CONTROVERSIES IN SOME OF THE COMMONLY USED DAMAGE MODELS INCORPORATED IN COMMERCIAL FE CODES

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Abstract

In composite materials, once damage initiates, material stiffness gradually reduces due to the evolution in damage. In particular, if damage is induced in a unidirectional composite by the load applied in the transverse direction, this would result in the degradation of the transverse elastic modulus as well as the associated shear moduli. The extents of the moduli degradation are usually neither independent nor identical. However, this is being ignored in many of the composite damage models available nowadays, even in those implemented as “built-in” material models in the finite element (FE) software packages that are commercially available nowadays and are widely used in industry. Examples of erroneous damage predictions as obtained from some of the commonly used FE packages are presented in this paper. The level of inconsistency is alarming, in particular, if these models and associated codes are supposed to facilitate practical designs of engineering artefacts. The objective of this paper is to bring to the attention of practitioners that some basic self-regulatory measures, the very least, those of a nature of common sense, are required in this respect of theoretical development before engineering exploitations.

1. Introduction

Modelling the constitutive behavior of the composites in real-life engineering applications is complicated due to the inherent anisotropy of these materials, as well as the complexity of the processes of damage and failure. Specifically, prior to the ultimate failure, which is associated with the formation of macro-cracks and a complete loss of load carrying capacity, damage often develops in form dispersed micro-cracks. Once damage is initiated in the composite, material stiffness gradually reduces due to the evolution in damage.

In particular, if damage is induced in a unidirectional (UD) composite by the load applied in the transverse direction, this would result in the degradation of the transverse elastic modulus as well as the associated shear moduli. The degradation of the elastic properties is incorporated into the composite material models as damage representation, which establishes the stress-strain relations in the damaged material via the appropriate definition of the stiffness or the compliance matrix. Since the definition of the damage representation relation is the first step in any damage model development, inconsistencies in its formulation could lead to inaccurate predictions of the overall damage.

Most of the commercial finite element (FE) software packages, that are commercially available nowadays, incorporate material models for simulating the gradual propagation of damage in composite materials. In this paper, the reliability of predictions of damage in UD composites resulting from the

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models implemented in Abaqus and LS-Dyna is questioned, following the assessment of the predictions given by the models in some basic loading cases. Lack of consistency in predicting the simple material behavior has been revealed, when different models give different predictions of the same physical behaviour. Since real engineering design problems are usually large in size, involving complex component shapes and large number of elements in the model, the users might not be able to identify the effects the inconsistencies in composite model formulation have on the structural behaviour of the components they design. As the commercial FE codes are commonly applied for practical engineering design, a question can be raised regarding the reliability of designs that were generated employing material models that fail to adequately capture some of the basic material behavior.

2. Composite damage representation employed in major FE software packages

The formulation of damage models for composites in Abaqus and LS-Dyna is based on the concept of continuum damage mechanics. Therefore, the material is considered homogeneous, and there is no need to explicitly define the cracks to reflect the damage in the material. A single element model was generated for each of the material models considered. To account for anisotropy of UD composite, the FE model was assigned with the material directions, where x- and y-directions correspond to the longitudinal direction and transverse direction, respectively. For simplicity, isotropic elastic material properties, Young's modulus E =70 GPa and Poisson's ratio ν=0.33, were defined in all the material directions.

To assess the model predictions, the loading cases were generated as follows.

1) In each model, the damage was introduced by applying deformation of 0.5% in a transverse direction. In all the models considered, the damage onset was defined via the stress-based criteria; hence the transverse damage initiation stress was assigned the value of 300MPa. At ε_2 =0.005 the damage threshold was exceeded and a certain degree of damage was introduced. The material was then unloaded and returned to a stress-free state.

2) Model was loaded to 0.5% strain in the fibre direction and then unloaded; the stress-strain output was recorded. Since all the strength properties, apart from the transverse strength, were set to very high values, loading in fibre direction did not trigger any damage initiation criteria hence did not lead to further increase of damage.

3) The previous step is repeated for the pure longitudinal shear loading. For the material models that involve the 3D stress formulation, previous step was repeated also for the through-thickness and the two remaining shear directions.

The stress-strain output was recorded for steps 1)-3), and the appropriate stiffness properties for each loading case were calculated as gradients of stress-strain curves. The discussion of the damage predictions given by each of the material models is given below.

