in Sweden, while glass fiber / vinyl ester was selected for use in the ships made by the United States Navy. Both Navies had reasons for their materials selections, but came to different conclusions. The purpose of this study was to test under identical conditions glass fiber / vinyl ester and carbon fiber / vinyl ester so that their performances can be directly compared.

The last topic dealt with in this thesis is the transverse tensile strength of carbon fiber / vinyl ester composite. This test provides insight into the adhesive strength of the fibers to the matrix. Carbon fibers have notoriously poor matrix adhesion. This poor adhesion is responsible for many carbon fiber composite failures. Various sizings provide vast improvements in strength over unsized carbon fibers [5,6,7]. This work addresses the effect of environmental conditions the fibers are exposed to prior to infusion on the transverse strength of resulting composite.

References


Dynamic Testing of a Proposed Peel Stopper Device

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ABSTRACT

A peel stopper device is a structure in composite sandwich structures that stops debonding of the composite skin from the foam core. Several tests have been performed to test the performance of a peel stopper that has been encountered by dynamic blister growth. First, an initial delamination was found that will cause a blister to grow in a predetermined direction. Secondly a preliminary test was performed on a peel stopper with a low weight foam core. Finally a peel stopper in a carbon fiber/ vinyl ester system was tested dynamically, and it performed its function. Dynamic growth was achieved by inflating an initial blister with compressed nitrogen.

INTRODUCTION

Composite materials are used in high speed ships for several reasons. They provide a weight savings, over traditional steel ships. Composite ships also can be made invisible to radar and mines. One of the disadvantages to composite sandwich structures is their susceptibility to debonding at the interface between the foam core and the fiber reinforced composite skin. Some initial damage may allow water into an initial blister. As the ship travels, the water can exert a pressure as high as the stagnation pressure of the
water flowing relative to the ship. When the blister reaches a critical level, catastrophic failure in the form of large scale peeling of the skin from the ship occurs. A device known as peel stopper has been proposed. Peel stoppers aim to stop this growth and localize debonding of the outer skin. The peel stopper developed by Grenestedt (figure 1) has been shown to be effective in static tests [1]. It is the aim of current research to investigate whether peel stopper is also effective in dynamic tests. These tests are necessary because the behavior of the crack growth may be different when it is dynamic. It is possible that the expanding crack may move from the interface of the materials into the core and travel under the peel stopper. It is also possible that the waves accompanying dynamic failure continue beyond the peel stopper and allow the debonding to defeat the peel stopper.

**EXPERIMENTAL SETUP (FIGURE 2)**

In order to produce dynamic debonding compressed dry nitrogen is introduced to an initial blister. A pressure gauge and 90psi safety valve were connected to the system near the tank of nitrogen. A needle valve and the pressure regulator on the nitrogen tank controlled the pressure supplied to an accumulator. A 2.7mm nylon hose longer than 6 meters connected this assembly to the accumulator. The accumulator was used to ensure that the specimen would fail by means of dynamic growth. Without the accumulator there would be no large collection of compressed air. The hose is relatively low in volume and is unable to provide a very high flow rate. Consequently, when the blister grew, the increase in volume would be accompanied by a decrease in pressure, which would stop the crack growth. Earlier tests confirmed that this was the case when the hose
was connected directly to the specimen. With an accumulator, the increase in volume caused by the blister's growth would result in a small decrease in pressure. As a result when the tank reaches the critical pressure to produce crack growth, the blister grows dynamically until failure. The accumulator, designed to hold about 2 liters, was built from galvanized 2” Iron pipe. It connected to the specimen at a steel plate with ¼” NPT threads through the center. The steel plate was placed under the plies of the specimen. After curing, the threads were liberated and the accumulator attached to the exposed threads. For safety the entire assembly was wrapped in safety netting before testing. The test, performed outside, was conducted on one side of a concrete barrier while controlled from a significant distance away on the other. Inserting a piece of vacuum bag between the foam core and outer skin made the initial blister.

EXPERIMENTS

There are some options on how the initial blister could be shaped. A perfectly round blister could grow in any direction. It is advantageous to know the direction the blister will grow so that the specimens could be prepared in less time, and also so that the blister encounters the peel stopper and measuring equipment, instead of only ruining the specimen. Several shapes for the blister were tested. The shapes were put into plates of glass fiber and vinyl ester 5-10A that were produced using Vacuum assisted resin transfer molding (VARTM). The plates were constructed as (0, ±45), (90, ±45), (±45, 90), (±45, 0), delamination, (0, ±45), (90, ±45), (±45, 90), (±45, 0). The plates were 500mm x 600mm to ensure that edge effects had no effect on the direction of growth and to see if the delamination continued in the direction that it began in. Before infusing the steel
plate was placed directly on top of the delamination. Three layers of glass fiber surrounded it as a fringe that protruded out 30, 20, and 10 mm respectively as they were placed. These were there to help with resin coverage by eliminating the fillet around the plate. Several shapes were tested (figure 3). The bubble was tested once with quasi static growth and once with dynamic growth using the accumulator. In both tests it seemed that the flat side of the bubble grew until the delamination was round and then grew unpredictably after that. The straw was tested once and it likewise seemed to grow to a rounded figure then continued in an unpredictable direction. The zipper was tested next. It grew to the right as shown on the page nearly to the end of the plate but also grew perpendicular to this far enough that the perpendicular direction is one from which the blister exited the plate. The fish delamination was tested twice and grew from the tail both times (towards the right if as pictured here). The fish design was then modified to smaller overall dimensions and slightly different proportions so that it could be used in the future for smaller plates (Figure 4).

The second set of experiments aimed to test a simple peel stopper with the test equipment. The specimen was produced from low density one centimeter thick H30 foam core. The skins on each side were 3 layers of Hexcel Schwebel bid 7725 woven glass fiber. The matrix used was SP System's Prime 20 epoxy resin. Prime 20 slow hardener was used because of the size of the specimen, and introduced by VARTM. Modifying a Dremel™ tool to cut on a 45-degree angle with its router bit produced the peel stopper troughs. When tested, the peel stopper did not
perform. Instead of the interface debonding, the foam core was torn as the growing crack oscillated between the two skins (figure 5). The final test performed was a more representative test. It was performed on 50mm thick H200 foam core from Diab. Carbon fiber from Devould (DBL 700-C12-R2VE and Lt 450-C10-R2VE) was used and Dow Derakane vinyl ester 510A as the matrix. The surface of the foam core is primed with fast curing 510A prior to infusing [2]. The lay up of the outer skin is, from the top, [$\pm 45, 0, 90, 0, \pm 45, 90, 0, 90, 0, \pm 45$]. The inner skin layup from the outer surface is, [$\pm 45, 0, 90, \pm 45, \pm 45, 90, 0, \pm 45$]. In this test the peel stoppers were combined with a panel joint. Five pieces were made separately and then joined together using putty and carbon fiber (figure 1). The dimensions of the top of the center piece were 400mm x 400mm. The depth dimension of short top side of the other four pieces was 190 mm. The width dimension was 780mm for the long pieces, and 400mm for the short pieces. The putty used to fasten them together was vinyl ester 510A mixed with microballoons until the consistency of about honey was reached. The cross section of the foam includes not only a notch to receive the fiber, but also a ramp across the top that is sloped at 1/30 as seen in figure 1. The 1/30 ramp is used so that when the layers that connect two pieces are added, the whole panel will be flat (figure 6). This profile is difficult to achieve because there aren’t any tools that cut such a shape easily. Therefore, an electric hand planer was modified to cut the shape profile of the pieces. The blade of the planer and the belt that drives it were removed. An aluminum box with an open bottom was built and fastened to the bottom of the planer. A new drum and spindle were made from aluminum and run through the box. A keyed gear connects outside the box to the spindle
and receives a new longer belt to connect to the planer motor. The blades were water jet cut and bolted to the drum.

**Step 1.** The foam core is cut using the modified planer and a 10¼ in circular saw then fit together and trimmed with an unmodified planer. The surfaces are also sanded to remove dirt and to smooth the planer's cut.

**Step 2.** Each piece is primed. It then has layers of carbon fiber affixed using VARTM. The layers are staggered so that step 3 produces a flat panel.
Step 3. All the Pieces are put tied together. Carbon fiber is then laid down across the joints. The strips of fiber match the stagers on one side and match the 1/30 slope onto the peel stopper.

