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A Nonlinear Viscoelastic Approach to Durability Predictions for Polymer Based Composite Structures

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ABSTRACT

Current industry approaches for the durability assessment of metallic structures are briefly reviewed. For polymer based composite structures it is suggested that new approaches must be adopted to include memory or viscoelastic effects which could lead to delayed failures that might not be predicted using current techniques. A durability or accelerated life assessment plan for fiber reinforced plastics (FRP) developed and documented by the author and his colleagues over the last decade or so is reviewed and discussed. Limitations to the plan are outlined and suggestions to remove the limitations are given. These include the development of a finite element code to replace the previously used lamination theory code and the development of new specimen geometries to evaluate delamination failures. The new DCB model is reviewed and results of the author and others are presented. Finally it is pointed out that new procedures are needed to determine interfacial properties and current efforts underway to determine such properties are reviewed. Suggestions for additional efforts to develop a consistent and accurate durability predictive approach for FRP structures is outlined.

INTRODUCTION

The procedure for assessing the durability of aerospace structures is well known and is based upon the concept of crack initiation due to fatigue followed by a well defined period of slow crack growth prior to catastrophic rupture [1]. With adequate da/dn testing it is possible to accurately estimate the length of time necessary for rupture and this knowledge, coupled with proper prototype inspection procedures to monitor the growth of cracks, provides information such that a structural component can be taken out of service before unsafe conditions occur. Durability concerns for polymeric structures not only include fatigue and subsequent crack growth but must also allow for the possibility of creep rupture due to the intrinsic viscoelastic or time dependent nature of the material. For such materials, crack growth due to fatigue is also affected by the viscoelastic nature of the material. As a result, assessing the durability of polymers is a much more difficult task than that for metals.

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Damage accumulation in laminated composites, regardless of whether due to fatigue or creep rupture caused by viscoelastic effects, does not occur by the formation of a single well defined crack. Rather, multiple damage processes occur simultaneously to give a damaged region which does not lend itself to an easy assessment of a critical size beyond which catastrophic rupture will occur. If through cracks transverse to the fiber do occur, da/dn and standard slow crack growth methods do work under certain conditions [2]. However, in many cases the damage and or crack growth which occurs is related to matrix dominated failure modes rather than fiber breakage. Matrix cracking or crazing, fiber matrix debonding and delaminations are examples of failure modes associated with the matrix and hence viscoelastic or time dependent processes. An illustration of a viscoelastic failure is shown in Figure 1 which gives the result of a tensile test on a [±45] crossply G/E laminate with a centrally located circular hole loaded under fixed grip conditions [3]. That is, several specimens were loaded under displacement control to different load levels at which the grips were then fixed to give a constant overall deformation. As may be observed, the applied stress relaxes significantly as a function of time. Interestingly, a relaxation-to-failure phenomena was observed and was due to the interaction of damage evolution and the viscoelastic response of the material. That is, small micro-cracks could be observed around the hole and quite apparently were present in all plies. Thus, because of the multi-phase nature of the material, cracks in internal plies could actually grow and rupture could occur as the load relaxed under fixed grip conditions. Obviously, the same phenomena could occur even if there were fibers in the principle load directions.

Industry approaches to durability of composite structures is largely related to fatigue concerns associated with fiber dominated failure modes. Matrix dominated modes as described above are evaluated through extensive testing programs under simulated environmental or life cycle testing on coupons, components and larger sections of the actual prototype structure. For present aircraft composite structural components (mostly low stressed secondary structure), the procedure used does lead to safe systems. Aerospace companies in cooperation with NASA are now planning for a new high speed civilian transport" (HSCT) which will contain large amounts of FRP materials operating at speeds as high as Mach 3.2 with resulting temperatures on the order of 700°F. Some of the skin surfaces as well as engine components will be operating at these extreme temperatures. New polymeric materials are being developed that potentially can operate at these temperatures, at least for limited times. Of course it would be desirable to have FRP material which could survive the entire design lifetime of 60,000 hours. Most likely, however, inspection and replacement of FRP parts will of necessity occur. In addition, because of the very large number of FRP parts with many different layups or fiber directions, it would be especially useful to have analytical and experimental accelerated lifetime (durability) prediction procedures which would allow the design engineer to determine in advance the likely time at which components should be replaced and to assist inspection procedures by identifying critical areas for regular inspection. The present paper outlines an approach developed by the author and his associates over the last decade or so which attempts to accomplish this objective for failures due to the viscoelastic nature of the polymeric matrix for FRP materials.