2.1. Damage modelling in Abaqus FEA

Abaqus offers a single material model that is applicable for modelling the onset and evolution of damage in elastic-brittle materials with anisotropic behavior, such as UD fibre-reinforced composites. It employs a plane stress formulation, hence three loading cases: loading in fibre and transverse direction, as well as the pure shear loading, were considered. The stress-strain curves calculated in those three cases are shown in Fig. 1. Under transverse tension (Fig. 1(a)), the material is initially linearly elastic, and the stiffness is equal to that of virgin material. Once the damage is initiated at

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σ_{22}=300MPa, the stress-strain dependence becomes nonlinear as the damage evolution takes place. On unloading, the response becomes linear once again, however, the stiffness is reduced.

The same model was then loaded under pure shear and in longitudinal direction, and the stress-strain curves calculated for those two cases are shown in Fig. 1(b). To demonstrate how the damage induced by the transverse loading affects fibre and shear material response, appropriate stress-strain curves were also calculated before the damage was introduced, and these are presented together with those of the damaged material in Fig. 1(b).

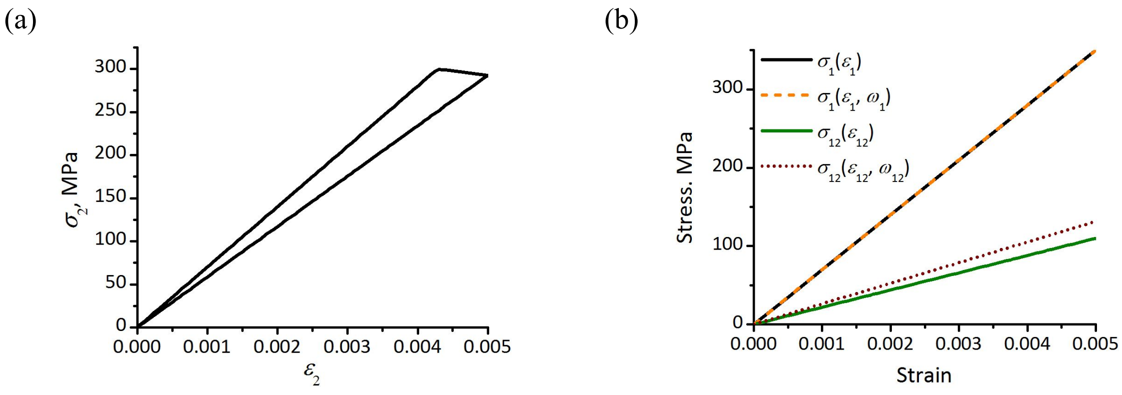

Figure 1. Stress-strain curves calculated for a single element model with material constitutive behavior being prescribed by a composite model from Abaqus.

The relative stiffness changes due to damage, ω_i , were quantified as follows.

$$\omega_1 = \frac{E_1^0 - E_1}{E_1^0}, \qquad \omega_2 = \frac{E_2^0 - E_2}{E_2^0}, \qquad \omega_{12} = \frac{G_{12}^0 - G_{12}}{G_{12}^0}, \tag{1}$$

where E_1, E_2 and G_{12} are the elastic properties of material with damage, while the quantities with superscript '0' refer to the properties of virgin material. As can be seen in Fig. 1(b), the value longitudinal stiffness was not affected by damage, hence its relative reduction was equal to zero, while the relative reductions in transverse and shear stiffness were found to be equal, $\omega_2 = \omega_{12} > 0$.

2.2. Composite damage models in LS-Dyna

There are a number of material models in LS-Dyna that are commonly applied for defining the constitutive behaviour of composites. Three of those models, MAT58, MAT59 and MAT162, have capabilities of describing in some form the material response following the onset of damage. Model MAT58 employs a plane stress formulation, MAT162 defines the full 3D response of the material, while MAT59 is available in both plane and 3D stress state formulations, hence can be used with both the shell and solid elements. Four single element models were generated covering all the material models as described above, and were tested under different types of loading.

The stress-strain curves calculated with the four models under loading in transverse direction are shown in Fig. 2. During the loading, the material response predicted with MAT58 model (Fig. 2(a)) becomes non-linear near the damage initiation stress, as the damage evolution takes place. On unloading, the material returns to the initial state following a linear path, with indicates stiffness reduction due to damage. The slope the stress-strain curve in Fig. 2(b), which was calculated with MAT59 model in its plane stress formulation, also changes during the loading. However, the transverse stiffness on the unloading remains exactly the same as the original one. This suggests that material should exhibit plastic-like response under loading in transverse direction. At the same time in the 3D stress formulation, MAT59 model predicts the ultimate material failure once the critical stress value of 300MPa is reached (Fig. 2(c)), which involves complete loss of stiffness in all the directions. Finally, the transverse stress-strain curve calculated employing MAT162 model are shown in Fig. 2(d). As can be seen, the response is qualitatively similar to that predicted with the composite model in Abaqus, as shown in Fig. 1(a).