DISCUSSION AND CONCLUSIONS

Several interesting results came from the test of the zipper shaped delamination. First, the delamination actually grew further in the predicted direction than in the failure direction. Secondly this shape produced the largest delaminated area of any of the shapes. Roughly 1/3 of the plate had been delaminated when the test was over. This indicates that if the growth was dynamic over a longer range, the zipper delamination
may work. Nevertheless, superior consistency was found using the fish delamination, and it became unnecessary to pursue the zipper shape.

One of the conclusions that can be drawn from the second set of tests is that the H30 foam, is a poor representation of the HD250 foam for these tests. This is evident after comparing the H30 / glass fiber blister growth to the blister growth of the third set of tests. In the second test, the growing blister plunged into the foam core and went under the peel stopper. One possible explanation for this is that the bonded region between the epoxy and the foam core was stronger than the foam core itself. This provides insight as to what may happen if the peel stopper fails to work.

The third test, performed on H200 foam core, provides insight into what should happen if the peel stopper performs correctly. The growing blister moved to the surface exactly as the peel stopper was designed to promote. The third test will be performed a second time on a larger H200 specimen with an accumulator designed to deliver a higher flow rate. Future tests will be conducted on even larger panels with a larger accumulator.

References


Figure captions

Figure 1. Basic peel stopper schematic.

Figure 2. Test setup

Figure 3. Initial delamination shapes

Figure 4. Final initial delamination geometry

Figure 5. Cross section of the H30/ glass fiber/ prime 20 panel

Figure 6. Schematic of panel flatness with peel stopper.
Figure 1.
Figure 2.
Figure 3.

All dimensions in millimeters
Figure 4.
Figure 5.
Figure 6.
Dynamic performance of a peel stopper for composite sandwich ship structures

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ABSTRACT
A device known as a peel stopper has been developed. This device aims to arrest dynamic debonding of the composite skin from the foam core material that can occur in composite sandwich structure ship hulls when exposed to initial damage. This work addresses the effectiveness of the peel stopper when faced with dynamic debonding of the skin. Several ship panels were produced and tested as well. Some tests to investigate whether the debonding could behave in a way that could defeat the peel stopper were also performed. Some of the issues surrounding the manufacture of the device were also addressed.

KEYWORDS: Peel stopper, crack arrestor, sandwich, damage tolerance

1. INTRODUCTION
Recently several problems of engineering interest have arisen that address rapid crack propagation and arrest. One such device is in use in gas pipelines. In gas pipelines a
crack may open in the axial direction of the pipe through a number of means including fatigue, or contact with an object. If the crack becomes of sufficient size, then rapid crack propagation may result. In some cases the crack can grow faster than the gas can decompress. Since the pipe pressure is not released, the dynamic crack driving force does not drop below the dynamic fracture toughness, and the crack can run through several miles of pipe [1,2]. To address this issue, a device known as clock spring was developed [3]. Clock spring is a tightly wound band of FRP with the fibers in the hoop direction placed around the pipe. Crack arrest devices in pipelines typically aim to reduce the opening of the crack and lower the crack driving force, which results in crack arrest [2]. Part of what has made clock spring successful has been the relative ease with which it can be employed.

Another device aiming to address rapid crack propagation is the buffer strip [4]. This device is produced in principle by adding strips of extra FRP among the plies intermittently along a composite plate. Because of the sometimes brittle nature of composite materials, they are susceptible to failure from small cracks and holes. The additional layers arrest growing cracks and allow a higher failure strain [5].

This paper addresses the arrest of crack growth in composite sandwich structures. Composite sandwich structures are used in ship hulls for numerous reasons. One advantage is that these materials can provide large weight savings without sacrificing stiffness or strength. One of the disadvantages of sandwich structures is that they can become susceptible to debonding at the interface between the foam and the skin. This is
well illustrated in the case of the Swedish JetRider FRP ship. Hitting some stone stairs in a harbor caused some small damage to the outer skin of the hull. Seawater was able to get between the outer skin and form a blister. The pressure in this blister can be on the order of the stagnation pressure of the water relative to the hull. Once the ship got underway the pressure became sufficient to begin dynamic crack growth between the skin and foam. A large area of the outer skin was peeled from the ship.

To localize peeling damage in sandwich structures, a device known as peel stopper \cite{6,7,8} was designed. Quasi static tests have shown its mechanical properties, and suggested that it is effective. For reasons that will be discussed shortly, it is necessary to investigate peel stopper's performance in dynamic peeling.

2. Function of Peel stopper

The studied ship hulls were an inner skin and an outer skin separated by and adhered to a PVC foam. Peel stopper is a device designed to stop the skin core interface debonding in sandwich structure composites. A schematic of peel stopper's function can be seen in Figure 1. The debonding of the skin is manifested as a blister filled with seawater between the skin and the core. In principal the peel stopper device is two outer skins that are joined in such a way that a blister growing under the first skin, is not able to enter the second skin. As the blister grows to the joint between the two skins, the first skin detaches and the second skin should remain bonded to the foam. In order for the panel to remain flat, and to avoid unnecessary stress concentration, the plies are of different length so that the edge is stepped causing a tapered thickness at the ends. The foam under this
portion of the skin is sloped to match this tapered thickness. The majority of these specimens were produced with a peel stopper and a panel joint together.

Peel stopper has been effective in quasi static loading [8]. There are some possible failure modes that may arise in dynamic peeling that may not be present in quasi static peeling. The first is the crack may begin growing in the foam instead of at the skin / foam interface. If the crack kinks into the core, it may travel under the peel stopper and continue growing. Another issue could come from the elastic waves that accompany this growth. These waves could cause a debonded area below the second skin, which would allow the blister to continue growing. These situations can be seen in Figure 2.

Three different sets of tests were developed to determine the effectiveness of peel stopper against dynamic peeling. Before addressing the sandwich panel peel stoppers, test set one was performed which developed a test setup and determined an initial blister shape that would cause growth in a predetermined direction. Knowing the direction the blister would grow was valuable because it assured the blister would encounter the peel stopper. For these experiments glass fiber / vinyl ester plates were made. A piece of plastic film and a steel plate with a threaded hole were placed between the middle plies. After curing, the threads were exposed and a pressure fitting was attached. The plate was then exposed to increasing pressure until initial delamination caused by the plastic film grew to the edge of the plate.
Test set two was to examine the peel stopper in a beam with different loading conditions. Beams were made with a peel stopper on one of the surfaces. The top skin was attached to a weight with a long stiff rope. The beams were clamped to a tall structure, and the weight was thrown from a high place. When the weight reached the end of the rope, the outer skin peeled.

Test set three examined peel stopper’s effectiveness in sandwich panels with a dynamically growing blister. These panels were the main focus of the research. Full-scale sandwich panels were made with an initial blister between the foam core and the top skin. As in the first tests the pressure was increased in this blister until it grew dynamically. The growing blister then encountered the peel stopper. All specimens were produced by means of vacuum infusion. The test setup diagram can be seen in Figure 3.

3. SPECIMEN MANUFACTURING

In this section the manufacturing of the specimens associated with each test is discussed. The testing of the specimens and the results are discussed in later paragraphs.

3.1 Manufacture of Delamination Shape Specimens (Test set 1)

B. The first set of specimens was produced using Dow Derakane 510A-40 vinyl ester. Six layers of triaxial glass fiber BTI TH4000 (0,±45°) were used. From the top, the layup was (0,±45°)2, (±45°,O), delamination and steel plate, (0,±45°), (±45°,O) 2. The plates measured 600mm x 500mm. The steel plate had a ¼ inch NPT threaded hole through the center was placed in the center of the plate. After curing the threads were exposed and
used to attach a pressure line. The dimensions of the steel were 101.6mm x 101.6mm x 4.8mm. The corners had a 12.7mm radius.

3.2 Manufacture of Beams (Test set 2)

The specimens for test set 2 were to composite beams. A 600mm square piece of 45mm thick Divinycell HD 250 foam from Diab was used. Both sides of the foam were scored with a grid. The scores were 2mm wide x 2mm deep. The score spacing was 25mm. The foam was then primed by rolling a fast curing (10min) application of the matrix. This scoring and priming will be refered to as standard foam prep in future tests.