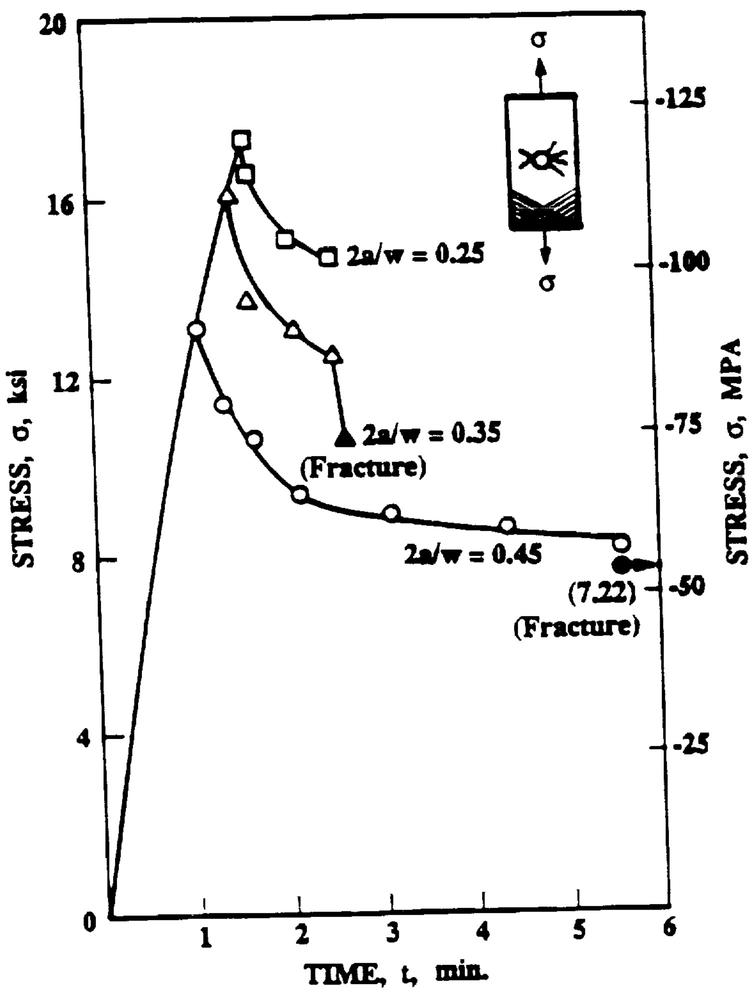


Figure 1. Delayed or Time Dependent Fracture of [± 45°]$_{4s}$ T300/934 G/E with Circular Holes

Equally important to a predictive approach is the development of test specimen geometries and measurement methods to evaluate material properties and to determine if new candidate materials are durable. Recent and current efforts in this direction will also be addressed.

Accelerated Life Prediction Plan

Obviously it is not feasible to conduct tests to determine viscoelastic compliance or failure properties of FRP materials over the intended design lifetime of a structure. Therefore a method is needed to extrapolate data developed from short term (a few hours or days) tests to long term (months or years) design information. The procedure we have used is based upon the principle that various factors such as temperature, stress, moisture, etc. accelerate deformation processes

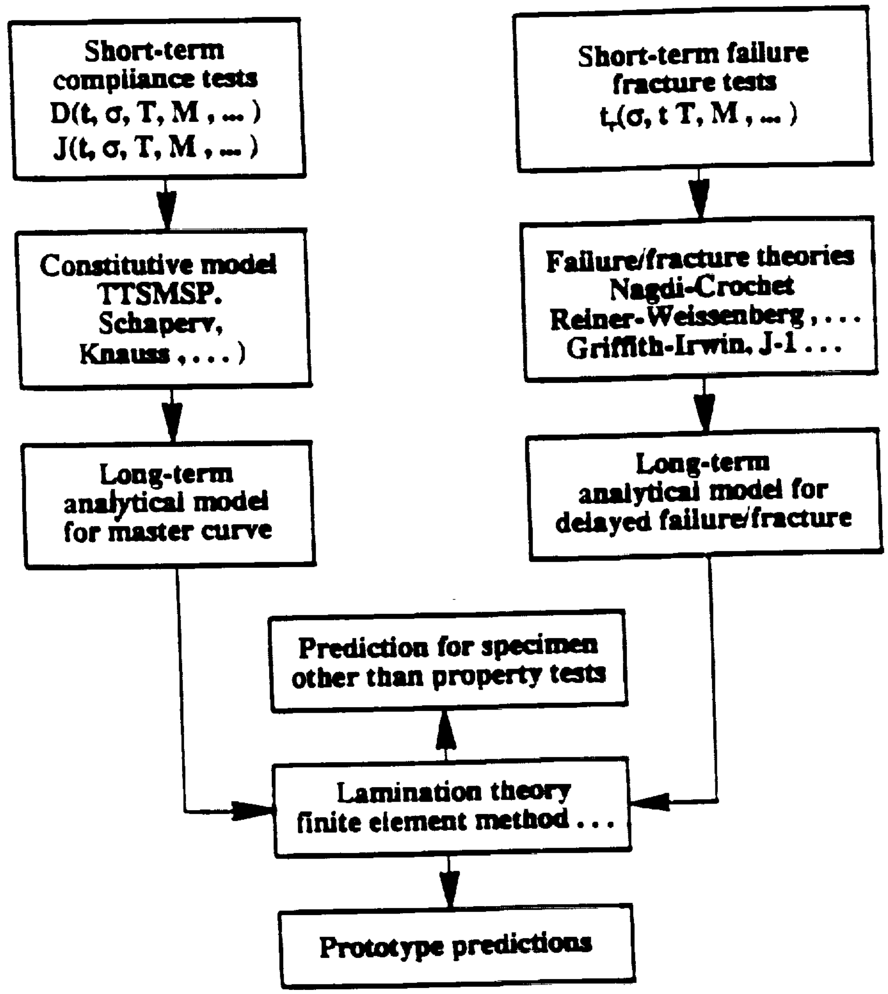


Figure 2. Schematic Of Durability Prediction Procedure

in polymer based materials. For example, the same deformation events that occur only over a long time at a low temperature will occur in a much shorter time interval at a higher temperature. A schematic of the analytical and experimental plan [4] we have used is shown in Figure 2. Short term creep tests are performed on tensile coupons of the unidirectional material with the tensile load or coupon axis in the fiber direction, transverse to the fiber direction and at ten degrees to the fiber direction. These are then fitted with a viscoelastic constitutive and failure model which allows the extrapolation of the short term data to the long term. Such a procedure is analogous to the well known time-temperature- stress-superposition-principle (TTSSP) which has been used for many years to produce "master curves" for polymers which extend over many decades of time using only short term data. The long term information so obtained can now be included in a computational model such as laminated plate theory or a finite element code and predictions of the degradation of moduli (compliances) and or failure times of arbitrary laminates can now be accomplished [4-10].