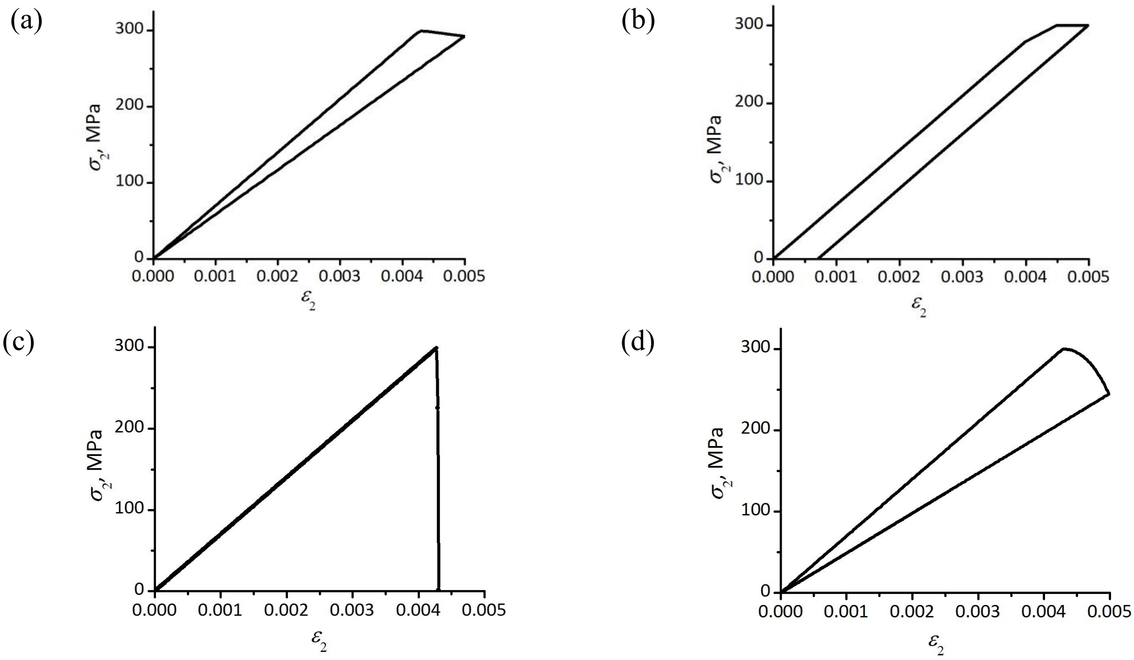

Figure 2. Stress-strain curves under transverse loading predicted with composite material models available in LS-Dyna: (a) MAT58 model; (b) MAT59 model (formulation for shell elements); (c) MAT59 model (formulation for solid elements); (d) MAT162 model.

The stress-strain curves were calculated for all the models under pure shear and uniaxial loading in the remaining material directions. Since no further damage evolution occurred in those loading cases, the stress-strain curves were linear. For each case, the stiffness value was extracted from the stress-strain curve.

The relative stiffnesses reductions, ω_i , as defined by Eq (1), where calculated for all the models considered here, and are summarized in Table 1. Additionally, to compare the relative reduction of shear and transverse stiffness,quantity k was introduced as follows.

$$\frac{\omega_{12}}{\omega_2} = k\,. \tag{2}$$

Analysing the data in Table 1, following conclusions can be made:

1) Two models out of five, MAT162 in LS-Dyna and composite material model in Abaqus, incorporate coupling between the tensile and the shear stiffness terms following the initiation of damage, where the extent of degradation of these properties is assumed to be identical.

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2) Material model MAT58 allows to model transverse stiffness reduction due to damage, however the shear stiffness terms remains unaffected by damage due to loading in transverse direction.

3) Model MAT59 employs two different damage formulations, one for the plane stress, and another on for 3D stress state. The prediction of ultimate failure provided by MAT59 material model in its 3D formulation is of conservative nature, as it suggests a complete loss of load carrying capability of the material following cracking of matrix. The material model MAT59 in plane stress formulation does not allow for modelling the stiffness reduction and suggests a plastic-like material response following the initiation of damage.

