# APPLICATION OF COHESIVE ZONE MODELS TO FATIGUE AND FRACTURE IN COMPOSITES AND ADHESIVE JOINTS

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## ABSTRACT

Cohesive zone models (CZM) have been applied to a range of fracture and fatigue problems in the delamination of composites and the fracture of adhesive joints. Specific problems include the bridging of delamination cracks in composites and adhesive joints by oblique fibers, the influence of ductile materials in adhesive joints, and the bridging of cracks in the metal layers of fiber-metal hybrid laminates by intact composite plies. In all cases a non-linear traction law is applied to the crack faces in the wake of the crack tip. The resulting crack-tip stress intensity factor or strain energy release rate is equated to a fracture or fatigue crack growth criterion in order to predict crack propagation. Data is presented in the form of R-curves, load-displacement graphs or fatigue crack growth da/dN curves. In the present work the distinction is made between phenomenological and physically-based models, based on the degree of independent calibration and verification applied, which provides physically-based models with increased predictive capability, beyond the data set on which they were calibrated. A brief overview of the individual models is provided, and the physically-based and phenomenological approaches are compared and contrasted.

## 1 INTRODUCTION

Cohesive zone models (CZM) have proven to be very capable for modeling non-linear fracture problems in which toughening processes act near a propagating crack tip. Such models are relatively easy to implement, and are compatible with finite element codes. The present author has experience in formulating such models for a wide range of problems, including delamination in polymer [1, 2] and ceramic matrix composites [3], fracture of polymer adhesive joints [4], metal thermocompression bonds [5] and solder joints [6,7]. In addition attempts have been made to develop CZMs for the growth of facesheet cracks in fiber-metal hybrid laminates [8,9] and for the failure of woven fiber-composite facesheets in honeycomb sandwich panels containing through-thickness holes [10,11]. In addition, some of these models have been developed to address fatigue crack propagation and the effects of varying temperature [1, 2, 6, 7, 8, 9]. These models have had varying degrees of success in meeting their intended purpose. In part, the success, or otherwise, of a CZM modeling scheme is strongly related to the extent to which the models have a sound physical basis, and this provides a useful means of classifying CZM's.

A physically (or mechanism-based) model is one in which the actual processes (in this case the mechanism providing cohesive forces between the crack surfaces) are explicitly modeled. In such cases it should be possible to measure independently the CZM parameters, and the model has predictive capability beyond the range of measurements on which it was calibrated. This contrasts with a phenomenological CZM in which the cohesive zone properties are adjustable parameters whose value cannot be independently measured, and which only allow interpolation within the data set on which they were calibrated.

This paper reviews the key features of the CZM's formulated in references [1-11], and identifies common features from the relative success of the individual models.

## 2 PHYSICALLY-BASED COHESIVE ZONE MODELING

The most straightforward physically based cohesive zone models are those associated with the modeling of fiber bridged cracks. Initial work was performed for cracks bridged by orthogonal fibers [13], which built on the earlier work of Dugdale [14] and has been adapted by many others for particular situations. The approach consists of ascribing non-linear spring properties to the bridging fibers in the crack wake which results in a traction-separation law acting between the surfaces of the crack. The bridging fibers result in a crack-closing stress intensity factor, which can be superimposed on the applied opening stress-intensity factor in order to calculate the effective stress intensity factor acting at the crack tip. This can then be equated to the matrix fracture toughness, in order to determine the form of the resulting R-curve. In general solution of problems of this type requires use of a numerical method approach to circumvent the integral equation resulting from the coupling of the closing traction to the crack opening displacement.

The approach outlined above can be applied directly to the case of delaminations in unidirectional composites bridged at oblique angles by fibers as shown in figure 1 (1, 3), and bridged cracks in adhesive joints (4). The non-linear spring parameters are generally calibrated by fitting to the measured R-curves from fracture tests. However, they can also be independently estimated by knowledge of the bending and shear stiffness of the bridging fibers (3). Additional independent calibration can be achieved by performing *in situ* measurements of the crack opening displacement profile in the wake of the crack (1, 3). Once thus calibrated such models can provide useful insights into the key elements of the bridging phenomena, such as the sensitivity to specimen geometry (large scale bridging effects) and the dependence of the fracture response on the particular form of the bridging traction law. More recent, additional work, illustrated in Figure 2, has allowed the extension of the modeling approach to predict the crack growth response in fatigue loading, and the sensitivity of the response to test temperature (1, 2), which opens the possibility of using damage tolerant design approaches to design large composite structures against fatigue delamination.