Constitutive and Failure Models

The approach briefly described above is based upon the development and use of viscoelastic constitutive and failure laws which accurately represent the shifting process of constructing long term master curves from short term creep tests conducted at different temperatures or stress levels. Experience has determined that some deformation modes of the FRP examined to be non-linear. As a result the majority of our recent efforts have used the following single integral non-linear viscoelastic relation between stress and strain.

$$\varepsilon(t) = g_0 D_0 \sigma + g_1 \int_0^t D(\psi - \psi') \frac{d(g_2\sigma)}{dt^1} dt' \qquad (1)$$

where

$$\psi = \int_0^t \frac{dt'}{a_\sigma}$$

is a reduced time parameter, ε is the strain, σ is the stress, t is time, and D is the linear viscoelastic compliance. In (1), g_o, g_1, g_2 and a_σ are non-linear parameters which must be determined by experiment. In the event that $g_o, g_1, g_2, a_\sigma = 1$, the relation then reduces to the usual representation for linear viscoelastic materials. This form of a single integral equation was first introduced by Schapery [11] and was developed on the basis of irreversible thermodynamic considerations. In his efforts and much of our work with composites, a power law was used to represent the compliance D(t). In such an approach, the additional parameters of the power law coefficient and exponent are introduced which again must be determined by experiment. Procedures for finding all parameters are well established and have been applied to a number of different types of composites [12]. Tuttle [13] performed a very careful error analysis which concluded that small errors in evaluating the power law exponent may result in large errors using equation (1) to extrapolate short term data more than one or two orders of magnitude on a log time scale. Hiel [12] has shown that these errors can be somewhat minimized by using a generalized power law. However, there is no question that attempting to fit the compliance with a single expression such as the power law likely introduces substantial errors for extrapolation to the very long term (perhaps years) needed for engineering design. For this reason, our more recent efforts [14] as well as that of others [15] has focused on the use of a prony series to represent the compliance. Equation (1) can be thought of as a mathematical representation of the time-temperature-stress-superposition-principle. For short term tests at various temperatures but at constant stress level, long term master curves can be represented very effectively. The same can be said for short term tests at various stress levels but at a constant temperature. Quite obviously, however, other parameters such as moisture effects the aging of the polymeric matrix and need to be included in any rational plan to extrapolate short term data to long times. By associating the time scale shift factor, a_σ, with free volume, Knauss [16] developed a procedure by which temperature, moisture and stress and their interrelation can be incorporated directly into the process of developing long term master curves from short term data. In our efforts to understand the effect of moisture on adhesive bonding this approach has been taken [17].

Perhaps at this point it is appropriate to note that there are many other possible representations for the relation between stress and strain for a viscoelastic material other than that given by equation (1). However, the Schapery and Knauss approaches are easily extended to three dimensions as is needed for detailed computations using either laminated plate theory or the finite element method. Further, they are firmly based upon concepts of irreversible thermodynamics as well as the observed behavior of a number of polymeric systems. More importantly, the approach can be easily applied to composites, adhesives or any polymer based system.

The failure process for polymer based materials is accelerated by the same parameters of temperature, stress, moisture, etc. as is the compliance or modulus. However, there is no accepted method of forming long term failure master curves from short term data but, needless to say, performing long term delayed failure tests for each possible composite layup over the intended life of a material would not allow the use of new materials in a reasonable time span. Further, time dependent failure theories are rare, especially for composite materials. Thus, we have elected to construct an "ad hoc" or modified Tsai-Hill orthotropic time dependent failure criterion to be used for individual lamina which can be written as,

$$\frac{\sigma_1^2}{[X(t_r)]^2} - \frac{\sigma_1\sigma_2}{[X(t_r)]^2} + \frac{\sigma_2^2}{[Y(t_r)]^2} + \frac{\tau_{12}^2}{[S(t_r)]^2} = 1 \qquad (2)$$

where the terms in the denominator are the axial, transverse and shear strengths expressed as a function of time for an individual lamina. For lamina or unidirectional materials we have used several time dependent failure laws to represent X, Y and S. For SMC (sheet molding compound), Cartner [18] used a criteria suggested by Crochet while Dillard [19] and Hiel [12] used a Zurkoff and a Reiner-Weisinberg criteria respectively for continuous fiber graphite/epoxy composites. A complete description of their approaches can be found in the cited references. Suffice it to say here that, while such a technique can be used to estimate the failure time for individual plies in a laminate and hence the failure time for a general laminate, the approach is empirical at best and gives only a crude guess of the time to failure.

The accelerated life prediction approach discussed above has been used for matrix dominated in-plane failures [19] with reasonable success but the method does not work well for fiber dominated modes nor out-of-plane matrix dominated modes. A damage evolution procedure as presented by others in the current volume is more highly developed and would be the preferred approach at the present time. Obviously, such an approached could be incorporated in to the predictive methodology outlined in Figure 2.

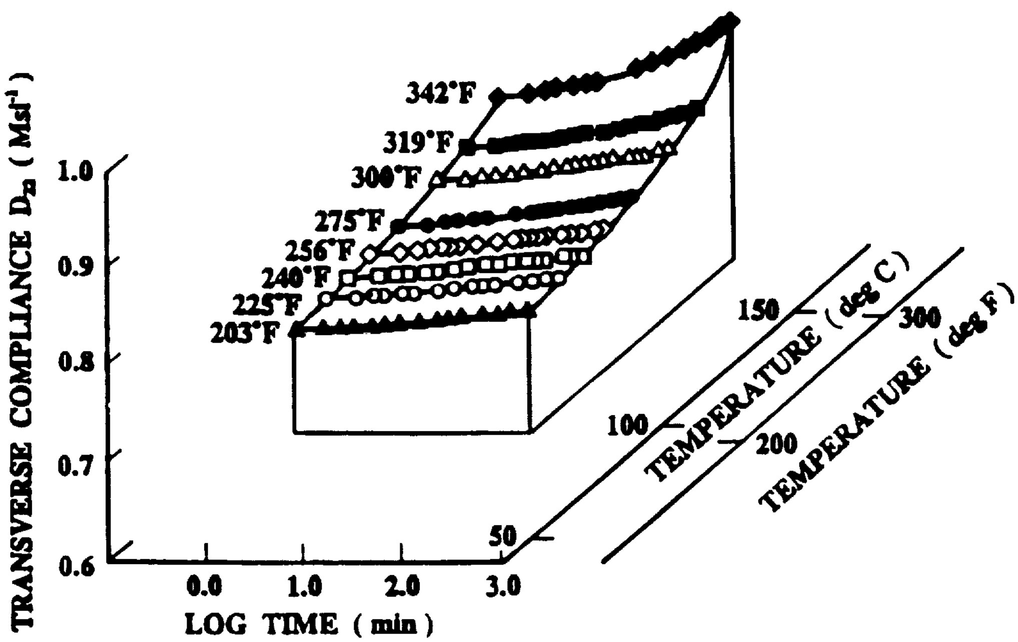


Figure 3. Transverse or D_{22} Compliance of T300/934 as a Function of Time and Temperature