Carbon fiber from Devould AMT was used (DBL 700-C12-R2VE and LT 450-C10-R2VE). DBL is knitted [-45°, +45°, 0°] where 0° is in the direction the material is rolled. LT is [0°, 90°]. Layers were also used that were DBL turned 90°. Devould AMT sells a DBT that is [-45°, 90°, +45°]. Therefore the convention DBL\textsuperscript{T} will be used to refer to [+45°, -45°, 90]. The layup for the top skin starting away from the core is DBL(45° up), LT(90° up), DBL\textsuperscript{T}(45° up), LT (0° up), DBL (0° up). This produces [±45,0,90,0, ±45,90,0,90,0, ±45]. The bottom skin, starting away from the core is [±45,0,90, ±45, ±45,90, 0, ±45]. This was achieved by taking DBL(45° up), DBL\textsuperscript{T}(90° up), DBL\textsuperscript{T}(45° up), DBL(0° up). Dow Derakane 8084 vinyl ester resin mixed with 1.5 wt% MEKP, 0.3 wt% CoNap (6% concentration), and 0.05 wt% DMA was used for the matrix. These layups and matrix will be referred to as the standard layup in future tests.

Both skins were infused at one time. A wood planer that had been modified to cut the peel stopper profile was used to cut a peel stopper trough through the middle of what was
to become the outer skin side. A spiral hose was placed in the bottom of the trough to introduce resin to the carbon fiber that extended from the trough bottom to the end of the panel. Figure 4 shows the triangular cross sectioned foam core strip was added to the trough to make the final panel flat and the skin that was placed over the strip and peel stopper.

The infusion of this specimen can be seen in Figure 5. Resin was introduced in the trough first, and drawn to one edge of the panel. A spiral wrap on that edge was then opened which infused the entire inner skin, and helped to infuse the remainder of the outer skin.

3.3.1 Manufacture of Lightweight Foam Core Epoxy Panel

The first specimen of test set 3 to be manufactured and tested was built with 10mm thick H30 foam core from Divinycell. This foam is very lightweight and not representative of an actual ship hull. The skins were made from 3 layers of Hexcel Schwebel 7725 woven glass fiber with SP System’s Prime 20 epoxy resin for a matrix. Prime 20 slow hardener was added to the resin and vacuum infusion was employed to produce the sample. The overall dimensions of the panel were 0.55 meters x 0.6 meters. Peel stoppers were cut into the foam using a high speed rotary tool mounted to a 45 degree jig. It cut a trough about 3 to 5 mm in width and half the thickness of the material. A peel stopper was cut along each long side of the foam 100mm from the edge on each side. On each remaining side a peel stopper was cut 100mm from the edge that spanned the two previously cut peel stoppers.
3.3.2 Manufacture of 780 mm Panel

A larger panel was produced as the first test on the peel stopper/panel joint combination. H200 foam core from Diab was used. The Standard layup (section 3.2) was employed. The panel was produced in five separate pieces that were joined together. The sides were beveled at 45°. Figure 6 shows the shapes of the pieces. The two long side pieces were 190mm x 780mm. The two short side pieces were 400mm x 190mm. The four side pieces had one long side that was cut with the modified planer. They were bevel cut at 45° below the planed cut. The outer and inner skin of each of these pieces was infused prior to joining. The inner skin layers were cut such that the layer closest to the core was 40mm smaller than the core on the three sides to be joined. Each successive skin layer away from the core was 18mm shorter than the one before. The center piece was 400mm square on top. On the center piece, the inner and outer skins were stepped every 18mm the same way the bottoms of the edge pieces were done. Putty was produced by mixing vinyl ester resin for a 10 minute pot life. Microballons were added until a thick syrup like consistency was obtained. This putty was added in excess to both faces to be joined. Then the pieces were clamped. After all the pieces were joined carbon fiber strips were added to produce the scarf joints and infused to make inner and outer skins flat. The basic process for producing peel stopper panel joint combinations can be seen in Figure 6.

3.3.3 Manufacture of 900 mm Panel.

A slightly larger panel was made using the standard layup. Divinycell HD250 foam was used. Instead of doing the bottom of each piece separately and then using strips to join the pieces together, the whole bottom was added after joining as one
continuous four layer skin to save time. This is not expected to have any effect on the peel stopper performance. The foam was joined using Diab Divilette NQ G1HV putty mixed with 1.5 wt% MEKP. All of the remaining panels that required joining, used this putty.

3.3.4 Manufacture of 500 mm Panel.

The 500mm panel was prepared from a single piece of HD250 foam with the standard layup. Standard foam prep was also used. Four cuts, each half the thickness of the foam and 2mm wide, were cut at a 45° angle away from the initial delamination. The plastic film used for the initial blister extended into the bottom of each trough. Thereby forcing the crack to begin in the middle of the foam. Figure 7 shows a diagram of the initial blister in this panel.

3.3.5 Manufacture of 2000 mm Panel

The 2000mm panel was made with HD250 foam core and the standard layup and standard foam prep. The foam sheets as obtained from the manufacturer were 1360mm x 680mm. Figure 8 depicts the necessary joining of the foams to obtain the correct size of each panel piece.

The rolls of carbon fiber used are 1270mm wide so it is was necessary to overlap layers. A 30mm overlap was used and the position of the overlap was staggered for each layer to avoid an appreciable increase in local thickness. The overlap of fibers that run 90° or 45° to the edge is necessary so that the stress they carry through one layer is transferred into the next. The fibers running parallel to the edge do not transfer stress between layers in
the overlap region. Therefore, if both layers have 0° fibers then these fibers are removed from one of the layers in the overlap region.

Because bumps and ridges on the surface of the hull decrease its stealth properties, it was important the peel stopper be designed to make the surface as flat as possible. The slope in the foam compensates for the extra overlapping skin along the lengths of the peel stopper allowing the panel to be flat. However, at the corners where two different peel stoppers meet each other and the center piece, a flatness issue results because of the tapered thickness of peel stopper's cross section as seen in Figure 9. With the foam exposed, there is an area where the height of the foam for all three pieces is different. This difference in corner heights was evident in the 900mm panel. To correct for the different height, the layup was altered around the corner in the 2000mm panel. Figures 9-12 illustrate both the issue of flatness and the shapes of the plies used to allow the panel to be flat.

The new layup caused the edge of the peel stopper to have a thickness equal to that of an uncut foam core. This is the same thickness as the center piece and peel stopper it butts into. Therefore, the joint of this edge to both pieces will be flat on the lowest layer. Figure 12 depicts how the corner would be flat after two adjacent scarf joints are added. The overall flatness was measured on the finished panel with a dial indicator in the region of this corner and the panel was found to be reasonably flat.
Sixteen strain gages were also attached to the panel. Due to the surface roughness in this specimen paste adhesive was used to affix the gages because of its high viscosity. The details of the use of these gages will be discussed later. The arrangement of these strain gages can be seen in Figure 13.

3.3.6 Manufacture of 1360 mm Panel

A panel was made that did not employ the peel stopper/panel joint that previous panels used. It has been the case in all previously made panels that the failure direction was the direction predicted with the selected initial delamination geometry. Also it was the case that the total delaminated area was nearly the size of the center panel piece. Taking this into consideration, the 1360mm panel was produced with two peel stoppers that were facing each other and 650mm apart. This means that for the panel to fail not in the peel stopper direction, the blister would have to grow twice as far in that direction as it did in the peel stopper direction.

The 1360mm panel was made with HD250 foam core and the standard layup and standard foam prep. It was made by joining two 1360mm x 680mm foam sheets. The modified planer was used to cut two peel stopper troughs 650mm apart. The carbon fiber was laid into these troughs with a ¼ inch spiral wrap that the resin would be introduced through. The first infusion produced the outer skin pieces that went from the trough to the edge of the specimen. After this, two trapezoidal cross sectioned foam strips were puttied into the trough so that the panel would be flat as seen in Figure 14. The remainder of the top was infused. Finally the inner skin was laid up and infused.
strain gages were again attached to the panel in the same general arrangement as the 2000mm panel. This time the closest four strain gages were 140mm away from the center of the panel and the spacing was 70mm.

4. PRELIMINARY EXPERIMENTS

4.1 Determination of an Initial Delamination Shape

The initial delamination was cut from a piece of 0.06mm thick plastic film. It could be virtually any shape. For a round delamination, the test would most likely cause the delamination to initially grow as concentric circles. It would eventually leave the panel in one direction. The direction could not be predicted if all the sides are the same distance from the delamination. If an initial delamination shape could be chosen such that the delamination growth occurred in a predictable direction then the panels could be constructed with one peel stopper instead of needing four that surround the blister. Several shapes were selected in a purely experimental attempt to find a working shape. These shapes can be seen in Figure 15. Some results of various tested shapes can be seen in Figure 16.