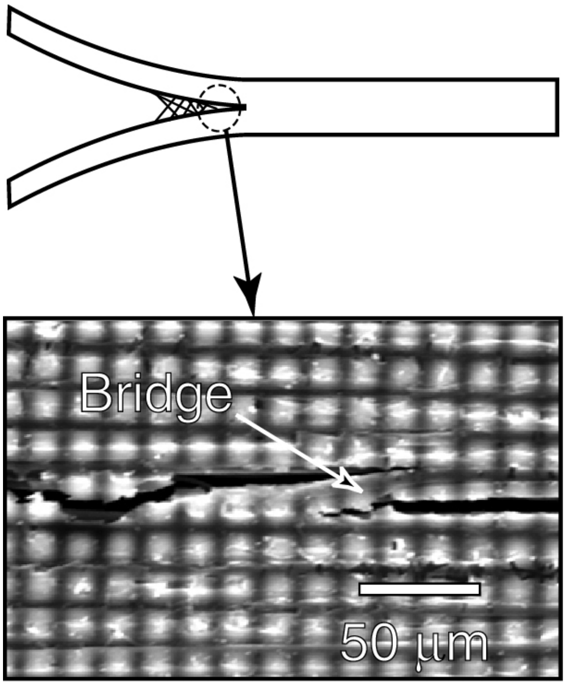

Figure 1  Schematic and micrograph of oblique angle bridging by fibers in a carbon-fiber composite DCB specimen.  The micrograph has an overlaid-grid used for in-situ strain mapping, an independent calibration of the bridging traction law parameters used in the CZM (1)

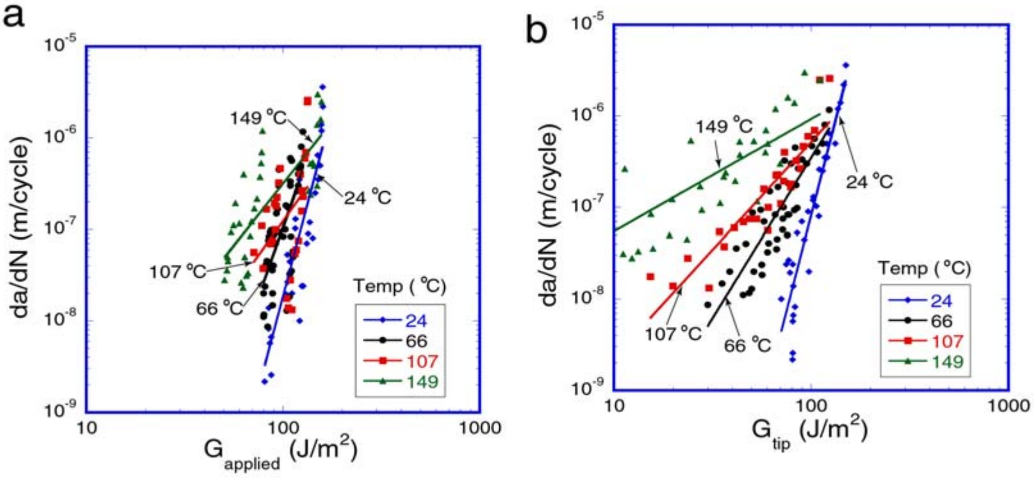

Figure 2 Model results for fatigue delamination growth in a unidirectional carbon-fiber epoxy composite. a) crack growth rate vs. nominal applied strain energy release rate. b) data replotted vs. crack tip strain energy release rate computed using a physically-based CZM. Trends with test temperature are clearly identified in b. (2)

## 3 PHENOMENOLOGICAL COHESIVE ZONE MODELING

The conceptual framework for phenomenological cohesive zone models is identical to that used for physically based ones. The difference is that no attempt is made to independently verify the bridging traction parameters used in the CZM. This limits the predictive capability of the model, but does not necessarily prevent it from providing insight as to the key parameters governing the physical reality being modeled. However, in some cases such an approach can result in a misintepretation of the underlying mechanisms.

An example of a phenomenological cohesive zone model is that developed to understand the delamination fracture of silicon wafers bonded together by thermocompression with a thin (1.8 μm thick) gold adhesive layer. The bonds were discontinuous, to mimic the typical discontinuous bond used in packaging or interconnect schemes. A schematic of the various bond configurations is shown in figure 3. A phenomenological CZM was constructed with a physically-unfounded non-linear traction-displacement model [5]. Despite the lack of an independent validation of the parameters used in the model, it provided useful insight as to the role of the discontinuous bond, and local variations in the toughness of the bond on the observed “saw tooth” load displacement curves during fracture testing. Example simulated load-displacement curves are shown in figure 4.

These observations in turn have allowed the sources of local toughness variation to be identified. It is important to note that the primary purpose of this modeling effort was to identify the key trends and parameters, rather than to achieve an absolute predictive capability. In principle a greater physical basis could be achieved if direct independent calibration of the load-displacement behavior was undertaken.

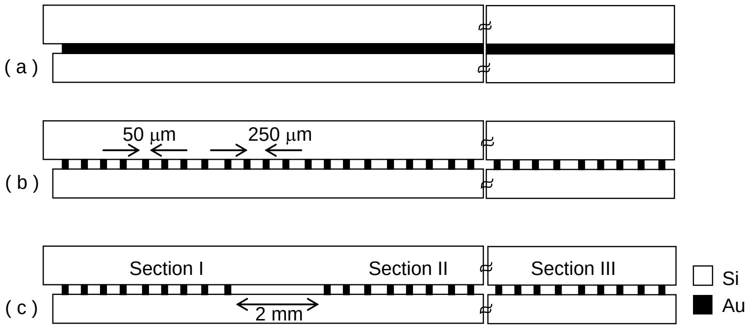

Figure 3 Schematic of continuous, discontinuous, and uneven discontinuous gold thermocompression bonds between silicon substrates.