Typical Results

The procedures outlined above have been used and evaluated extensively for two types of graphite/epoxy composites (T300/934 and T300/5208). In the former a large amount of testing of the resin, unidirectional materials and various matrix dominated laminates has been completed and reported [12-14, 19]. For example, Figure 3 shows the transverse compliance, D_{22}, resulting from the short term creep response of T300/934 at various temperatures [12]. This data was used to form the TTSP master curve shown in Figure 4 by the solid triangles. The solid line is the analytical representation of the master curve using equation 1. Obviously, the mathematical model can be used to extrapolate data about two orders of magnitude quite accurately. Similar tests were performed on the same material at a constant temperature but at various stress levels and TSSP master curves were again fitted with equation 1. Again, it was shown that the approach allowed an accurate extrapolation of approximately two orders of magnitude [12, 20]. Initially the following conclusions were drawn for T300/934 lamina,

- The short term bulk resin response was linearly viscoelastic.
- The short and long term axial compliance, D_{11}, was linearly elastic.
- The short term transverse compliance, D_{22}, was linearly viscoelastic.
- The short term shear compliance, S_{66}. was strongly non-linearly viscoelastic.

When the transverse compliance TTSP master curve [12] represented by the solid triangles of Figure 4 were compared to an earlier master curve [20], shown also in Figure 4 by the open circles, it was discovered that the material, while linear on the basis of the short term tests, was very definitely non-linear if comparisons were made using the developed master curves valid for a time scale of about a week. Subsequent testing of a new bulk resin, FM 300, often used in adhesive applications confirmed this result [21]. Thus, it would appear that short term creep testing only as a function of temperature may lead to erroneous conclusions and non-conservative results as illustrated by the data in Figure 4. It suggests that the transition from linear to non-linear behavior is also a function of the stress level. That is, at sufficiently high stress levels, polymer based composites are non linear even for very short creep time as we might expect but, for very low stress levels, non-linearity is not apparent except over very long times. Thus, if design is accomplished using only short term data at low or moderate stress levels, non-conservative results are likely to occur. The conclusion is that creep testing should be accomplished with unidirectional materials at a large number of stress, temperature, moisture, etc. levels in order to be sure that proper mathematical models (linear or non-linear) are being used in design.

Tuttle [13] and Gramoll [14] have used the procedures outlined above to evaluate the response of T300/5208 graphite/epoxy and Kevlar 49/Fiberite 7714A epoxy laminates. Tuttle conducted very careful long term tests of about three months duration and verified that the accelerated prediction plan works well to predict response over this time scale within the limitations of the mathematical model. His results does indicate that the use of a power law to fit the linear viscolelastic compliance will likely lead to substantial errors in predicting response for times more than two orders of magnitude longer than the measured short term data. Gramoll modified the incremental time dependent lamination theory algorithm in the plan shown in Figure 2 and also made very careful measurements to predict the long term response of glass/epoxy laminates from short time data. Unlike graphite/epoxy laminates, not surprisingly, he found that the axial compliance, D_{11}, to be time dependent or viscoelastic. Again, he was able to well predict matrix dominated laminate creep behavior for a period of time about two orders of magnitude longer than the short term lamina data. Examples of the comparison between prediction and experiment are shown in Figure 5.

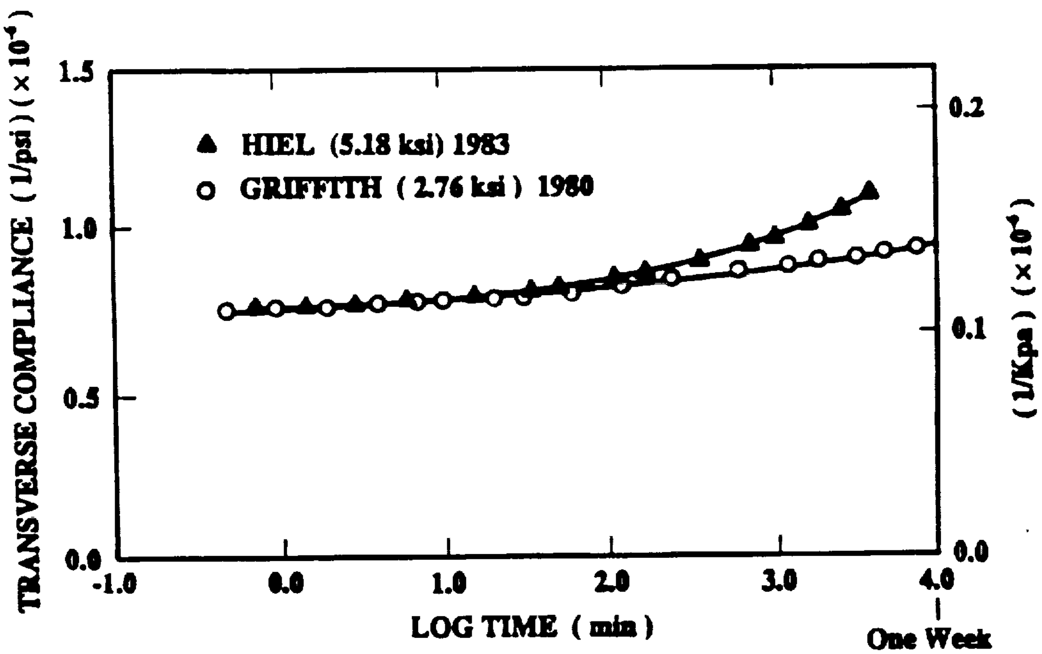


Figure 4. Comparison of Transverse Compliance Versus Time for Moderate (2.76 Ksi) (19 Mpa) and High (5.18 Ksi = 35.7 Mpa) Stresses