4.1.1 The bubble. The thought was that the local energy release rate on the flat side is higher than the remainder of the delamination front which should favor crack growth in the direction perpendicular to the flat side. In practice however, the shape did not produce a predictable direction of growth. It was suspected that its lack of success could be attributed to the bubble slowly growing until circular and then being unpredictable after that. Two of these bubble specimens were produced. Neither one produced a crack in the predicted direction.
4.1.2 The straw. The straw shape has two interior corners and also should resist growing into a circular shape. It also failed to produce predictable growth, however. It grew in a direction $90^\circ$ to the predicted direction. Because of symmetry, this result showed that the shape would yield unpredictable results.

4.1.3 The zipper. The zipper aimed to cause the energy release rate to be highest in the zipper direction. Although the blister did not exit the panel in the predicted direction, it did travel as far in the zipper direction as in the failure direction.

4.1.4 The Fish. Several trials provided consistent growth from the tail of the fish shape. A smaller version of the fish shape was employed for future tests as seen in Figure 17. Due to its continued success, this shape was employed in all further blister tests. Evidence has suggested that the fish shape has been successful in providing a consistent growth direction in all of these.

4.2 Experimental Beam Peel Tests

Five peel stopper beams were produced and tested by means of a drop test. A concrete structure approximately 15 meters high was used. The beam was affixed to the top of the structure with the outer skin facing down. A piece of one inch nylon webbing that was about 14 meters in length was tied to the outer skin. This test setup along with the test results can be seen in Figure 18. This webbing was used because of its high stiffness in tension, and its limp nature. The other side of the webbing was attached to a weight. The weights used were 2 liter plastic bottles that were filled with water and frozen. A piece of webbing with several knots was frozen into the bottles. A piece of spectra cordage was attached to the leading edge of the skin and then to the structure to ensure that when the
skin was ripped free it would not fall to the ground. This was done both for safety and so that the wires connecting the strain gages on the skin to the measurement hardware were not pulled.

The first specimen was made with a 20mm initial delamination, and tested with one bottle and with the metal insert. When dropped there was a tearing noise, and the skin broke in bending at the beginning of the peel stopper trough. The weight was pulled up and dropped again. The second drop failed to inflict any further damage on the beam.

The second beam had the initial delamination extended by sawing into the foam just below the skin. The new debonded length was 150 mm. Two bottles were tied together with a double overhand knot. The long section of webbing was then attached to the bottles with a figure eight knot. The test caused the skin to separate leaving approximately two layers of carbon fiber on the face of the beam. In this test the failure was a delamination, and not a debonding of the interface. Peel stopper was effective at stopping this delamination.

For the third beam a 150 mm crack was cut into the foam about 15 mm in from the outer skin. Two bottles were again dropped simultaneously. Examination of the failure indicated that the crack turned 90° towards the outer skin and came to the foam / carbon fiber interface. It then proceeded along this interface and detached as the peel stopper was designed to promote. Again approximately two layers of carbon were left on the foam.
It was desired to have some mixed mode loading since the actual ship hull will likely be subject to mixed mode loading. Therefore, a beam was mounted to the structure so that it pointed up at 45 degrees. Two bottles were used in this test. The skin peeled and the peel stopper functioned as intended. As with the previous beams the initial crack had been extended to 150 mm in length and slightly into the foam core. In this specimen the crack grew to the outer skin at approximately a 45 degree angle and then proceeded as a delamination until exiting the beam by means of the peel stopper.

The fifth beam tested was fitted with three strain gages with 100 mm between each one. The first one was 100 mm from the leading edge. The peel stopper functioned and the skin was liberated from the beam. The cordage was successful in stopping the skin and bottles before they could damage the acquisition hardware. The data was collected and plotted.

5 PANEL EXPERIMENTS

After these preliminary tests, numerous full scale panel tests were conducted, on various sized panels, and different types of panels. A test was also performed to observe the tendency of a crack to propagate through the core instead of the core skin interface.

5.1 Developing a test setup

The sandwich panels were manufactured with initial delaminations between the top skin and the foam core. A threaded steel plate was embedded in the foam on the opposite side
of the panel from the blister. A hole through the foam connected the blister to the steel plate. A tank of compressed nitrogen was attached to the plate by a long thin hose. The pressure permitted to enter the blister was increased until it became high enough that the blister would grow. One problem with this setup is that the volume of the blister increases as it grows. As a result the pressure in the blister decreases, which would slow or stop the growth. To prevent this from happening an accumulator was attached to the plate, and the nitrogen hose was attached to the accumulator. The percent increase in volume of the accumulator and the blister together changes relatively little when the blister grows if the tank is sufficiently large. As a result, when the pressure reaches a certain level and growth begins, the resulting pressure drop should be so small that the energy release rate would not decrease before the blister grows past the peel stopper.

It is important to know how large the volume of the accumulator should be so that the pressure drop of the system does not cause the energy release rate to become subcritical. In order to estimate the needed tank volume, some simplifications were made. The first was to treat the delaminated area as a round plate. Kirchoff plate theory was also assumed. For simplicity, the plate was treated as isotropic. The boundaries of a blister are not exactly clamped or exactly simply supported. Therefore the calculations for both boundary conditions were found and the actual energy release rate is taken to be somewhere in between the two. The out-of-plane deflection \( w \) of a rotationally symmetric isotropic homogeneous plate of radius \( R \), subjected to an evenly distributed pressure \( p \) is
for a clamped plate and

\[ w^{cc}(r) = \frac{p}{64D} (R^2 - r^2)^2 \]  \hspace{1cm} (1)

for a simply supported plate; \( D = \frac{Eh^3}{12(1-\nu^2)} \), \( r \) is the radial coordinate, \( E \) is Young's modulus and \( \nu \) is Poisson's ratio. The strain energy is

\[ W = \frac{1}{2} \int D_{\alpha\beta\gamma} \kappa_{\alpha\beta} \kappa_{\gamma\delta} dS \]  \hspace{1cm} (3)

where \( \kappa_{\alpha\beta} \) is the curvature tensor and \( D_{\alpha\beta\gamma\delta} \) is the bending stiffness tensor. This leads to

\[ W^{cc} = \frac{p^2 R^6 \pi}{384D} \]  \hspace{1cm} (4)

and

\[ W^{ss} = \frac{(7 + \nu) p^2 R^6 \pi}{(1 + \nu) 384D} \]  \hspace{1cm} (4)

for the clamped and simply supported plates, respectively. Energy release rates are

\[ G^{cc} = \frac{\partial W}{\partial S} = \frac{1}{2\pi R} \frac{\partial W}{\partial R} = \frac{p^2 R^4}{128D} \]  \hspace{1cm} (5)

and
\[ G'' = \frac{(7 + \nu) p^2 R^4}{(1 + \nu) 128 D} \]  \hspace{1cm} (6)

Integrating the deflection produces the volume of the blister,

\[ V_b = k \frac{pR^6 \pi}{192 D} \]  \hspace{1cm} (7)

where \( k = 1 \) for clamped and \( k = \frac{(7 + \nu)}{(1 + \nu)} \) for simply supported boundaries. The total volume of the system is the volume of the accumulator, \( V_a \), plus the volume of the blister, \( V_b \), together. Substituting this into Boyle’s law produces

\[ p \left( V_a + k \frac{pR^6 \pi}{192 D} \right) = p_0 \left( V_a + k \frac{p_0 R_0^6 \pi}{192 D} \right) \]  \hspace{1cm} (8)

where \( R_0 \) is the radius of the initial blister and \( R \) is the radius of the expanded blister. Solving this for pressure and entering it into the equation for energy release rate yields,

\[ G = \frac{\left( 192V_a D - 2\sqrt{9216V_a^2 D^2 + 192 kR^6 \pi p V_a D + k^2 R^6 \pi^2 p^2 R_0^6} \right)^2}{512 kR^8 \pi^2 D} \]  \hspace{1cm} (9)

This energy release rate is a function of the radius of delamination, and accumulator volume. If the tank volume is sufficient then the energy release rate at the radius of the final delamination size should not be lower than the energy release rate at the initial delamination size.
Figure 19 suggests that for a delamination that must travel no more than one meter, a 20 liter tank is sufficient. The energy release rate immediately drops for a delamination without an attached tank as seen in Figure 20.

