Predicting damage propagation of composite T-joints using a mixed damage model

J Chen
Faculty of Technology, University of Portsmouth, Portsmouth PO1 3AH, UK
Corresponding address: jiye.chen@port.ac.uk

Key words: mixed damage model, composite T-joint, damage propagation, finite element analysis

1. Introduction
A mixed cohesive damage model was introduced in this paper to study the crack propagation of composite T-joint components under pulling and bending. This study indicated that the mixed damage scale plays an important role in the progressive damage analysis of T-joint components. The mixed damage scale properly reflected the effects of interaction between different damage modes in simulating damage propagation of an object with strong coupled effects. This coupled damage effect was considered from the material softening stage to final crack. Thus a proper damage accumulation was accounted since materials begin damage. An example given in this paper shown the crack propagation in the deltoid region of T-joint was simulated very well.

2. Formulation
This study continued from authors’ previous work [16-17]. A bilinear relationship between traction and relative displacement shown in Fig. 1 was still employed and expressed by Equ. 1.

\[ \sigma_j(\varepsilon) = \begin{cases} 
K_j \varepsilon_j & \varepsilon_j \leq \varepsilon_{j0} \\
(1-d_j)K_j \varepsilon_j & \varepsilon_{j0} < \varepsilon_j < \varepsilon_{jc} \\
0 & \varepsilon_j \geq \varepsilon_{jc} 
\end{cases} \]

(1)

Where, \( \varepsilon_j \), \( \varepsilon_{j0} \) and \( \varepsilon_{jc} \) (j=I, II, III) are the interface relative displacement, initial damage relative displacement and maximum relative displacement corresponding to mode I, mode II and mode III fracture, respectively.

The change of material state is a material softening progress with damage accumulation, which was presented by a coupled damage scale \( d \) in Equ. 1. This includes three damage components corresponding to three fracture modes, and it was proposed to be expressed by a quadratic relationship in Equ. 2.

\[ d = \sqrt{(\gamma_I d_I)^2 + (\gamma_{II} d_{II})^2 + (\gamma_{III} d_{III})^2} \]

(2)

Each individual damage scale \( d_j \) (j=I, II, III) in Equ. 2 is used to measure the reduction of stiffness by Equ. 1 in the material softening stage \( \varepsilon_j > \varepsilon_{j0} \), and is determined by the reduction of stiffness from elastic stage to softening stage. This can be expressed by Equ. 3.

\[ K_j = (1-d_j)K_{j0} \]

(3)

In Equ. 3, the individual damage scale \( d_j \) can be accounted by Equ. 4.

\[ d_j = Q(1-\frac{\varepsilon_{j0}}{\varepsilon_j}) \]

(4)

Where, \( Q \) is a material coefficient consisting of \( \varepsilon_{j0} \) and \( \varepsilon_{jc} \). The damage coupling factor \( \gamma \) in Equ. 4 is determined as \( 0 \leq \gamma \leq 1.0, \quad j = I, II, III \).

Three damage coupling factors \( \gamma_I, \gamma_{II} \) and \( \gamma_{III} \) are simply treated to have a same value as \( \gamma = \gamma_I = \gamma_{II} = \gamma_{III} = \gamma \) to simplify the problem in this investigation, and assume the mixed damage ratio is taken as \( \beta = d_{II} / d_I \) and \( \eta = d_{III} / d_I \). Using Equ. 2, \( \gamma \) can be worked out by Equ. 5.

\[ \gamma = \frac{1}{\sqrt{1 + \beta^2 + \eta^2}} \]

(5)

The total damage rate can be expressed by Equ. 6.

\[ d' = \frac{\gamma_I^2 d_I A \varepsilon_{I0}^2 \varepsilon_I'(t) + \gamma_{II}^2 d_{II} B \varepsilon_{II0}^2 \varepsilon_{II}'(t)}{\sqrt{\gamma_{II}^2 d_{II}^2 + \gamma_{II}^2 d_{III}^2}} \]

(6)

Where, A and B are two material constants given by Equ. 7.
\[ A = f_A(\varepsilon_{i0}, \varepsilon_{ic}) \quad B = f_B(\varepsilon_{i0}, \varepsilon_{ic}) \]

The total mixed mode damage rate in current incremental step can be expressed as

\[ \dot{d}_{j(i+1)} = \frac{\dot{\gamma}_i^2 d_H A \dot{\varepsilon}_{i(i+1)} + \dot{\gamma}_H^2 d_H B \dot{\varepsilon}_{H(i+1)}}{\sqrt{\dot{\gamma}_i^2 + \dot{\gamma}_H^2}} \]

(8)

Where, the relative displacement rate in current incremental step can be obtained by Eq. 9.

\[ \dot{\varepsilon}_{j(i+1)} = \frac{\Delta \varepsilon_{j(i+1)}}{\Delta t}, \quad j = I, II \quad (9) \]

Then, current relative displacement can be calculated by Eq. 10.

\[ \varepsilon_{j(i+1)} = \varepsilon_{j(i)} + \int_{\Delta t}^{\Delta t+1} \dot{\varepsilon}_{j(i+1)} \, dt, \quad j = I, II \quad (10) \]

Thus Eq. 4 for accounting current individual damage can be rewritten as Eq. 11.

\[ d_{j(i+1)} = Q(1 - \frac{\varepsilon_{j(i+1)}}{\varepsilon_{j(i)}}) \quad (11) \]

In numerical integration, the total damage can be accounted by Eq. 12 using the damage rate.

\[ d_{j(i+1)} = d_{j(i)} + \int_{\Delta t}^{\Delta t+1} \dot{d}_{j(i+1)} \, dt, \quad j = I, II \quad (12) \]

3. Application

Eqs. 1-12 were programmed into a user element by UEL in ABAQUS [17]. As an example, this developed mixed damage model was used to predict damage propagation in deltoid of composite T-joints shown in Fig. 1. Two major services loading cases, pulling and bending, were investigated in this paper. Fig. 2 shows load-displacement curves predicted by this developed mixed damage model and ABAQUS standard cohesive model together with a test mean value of failure load. The averaged test value 50N/mm was worked out from 6 specimens with all different manufacturing quality levels [12]. Predicted failure load given by ABAQUS cohesive model was 54.9N/mm, which was higher than the tested average failure load by 9.8%. Meanwhile, the failure load predicted by the developed mixed damage model was 52.7N/mm. The difference reduced to 5.4% comparing to the test mean. This example has shown that the prediction of damage propagation using the proposed mixed damage model in the deltoid region of T-joint was obviously improved.

Fig 1. a. Deltoid of T-joint, b. tested failure under pulling, c. predicted crack in a half model

Fig. 2. Load-deflection curves

Reference