Limitations

The basic plan outline above and shown in Figure 2 has been shown to be an excellent approach for the accelerated life or durability predictions of those deformation events caused by the viscoelastic behavior of the polymeric matrix. That is in-plane matrix dominated time dependent deformations are well predicted by this approach within the limitations of the mathematical models used. There is no doubt in the author's mind that improvements to the mathematical constitutive and failure models such as extension to large deformations, rotations and strains as well as the use of a prony series to fit the linear viscoelastic compliance would allow the extrapolations necessary for realistic design. However, most composites are currently designed to be fiber dominated or to have fibers in the major principle load directions and the lamination theory computational procedure currently used on our predictions also tends to emphasize fiber dominated properties. Thus, as long as fibers are present in the directions of the principle external loads, experience has shown that our procedures indicate time dependent failures will occur only if fibers fail. This leads to very long failure times especially when graphite fibers are present and, unfortunately, does not represent some of the failure modes that are more likely to occur in a short time. Such modes are related to the failure of the matrix which is most likely to occur at the free edge of a composite plate, at bolted or bonded joints or at any time out of plane deformations are likely. Thus, it now appears that strong consideration should be given

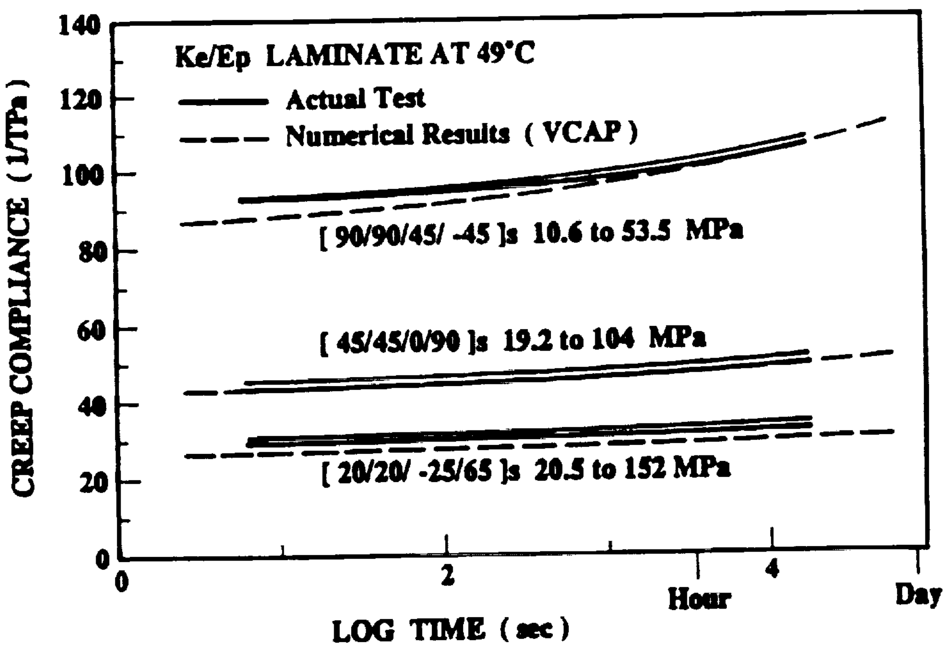


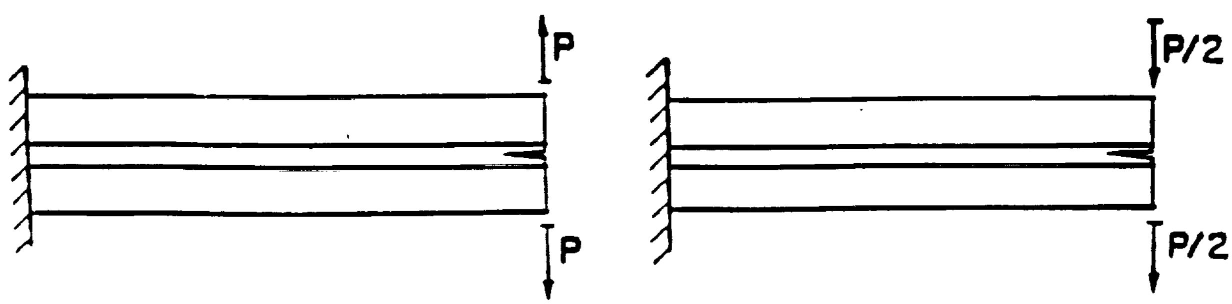
Figure 5. Numerical Predictions and Actual Test Results

to the development of both analytical and experimental techniques that can properly quantify and model out of plane deformations which will lead to time dependent delamination failures. It is the opinion of this author that both moisture effects and fiber matrix effects will be of great importance in properly evaluating out-of-plane failures by delamination. The next section will outline a specimen geometry which it is felt will be useful in evaluation the effects of stress, temperature and moisture on delamination failures and may also prove useful in providing an approach to quantify ply debonding and/or associated fiber matrix debonding properties. The analytical approach to design composite structures of necessity, it is felt, will be a fully three dimensional finite element procedure. Much progress has already been made in the development of a FE code NOVA (Nonlinear Viscoelastic Analysis) which incorporates both the Schapery and Knauss constitutive models and the Reiner Weisenberg failure law [22]. A unique stress assisted moisture diffusion model developed by Lefvebvre [17] is included in NOVA which permits a solution for a coupled moisture-stress boundary value problem. The approach has been used principally for metallic adhesively bonded joints but can be used to analyze composite structures or adhesively bonded composite/metallic structures.

It should be pointed out that new techniques and procedures are emerging which could greatly simplify the process of developing master curves or of extrapolating short-term data to the long-term. For example, Brinson [15] has shown that multi-phase materials such as composites are thermorheologically complex rather than thermorheologically simple and that master curves over the entire response domain cannot be developed in the usual manner. She has shown, however, that proper master curves can be found knowing only the viscoelastic response of the separate phases provided that interfacial properties are known. Very likely, these new methods could be adapted to the techniques described herein.

