DYNAMIC TESTING OF CARBON FIBER SKIN / FOAM CORE SANDWICH PANELS WITH PEEL STOPPERS

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Nonmagnetic Stainless Steel for Double Hull Ship Construction

by

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ABSTRACT

The research under this program concentrated on dynamic testing of relatively large carbon fiber skin / foam core sandwich panels with peel-stoppers. Devices known as peel stoppers were manufactured in composite sandwich panels and tested under dynamic conditions. Peel stoppers aim to arrest peeling, or debonding, of the composite skin from the core in composite sandwich ship hulls. The present work addressed the effectiveness of the peel stopper when faced with dynamic peeling of the skin. Several ship panels were produced and tested. Some tests to investigate whether the debonding could behave in a way that could defeat the peel stopper were also performed. Various issues surrounding the manufacture of the devices were addressed. Original contributions include the manufacturing procedure of sandwich panels with multiple peel stoppers, the testing of panels (as opposed to beams) containing peel stoppers, and dynamic testing of peel stoppers.

Results from this investigation appear in two publications, the latter being essentially equivalent to this report:


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 disadvantage of sandwich structures is that they can become susceptible to debonding at or near the interface between the foam and the skin. There are FRP ships which have lost large areas of their outer skin laminates due to peeling that started from rather small damages in the bow regions. The mechanism is believed to be that seawater gets between the sandwich core and the damaged outer skin and thus forms a blister. The pressure in these blisters can be on the order of the stagnation pressure of the water relative to the hull. The blisters may initially grow slowly in fatigue, until reaching a size sufficient for unstable growth.

To localize peeling damage in sandwich structures, a device known as peel stopper [6,7,8] was designed. Quasi-static tests with beams have shown its mechanical properties, and suggested that it is effective. To the best of the authors' knowledge, there are no published reports on dynamic peeling in panels containing peel stoppers. 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. Debonding of the skin is manifested as a blister filled with seawater between the skin and the core. In principle, the peel stopper device consists of 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 that the crack may begin growing in the foam instead of at the skin / foam interface. This could naturally occur also under quasi-static conditions, although in [8] this never happened. 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
The manufacturing of the specimens associated with each test is discussed in this section. The skins where joined near the peel stoppers by what essentially amounts to a scarf joint using the same procedure as in [8]. The joint was manufactured concurrently with the skins by vacuum infusion of the vinyl ester resin. Such joints have been shown experimentally to be almost as strong as continuous skins, e.g. [8].

3.1 Manufacture of Delamination Shape Specimens (Test set 1)
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°)₃,
(±45°,0), delamination and steel plate, (0,±45°), (±45°,0) 2. The plates measured 600mm x 500mm. The steel plate had a ¼ inch NPT threaded through-hole 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 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 referred 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 DBLT 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), DBLT(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), DBLT(90° up), DBLT(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 that 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 Manufacture of Panels

3.3.1 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 0.55m x 0.6m. 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.

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3.3.2 780 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 jointed 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.

3.3.3 900 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.

3.3.4 500 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 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 were 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 was necessary so that the stress they carry through one layer was 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 that 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 abuts. 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 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 not to fail 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. 16 strain gages were again attached to the panel in the same general arrangement as with 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 have been virtually any shape. For a round delamination, the test would most likely have caused the delamination to initially grow as concentric circles. It would eventually have left 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 purpose of this shape was to promote delamination growth in the direction of the "straw" However, this did not occur as seen in Figure 16.

4.1.3 The zipper. The delamination from this shape grew only partially in the intended direction as seen in Figure 16.

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 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. 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. Data were collected and plotted.

5 PANEL EXPERIMENTS
After the 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 was that the volume of the blister increased as it grew. As a result the pressure in the blister decreased, which slowed or stopped 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, and the plate was treated as isotropic. The boundaries of a blister are not exactly clamped or exactly simply supported. Therefore calculations for both boundary conditions were made and the actual energy release rate was taken to be somewhere 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

\[
w^{\infty}(r) = \frac{p}{64D} \left( R^2 - r^2 \right)^2
\]

for a clamped plate and

\[
w^{\infty} = \frac{p\left( R^2 - r^2 \right)}{64D} \left( 5 + \frac{\nu}{1 + \nu} R^2 - r^2 \right)
\]

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

\[
W = \frac{1}{2} \int D_{a\beta\gamma\delta} \kappa_{a\beta} \kappa_{\gamma\delta} ds
\]