Table 1. Ratio of relative reduction of in-plane shear to transverse stiffness predicted with different models

	ω_1	ω_2	ω_3	ω_{12}	ω_{23}	ω_{13}	k
Abaqus	0	0.164	—	0.164	—	—	1
MAT58	0	0.158	—	0	—	—	0
MAT59 (solid)				Instant failure			—
MAT59 (shell)	0	0	—	0	—	—	—
MAT162	0	0.299	0	0.299	0.299	0	1

It is clear that the models employ different assumptions with respect to coupling between the relative reduction in the transverse and shear stiffness terms. In the models where the coupling was incorporated, it was assumed to be identical. Decoupling of damage in transverse and shear stiffness terms in models MAT58 and MAT59 (shell formulation) is yet another extreme assumption on the material response. Furthermore, absence of both transverse and shear stiffness degradation predicted by model MAT59 (3D formulation), while allowing plastic-like transverse response of the material is not a realistic representation of UD composite behavior under the transverse loading.

3. Different degree of stiffness reduction due to cracking

The lack of consistency in predicting the damage in composites as provided by various FE models is apparent from the analysis presented in Section 2. In particular, it has been shown that the models employ various assumptions regarding the coupling between the relative reduction of transverse tensile and longitudinal shear stiffness terms. However, none of the models presented reflected the physical reality, namely, that the extent of stiffness degradation of the tensile and shear moduli should in fact be different.

This effect can be captured numerically, analysing a relatively simple model. A finite element model of the plate with in-plane dimensions of 10 mm ×10 mm was generated in Abaqus. It contained a stationary crack directed along the x-axis. The crack was completely flat with closed crack surfaces prior to the loading, and it was modelled as a seam. The plate was considered to be under the plain stress. Isotropic elastic material properties were assigned to the material of the plate, E =70 GPa and ν=0.33.

Displacement boundary conditions were applied to the edges and corners of the plate according to the definition of boundary conditions for square unit cell [1]. Defined this way, the plate model

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represented a unit cell of the material with uniformly distributed cracks. The loads were applied in terms of concentrated forces at the reference points, which allowed for the direct calculation of the elastic properties [1]. The correctness of implementation of the boundary conditions and loads applied was verified by carrying out analysis with an equivalent model without a crack. It has confirmed that uniaxial/pure shear stress state was achieved in all the loading cases.

Three models, with 1, 3 and 6 mm long cracks, were generated and analysed. To each unit cell model, two direct and a pure shear load were consecutively applied and the equivalent elastic properties E_1, E_2 and G_{12} were calculated. The contour plots of stresses over the plate with 3mm long crack under loading x-, y-direction and pure shear loading, are shown in Fig. 3(a) - (c), respectively.

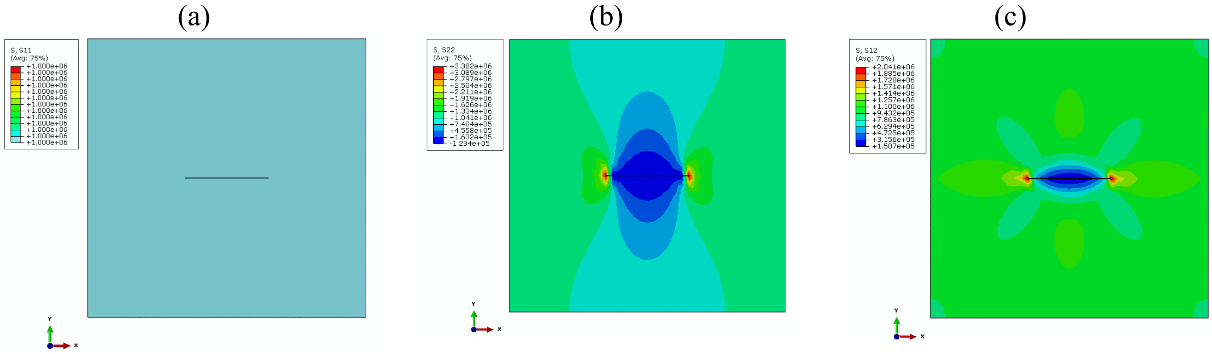

Figure 3. Contour plots of stresses over a unit cell model of cracked material: (a) σ_{11} under tension in *x*-direction; (b) σ_{22} under tension in *y*-direction; (c) σ_{12} under pure shear load.