A DCB SPECIMEN GEOMETRY FOR PURE SHEAR DEFORMATIONS

As indicated in the last section, it is felt that most premature time dependent failures are related to matrix dominated deformation modes and the bulk of these are related to delaminations which occur due to the development of out-of-plane stresses at free boundaries, ply drop-off locations and at bolted or adhesively bonded connections. The Double Cantilever Beam Specimen (DCB) shown in Figure 6a has long been used to determine the fracture toughness associated with mode I delaminations of both composite and adhesively bonded structures. However, more recently Bradley and others have used this specimen to gain insight to mode II delaminations of composites [23] where the loading is as shown in Figure 6b. Brinson, Moussiaux and Cardon [24] have shown that the same specimen can be used effectively to determine the shear modulus and fracture properties of adhesive joints when no crack is included at the end. The following sections describe this latter use and introduces a new measurement procedure to quantify *in situ* mechanical properties using the DCB specimen.



a) Mode I Loading b) Mode II Loading

Figure 6. Double Cantilever Beam for Modes I and II Delamination Studies

DCB Specimen for Adhesive Shear Property Determination

Moussiaux [24] developed an elementary strength of materials solution for stress distribution in the adhesive layer of the beam shown in Figure 6b but without a crack at the end. The state of stress is shown to be pure shear and is given by the following equation,

$$\tau_{xy} = \frac{P}{b\gamma^2(h+2t)}[1 - \cosh\bar{\alpha}x/\gamma + \tanh\bar{\alpha}\sinh\bar{\alpha}x/\gamma] \qquad (3)$$

where

$$\bar{\alpha} = \alpha\gamma,\ \alpha^2 = \frac{3G}{E}(l/h)^2\frac{(1+2\,t/h)^2}{t/h},\ \gamma^2 = 1 + \frac{1}{3\,(1+2\,t/h)^2}$$

and where τ_{xy} is the in-plane shear stress, P is the applied load, E and G are the Young's modulus of the adherend and the shear modulus of the adhesive layer respectively, l is the beam length, h is the adherend thickness, b is the specimen width and t is the adhesive thickness. By optimizing the specimen dimensions, the shear stress can be made to be independent of the properties E and G and the shear stress becomes nearly uniform over the entire the entire length of the specimen. This circumstance is convenient for experimental investigations as the shear stress can be calculated with only knowledge of the load magnitude and the specimen dimensions and, therefore, by measuring the shear strain in the adhesive layer, the shear modulus can easily be determined. The non-dimensionalized stress distribution is given in Figure 7 for several values of the parameter $\bar{\alpha}$. Also shown in Figure 7 is a comparison of the stress as given by equation (3) and that obtained using the finite element code NOVA discussed briefly previously. As may be observed excellent agreement is obtained except near the end where the size and aspect ratio of the elements become important. With a sufficient number of elements the perturbations from uniformity would be minimized and occur only over a very small region. However, a discontinuity must occur in the finite element approach at the end because of the imbalance of stresses at the interface between the adherend and the adhesive.

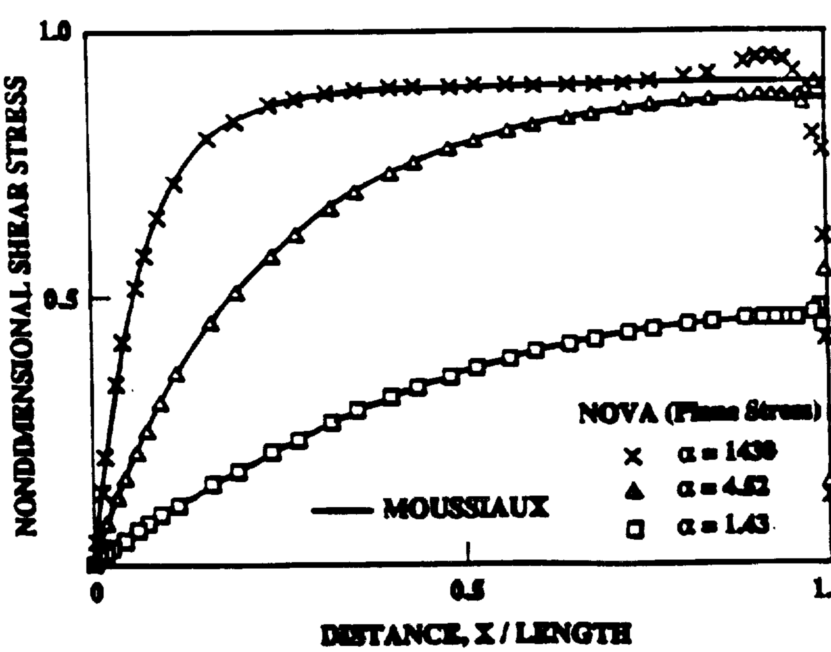


Figure 7. Comparison of DCB Shear Stress from Moussiaux and NOVA Analyses

Moussiaux also obtained a solution for the end deflection of the beam to be,

$$\delta = \beta \frac{P\gamma^3}{2Eb(h+t)^3} \tag{4}$$

where

$$\beta = (1+t/h)^3 \left\{ 4\left(1-\frac{1}{\gamma^2}\right) + \frac{3E}{G}(h/l)^2 + \frac{12}{\gamma^2}\left[\frac{1}{\bar{\alpha}^2} - \frac{1}{\bar{\alpha}^3}\tan\bar{\alpha}\right]\right\}$$

and all other quantities are as previously defined. Deflections as given by equation (4) were compared with those of NOVA and are shown in Figure 8. Quite obviously the elementary solution is quite accurate and the end deflection can be used as a means of determining the adhesive shear modulus.