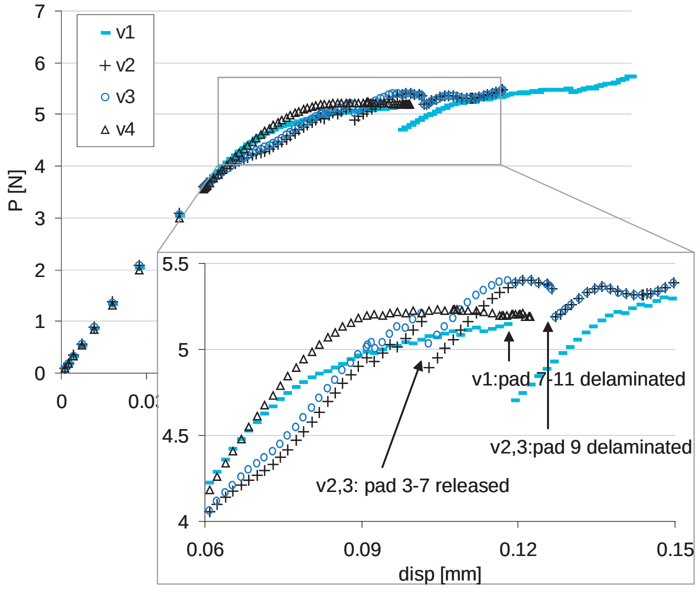

Figure 4. Simulated load-displacement curves for the delamination fracture of specimens such as those shown in figure3. The different behaviours correspond to variations in the toughness distribution between bonding pads.

A second example of a phenomenological CZM is that developed to model the fatigue response of solder joints under thermal cycling, and an analogous piezomechanical loading. The model includes an internal damage parameter which alters the CZM parameters with accumulated load cycles [6]. The model was fitted to literature data for lead-tin eutectic solders under thermal cycling, and successfully described the response of the same solder under piezomechanical loading [7]. In this case, since the joint geometry and solder material were common to the calibrating and predicted cases, the model was not required to work beyond the range over which it was calibrated. Nevertheless this approach provides a useful means to make solder fatigue data transportable between different joint configurations and loading conditions. The modeling approach has the potential to bridge the lengthscales of the macroscale processes involved in the fatigue of the overall joint and the thermal and loading environment, with the microscale processes of material degradation and fatigue crack initiation. The use of a numerically robust CZM can allow for the almagamation of a fracture mechanics approach, with its implicit geometric discontinuity and stress singularity with a continuum mechanics modeling framework. Furthermore, by direct observation of the strain fields within the solder, it should be possible to increase the physical basis.

Finally, An attempt was made to use a CZM to model the growth of facesheet cracks in a titanium-graphite hybrid laminate subject to fatigue loading [8,9]. In this case the fatigue cracks in the titanium are bridged by the intact graphite fiber composite plies, with an accompanying delamination between the titanium and the composite. Attempts were made to fit a CZM to the fatigue crack growth data. However, regardless of the CZM parameters chosen, a poor fit was achieved, and the model was unable to describe the effects of changing the laminate stacking sequence and specimen geometry. Further modeling efforts showed that a full 3-D or quasi-3-D (superimposed 2-D models) was required in order to adequately describe the crack tip stress intensity factor. The key omission from the CZM was that the crucial lengthscale in the problem was the thickness of the titanium plies, rather than the crack length, so fitting the model to crack growth data, using the crack length as the controlling dimension produced erroneous results.

## DISCUSSION AND CONCLUDING REMARKS

The foregoing examples, although only briefly described, provide some indication of the utility of CZM models. In all cases they have provided useful insight as to the key parameters affecting the fracture response of laminated engineering materials and components. In some cases it has been possible to link multiple factors, such as the fracture and fatigue response, or the interaction of temperature changes and mechanical loading. In these cases physically-based models are particularly powerful as they capture the underlying mechanisms responsible for the failure and degradation processes. Even for cases in which constructing a physically-based CZM is not possible, phenomenological models can provide useful insights as to the sensitivities of the structural response to geometric or loading factors, or simply to make test data portable between geometries and loading cases.

The distinction between physically-based and phenomenological models may be viewed as somewhat arbitrary, given that additional physical basis can be often be added by further testing in order to independently verify the cohesive zone parameters used in the model. However, the absence of a physical basis may leave the model prone to inaccuracies if attempts are made to extrapolate beyond the range over which it was calibrated. Furthermore, key dependencies or changes in mechanism may be missed, leading to non-conservative predictions. These limitations should prompt developers of CZMs to seek to increase the physical basis by using independent means to validate the chosen CZM parameters.

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