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Development of a New Mixed Mode I-II-III Delamination Toughness Test

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Optimal use of laminated composite materials can only be achieved if its most common failure mechanisms are well understood. One of the most common modes of failure in laminates is delamination, or the separation of adjacent material layers. Therefore, there is a need to be able to predict a laminated composite's resistance to delamination growth due to the complex real-world application loadings that it may experience. These complex loadings are made up of three primary modes of delamination growth, known as modes I, II, and III. Test fixtures for a new mixed mode I-II-III delamination toughness test were designed, built, and used to perform exploratory experiments. The test utilizes laminated composite test specimens that are similar to those used in other established toughness tests. The specimen is approximately 25 mm wide, 150 mm long and between 3 and 6 mm thick. The new test fixture may be installed in a standard uniaxial tension load frame, and includes two screw driven actuators. Three separate loads are applied to the specimen: one through the test machine's hydraulic actuator and two using the screw driven actuators. The relative amounts of mode I, II and III loading may be adjusted by varying the relative magnitudes of these three loads. The new test set-up was used to perform a series of mode I, mode III, and mixed mode I-III delamination toughness tests on unidirectional T800S/3900-2B graphite/epoxy specimens. These tests yielded promising results, but a limited amount of fixture modifications were required to reduce frictional resistance. A set of proposed fixture modifications were therefore devised and are described herein.

Contents

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Introduction

One common mode of failure in laminated composites is delamination, or the separation of adjacent material layers. As load is applied to a composite structure, energy becomes available to propagate any pre-existing delamination. This energy associated with delamination advance is referred to as the strain energy release rate (ERR), where the “rate” refers to energy per unit of new surface area created as the delamination advances. If the ERR exceeds the material’s toughness, G_c, the delamination will grow. Thus, delamination growth can be predicted by comparing the ERR, a parameter determined via analysis, to the material’s toughness, which is determined from a separate set of experiments.

In order to better understand the concept of toughness in the use of composite materials, the reader is reminded of how yield stress is used to predict failure in metals. Yielding may be predicted by comparing the von Mises stress in a part to the yield stress, defined to be the critical stress at which yielding will occur. The yield stress is determined through a simple uniaxial test, where a specimen of known geometry is put through a “load-unload” process in which the specimen is successively loaded with increasing load until yielding is observed to occur. The applied load and cross-sectional area are then used to compute the material’s yield stress (yield stress = yield force divided by cross sectional area). In practice, a part will experience a loading, and as this loading increases, the stress increases. This von Mises part stress, determined via structural analysis, is then compared to the experimentally determined yield stress in order to evaluate whether or not yielding will occur.

Analogously, in laminated composite materials, the ERR, which is determined analytically, is compared to the experimentally determined material toughness. The difference lies in that ERR can be decomposed into three orthogonal directions, yielding three primary modes of delamination growth which will affect the toughness. These modes of delamination growth are known as modes I, II, and III, and are represented schematically in Fig. 1. Mode I growth occurs due to local tensile loading that opens the crack. Mode II is defined by in-plane shearing loads that act in a direction perpendicular to the crack front. Out-of-plane shearing forces, or tearing, cause mode III. Since ERR can be decomposed by mode, toughness is therefore dependent upon the percent of modes I, II, and III that are present. The experimental determination of toughness, which is necessary to predict delamination growth, is therefore required under a full range of mode I, II, and III conditions.

Existing toughness tests of today are limited to the determination of G_c for each mode individually (I, II, or III) and to mixed mode I-II loadings. In this work, a new test is introduced to allow for the testing of any combination of all three modes. The validity and usefulness of this test are demonstrated and preliminary experimental results are presented.

Existing Test Methods

A variety of test methods are currently being used to determine delamination toughnesses of laminated composites under mode I, II, I-II, and, to a lesser extent, mode III loadings. Most commonly, these established tests utilize beam-type specimens. The specimen is composed of multiple plies which are then stacked and cured in an autoclave. The plies contain fibers orientated in a parallel manner and each ply is laid in the same direction, creating a unidirectional specimen. Two “legs” are created by placing a Teflon insert between the center-most plies during manufacture so as to create a pre-existing delamination during manufacture. The specimen is approximately 25 mm wide and lengths vary with test, but are approximately 150 mm or greater. Thicknesses also vary, but are usually on the order of 3-5 mm.

The double cantilever beam (DCB) test applies a mode I tensile loading to each of the specimen’s legs, causing delamination growth.[1] The DCB test is conducted using uniaxial loading. As shown in Fig. 2a, the specimen is only supported at the point of load application, that is, at the tips of the specimen’s legs. As load is applied the legs separate and the entire specimen rises by about half of the total leg separation distance. During a DCB test, the tensile load is applied to the specimen through a hinge-type connection so that each leg can bend freely without constraint.

The mode II end notched flexural (ENF) test uses a three-point bending set-up, as depicted in Fig. 2b. A load is applied to the specimen at the middle point and the resulting bending causes mode II conditions at the crack tip.[2,3] The mixed mode bending (MMB) test shown in Fig. 2c, combines the DCB and the ENF by superposition to create a mixed mode I-II test.[4] Again, a three point bending setup is employed and forces are applied at the specimen mid-length (to create bending for mode II) and at the ends of the specimen’s legs (for mode I).

There have been numerous attempts to develop a test to determine toughness due to out-of-plane shearing forces, or mode III conditions. The split cantilever beam (SCB) test is one such test.[5] The SCB, as shown in Fig. 3a, applies a load to each of the legs of the specimen in a direction that is parallel to the crack front. The side forces create an ERR that was originally thought to produce mode III growth. However, it was later determined that the bending moment at the crack tip causes high mode II components to occur at the specimen's edges. This is illustrated in Fig. 4, which presents three-dimensional finite element results for the mode II and mode III ERRs across the width of an SCB specimen.[6] The mode II and mode III ERR components, defined as G_{II} and G_{III} respectively, are presented as functions of the normalized location across the crack width. Notice that the total ERR ($G = G_{II} + G_{III}$) is very high at the SCB specimen's edges. Here, the total ERR is composed of approximately 80% mode III and 20% mode II.

Note from Fig. 4 that both the total ERR, G, and the mode mix, or percentage of each ERR component, (i.e., G_I, G_{II}, G_{III}), to the ERR, varies across the specimen's width. This means that growth will not occur uniformly. That is, due to the large ERR at the specimen's edges, it is likely that crack advance will occur first at these locations. This non-uniform crack advance across the specimen's width makes it essentially impossible to extract an accurate delamination toughness from the test data. Even if one could accurately extract the toughness, G_c, from such a test, it will have no clear physical meaning, i.e., it will not be connected with a single mode mixity. Thus, the goal in test design is to have any non-zero ERR components be essentially uniform across the width of the specimen. In this way, the entire delamination front will grow uniformly and accurate toughness values that are associated with a single, unambiguous mode mix can be extracted.

To address the deficiencies of the SCB, a modified split cantilever beam (MSCB) test was developed. This test is shown in Fig. 3b. In the MSCB, additional shear loads are applied to eliminate the bending moment at the crack tip.[7,8] This modification successfully removed the mode II component from the test, thus resulting in nearly pure mode III conditions. Although the MSCB is promising as a pure mode III test, it is not suitable to be used as a platform from which to expand to a mixed mode delamination toughness test as the goal of this paper specifies.

STB Test Design

The test studied in this work was proposed by Davidson and studied by Sediles and Davidson at Syracuse University and, is called the shear-torsion-bending (STB) test. The idea behind the test is to produce mode III via a modified MSCB-type loading while still allowing for the addition of any percentages of modes I and II. Ideally, the test would use a specimen that is very similar to those used in the DCB, ENF, and MMB tests. In this way, the same type of specimen could be used to determine G_c over the complete mode I-II-III loading range.

A. Overview

The new test was also designed via the superposition of established tests. In this case, the concept was to combine a modified version of the MSCB with the DCB and the ENF. The resulting test would apply modes I and II (as from the DCB and ENF) and then include mode III loads as well (from a modified MSCB).

Modes I and II loadings are easily identifiable, so they are first described in the STB test schematic shown in Fig. 5. The mode I loading, P_I, is applied to the specimen through an actuator that pulls upwards (positive z) on the top leg of the specimen while the lower leg of the specimen is fixed in place vertically via a connection to a linear bearing. The mode II loading is applied through an externally mounted screw-driven actuator (P_{II} force) in a three point bend configuration.