Figure 21 shows the two accumulators built. Both accumulators have 2 inch NPT thread outlets that mate with the embedded steel plates in the specimens. Attaching two 300 mm pieces of iron pipe into a tee made the smaller accumulator. A coupling on each end allowed for the pressure inlet and for the pressure sensor. On the 20 liter tank a braided pipe was added between the tank and the panel to help protect the tank from shock during the test. A threaded insert was welded to the large tank to receive the pipe. A ¼ inch NPT connection was already present at the safety relief valve. It was used to connect both the pressure inlet and the pressure sensor. To ensure safety, the tank was first pressure tested with water.

5.2 Data acquisition system

In a number of experiments strain gages were used and it was necessary to employ data acquisition software. The program written for collecting data establishes an 80000 sample ring buffer. Each sample is comprised of a scan of each strain gage and one scan of the pressure sensor. The ring buffer collects 15000 samples per second for one second. Then one sample is read and added to a separate array. This process writing to the buffer for one second then adding to the array is continued until the retrieval condition is met. Then the piece of the buffer surrounding the condition is written to one file, and the array of data taken at 1 Hz is written to a separate file. Two plots can then
be generated; one high resolution plot (15000 points per second) of the blister growth, and one lower resolution plot (one point per second) of the entire test.

5.3 Calculation of crack growth speed

As the growing blister travels under each strain gage, a large strain followed by damped oscillations is recorded. The acquisition rate is fast compared to the speed that the blister grows at. Therefore it is assumed that all the gages are acquisitioned simultaneously.

The error for this assumption is on the order of 0.01 m/s if the crack is growing at 15 m/s. The plots for displacement of two strain gages that are separated in distance look similar, but are shifted in time. Since the distance between the gages is known, and the acquisition rate is known, the average speed of the crack between the two gages can be determined. To increase the accuracy in finding this speed, a convolution function defined as \( P(s) = \int f(t) \cdot g(t - s) dt \) is used. This function has a relative maximum at the value corresponding to the time shift between \( f(t) \) and \( g(t) \). The data of two separate strain gages are \( f \) and \( g \). Using the trapezoidal rule to integrate the convolution function a plot for \( P(s) \) was generated. A relative maximum in \( P(s) \) reveals the shift, \( s \), in time between \( f \) and \( g \).

6. EXPERIMENTAL RESULTS

In the following sections the results of the experimental tests are described.

6.1 Results from the Lightweight Foam / Epoxy Panel.

The first peel stopper panel was made from a lightweight H30 foam and glass fiber as described in section 3.3.1. This peel stopping device did not function as intended. The crack oscillated between the two skins as it traveled out as depicted in Figure 22. The
entire accumulator emptied into the panel filling it like a balloon without opening the peel stopper or the side of the panel. This behavior was not seen in any other tests. The test is not considered to be representative of a ship hull. It was done to provide insight into possible testing and manufacturing issues. The test hinted that a crack may oscillate between two skins in a sandwich.

6.2 Results from the 780 mm Panel

A more representative panel was produced next using H200 foam from Diab. Four panel joint/peel stoppers were arranged in such a way to surround the initial blister as described in section 3.3.2. The panel was tested with the 2 liter accumulator. The accumulator had a ½ inch outlet. After this test, a 2 inch outlet was always used to permit a larger flow rate into the panel to assure a more dynamic growth. The panel failed at a pressure of approximately 0.62MPa. The skin separated from the foam throughout the inner panel piece. When the crack reached the peel stopper, it successfully stopped the delamination. Cutting cross sections from the panel with an abrasive waterjet cutter confirmed the success of the peel stopper.

6.3 Results from the 900 mm Panel

The next panel tested was also more representative of an actual ship hull. Diab’s more ductile HD250 foam was used. Two strain gages were used on this panel. Each one was located 100 mm from the center of the panel and on opposite sides of the blister. The peel stopper functioned as intended in this experiment. The crack grew in the intended
direction and the panel was again cut up to confirm the success. The Strain gages slipped or broke during the experiment.

6.4 Results from the 500 mm Panel

There were two purposes of this test. The first was to ensure that the newly written acquisition program was working correctly and collecting data when the retrieval conditions were met. The second purpose, was to see if it was possible to “sabotage” the test. Concerns have been expressed that this type of peel stopper may be ineffective if the crack kinks down into the core, because it could travel under the peel stopper and continue to grow. In this test the delamination was forced to begin its growth down in the core in hopes that its growth would provide some evidence as to how readily the crack would tend to kink down from the skin and continue growing in the core.

The iron pipe accumulator with the 2 inch outlet was used. This panel was made from HD250 foam and the initial blister extended down to the half thickness of the foam. Six strain gages were placed on the panel. The settings for the strain gages were 5V excitation, quarter bridge. A 10 Hz filter was applied. The pressure sensor was used with a 4 Hz filter. In this test, and all subsequent tests the strain gages were affixed with epoxy adhesive. A piece of cloth was taped over the gages to protect them.

Initial loading of pressure into the panel caused the values of strain gages 1, 2 and 3 to change indicating that they were too close to the initial blister. Strain gage four was made the trigger as a result and the number of pretrigger scans was increased to 7500
(half the data before the trigger and half the data after the trigger). The trigger level was set to be rising and very slightly higher than the average value that the strain gage four read in its resting state. The pressure was increased to 1.03 MPa (150 psi) twice with no event. The third time the panel was brought to this pressure and held there. After 15 seconds a few slight pings were heard. Five seconds later a loud boom followed and the air rushed from the accumulator. The conditional retrieval worked and both files were produced.

Several visual observations were made after recovering the panel. Strain gages 1 and 3 had blown leads. This was expected to happen. Strain gage four was loose from its glue. Roughly half of the panel, in the direction of strain gage three and strain gage six was debonded with a 10 mm gap between the carbon fiber and the foam. Visual observation also revealed that the crack beginning in the foam immediately climbed to the skin at about a 45 degree angle and then continued along the foam/skin interface as the other panels did. This reinforced the Beam test data that suggested that there is no tendency for the crack to kink down into the foam.

6.5 Results from the 2000 mm Panel

The panel was filled with air up to roughly 1.03 MPa (150 psi) several times and held there. After several iterations the pressure was brought as high as 121 MPa (175 psi). The panel was unwrapped and the accumulator was removed. A wooden dowel was placed in the hole against the top skin and beat repeatedly with a hammer. No cracks were heard, but some movement was felt and the accumulator was reattached and the
panel was rewrapped. The test then continued and the panel failed at 1.16 MPa (168 psi) with a loud boom. The trigger was realized and the two files were recovered. Strain gages 16 and 12 failed to return any data. It appeared that they failed just prior to the test. The panel failed in the direction of strain gages 9-12. The crack speed was determined to be about 10.5 m/s when it encountered the peel stopper.

6.6 Results from the 1360 mm Panel
The regulator was set to deliver 1.03 MPa (150 psi). Near a 130 psi, a loud boom was heard. The peel stopper functioned as intended. The trigger level for the strain gage, however was too aggressive, and the program triggered acquisition before the crack growth. No useful strain gage data could be recovered.

6.7 Summary of Panel Test Results
In all carbon fiber panel tests, the peel stopper functioned as intended. None of the tests revealed a tendency of the crack to kink into the core. In the case of the 500 mm panel, the crack that was forced to begin growing at the half thickness of the panel, grew at a 45 degree angle up to the outer skin / foam interface, then continued the same way as the other panels. Cutting up the tested panels revealed sections of the debonded area that had some foam on the detached skin. However, it was never more than 5 mm thick. While the test of the lightweight foam / epoxy sandwich did exhibit the crack growing through the foam, the panel was not considered representative of the peel stopper system used in ships.
The 2000 mm panel test results seemed to suggest that the crack speed decreased as the blister radius increased. This is suspected to be caused by the fact that, although the accumulator was sufficiently large, the nitrogen was forced to flow through the crack between the foam and the skin. This may have reduced the flow rate of nitrogen into the panel and slowed the crack growth. The speed of blister growth seemed to increase in the intended direction and decrease in the other directions as the blister grew. The reason for this can only be speculated upon at this point, but the geometry of the fish delamination is suspected to be the cause of this. The exit speed of the crack in the large panel was about 10.5 m/s. However, the velocity of the crack in the peel stopper beam was 129 m/s. At both of these speeds, the peel stopper was effective.