The calculated equivalent elastic and shear moduli are summarized in Table 2, along with the values of the relative reduction of the elastic moduli, as defined by Eq. (2), due to damage present in the material.

Table 2. Stiffness reduction due to presence of the cracks of various lengths

Crack length, mm	Loading in *x*-direction		Loading in *y*-direction		Pure shear loading	
	E_1 (GPa)	ω_1	E_2 (GPa)	ω_2	G_{12} (GPa)	ω_{12}
No crack	70.00	0	70.00	0	26.32	0
1	70.00	0	69.17	0.0118	26.21	0.0039
3	70.00	0	61.76	0.1177	25.09	0.0465
6	70.00	0	42.94	0.3866	21.23	0.1934

Considering the data presented in Table 2, it becomes clear that the Young's modulus E_1 is not affected by the presence of cracks aligned in *x*-direction. The stiffness in direction transverse to that of the crack, E_2, shows the maximum degradation among all the elastic properties, while the shear stiffness reduces substantially slower. The extent of stiffness degradation is more significant for models with longer cracks. Also, it is worth noting that there is a nearly linear dependence between the ω_2 and ω_{12}, as can be seen in Fig. 4, where ω_2 is plotted as function of ω_{12}. By linearly fitting the data in Fig.4, this relative stiffness reduction can be determined as $k = 0.491$, which means that in a simple example considered here the shear stiffness reduced two times slower than the transverse stiffness.

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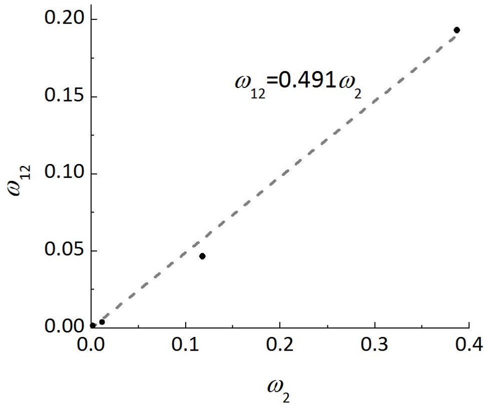

Figure 4. Relative reduction of shear stiffness as function of relative reduction of transverse stiffness.

The analysis as presented above was also repeated for tranversely isotropic materials, by assigning to the models the in-plane material properties of two types of UD composites. Since the damage in UD composites is associated with cracking of the matrix, which is a weaker material as compared to the reinforcing fibres, the unit cell model represents the UD composite with evenly distributed micro-cracks aligned in a fibre direction.

The material properties for the UD composites are given in Table 3, along with the calculated values of the parameter *k*. The It is easy to see that the difference between the extent of the transverse and the shear moduli degradation can become even more significant in those cases.

Table 3. Ratio of relative reduction of in-plane shear to transverse stiffness calculated for transversely isotropic materials

	E_1 (GPa)	E_2 (GPa)	ν_{12}	G_{12} (GPa)	k
Glass fibre/epoxy composite [2]	41.7	13	0.30	3.4	0.215
T300 carbon fibre composite [3]	138	11	0.28	5.5	0.177

Different extent of transverse and shear stiffness reduction has also been recorded in the experiments carried out by Knops and Bögle [4]. In the experiments, the tubular specimens were loaded in an axial direction until the inter-fibre damage was initiated and then was subsequently unloaded. The reduced value of the transverse modulus E_2 was determined from the experimental stress-strain curves. Next, a small amount of torsion was applied to the specimen, and the value of the damaged G_{12} was calculated from a stress-strain curve. The procedure was repeated several times until the crack saturation was reached. The obtained elastic and shear moduli were plotted as functions of crack density, and the comparison of the plots revealed that G_{12} degraded substantially slower than the transverse modulus E_2.

4. Conclusions

The effects of damage in UD composites on the reduction of the stiffness terms have been presented and discussed. By means of a simple numerical experiment, it was shown that the reduction of the transverse and shear stiffness terms is not identical, as the latter one degrades substantially slower than the former one.

Despite the experimental evidence being available confirming that the degradation of the elastic properties due to damage should be neither independent nor identical, it is still being ignored in many

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of the models available nowadays. A comparative assessment of damage predictions given by some of the commonly used material models implemented into FE software packages has been carried out, revealing inconsistencies in definition of the material response following the initiation of damage. Provided that FE modelling is an important stage of the engineering design nowadays, reliability of predictions provided by the models is crucial. Therefore, when making assumptions in model formulations, those should be validated to ensure they do not affect some basic material response.

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