The mode III component of the delamination toughness test is produced via a modified MSCB-type loading. In this approach, as with the SCB and MSCB, a side load (P_{III}) is applied to one leg of the specimen. An out-of-plane shear load (in y direction), characteristic of mode III loading, is thus created when the top leg of the specimen reacts against its support. In order to eliminate the bending moment at the crack front, a torque is applied to the upper leg of the specimen. The magnitude of the torque may be chosen as P_{III}•a, where a is crack length. This produces a loading that is identical to that induced by the MSCB test. Alternatively, a lower torque can be applied if the rotation of the upper leg is fully constrained during the test. The advantage of this approach is that the test can be preformed in a uniaxial load frame. Conversely, an axial-torsional load frame is required if a torque equal to P_{III}•a is to be applied. The “fixed torque” and “fixed rotation” options were both studied via finite element analysis. It was found that a more uniform ERR was obtained for the fixed rotation (θ=0) case. Clearly much simpler to carry out, the fixed rotation method is used in the STB test.

B. Test Fixture Development

Figure 6 provides a solid model of the STB test. As shown in the figure, the test fixtures are built around an existing uniaxial load frame. A large support frame is used to provide mounting options for the linear actuators and to provide smooth load transfer throughout the set-up.

In order to apply mode I load, P_I, the load frame’s hydraulic actuator is utilized. A clevis connection is used to connect the upper leg of the specimen to the hydraulic actuator. The lower leg of the specimen is fixed vertically. As the hydraulic actuator applies tensile load a reaction forms in the downward (negative z) direction and a mode I loading is created at the crack front similar to the DCB test. The P_I actuator and the linear bearing used to hold the lower leg of the specimen are also clearly visible in Fig. 7, which presents a photograph of the actual test set-up.

In order to apply mode II loading, the specimen is held in a three point bending type configuration. The cracked end of the specimen is supported as for mode I testing: the load frame actuator above and a rigid mount (linear bearing) below. The other end of the specimen is held in place by an end support. The center point of the three point bending configuration is called the P_{II} loading roller and is located at the specimen’s mid-length. Here, the P_{II} actuator applies a vertical load to the specimen so as to cause it to bend, thereby causing a mode II loading at the delamination front. This configuration is easily identified in Fig. 5-7.

It should be noted that both the end support and the P_{II} loading roller contact the specimen through roller-type components. In this way, the area of contact is reduced, the location of the load resultant is well defined, and problems due to local crushing are minimized.

With the mode I and II loadings established, mode III was next integrated into the set-up. Recall that the mode III loading is induced by applying a shearing side load to the lower leg of the specimen, and the torque is applied by restraining the end of the upper leg from rotating. In the STB, a P_{III} actuator is used to apply the side load to the specimen's lower leg. As can be seen in Fig. 6 and 7, the P_{III} actuator's line of action coincides with that of the linear bearing on which the lower leg of the specimen is mounted. The linear bearing constrains the specimen from rotation and also ensures that the P_{III} force is applied in the correct direction. The upper leg of the specimen is fixed from rotation about the P_I axis by the upper hydraulic actuator, which is held under zero rotation control by the load frame's control system. This allows the actuator grip and clevis to apply the zero rotation constraint of the modified MSCB to the upper leg of the specimen. The hydraulic grip is evident in the photograph of the STB test set-up, Fig. 7.

C. The Specimen

Edge delaminations are used to obtain uniform ERRs across the specimen's width.[9,10] That is, a delamination can be created in a laminated composite simply by inserting a sheet of Teflon at the desired location while the material is being made. The curing cycle bonds all adjacent material layers together except those that are separated by the insert. In this manner, cracks are pre-implanted into the cured specimen. Edge delaminations are formed by implanted inserts that run down the length of the specimen's free edges as shown in Fig. 8. In the figure, the darker portion of the specimen corresponds to the material that does not have a delamination. The specimen is of width, B, and the edge delamination penetrates a depth of β*B on each side of the specimen.

Several different edge delaminations depths were considered of varying fractions, β, of the width. Figure 9 plots the mode III ERR versus the normalized crack width. The crack width is defined as the portion of the specimen width that is not already previously delaminated by an edge delamination. It is then normalized for use in the plot so that 0 corresponds to one edge and 1 to the opposite edge. This is illustrated in Fig. 8. This approach allows for easy comparison of plots of specimens with different sized edge delaminations. In Fig. 9, the mode III ERR is also presented as a normalized quantity. Denoted as G_{III}/G, it is a ratio of the local mode III ERR, G_{III}, to the average mode III ERR (across the specimen's width), denoted as G.

As shown in Fig. 9, without EDs (β=0), the normalized energy release rate is at a maximum at the center of the specimen and then decreases towards its edges. Thus, the β=0 curve does not meet the desired uniform ERR distribution. As β increases, G_{III}/G initially becomes more uniform, but as β become larger the values near the edges of the crack become large. An edge delamination depth corresponding to β = 1/16 is observed to produce the most uniform ERR distribution and is therefore chosen for use.

The STB specimen is a 20 ply, unidirectional laminate similar to those used in the DCB, ENF, and MMB tests. As shown in Fig. 8, each specimen is approximately 25 mm in width and 3-5 mm thick while the length varies with the crack length. The specimen length is divided into two equal portions, L, the half-span length. L, as can be seen in Fig. 5, is the distance separating the load pins of the P_I fixture and the P_{II} loading roller, and is also the distance between the P_{II} loading roller and the end support. The crack length, a, is chosen to be one-half of the half-span length, i.e., a = L/2. A 0.127 mm thick sheet of Teflon is inserted at the mid-plane during the material lay-up so that a pre-implanted delamination is formed. This pre-implanted delamination spans the width of the specimen and runs 63.5 mm into the specimen from its end. Edge delaminations extending the full specimen length are also constructed in this manner, to a depth of 1.6 mm for a 25 mm wide specimen (i.e., corresponding to β = 1/16).

D. Load Tab Design

Design of the load tabs was a vital part of the STB test implementation. The load tabs are responsible for the application of two different kinds of loads to the specimen and for holding the specimen in the test fixture. The original concept was to cut grooves into the specimen about which the tabs could be clamped, and via the contact friction, grip the specimen. Unfortunately, the original load tabs damaged the specimen with their sharp corners and edges, were not rigid enough (as they were composed of multiple parts), and could not perform to the required loads. The first design iterations demonstrated that the original load tab scheme was not adequate for the needs of the STB test.

The concept for gripping the specimen was finally entirely re-evaluated. In the new design, the load tabs are composed of two main parts: spacer tabs and load blocks, shown in Fig. 10. A steel spacer tab is bonded to each of the flat surfaces of the specimen's legs using a two-part room temperature epoxy (DP-420 was used in this study). The spacer tab is bonded to the specimen such that the center of the spacer tab is located a distance equal to the crack length away from the delamination front. Screws, located at the center of the spacer tabs, are the primary means of transfer of tensile loads (P_I) to the specimen.

Each of the load blocks has two diagonally placed pins that protrude from the surface and contact the spacer tab and specimen. These pins fit snuggly into semi-circular cutouts at the edges of the spacer tabs and specimen and they extend to the specimen's midplane. The other loading block (used on the other side of the specimen) has its pins protruding such that they fit in the remaining semi-circular cutouts. The pins are the means through which both the P_{III} load and the associated torque are introduced into the specimen. The direction of torque application was carefully chosen such that the force concentration on the specimen due to the pins would be directed away from the load tab assembly. This ensures that all loads are directed away from the region of the specimen that has been weakened due to the pin's semi-circular cutouts.

The load blocks are connected to the remainder of the test fixtures and actuators by means of pin-and-clevis connections. As the load frame's hydraulic actuator applies the P_I load, the load is transferred through the pin-and-clevis connection to the load block, through the screw, into the spacer tab and, ultimately, to the specimen.

Test Methodology

To conduct a mode III test, the specimen is first placed in the fixture and the end support is lowered to contact the top of the specimen, as shown in Fig. 5. Two side fixtures are used to restrain the specimen's bending tendencies during the application of mode III loads. One of these side fixtures is part of the end support, while the second side fixture is part of the P_{II} loading roller. The side fixtures, shown in Fig. 5, contact the sides of the specimens and help to restrain specimen bending tendencies that arise from the applied mode III load (P_{III}). The P_{II} loading roller is also raised to apply a small load (approximately 50 N) so as to ensure contact with the specimen.

To run the test, the P_{III} actuator is moved at a constant displacement rate until fracture occurs. Figure 11 presents a typical plot of the P_{III} load versus the displacement of the linear bearing to which the specimen is attached. As can be seen in Fig. 11, this plot is reasonably linear until the point of delamination advancement (indicated by a sudden decrease in P_{III} load). This indicates that the test is proceeding essentially the same as is assumed in the associated analyses (described subsequently).