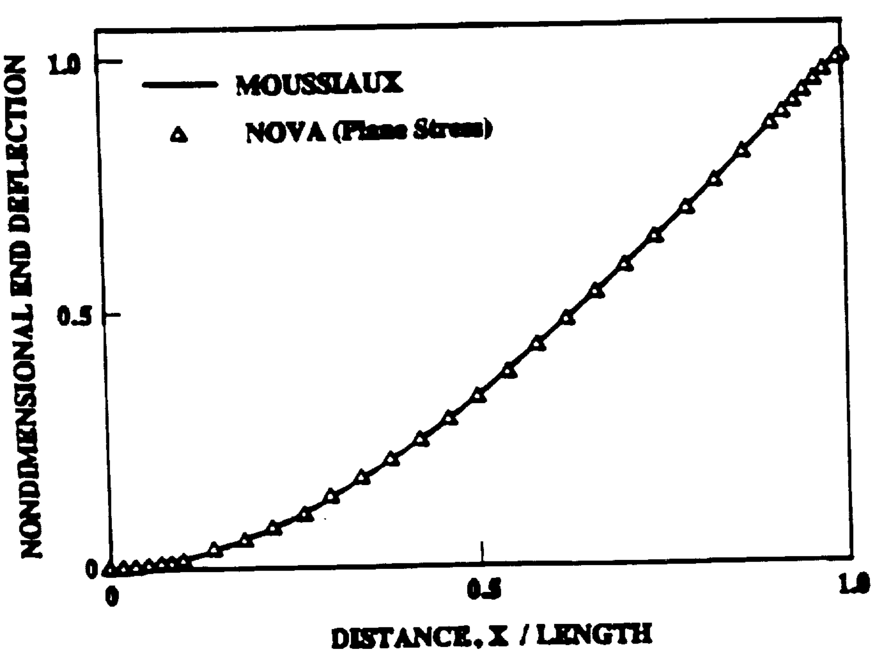


Figure 8. Comparison of DCB End Defelection from Moussiaux and NOVA Analyses

Fior [25] performed an optimization study to determine the appropriate beam dimensions for making both strain and deflection measurements to determine the adhesive shear modulus for different classes of adhesives. She also performed experiments to validate the theory represented by Equations (3) and (4) using aluminum and steel beams bonded with both elastomeric and epoxy adhesives. Figure 9 shows the comparison of theory and experiment using strain measurements within the bond line and Figure 10 shows the comparison between theory and experiment using end deflections. As can be observed, close correlation was obtained.

Moussiaux's analysis assumes that both the adhesive and the adherend is linear elastic, but the solution can be extended quite easily to that on a linear viscoelastic adhesive and an elastic adherend using the correspondence principle. The real value of the approach may be its extension to the non-linear viscoelastic case where it is felt that it would be possible to develop a relatively simple but accurate closed form solution. This specimen should then become very useful in evaluating the pure shear properties of non-linear viscoelastic materials.

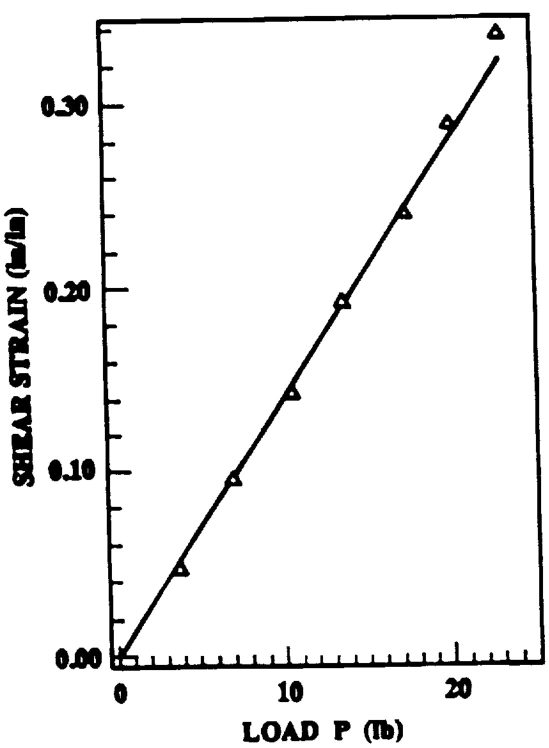


Figure 9. Comparison of Bond Line Strains from Theory (Symbols) and Experiment (Solid Line)

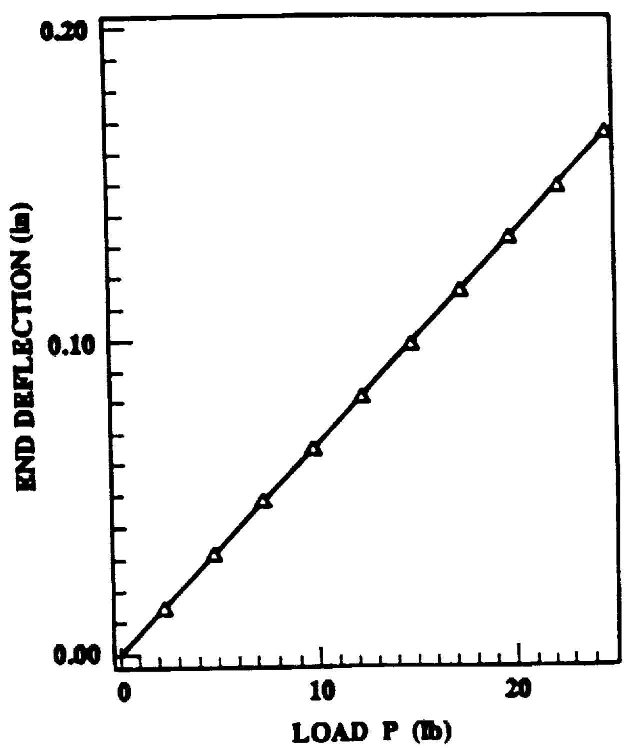


Figure 10. Comparison of End Deflection from Theory (Symbols) and Experiment (Solid Line)

Moussiaux has adapted the solution for the circumstance with three layers of unequal thickness between the two adherends raising the interesting possibility of evaluating interfacial properties under pure mode II loading [26].

It should be noted, of course, that the results of this section, while developed for a DCB (cantilever beam), can also be used to evaluate the stresses, strains and deflections in a beam in three point bending. Thus, the entire experimental procedure is greatly simplified, and it is suggested that the measurement of strains or deflections in a three point bend specimen might represent a useful test for industry in screening materials to evaluate relative durability of new materials from a viscoelastic or creep standpoint. It should also be pointed out that this approach is very different from the usual short beam shear test as the equations are different and, in fact, the beam no longer needs to be short (see references [24-25] for a discussion of optimum dimensions).