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

\[
W = k \frac{p^2 R^4 \pi}{384D}
\]

where \( k=1 \) for clamped and \( k=(7+\nu)/(1+\nu) \) for simply supported boundaries. The energy release rate is

\[
G^{\infty} = \frac{\partial W}{\partial S} = \frac{1}{2\pi R} \frac{\partial W}{\partial R} = k \frac{p^2 R^4}{128D}
\]

Integrating the deflection produces the volume of the blister,

\[
V_b = k \frac{pR^6 \pi}{192D}
\]
The total volume of the system is the volume of the accumulator, $V_a$, plus the volume of the blister, $V$. Substituting this into Boyle’s law produces

$$pV_a + k{pR_0^6\pi\over 192D} = p_0\left(V_a + k{pR_0^6\pi\over 192D}\right)$$

(7)

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,

$$G = \frac{\left(192V_aD - 2\sqrt{9216V_a^2D^2 + 192kR_0^6\pi p_0V_aD + k^2R_0^6\pi^2 p_0^2R_0^6}\right)^2}{512kR^8\pi^2D}$$

(8)

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 \( \frac{1}{4} \) inch NPT connection already present at the safety relief valve 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
Strain gages were used in a number of experiments, and it was necessary to employ data acquisition software. The program written for collecting data establishes an 80,000-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 15,000 samples per second for one second. Then, one sample is read and added to a separate array. This process of writing to the buffer for one second then adding to the array was continued until the retrieval condition was met. Then the piece of the buffer surrounding the condition was written to one file, and the array of data taken at 1 Hz was written to a separate file. Two plots were then generated; one high resolution plot (15,000 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 traveled under each strain gage, a large strain followed by damped oscillations was recorded. The acquisition rate was fast compared to the speed at which the blister grew. Therefore, it was assumed that all the gages were acquisitioned simultaneously. The error for this assumption is on the order of 0.01 m/s if the crack is growing at 15m/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 $P(s) = \int f(t) \cdot g(t - s) dt$ was 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 $P(s)$ revealed the shift, $s$, in time between $f$ and $g$.

6. EXPERIMENTAL RESULTS

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 test. 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, the peel stopper successfully arrested 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 with a quarter bridge. A 10 Hz filter was applied. The pressure sensor was used with a 4 Hz filter. In this 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 gages three and 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 1.21 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 about 10.5 m/s when the peel stopper was encountered.

6.6 Results from the 1360 mm Panel
The regulator was set to deliver 1.03 MPa (150 psi). Near 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.

7 SUMMARY
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 conducive Mode II geometry, and the case when the initial crack extended deeply into the foam, the crack grew to the interface immediately.
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REFERENCES
Figure 1. *Top:* basic peel stopper cross section. *Lower:* intended function of peel stopper.
Figure 2. Possible failure scenarios.

A) growing blister. B) properly functioning peel stopper.
C) crack kinking into foam.
D) waves continuing the blister through 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. The attached pressure sensor and strain gages were 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 infusion begins with only bottom vacuum source active.  
B. As the resin reaches the bottom of the front side the lower spiral wrap is opened.  
C. The lower spiral wrap is open and the resin is being drawn up the backside.
Panel | A | B | C
---|---|---|---
780 | 780 | 190 | 400
900 | 900 | 200 | 500
1360 | 1360 | 320 | 720
2000 | 2000 | 320 | 1360

All measurements in mm

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 peel stopper. 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 500mm panel with initial blister that extends into foam.
Figure 8. The 2000 mm panel with dark lines representing where foam had to be joined with putty to achieve desired dimensions.

Figure 9. The corner where two peel stopper foams meet creates an issue with flatness. Foams B and A 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.
Figure 10. Left column is a picture of each layer. Middle column is a diagram of each layer added. Right column is the contour plot after each layer is added. For the panel to be flat, the height on each side of a puttied joint must be the same. Although the diagrams show a sharp corner, a 35mm radius was used on each layer.
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 2000mm panel.

Strain gages 1 through 8 were connected to one terminal block, and gages 9 through 16 were connected to another. The bold numbers indicate the average speed in m/s of crack growth between 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 delaminations that occurred while testing proposed shapes.

Figure 17. Final geometry used as an initial delamination.
Figure 18. Top image shows the basic test set up of the peel stopper beams. The outer skin is facing down. Bottom images show 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 one 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 delamination grows.

Figure 21. Left. A 2-liter accumulator built from iron pipe. Right. A 20-liter accumulator using 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.