To conduct a test that includes a mode I component, it is especially important that the specimen is properly mounted in the test set-up. One key issue is that the specimen must be perfectly centered with the clevis so that no undesired shear loads are applied to it. For this reason, specimen centering was accomplished by employing a combination of pins and threaded rods. One threaded rod was used in the upper clevis and a second was employed in the lower clevis. The second threaded rod was used on the other side of the specimen so as to be able to center the specimen in the clevis. Once centered, the remaining pins were put in place and the threaded rods were backed out a small amount so that they allowed free rotation within the clevis. Figure 12 presents the upper clevis design; the pin and threaded rod are used to center the upper load block in the clevis that is held by the load frame's hydraulic axial actuator.

When performing a mixed mode I-III or II-III test, the mode I or mode II load is always introduced first. For mode I-III, the mode I load is applied at a constant rate up to the value that corresponds to a desired percentage of the material's mode I toughness, G_{Ic}. After the P_I load has reached this level, it is held constant while the end support is brought into visual physical contact with the specimen. The P_{II} actuator is also moved so that a small load (approximately 50 N) is applied to the specimen. At this point, the mode III load is applied until fracture (crack advancement) occurs.

Similarly, for mixed-mode II-III, the P_{II} load is applied until the desired percentage of G_{IIc} is reached. The load frame is then set to enforce a $P_I = 0$ constraint so that a mode I component cannot arise. Then the mode III load is applied until fracture occurs. For mixed-mode I-II-III, the order of mode application is always I, II, and then finally III.

Toughness Determination

For this work, finite element analysis was used in the determination of fracture toughness. The model's geometry was defined to match each specimen as accurately as possible. The finite element model, shown in Fig. 13, includes the specimen, the pre-existing delamination, the boundary conditions that are imposed by the supports and load tabs, and the applied loads. In an effort to ensure accuracy, the element density near the crack tip is greater than at the edges of the specimen. This is evident in Fig. 13, as are the load tabs. The end and P_{II} supports are modeled as "line loads" to simulate the roller's contact method. The model also includes the adhesive layer between the specimen and the load tabs. To determine the fracture toughness, the loads in the specimen at failure (P_I, P_{II}, and P_{III}), are applied to the finite element model, and the model is used to extract the values of G_c and the mode mix.

Test Results

Preliminary testing led to the redesign of load tabs and fixtures on several occasions. Most of the time and effort spent in redesigning as a result of test experience was invested in two aspects of the load tabs. First, the original design of gripping the specimen often led to direct damage as sharp edges dug into the specimen. Second, the original load tabs often were not capable of applying the required loads; they often damaged the specimen, yielded and deformed themselves, or broke off of the specimen. Once these fixture issues were resolved, exploratory mode III, mode I and mode I-III testing was performed on unidirectional T800S/3900-2B graphite/epoxy specimens.

A. Pure Mode III Test

Two specimens were tested under pure mode III loading. The load versus deflection plots were somewhat less linear than the plot shown in Fig. 11, which was traced to rotation of the specimen until a solid contact with the side fixtures was achieved. The mode III fracture toughness, G_{IIIc}, was determined via FEA and an average value of approximately 1000 J/m^2 was obtained. For comparison purposes, G_{Ic} of this material is approximately 600 J/m^2 and G_{IIc} is approximately 2100 J/m^2. Previous studies[11,12,13] have found that G_{IIIc} is typically similar in magnitude to G_{IIc}. It is possible that the ability of the specimen to rotate within the STB fixture affected the accuracy of the perceived toughness, and fixture modifications are being performed to address this issue. However, although the value of G_{IIIc} may or may not be quantitatively accurate, the entire (full-width) delamination front advanced. This is in contrast to existing mode III tests, which typically evidence non-uniform crack advance. Therefore, the present results hold great promise that the STB will provide highly accurate results once the fixture problems are resolved.

B. Pure Mode I Test

Figure 14 depicts the mode I (P_I) load versus displacement plot from a pure mode I test within the STB fixture. The test was run in a typical DCB fashion; the specimen was loaded to fracture, unloaded, and the process repeated seven times.

Figure 14 shows that the mode I clevis design arrangement yields an unrealistically high initial stiffness (as evidenced by the much steeper slope at low loads). The high stiffness indicates that that the pin-and-clevis joint shown in Fig. 12 is creating more frictional resistance at low loads than was expected and so cannot rotate freely. This will affect the accuracy of the perceived toughness under mode I conditions. However, as described below, a mixed-mode I-III test was still performed to assess if there were any other issues that needed to be addressed and it had encouraging results.

C. Mixed Mode I-III Test

A mixed mode I-III test was performed according to the test procedure described previously and consisted of a low mode I, high mode III mode ratio of approximately 25% mode I and 75% mode III. The mode I loading was applied up to a value of 155.69 N and then held constant. Then, the mode III loading was applied until fracture. Delamination advance occurred at approximately 2318 N. Fracture occurred in the desired manner with crack advance across the entire width of the specimen. Thus, although an accurate toughness cannot be extracted due to the fixture issues, this test provides proof of concept and indicates the promise of the STB test for mixed-mode loadings.

Fixture Redesign

As discussed in the mode I test results, the low load portion of the P_I load versus displacement plot of Fig. 14 indicated that the system had a very high initial stiffness. This stiffness was attributed to a large frictional resistance to rotation in the pin-and-clevis arrangement. For this reason, a fixture redesign was required.

There are several key issues that must be identified in the redesigned fixture. Firstly, it is important to recognize that the P_{III} load is applied to the specimen through the lower clevis. Transfer of load can be carried out through two paths; direct contact between the load tabs and the clevis or through the pins. The current design transfers load through the pins. This allows for precise specimen centering and, as will be shown subsequently, load sharing by both sides of the clevis (e.g., in the direct contact method, all load must be transferred via the contacting surfaces). Secondly, the pinned connection must rotate freely. In general applications, rotational friction can be greatly reduced with the use of a simple roller bearing, but roller bearings generally do not function well when they are loaded in their axial direction. Thus, a roller bearing is not sufficient for this application. Thrust bearings, conversely, are designed specifically to allow rotation about an axis that is under axial loads. While thrust bearings can withstand radial loads, in the application herein required, a thrust bearing alone would not be sufficient. This is because it would be difficult to fully seat a thrust bearing this application, but more importantly, thrust bearings are generally meant for applications where they function as a turntable in which case there is no shaft that passes through the center of the bearing. The STB application, on the other hand, requires that the pin pass through the center of the bearing.

In view of the above, the redesigned fixture employs both roller bearings and thrust bearings, as shown in Fig. 15. The roller bearings allow the assembly to freely rotate about the axes defined by the two sets of pins. The head of the each pin rests against a thrust bearing which is mounted in a recess in the outside of the clevis. In this manner, even as the pins experience both radial (P_I) and axial (P_{III}) loads, they maintain the ability to freely rotate (and hence significantly reduce frictional resistance).

Physically, there are several restrictions to be considered; particularly with the thrust bearing. Firstly, the outside diameter should be as large as possible so that the contact surface area over which the axial load is distributed is maximized, thereby helping to reduce the bearing's deflection. To aid in this, the width (depth into the page in Fig. 15) of the clevis is increased so that its available contact area is also increased. In the height direction, however, the outside diameter is restricted by the distance separating the upper and lower clevises. The specimen is a minimum of 3.4 mm thick, the spacer tab is 6.3 mm thick, and the load tab (with the pin axis at mid-thickness) is 22.2 mm thick. A minimum separation distance between the axes of the upper and lower clevis pins is therefore 38.2 mm. This separation distance limits the maximum outside diameter of each thrust bearing to less than 38 mm. In addition, in order to limit the nonlinearity in the P_{III} deflection, the thrust bearing should be capable of withstanding loads that are at least twice the expected maximum value of P_{III} of approximately 4500 N (value based on experimental and finite element results to-date).

In the redesigned fixture, a radial bearing that uses rollers is press fit into the inside of each clevis. The roller bearing has an outside diameter (OD) of 14.3 mm, an inner diameter (ID) of 9.5 mm, a width of 14.3 mm, and is rated at 5783

N of dynamic radial load.[1] Its high load carrying capacity and large internal surface area (by width) over which to distribute the P_I load makes it an appropriate choice. A thrust bearing using balls is mounted in a recess in the outside of each clevis. It has an OD of 35 mm, an ID of 18 mm, is 12 mm wide, and its dynamic thrust load capacity is rated at 14900 N.[2] The OD of the thrust bearing is less than the maximum allowable value of 38 mm, so contact between upper and lower fixtures is not a concern. The thrust bearing's ID is large enough that an expanded portion of the pin shank could be inserted into the outer portion of it so that alignment is ensured.[3]

The pins have been designed according to the choices in thrust and radial bearings. The pin's head has a diameter equal to that of the OD of the thrust bearing so as to maximize contact area. The thrust bearing that was chosen is a "split bearing", i.e., it is comprised of two rings with the ball races in the center. The pin shank diameter near the pin head should match the thrust bearing ID for the width of the first ring (approximately 5 mm). The remaining diameter of the pin is 9.5 mm to match the ID of the radial roller bearing. The pin's length is defined by the bearing widths and the depth of the load tab threads. The end of each pin is threaded to match the loading tabs so that each pin can transmit load to the specimen. Regardless of the direction of motion of the P_{III} actuator, the load is easily transferred through the pins to the specimen. In addition, the loads are

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[1] McMaster-Carr Part No. 5905K42
[2] McMaster-Carr Part No. 6681K14
[3] Other thrust bearings could also be used. For example, a smaller thrust bearing OD may allow better viewing of the specimen during the test.

distributed (although not always evenly) between the sides of the clevis assembly so as to ease the burden and minimize bearing deflection.

