

## DAMAGE PROGRESSION BY THE ELEMENT-FAILURE METHOD (EFM) AND STRAIN INVARIANT FAILURE THEORY (SIFT)

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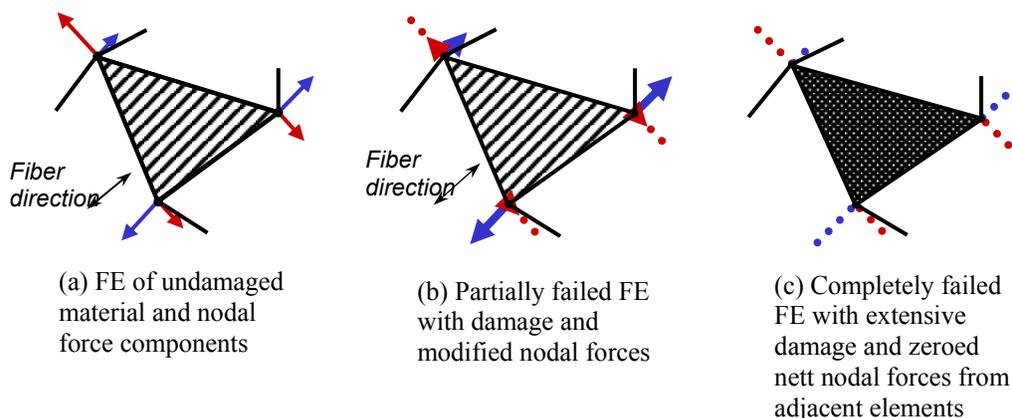
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**Summary** The element-failure method (EFM) is a novel finite element-based method for the modelling of damage, fracture and delamination in fibre-reinforced composite laminates. The nature of damage in composite laminates is generally diffused and complex, characterized by multiple matrix cracks, fibre pullout, fibre breakage and delaminations. It is usually not possible to model or identify crack tips in the conventional fashion of fracture mechanics. The central idea of the EFM, on the other hand, is to model the damaged portions with partially failed elements, whose nodal forces have been modified to take into account the local damage modes. This has the additional benefit of unconditional computational stability compared to other methods such as material property degradation (MPD) models. Here, we present the application of EFM with a recently-proposed failure criterion called the Strain Invariant Failure Theory (SIFT) in the prediction of damage progression in a composite laminated structure, and show that the damage patterns are in very good agreement with experiments. It is also shown that the EFM is more versatile and general than the MPD method.

### ELEMENT-FAILURE METHOD (EFM) FOR COMPOSITES

The central concept of the EFM for fiber-reinforced polymeric composites is that the effects of damage on the mechanical behaviour can be essentially described by the effective nodal forces of a finite element (FE). The manner by which these effects of damage translate to the effective nodal forces will in general depend upon the damage evolution law appropriate to the local mode of damage experienced by the composite material, as well as the FE formulation. For the purpose of illustration, consider an FE of a virgin (undamaged) composite material (Fig.1 (a)), experiencing a set of nodal forces. Suppose damage in the form of transverse matrix microcracks are formed (which may or may not be uniformly distributed within the FE), the load-carrying capacity of the FE will be compromised, very likely in a directionally and spatially dependent manner (Fig.1 (b)).

**Fig.1 The element-failure or force modification method**



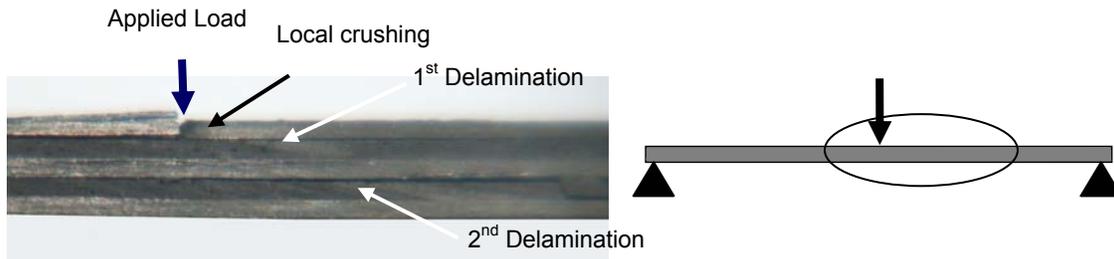
In conventional material degradation models, this reduction in load-carrying capacity is achieved by reducing or zeroing certain pertinent material stiffness properties of the damaged finite element. In the EFM however, the reduction is effected by applying a set of *external* nodal forces such that the *nett internal* nodal forces of elements adjacent to the damaged element are reduced or zeroed (the latter if complete failure or fracture is implied (Fig.1 (c))). The decision whether to fail an element is guided by a suitable failure theory and in each step, only one or two elements are failed at a time. The “correct” or required set of applied nodal forces to achieve the reduction within each step is determined by successive iterations until the nett internal nodal forces (residuals) of the adjacent elements converge to the desired values. Typically, less than 20 iterations are required and convergence is guaranteed. Note that it is not the internal nodal forces of the damaged element that is zeroed (for the case of complete failure (Fig.1 (c))), but the nett internal nodal forces of adjacent elements. Thus the “stresses” within the failed element no longer have physical meaning although compatibility may be preserved. This process leaves the

original (undamaged) material stiffness properties unchanged, and is thus computationally efficient as every step and iteration is simply an analysis with the updated set of loading conditions at the nodes. In contrast to the MPD method, computational stability is always guaranteed, as the stiffness matrices are untouched.

**DAMAGE PROGRESSION IN A THREE-POINT BEND SPECIMEN**

The EFM is used to analyze a  $[0_3/90_3/0_3/90_3/0_3]$  graphite-epoxy laminate under three-point bend test until failure (Fig.2). Shortly after the maximum load is attained, damage propagated rapidly, resulting in final failure. The first sign of damage occurred in the form of local crushing of the first  $0^\circ$  plys near the point of application of load and the growth of the first delamination at the interface between the first ( $0^\circ$ ) and second ( $90^\circ$ ) layers. This is rapidly followed by the initiation and growth of the second delamination at the interface between the third ( $0^\circ$ ) and fourth ( $90^\circ$ ) layers. Here, the layers are referred to consecutively from the top surface; each layer consists of 3 plies of unidirectional tape. After the second delamination has propagated some distance to the right, it kinks into the fourth ( $90^\circ$ ) layer and continued along the interface with the fifth ( $0^\circ$ ) layer.

**Fig.2 The three-point bend test and damage in specimen**



The predicted progressive damage pattern is shown in Fig. 3. The qualitative agreement with the observed experimental damage pattern of Fig. 2 is remarkable. It is seen that the EFM coupled with the new micromechanics-based failure theory SIFT, is able to predict the local crushing in the top  $0^\circ$  layer, as well as the first delamination near the interface of the first and second layers. It is also able to predict the onset of the second delamination, although the position at the interface of the fourth and fifth layers is not quite correct.

**Fig.3 Predicted damage pattern by EFM and SIFT**