It was very common to see about two layers of the detached skin left bonded to the core. In some cases it seemed that for large fractions of the panel the crack grew as delamination rather than interfacial debonding. In the beam tests, the crack was invited to begin its growth either in the foam or at the interface between the foam and carbon. In every case it quickly moved into the outer skin and grew as a delamination. In the cases of the 780 mm and 900 mm panels, the cracks grew in the foam very close to the interface until it came within roughly 30 mm of the peel stopper, whereupon it moved into the skin and grew as a delamination. In the two largest panels, the cracks grew at the interface, in the foam, or as delamination in different sections. Near the peel stopper in the 2000 mm panel, there was always delamination failure, however. In the 1360 mm
panel, the crack did grow into the peel stopper as interface debonding. However, in this region the skin was also delaminated.

Another trend that seems important was that there seemed to be no tendency for the crack to kink into the core. The lengthened initial cracks all extended into the foam by varied amounts. In all those cases the crack grew to the foam composite interface immediately, then continued. Also with a more Mode II conducive geometry, and the case when the initial crack extended deeply into the foam, the crack grew to the interface immediately.

ACKNOWLEDGEMENT

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Dr. Grenestedt is an Associate Professor in the Department of Mechanical Engineering and Mechanics at Lehigh University since 2000. He developed the Lehigh Composites Lab, currently employing seven fulltime researchers working on projects ranging from composite ship structures to printed circuit boards. He has held positions at the Royal Institute of Technology (Sweden), Ancos Ltd. (Sweden), Japan National Aerospace Laboratory (Japan), and Brown Boveri Research Center (Switzerland). He received his education from the Royal Institute of Technology and KyotoUniversity (Japan). Grenestedt was deeply involved in the development of the 72 meter all-carbon fiber stealth ship Visby.
FIGURE CAPTIONS

**Figure 1.** *Top:* basic peel stopper cross section. *Bottom:* intended function of peel stopper.

**Figure 2.** Possible failure scenarios. *A)* growing blister. *B)* properly functioning peelstopper. *C)* crack kinking into the foam. *D)* waves continuing the blister through the peel stopper.

**Figure 3.** Test setup. A nitrogen tank filled the accumulator. When the accumulator pressure became high enough dynamic growth of the initial delamination resulted. A pressure sensor and strain gages were attached and connected to data acquisition equipment.

**Figure 4.** Panel for the beam peel tests prior to infusion. An infusion hose was part of the layup and allowed both skins to be infused at the same time.

**Figure 5.** *A.* The outer skin side as the infusion begins with only the bottom vacuum source active. *B.* As the resin reaches the bottom of the front side the lower spiral wrap will be opened. *C.* The lower spiral wrap is open and the resin is being drawn up the backside.

**Figure 6.** *Top:* The foam is cut and shaped with a center piece surrounded by four peel stoppers. An initial delamination was centered and pointed at the long peelstopper. *A*
hole through the foam is under the delamination. *Middle:* Each piece is separately infused with each layer staggered in length. *Bottom:* The pieces are puttied together and a final infusion connects all the skins.

**Figure 7.** Diagram and picture of the 500mm panel with the initial blister that extends into the foam.

**Figure 8.** The 2000 mm panel. The dark lines represent where foam had to be joined with putty to achieve the desired dimensions.

**Figure 9.** The corner where two peel stopper foams meet creates an issue with flatness. Foams B and A both have peel stoppers milled into them as seen in the profile views. The initial blister is in piece C. No skin is on piece A in this diagram to illustrate the flatness issue. The puttied joint between A and C has a height difference of 5 layers. Since the skin is five layers thick, joint A/C will be flat when the skin is added. Joint A/B is already flat as seen at the top of the diagram. The taper in A from the peel stopper causes an increasing height difference towards C. The skin for A must be added in a special way for the panel to be flat in this region. with C.

**Figure 10.** The left column is a picture of each layer. The middle column is a diagram of each layer added. The right column is the contour plot after each layer is added. In order for the panel to be flat the height on each side of a puttied joint must be the same.
Although the diagram shows a sharp corner, a 35mm radius was used on each layer as seen in the picture.

**Figure 11.** Image of the overlapping to improve the flatness of the panel.

**Figure 12.** For the panel to be flat each layer of the scarf joint must connect layers of equal height. Two scarves were placed and infused at the same time.

**Figure 13.** Strain gage arrangement for the 2000mm panel. Strain gages 1 through 8 are connected to one terminal block. While 9 through 16 were connected to another. The bold numbers indicate the average speed in m/s of the crack growth between the strain gages.

**Figure 14.** A foam plug was placed in the trough of the 1360mm panel to promote flatness.

**Figure 15.** Dimensions of the proposed delamination shapes.

**Figure 16.** Some of the resulting delaminations that occurred while testing proposed shapes.

**Figure 17.** The final geometry used as an initial delamination.
Figure 18. The top image shows the basic test set up of the peel stopper beams. The outer skin is facing down. The bottom image shows the beam results. Beams 2, 3, and 4 had their initial cracks extended with beam 3 having its crack begin deeply in the foam. In all cases, the crack quickly grew to the foam skin interface and reached the peel stopper as a delamination.

Figure 19. With the 2 liter tank, the energy release rate after propagating one meter, is relatively close to the initial energy release rate. The 20 liter tank maintains a higher energy release rate after the blister has traveled on meter. Constants used for these graphs were $P_0=1$ MPa, $r_0=0.05$ m, $D=80$ Nm $k=1$ for clamped boundaries and $k=5.62$ for simply supported boundaries.

Figure 20. When no accumulator is present, the energy release rate decreases quickly as the delamination grows.

Figure 21. Left. A 2 liter accumulator built from iron pipe. Right. A 20 liter accumulator built from a compressed air tank and a steel and Teflon braided hose.

Figure 22. The H30/ epoxy panel delaminated in the foam, with the delamination oscillating between the skins.
Figure 1.
Figure 2.
Figure 3.
Figure 4.
Figure 4.
Figure 5.
A. Outer skin
B. Outer skin
C. Inner skin

Figure 5.
Figure 6.

<table>
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All measurements in mm
Figure 7.
Figure 7.
Figure 8.
Figure 9.
Figure 10.
Figure 11.
first scarf diagram

second scarf diagram

first scarf contour

second scarf contour

Figure 12.
Figure 13.
Figure 15.
Figure 16.
Figure 16.
Figure 17.
Figure 18.
Energy release rate for a 20 liter tank

Energy release rate for a 2 liter tank

Figure 19.
Energy release rate for no tank

Figure 20.
Figure 21.
Figure 22.
Comparison of Mechanical Properties of
Glass Fiber / Vinyl Ester and Carbon Fiber / Vinyl Ester.

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Abstract

Specimens of glass fiber composite and carbon fiber composite each with vinyl ester matrix were prepared. The strengths of the specimens in tension, compression, open hole tension, open hole compression, transverse tension, and slow impact were compared. Carbon fiber composite proved superior in all categories except for transverse tension and compression. Additionally the two were found to be equal in open hole compression.

Keywords: A. Carbon Fiber: A. Glass Fiber: B. Mechanical Properties: B. Strength

Introduction

The Swedish Navy has chosen to use carbon fibers for their advanced surface combatant Visby, whereas the US Navy has selected to use glass fiber for their structures. Both Navies base their choices of materials on cost and performance data, but their conclusions differ. For aerospace structures, it is clear that carbon fiber is “better” than glass fiber from a performance standpoint since superfluous weight is very costly. In the case of
ships, the requirements are quite different and the structures are not as sensitive to excess weight. The manufacturing of ships cannot, due to cost, be as meticulous. It also does not need to be because the damage tolerance requirements are so high. That is, if a ship is designed to withstand holes shot into it that are meters wide, then many types of manufacturing flaws are benign by comparison. Typically each layer of a ship's composite is an order of magnitude thicker than that of aerospace prepregs. The most economical choice of material depends on the costs of material, production cost, and life cycle cost. Weight savings and performance, naturally, also play a major factor in the choice of materials.

The purpose of the present project is to make a comparison between a glass and a carbon fiber system suitable for use in large ship structures. The mechanical properties of vacuum infused E glass / vinyl ester have been investigated [1,2]. The sizing of the carbon fiber has a very significant effect on the properties [3,4,5,6]. The carbon fiber used for these tests was Torayca's vinyl ester sized T700SC-12K-F0E fiber. This fiber was compared to DB800-E06 HD made with Owens Corning 111A glass fibers. Dow Derakane 8084 vinyl ester resin was employed for all specimens. Both the glass and carbon fiber reinforcements were obtained from Devold AMT in the DB arrangement (-45,+45).