When the specimen is placed in the fixture, one of the lower pins is put in place and threaded into the load tab until the specimen is centered within the lower clevis. Then the other lower pin is inserted and threaded until snug. Here, the goal is for the two lower pins to have essentially equal torques, and a torque wrench could be used for this purpose. Next, the two pins are placed into the upper clevis and each side is tightened in small amounts so that the specimen remains straight and centered and both pins have essentially the same torque as the lower two pins.[4] The upper and lower clevises are then clamped together with an external clamp and the hydraulic grip of the load frame actuator is used to grip the upper clevis; it is important to ensure that little torque and/or load is induced during this process. Next, the vertical alignment clamps are removed. It is vital that each component of this fixture is machined to high tolerances so that there are no axis misalignments as the pins are tightened.

The redesigned fixture concept shown in Fig. 15 should provide marked improvement over the original design. The combined use of radial and thrust bearings helps to minimize the frictional resistance of the fixtures. The modified pin aids in alignment issues, and the threaded ends ensure load is now transmitted into both sides of the clevises. It is believed that these modifications will address

[4] Upon initial use, once the lower pins have been installed it should be confirmed that the specimen can rotate freely. Then, the lower pins should be removed, the upper pins should be installed, and free rotation of the specimen should again be confirmed. These checks will verify that the redesigned fixture functions as expected.

the previously described deficiencies with the original fixture and will allow reliable mixed-mode I-II-III data to be obtained via the STB test.

Conclusions

A delamination toughness test for mixed mode I-II-III loading has been successfully designed in both a conceptual and physical manner. The shear torsion bending test was then successfully implemented on a load frame. It is capable of applying any single or combination of the three delamination growth modes. The test design and set-up are reproducible and it is hoped that the test will eventually become the basis or role model for future test standardization.

Exploratory mode I, III and I-III experiments have been successfully performed on unidirectional graphite/epoxy specimens. The tests have shown that there are a few issues with fixture alignment and rotational friction that have yet to be addressed in order to obtain quantitatively accurate values of toughness. Some of these fixture adjustments have been successfully carried out on paper; however they have not yet been implemented. However, in the tests that were carried out delamination growth occurred in the desired manner, with the full width of the delamination front advancing. Full width growth indicates a relatively uniform energy release rate, which in turn indicates that this test holds great promise for accurately determining the mixed-mode I-II-III delamination toughness of laminated composites.

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Appendix

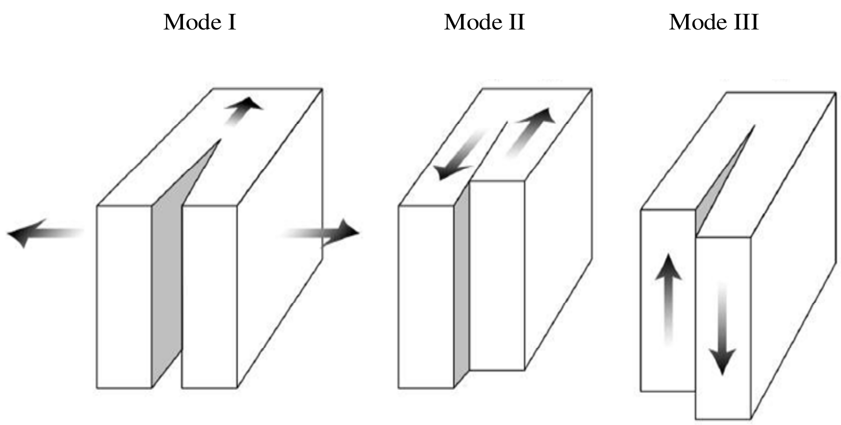

Figure 1: Three Modes of Delamination Growth

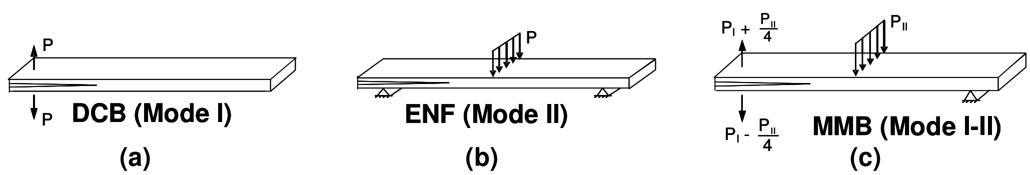

Figure 2: (a) Double Cantilevered Beam, (b) End-Notched Flexure, and (c) Mixed Mode Bending Tests

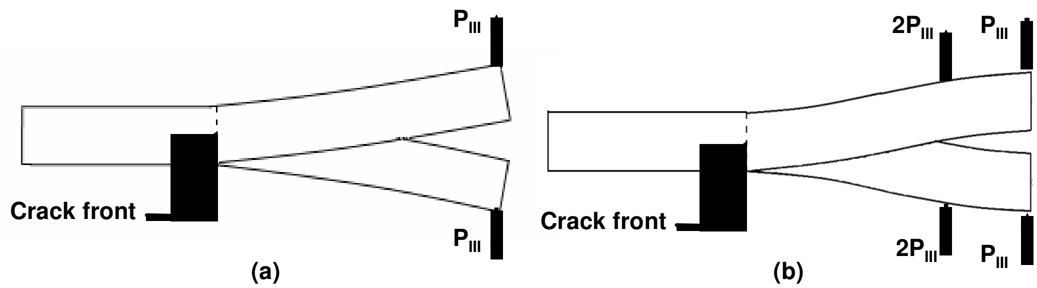

Figure 3: (a) Split Cantilevered Beam, and (b) Modified Split Cantilevered Beam Tests