DCB Specimen for FRP Mode II Delamination Studies

Hiel [27] has developed a solution for thick laminated composite plates using a method of Biot [28] which is similar to the approach taken by Moussiaux. He has demonstrated that simple closed-form solutions are obtained for interlaminar shear stresses and plate deflections. He has also shown that his solution, and that of Moussiaux, are in close agreement for the case of a bonded beam as well as each agreeing with measurements of deflections by others.

As indicated earlier, Bradley [23] has used the DCB specimen shown in Figure 6 (or its three point bend counterpart) to study the mode II fracture behavior of a modified epoxy resin and two graphite/epoxy laminates, one with a rubber toughened matrix and one with a brittle matrix. His efforts have produced interesting observations about the fracture mechanisms associated with crack growth for both modes I and II. As described in the next section, he has developed a unique technique to measure the strains between plies directly in the form of a crack in a scanning electron microscope (SEM). As a result, he has been able to directly measure fracture energies associated with a pure shear stress field in front of a delamination between plies and to compare the relative fracture energies of brittle and rubber toughened matrix materials.

A New Measurement Technique for the *In-Situ* Measurement of Local Interlaminar Shear Properties

Quite obviously, the measurement of beam or plate deflections using the analytical approaches described above leads to a simple technique to evaluate the pure shear properties of adhesives or composites and represents an expedient possible approach for industry to use in evaluating the creep or viscoelastic behavior of new materials, and, hence, estimating their durability. However, it would be beneficial to have a measurement method which could determine the local interlaminar tensile and shear strains between plies or in the adhesive layer between bonded parts. This would lead to a more direct determination of the relation between stress and strain and would be the preferred method for the non-linear viscoelastic case. Bradley [23] has developed a new measurement procedure to accomplish this result on *in-situ* measurements in an SEM. The approach uses the electron gun of the SEM to burn a small hole in the gold palladium coating normally placed on a composite to be able to observe features in the SEM. A series of holes or a "dot map" is placed on the surface of a composite over the region of interest. The relative locations of the dots before and after deformation are determined using an image analysis system which provides the necessary information to determine strain fields. If the stress field is also known using the analyses described herein, then a simple method is now available to determine local properties. In his efforts to date, Bradley has used holes of about one micron diameter and a spacing of about 5-10 microns. However, he has demonstrated that it is possible to make holes (actually, small blisters, in this case) of about 1/10th of a micron in diameter in a spacing of about 1/2 micron. Currently, Bradley and the author are collaborating to attempt to make even smaller dots with an even smaller spacing. This approach is being used to measure the strains in an adhesively bonded butt joint (poker chip or button specimen) at the juncture of the adhesive and adherend at the free edge. As is well known, a singular stress field exists at this location due to the mismatch in material properties. By using a very small dot map, it is felt that there is the possibility of measuring the strength of the singular zone and, perhaps, obtaining an estimate of the properties of the interphase layer. If the approach is successful, then it is anticipated to next measure the interlaminar strain fields in laminated beams and plates and to use the analysis in the previous section to determine the pure shear stress fields. Thus, an approach is at hand to directly measure interlaminar shear properties, perhaps even in the interphase region for either bonded metallic/composite plates or between fiber and resin.

SUMMARY AND CONCLUSIONS

An approach developed by the author and his colleagues to determine the life (durability) of an FRP structure due to the intrinsic viscoelastic response of the individual lamina has been presented. The approach is based upon the use of analytical models to extrapolate short-term compliance data to the long-term, or to fit master curves as developed using time-temperature-stress-moisture-superposition-procedures. It has been shown that non-linear viscoelastic constitutive approaches are essential in order not to have non-conservative predictions. Both the Schapery and the Knauss analytical approaches have been embedded in a lamination theory (VCAP) and a finite element (NOVA) computational method to determine the response of laminated composite structures. Experimental data was presented which verifies that the constitutive models can be used to extrapolate data about two orders of magnitude with good accuracy. Further, the incremental computational approach using the lamina master curves give a good prediction of actual laminate response for matrix dominated deformation modes. This has been verified for graphite/epoxy and kevlar/epoxy structures.

Limitations to the predictive approach are given, and it was pointed out that the procedures work well for in-plane matrix dominated deformation modes but not for out-of-plane modes such as delaminations associated with free edges, connections, ply drop-offs, etc. For that reason, it is suggested that the NOVA finite element computation approach needs to be further developed to handle out-of-plane loading modes.

A new DCB specimen was introduced which provides a simple procedure to determine interlaminar shear and fracture properties for bonded beams and thick composite plates. Comparisons between the new theory, NOVA, and experimental measurements were given. It was pointed out that the same approaches could be used for adhesively bonded or composite plates in three point bending and would avoid the controversy surrounding the short beam shear test. As such, the new method would represent a simple approach for industry to use as a means of assessing the relative merits of new materials with regard to durability caused by the intrinsic viscoelastic response of the resin.

A new method to measure or quantify local interlaminar strains was briefly described. The method has been used by others to determine the interlaminar fracture energies associated with modes I and II delaminations. The technique is currently being used to attempt to quantify the singular strain field in a button or poker chip specimen and perhaps to gain insight to the determination of the mechanical properties of the interphase region between adhesive and adherend or fiber and resin.

The basic scheme as outlined in Figure 2 has been shown to be valid for estimating the durability of FRP structures as related to viscoelastic effects for in-plane loadings. By incorporating information for mode I and mode II delamination, as obtained from the new DCB specimen, it is felt that out-of-plane failures can now be estimated quite well, but that remains to be illustrated. It is certainly necessary to also include in our computational and experimental investigations fatigue crack or damage growth procedures as discussed by others in the current volume. The author is convinced that this can be accomplished in a reasonable time frame and that a procedure is at hand by which an engineer can, at the moment of initial design, estimate the life of composite component parts and thereby provide a rational basis for their timely removal from service using careful inspection procedures such that composite structures will indeed be durable.

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