Damage tolerance is important for composite ships. Therefore for this comparison the slow impact test, a simple impact and handling strength test, was employed. The other tests are standard coupon tests. The results from coupon tests may be scalable to full size
The results from tension, compression, open hole tension, open hole compression, transverse tension, and slow impact were compared. All specimens were produced by means of vacuum infusion and cut with a CNC abrasive waterjet cutter. Measures were taken to limit or eliminate the amount of delamination associated with the cutting. All the specimens were all cut on a 45 degree bias so that the layup was [0,90]₃s. A few slow impact specimens had a [0,90]₄s layup. The thickness of the carbon specimens was 2.7 mm. The thickness of the glass specimens was 3.4 mm.

**Tensile Strength Comparison**

The tensile experiments were performed according to ASTM D 3039/D 3039M –95a. The specimens had end tabs that were produced from glass fiber reinforced vinyl ester with the layup [±45]₅. The tests were performed on a Baldwin 270 kN (60 kip) hydraulic test machine. The carbon fiber specimens typically failed with a clean lateral break. The glass fiber specimens typically saw damage sprawling over the entire specimen. The majority of the specimens had splayed out into small bundles of fibers. Examples of typical failure of these specimens can be seen in Figure 1. The specimen dimensions were 25.4 mm wide and 250 mm long. The results of one carbon specimen and three glass specimens were invalidated because the adhesive between the tab and the specimen failed causing the specimen to slip out. The results of 10 carbon fiber specimens and 8 glass fiber specimens were averaged. Failure stress was calculated by dividing the failure load by the cross sectional area of the original specimen. The average failure stress with one standard deviation is 958.0 ± 109.3 MPa for the carbon fiber and 544.4 ± 10.6 MPa.
for the glass fiber specimens. The carbon specimens saw several different failure modes. This may be partially to blame for the larger standard deviation.

**Compression Strength Comparison**

The compression experiments followed ASTM D 6641 - 01. Wyoming Test Fixtures WTF-EL-29 was used. The testing was carried out on a 44kN (10 Kip) screw driven MTI modified Instron universal test machine. The specimens were 12 mm wide by 140 mm long. The crosshead speed was 1.3 mm / min. An average of 10 carbon fiber and 11 glass fiber specimens was measured. Examples of failed specimens can be seen in Figure 2. The failure stress was calculated by taking the failure load and dividing by the cross sectional area. The average failure stress with one standard deviation was 328.0 ± 37.9 MPa for the carbon fiber and 396.2 ± 20.3 MPa for the glass fiber.

**Open Hole Tensile Strength Comparison (OHT)**

The open hole tensile experiments were performed according to ASTM D 5766/D 5766M -95 on the Baldwin machine. The specimens were 250 mm long and 38 mm wide. There was a 6 mm diameter hole in the middle of each specimen. The results of 11 carbon fiber and 8 glass fiber specimens were averaged. Examples of the failures can be seen in Figure 3. As with the Tensile tests the Glass fiber composite specimens typically splintered apart splaying out the fibers. This was seen to a lesser extent in the carbon fiber specimens. A clean lateral break was also seen in some specimens. The average failure stress was found by taking the failure load and dividing by the cross sectional
The area of the hole was not subtracted from the cross sectional area. The average stress with one standard deviation was $621.2 \pm 39.9$ MPa for the carbon fiber and $367.4 \pm 13.6$ MPa for the glass fiber.

**Open Hole Compression Strength Comparison (OHC)**

The open hole compression experiments were conducted according to the Northrop Grumman standard for 1.5 inch open hole compression. Although an ASTM standard exists for the Boing open hole compression test, the Northrop test was used because it has been shown to produce more consistent data [8]. The results cannot, however, be directly compared to those of the Boing test. The specimens for the Northrop test were 38.1 mm (1.5 inch) wide and 76.2 mm long. There was a 6 mm hole in the middle of each specimen. The waterjet cutter that was used for all cutting in these tests had a tendency to cause local delamination when piercing a center hole in a specimen. In the case of open hole compression this delamination could significantly affect the strength. Therefore a fixture was produced such that the hole could be produced in a lathe by means of orbital drilling (Figure 4) [9]. A hollow 1 inch tube was welded to a $\frac{1}{4}$ inch plate and gripped in the chuck. A fixture was welded to allow a high speed rotary tool to be attached to the lathe carriage. A straight cutting ball end carbide bit was used. The lathe was run at medium speed and the rotary tool was run at its highest speed (~30,000 rpm). The automatic feed for the carriage was used to bring the tool into the spinning specimen. The offset was adjusted to get the desired hole size. All the holes were to size within 0.025 mm and within round to the same tolerance.
Wyoming Test Fixtures WTF-NH-11 was used with the Instron test machine for these tests. 10 carbon fiber and 9 glass fiber specimens were tested and averaged. A crosshead speed of 1mm / min was used. The failed specimens all had a clean lateral break through the middle as seen in Figure [5]. The average stress for the samples was calculated by using the cross sectional area (not subtracting the hole’s area). The results were 234.6 ± 18.0 MPa for the carbon fiber specimens and 238.9 ± 14.2 MPa for glass fiber.

Transverse Tensile Strength Comparison

The transverse tensile tests were performed according to ASTM C 297-94. The standard was designed to address the transverse tensile strength of sandwich structure composites. However, it has proven suitable for testing composite plates as well. Square specimens that were 35mm on a side were used. The squares were sanded and cleaned with trichloroethylene. Locktite Hysol 9430 epoxy based adhesive was used to bond the specimens to the blocks. After applying the adhesive to each face, each pair of blocks was squared on an aluminum angle block. They were clamped long ways lightly and then clamped to the aluminum block to ensure everything remained square. The adhesive was allowed to cure for five days. A crosshead speed of 0.5 mm / min was used. The failure for the glass fiber specimens was primarily interlaminer, but there were occasional intralaminar failures. Both interlaminar and intralaminar failures were common in the carbon fiber specimens. Examples of some failed transverse tensile specimens can be seen in Figure 6. Eight specimens of each were tested and the failure stress for the glass fiber specimens was 17.79 ± 1.0 MPa for the carbon fiber and 23.6 ± 1.9 MPa for the glass fiber.
Slow Impact Strength Comparison

A slow impact test was developed by Grenestedt and Kuttenkeuler [10] to simulate the performance of composites against a variety of impacts including dropped tools, harbor touches, and collisions with floating debris. An 18 mm diameter steel ball was used to simulate the impact. A crosshead speed of 1.3 mm / min was used. The specimens for this experiment were foam core sandwich panels. The same lay up was employed, but the plates were infused onto 50 mm thick Divinicell H200 foam cores from Diab. During testing the panels were supported on a solid base. There was a hole in the base directly under the impact area to receive the ball when it exited the other side. However the peak force was achieved before half of the ball was below the skin. At the maximum load the skin failed and the load dropped. This load remained constant as the tip was pushed through the panel. In addition to the same lay up between carbon and glass fiber, it was desired to compare the same skin thickness between the two. Therefore, carbon specimens that were 8 layers thick with the lay up [0,90]_4s were also tested. In order to compare the slow impact results to ballistic data, slow impact data was also collected with a 5.58 (0.22 inch) mm diameter hardened steel rod.

Examples of the damage caused by the slow impact test can be seen in Figure 7. The hardened steel rod caused some surface cracking and a sharp lip. During the test, the rod pushed an indentation about 2 cm wide down until the failure load was reached. A loud pop was heard as the rod punched through the skin. In the case of the 18 mm ball, the damaged area and cracking was larger. There was a pop at the failure load, but damage
seemed to occur steadily throughout the test rather than with a sudden pierce. The edge of the fractured area was not as sharp.

**Summary and Conclusions**

These tests investigated the mechanical properties of two composite materials. The results were directly compared. The standard deviation in these tests was acceptable and each experiment was considered a success. Tables 1 and 2 summarize the results of all tests. Figure 8 shows the comparison results for this study. Each bar is the average failure stress of the carbon specimens divided by the average failure stress of the corresponding glass fiber specimens. In the case of the slow impact tests, the failure loads were used. One notable result from these tests is that carbon fiber did not provide an advantage over glass fiber in tests of compressive strength. Another notable result is that carbon fiber showed an increased advantage for a blunter tip in the slow impact tests.