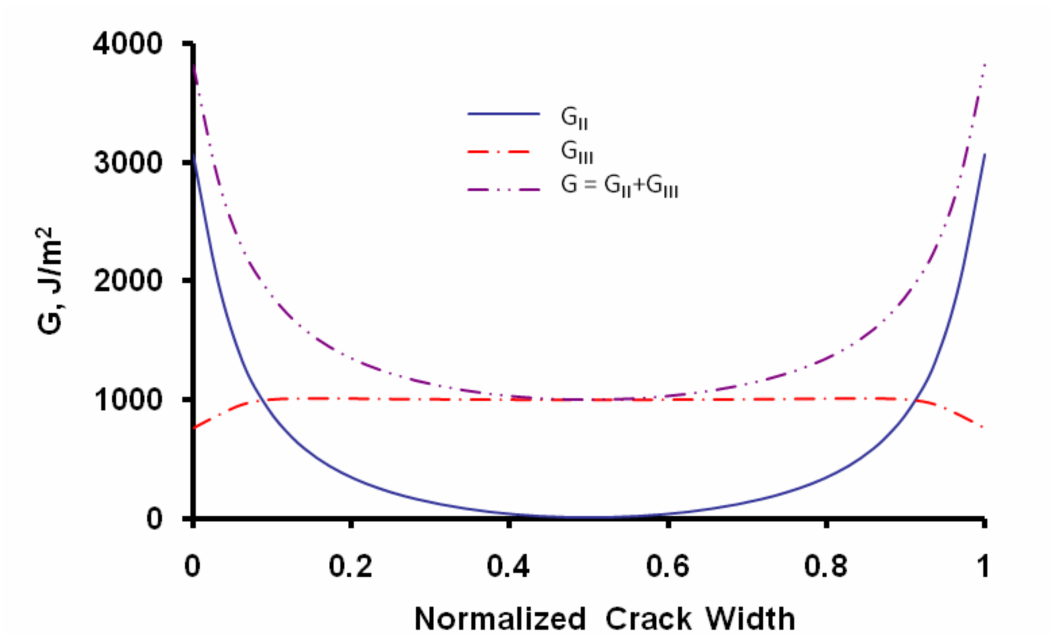

Figure 4: ERR Distribution in the SCB Test

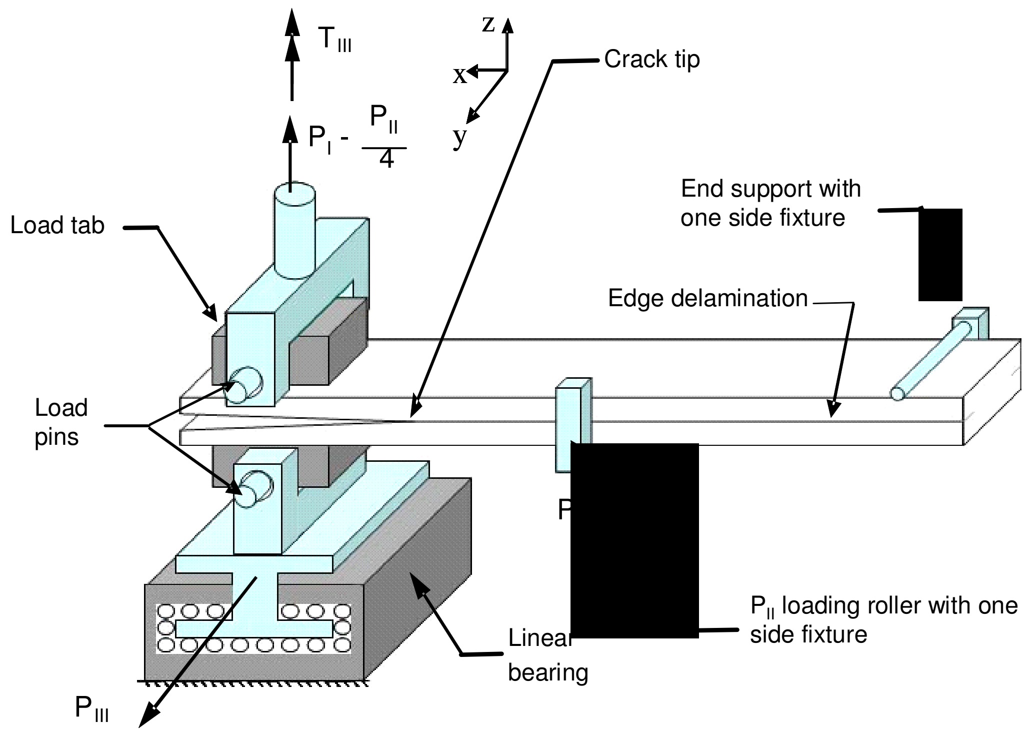

Figure 5: STB Test Schematic

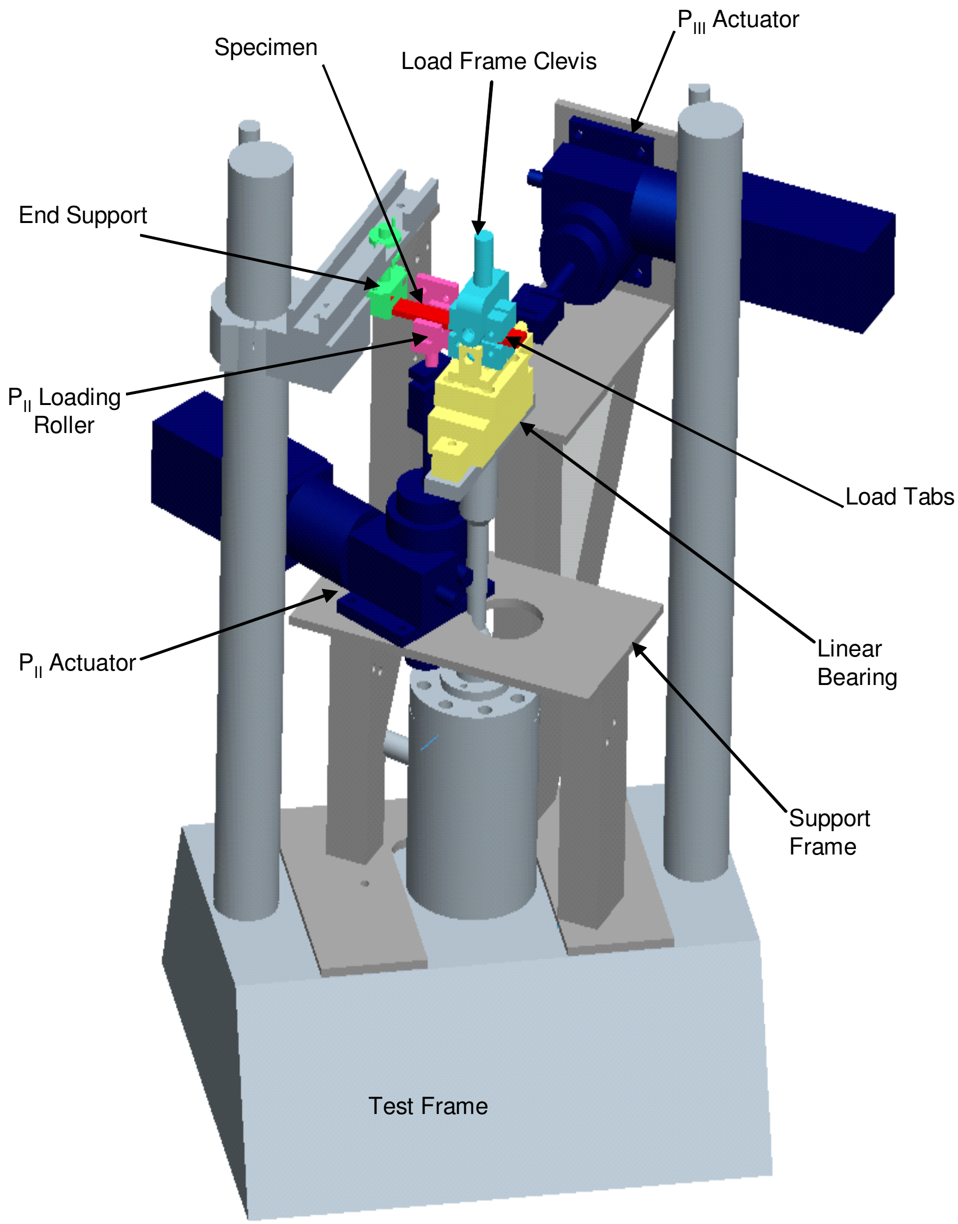

Figure 6: STB Solid Model

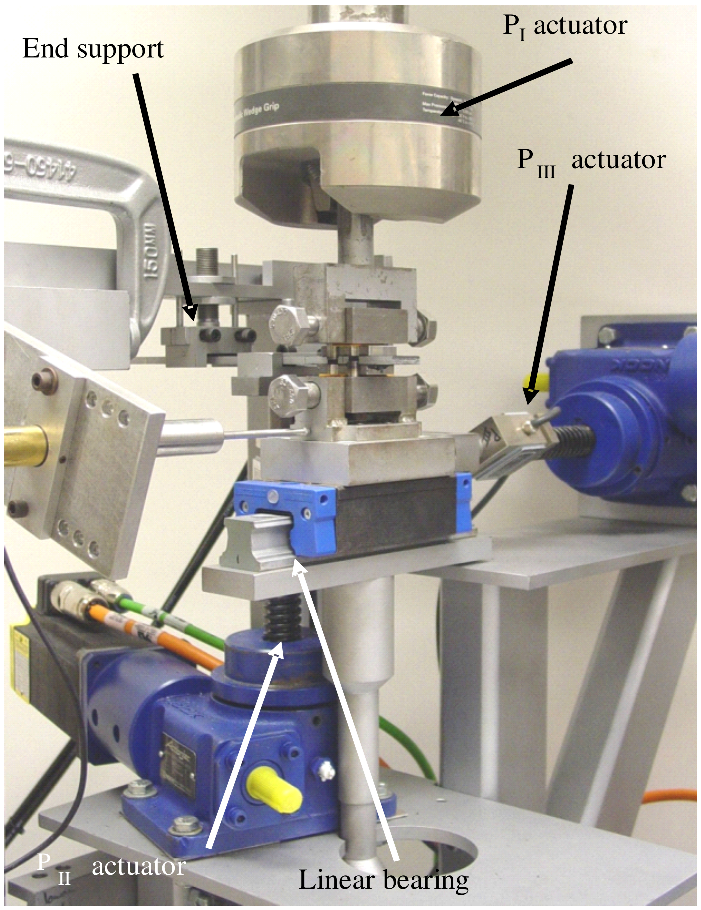

Figure 7: Photograph of STB Test Setup

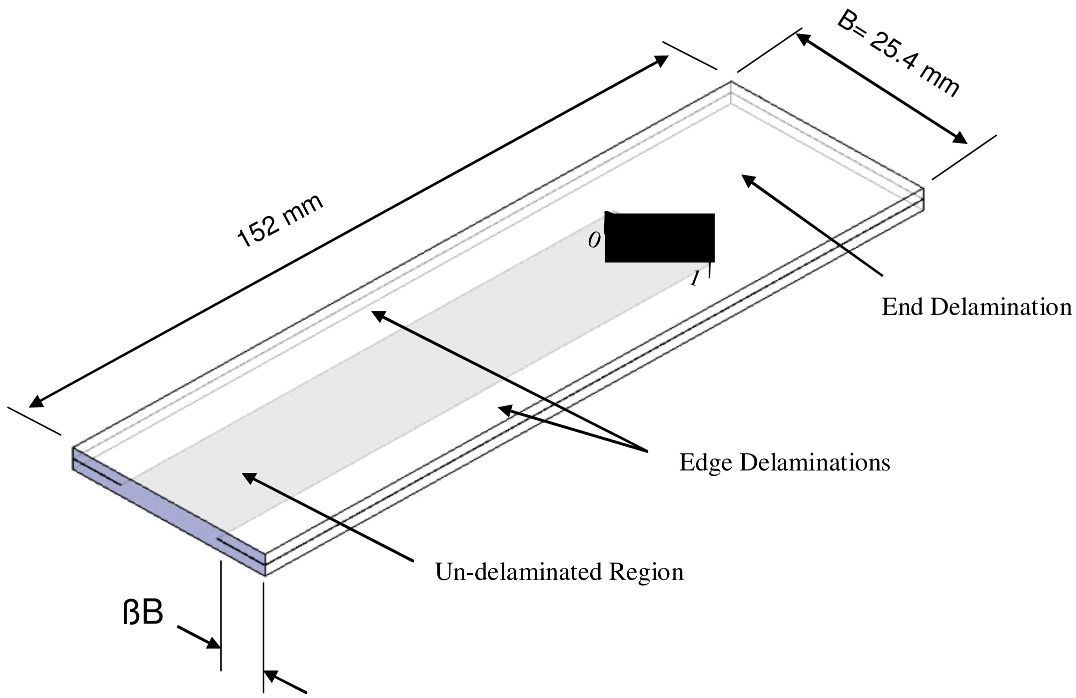

Figure 8: Specimen Schematic Showing Edge Delaminations

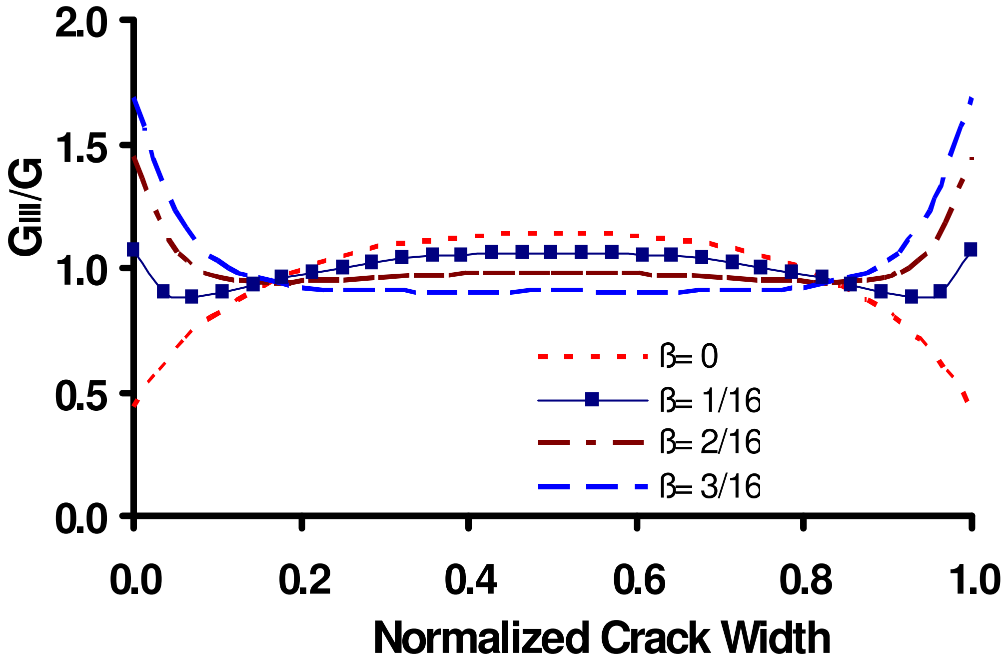

Figure 9: Effect of Edge Delamination Length on Mode III ERR Distribution

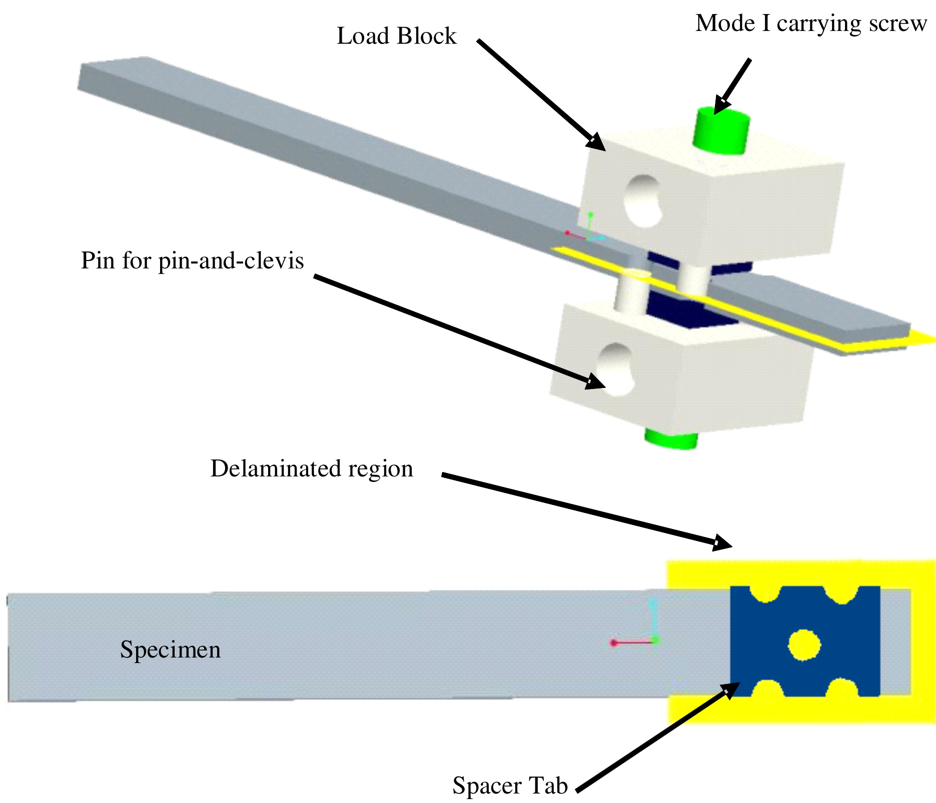

Figure 10: Load Tab Design

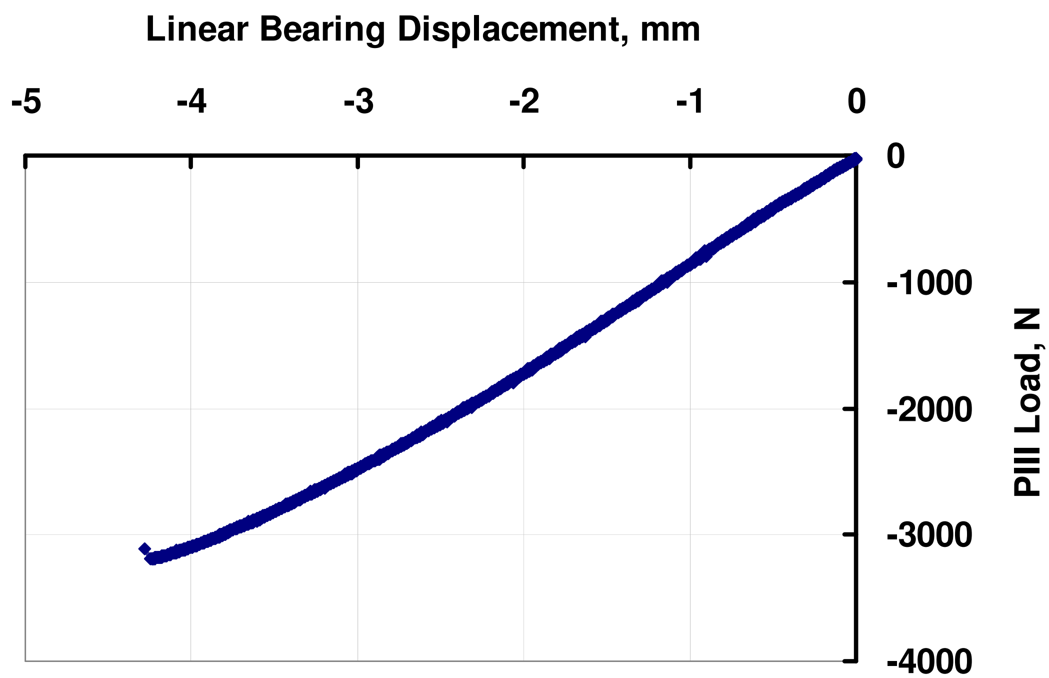

Figure 11: Typical Mode III Loading Curve

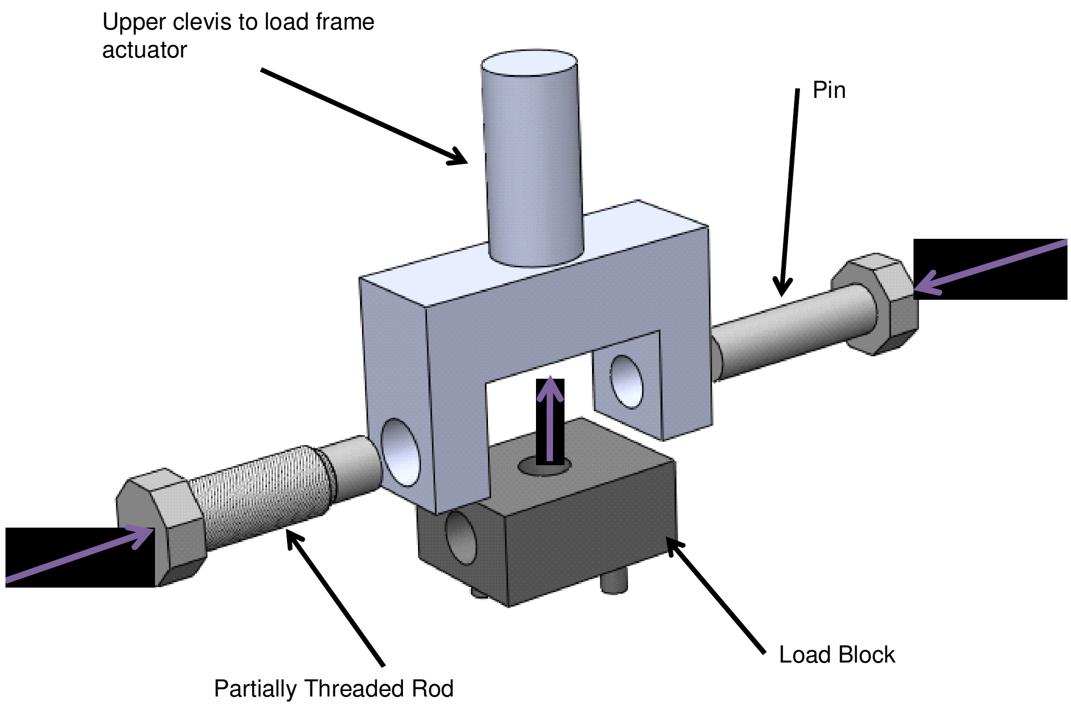

Figure 12: Original Upper Clevis Design

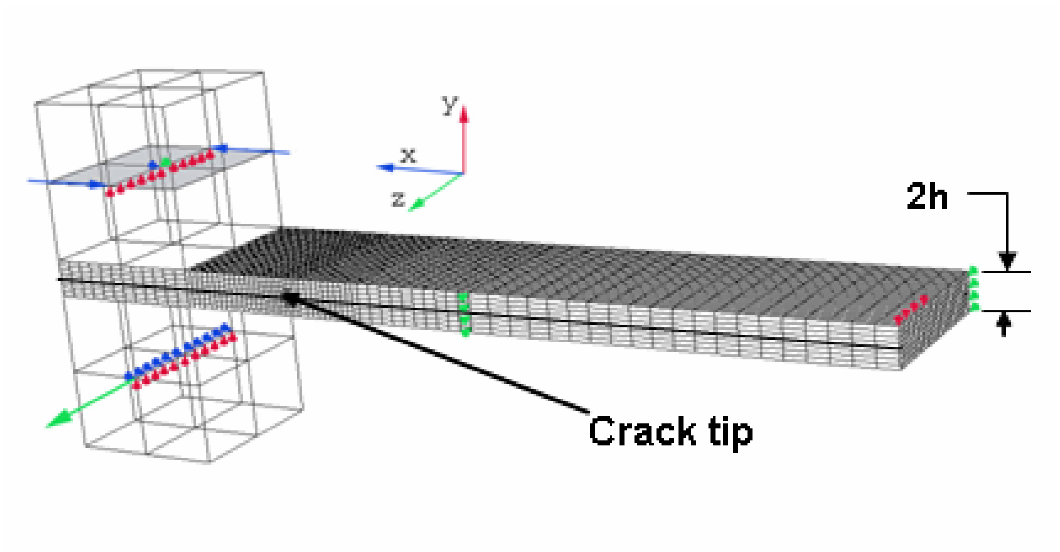

Figure 13: Finite Element Model of STB Specimen

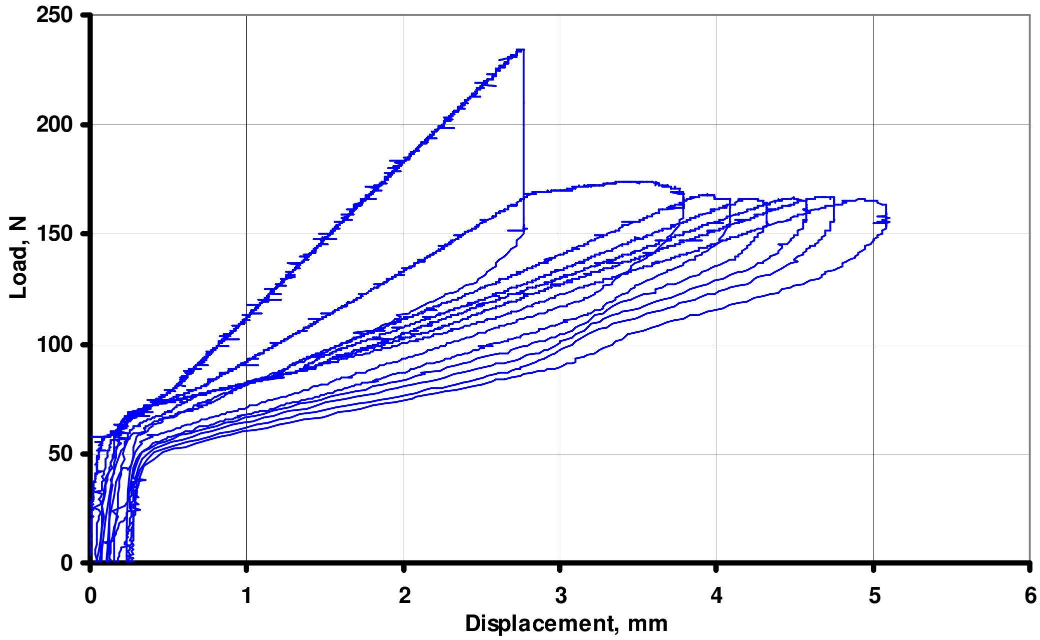

Figure 14: Mode I Repeated Loading Test

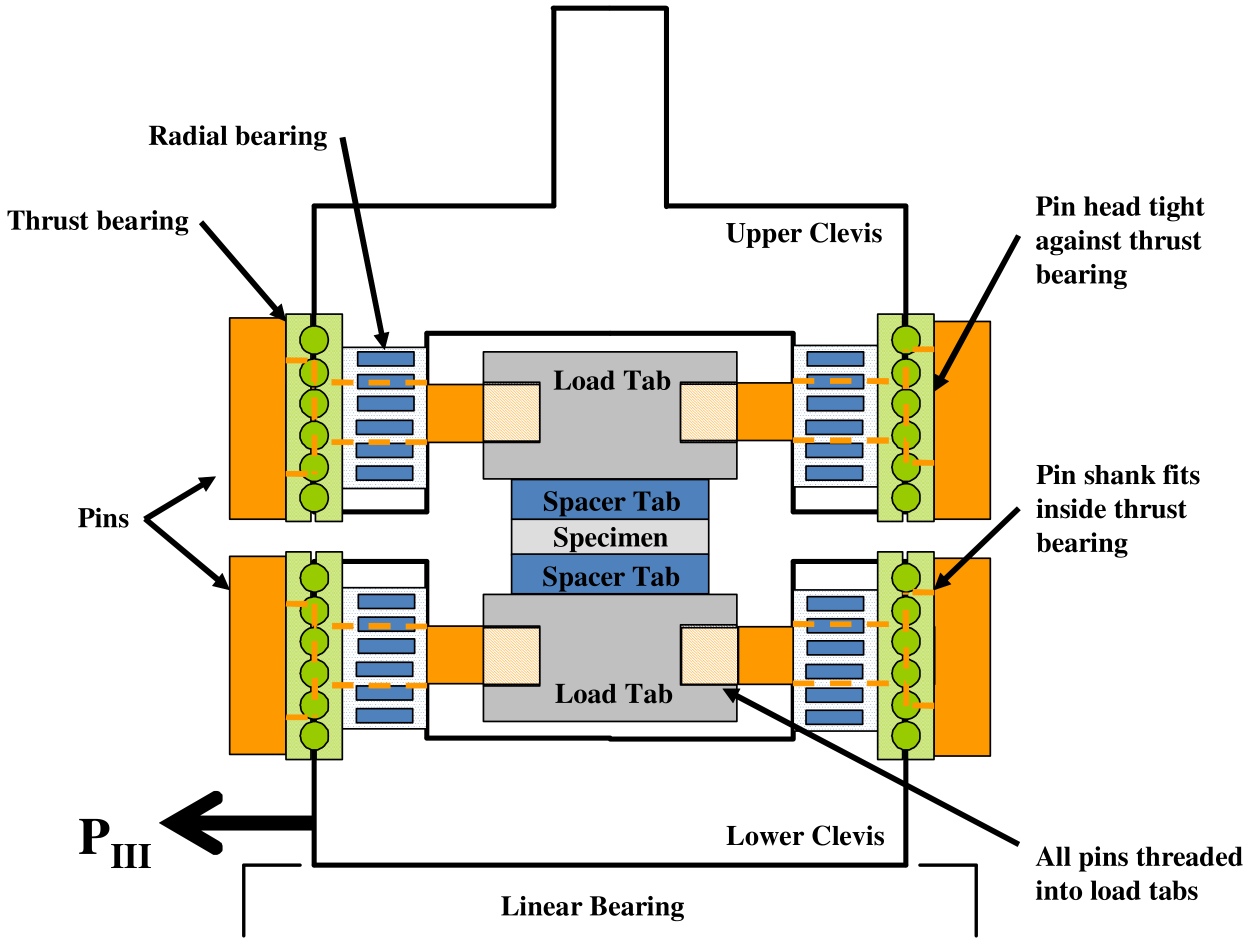

Figure 15: Modified Upper Clevis Design

Written Summary of Capstone Project

In the study of laminated composite materials, one of the most common modes of failure is delamination. A material's resistance to delamination growth, or the separation of material layers, can be quantified by a material property known as the fracture toughness. Once the material's toughness, Gc, has been exceeded, the delamination advances.

As a composite structure is loaded, energy builds up at the location of any cracks, or crack fronts. This energy is described by its "release rate", or the amount of energy per unit of new surface area created as a delamination grows. Known as the strain energy release rate, or ERR, it can be used to predict delamination growth by comparing it to the experimentally determined G_c.

ERR can be divided into three components, one associated with each of the three primary modes of delamination growth (known as mode I, II, and III). Fracture toughness, therefore, is a function of the percentages of the ERRs corresponding to each of the three delamination growth modes.

Tests exist to determine toughness for modes I, II, I-II, and III. A test that includes mixed mode III components, that is I-III, II-III, and I-II-III, did not exist until recently and is the subject of this capstone project.