**Acknowledgment**

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**References**


**Figure Captions**

**Table 1.** Average failure stress for carbon fiber and glass fiber reported in MPa with the standard deviation underneath. The percent row is the percent of the average represented by the standard deviation. Number tested, is the number of specimens in the sample. The bottom row is the ratio of carbon failure stress to glass fiber failure stress.

**Table 2.** Results for the slow impact test. The first line is the number of specimens tested. The second line is the average of the data points. The third line is one standard deviation of the collected data.

**Figure 1.** Failed tensile specimens. The carbon specimens typically failed laterally. The glass specimens typically failed with a sudden splaying of the fibers and emitted a cloud of glass fiber dust.
Figure 2. Results from the compression test. *Left.* Carbon fiber. *Right.* Glass fiber.

Figure 3. Open hole tensile results. The splaying of tows can be seen in both carbon fiber and glass fiber specimens. The carbon fiber specimens also exhibited lateral failure at the hole.

Figure 4. The specimen is between two steel plates and in the chuck. A fixture was made to tightly grip a high speed rotary tool and attach to the carriage.

Figure 5. Open hole compression specimens. Top: Glass specimens have apparent lateral cracks with some delamination. Bottom. The lateral cracks in the carbon fiber are present although more difficult to see.

Figure 6. Examples of failed transverse tensile specimens. Note the presence of both interlaminar and intralaminar delaminations. *Left.* carbon fiber. *Right.* glass fiber.

Figure 7. *Left.* Damage caused to the glass fiber sandwich with the 5.58 hardened steel rod. The light area is delamination. In these tests cracks transverse and parallel to the fiber directions were common. *Right.* Damaged caused by pushing the 18 mm steel ball through the entire sandwich glass fiber sandwich.
Figure 8. The failure stress of carbon fiber divided by the failure stress of glass fiber. In the slow impact tests the failure load was used instead of stress. OHT and OHC are open hole tension and open hole compression respectively.
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Table 1.
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Table 2.
Figure 1.
Figure 2.
Figure 3.
Figure 4.
Figure 7.
Comparison Results

Figure 8.
Environmentally Preconditioning Fibers
to Increase Composite Strength.

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Abstract
In this study the relationship between the effect of environmental conditions of dry fibers and the transverse tensile strength of the composite plates that are made from them was examined. The system used was carbon fiber / vinyl ester. Different specimens of dry fibers were exposed to various conditions including ambient, heat, vacuum, heat and vacuum, and heat and humidity. After the environmental preconditioning, these dry fibers were then made into composite plates. After storing the plates for one year, the adhesive strength between the matrix and the fibers was tested. The highest interfacial strength resulted when the fibers had been exposed to heat and vacuum before being made into composites.

Introduction
It is well known that exposure to moisture has a significant and adverse effect on the transverse tensile strength of composite materials [1,2,3,4]. However an investigation of how the environment seen by the dry fibers affects the transverse tensile strength of the
composite made from the fibers has not been seen. In general, accommodations are not
taken with respect to the environmental treatment of dry fibers. However, it is the aim of
this study to show that these conditions do have an effect on the transverse tensile
properties. This research is significant because the transverse strength of carbon fiber
composite is frequently a limitation. Any measures that can be taken to increase this
strength is valuable. Some preliminary work was done that seemed to indicate that
exposure to vacuum or heat prior to infusion caused a higher transverse tensile strength
than fibers that were exposed to room temperatures and atmospheric pressures. The
preliminary study also indicated that exposure to both heat and vacuum caused the
highest transverse tensile strength. This paper attempts to verify the preliminary results
by examining a larger sample and testing it more meticulously. In addition a sample of
specimens was prepared that saw both increased heat and very high relative humidity.
This sample was prepared to simulate the sultry conditions of the Mexican Gulf coast.

Test setup

The fibers were Torayca T700SC-12K-F0E. They were obtained from Devold AMT in
the DB 450 – C06 (424 g/m²) arrangement [-45, +45]. The lay up was [-45, +45]₄. The
resin used was Dow Derakane 8084 vinyl ester with 1.5% MEKP, 0.3 CoNap, and 0.03%
DMA. The fibers that were to be used for the composite were each exposed to different
environmental conditions for 240 hours before they were infused. All specimens were
prepared simultaneously. Fibers to produce five plates were prepared.
Fiber set one saw ambient conditions. The fibers were placed between two peel plies and placed on a shelf (23°C) for 240 hours.

Fiber set two was subjected to heat only. The temperature was slowly raised to 105°C, but then lowered to 84°C. The total time above 100°C was approx. 10 hours. The fabrics were held in the oven for 240 hours. Fiber set two was between two peel plies.

Fiber set three was exposed to vacuum only. The fibers were placed between peel plies and vacuum bagged to a mould. The temperature was room temperature (23°C). A 90% vacuum was pulled for 240 hours.

Fiber set four was exposed to heat and vacuum. The specimen was vacuum bagged and placed in the same oven at the same time as fiber set two. It saw the same temperature profile as fiber set two. The vacuum was from the same source and at the same time as the fiber set three vacuum (90%).

Fiber set five was conditioned with heat and humidity. The fibers were placed on top of a breather and a peel ply in an environmental chamber. The temperature was 35°C and the relative humidity was 90% for 240 hours.

After the 240 hours had elapsed all of the specimens were removed from their conditions and vacuum bagged under the same bag as quickly as possible. The fibers were all immediately infused with the 8084 vinyl ester resin and permitted to cure fully.
curing, the peel ply was left on each composite plate and they were placed together in ambient conditions for one year.

Testing followed ASTM C 297 - 94. After one year had elapsed, the specimens were cut into 35mm squares with an abrasive CNC waterjet cutter. The squares were all kept in jars of desiccant until mounting prior to testing. The squares were then sanded and cleaned with trichloroethylene. They were then glued to steel blocks with Locktite Hysol 9430 epoxy based adhesive. After applying the glue to each face the blocks were squared in an aluminum angle block. They were clamped long ways lightly and then clamped to the angle block to ensure everything remained square. The glue was allowed to cure for 5 days. The specimens were then tested using a MTI modified Instron screw driven universal test machine. The crosshead speed was 0.508 mm / min. The specimens were prepared and tested in groups of ten (two from each environmental condition) until 110 specimens, 22 of each condition, had been tested. Both interlaminar and intralaminar failures were common. Examples of failed specimens can be seen in Figure 1.

**Conclusions and Discussion**

The results from testing 22 of each set of conditions can be seen in table 1. Statistically, the results may not be conclusive. One standard deviation of any average strength is within one standard deviation of any other average strength. Transverse tensile strength has been shown to be very highly influenced by edge effects [5]. After about 10 to 12 specimens the standard deviation for each average began changing by small amounts with each new test. This seemed to reveal that either the specimens themselves had a
consistent amount of scatter, or the limitations of the equipment and test were beginning to present themselves. While the results after 22 specimens are not statistically distinct, they do support the preliminary findings that applying heat and vacuum to dry fibers prior to infusion increases the transverse tensile strength of the composite. It may be added in closing that preliminary calorimetry experiments were performed. However, as of present there are no conclusive results from these tests.

Acknowledgements

This material is based upon work supported in part by the National Science Foundation and in part by the Department of Mechanical Engineering and Mechanics, Lehigh University. Stephen Antalics is acknowledged for preliminary calorimetry investigations.

References


Figures

Table 1. The first row is the average failure stress. The second row is one standard deviation of the data. The third row is what percent of the average is represented by the standard deviation

Figure 1. Examples of failed specimens. 1: vacuum only. 2: ambient. 3: heat and vacuum. 4: hot and humid. 5: heat only.
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</table>

Table 1.
Figure 1.
Figure 1.
Vita

Christopher Thomas Wonderly was born to Thomas and Marcia Wonderly, December 13, 1978 in Erie, Pennsylvania. He attended Klein Elementary School in Erie, Pennsylvania Wilson Middle School in Plano, Texas, Vines High School in Plano, Texas, and graduated from Dixie Heights High School in Crestview Hills, Kentucky in 1997. He attended the University of Kentucky where he obtained a B.S. in Materials Science and Engineering with a minor in Mathematics in May 2001. During his studies he received the Jerry L. Mercer Scholarship, was inducted into The Alpha Sigma Mu Honorary Materials Science Fraternity and was also presented with The Outstanding Senior in Materials Science award. He began work for his Master of Science in August 2001 in the composites lab at Lehigh University. While there he received the Textile Veteran's Award and a Hybrid fellowship.