In order to successfully implement such a test, established tests were superposed so as to create a single test that combined the desired attributes of each. The new test, known as the shear-torsion-bending test, or STB, uses three established tests to build from: the mode I double-cantilevered beam test, the mode II end-notched flexure test, and the mode III modified split cantilevered beam test.

The design process started by developing a complete understanding of the proposed test schematic which was provided and developed by my capstone advisor, Dr. Davidson. This understanding included the tentative physical set-up, method of load transfer within the specimen and structure (a field known as statics), proposed test procedure, and methods of data acquisition and test control. Felipe Sediles, a Ph.D. candidate, whose dissertation focuses on the pure mode III toughness test was also very helpful as he taught me, mentored me, and helped me in many aspects of the project.

Initially, I spent a great deal of time familiarizing myself with the products available for purchase. I explored options for linear actuators with which to apply load, controller options and methods, load cells with which to collect data, and linear bearings with which to guide the moving parts of the test set-up. Although very difficult and intimidating at first, I very quickly became much more comfortable calling, speaking with, and meeting sales representatives as I tried to explain our needs so that their expertise could be utilized in our search for products.

I also invested many hours in developing a CAD model of the test set-up as it evolved. As Dr. Davidson and I settled on specific products that we would purchase, the model slowly became began to resemble the finalized product. Once the model had been approved, I began to work with both the engineering and physics machine shops to build our required fixtures, jigs, and large steel support frame on which much of the test was built. I completed and submitted technical drawings for each part that was manufactured and once built, I assembled the parts on-site to bring the CAD model to life. This was a very significant time, particularly for me, as I began to see the tangible results of all of my hard work and realize that this was a "real" project.

Once the test set-up was complete, we spent time running preliminary tests and working the obvious kinks out of the system. This portion of the project was characterized by an alternating theme of very frustrating and tedious setbacks and great leaps forward. One of the aspects of the project that we had the most trouble with was the "load tabs" that are used to grip the specimen while in the test fixture. The first design iterations damaged the specimen. Later iterations would pop off of the specimen before test loads had been achieved. Other iterations withstood testing loads, but actually (and incredibly) permanently deformed the steel tabs instead. It wasn't until many weeks had been spent before we finally entirely re-evaluated the concept and decided to try a different approach instead. Much to everyone's satisfaction, the new design's second iteration performed even better than the test had required.

The next step in the STB test's development was to start running preliminary tests. As Felipe's dissertation focused on the pure mode III component of the test, we started with that test. Again, this period was filled with great successes and disappointing setbacks. As we ran tests, we almost invariably discovered a fixture issue that needed to be resolved (by redesign or modification). Each modification necessitated a change in test procedure, and it was sometimes very difficult to follow the procedure as it became more and more complex. Eventually, however, the mode III aspect of the test stopped evolving and we began to record semi-consistent results between similar specimens.

After performing exploratory pure mode III tests, I ran a pure mode I test. This yielded some disappointing results as it became obvious that there was a serious issue with the mode I fixtures; there was simply too much frictional resistance in the system and it was corrupting the recorded data significantly. Redesign was required, and although only completed on paper, Dr. Davidson and I are confident that it will greatly decrease friction and thereby improve our results.

Despite the fact that we knew that the mode I fixtures needed modification, we decided to run a proof of concept mixed mode I-III test. This test was extremely encouraging as the specimen fractured in the expected manner. Upon inspection of the specimen afterwards by ultrasonic inspection, we also found that the specimen's delamination had grown in a uniform manner (that is, evenly across the width), an indication that the specimen had indeed behaved as predicted. The proof of concept was a very encouraging development in the STB test's development, and it was at about this time that I presented our initial findings at the NE-Region 1 American

Institute of Aeronautics and Astronautics (AIAA) Student Conference where the results of our work was well received.

The initial goal of this study was to explore all possible tests that the STB set-up was capable of. As time ran short, I was limited to the tests that have already been described: pure mode III, pure mode I, and mixed mode I-III. Unfortunately, I was unable to conduct any pure mode II, mixed mode II-III, or mixed mode I-II-III tests with this fixture. Although my work has not included this aspect of the test, another undergraduate will succeed me and continue my work.

I have, however, successfully laid the foundation for others to follow. I know that Dr. Davidson, Felipe, and others will continue this project once I have left. They will bring the STB test full circle; conducting mixed mode II-III and mixed mode I-II-III tests. Eventually, the STB test (or some close derivative) may become a standard toughness test similar to those already established for modes I, II, and mixed modes I-II.

Personally, this work holds great significance. It has most certainly increased my academic aptitude and my graduate researcher potential. I have learned a great deal concerning composite materials, working under a graduate advisor, research from the student's perspective, and the opportunities available to graduate students. I have confirmed my previously held suspicion that I do want to pursue: a) graduate studies, and b) an academic position at a research university in my professional career.

Furthermore, this work has allowed me to demonstrate a long term commitment towards a singular goal. I have been able to see a conceptual sketch evolve to turn into a tangible product with tangible results and a real publishable paper. I am immensely proud of what I have accomplished and I know that I have the approval of my advisor.

I have seen my relationship with my Dr. Davidson grow from a strictly professional and formal level to one where he is truly my advisor and mentor, on a professional, academic, and personal level. My undergraduate experience has been greatly enhanced by the work that I have been able to complete in a research laboratory.