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T^*_ε Integral of a Particulate Composite

J.H. Jackson[1], H. Lu[2], and A.S. Kobayashi[3]

Summary

Digital image correlation data and the Osgood-Ramberg constitutive relation were used to evaluate the T^*_ε integral of a particulate composite SEN specimen subjected to stable crack growth. The domain size independency of the T^*_ε integral of this rubbery composite subjected to large deformation was also assessed with varying inner contours ranging from 2.0 to 5.0 mm with domain sizes of 0.25, 0.50, and 0.75 mm. The near field J-integral decreased while the far-field J-integral continually increased with stable crack growth. The T^*_ε integral, on the other hand, approached a steady value with crack extension.

Introduction

Brust et al [1], and Atluri [2] defined a local value of the T^*_ε integral, T^*_ε , on a small contour, Γ_ε surrounding the crack tip as;

$$T^*_\varepsilon = \int_{\Gamma_\varepsilon} \left(W n_1 - t_i \frac{\partial u_i}{\partial x_1} \right) d\Gamma \qquad (1)$$

$$W = \int_0^{\varepsilon_{ij}} \sigma_{ij} d\varepsilon_{ij} \qquad (2)$$

Here, W is the stress work density, rather than the strain energy density in Rice's J-integral. In this total form, T^*_ε is calculated along an "elongating contour" which grows as the crack extends. Pyo [3] showed, through a series of FEM analyses, that T^*_ε could be used to predict the load carrying capacity of a cracked structure if the stress and strain were obtained using the incremental theory of plasticity. Using the divergence theorem, Equation 1 can be converted to a summation of a far-field contour integral plus a finite domain integral as in Equation 3 [4]. Here the subscripted

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numeral 1 indicates that T^*_ε is a vector quantity and in this case refers only to the x_1 component.

$$T^*_{1\varepsilon} = \int_\Gamma \left(Wn_1 - t_i \frac{\partial u_i}{\partial x_1} \right) d\Gamma - \int_{A-A_\varepsilon} \left(\frac{\partial W}{\partial x_1} - t_{ij} \frac{\partial \varepsilon_{ij}}{\partial x_1} \right) d(A - A_\varepsilon) \qquad (3)$$

The first term on the right hand side in Equation 3 is equal to Rice's J-integral and in the limit as the area tends to zero, T^*_ε becomes equal to J. In a series of FE analyses, Brust et al [4] observed that the second term became larger with crack growth. That is, as J continued to increase, T^*_ε reached a plateau. Like the J-integral, the T^*_ε integral becomes path dependent in the presence of large plastic yielding, or unloading. Thus, T^*_ε must be evaluated along a fixed contour close to the crack tip to be used as a valid fracture criterion. The size of this contour was set to be approximately equal to plate thickness for a state of plane stress to prevail as per Narshimhan and Rosakis [5].

Okada et al [6] investigated the difference between the "moving" contour, which moves along with the crack tip, and the "elongating" contour, which grows with the crack. The moving contour provided the energy released at the crack tip while the elongating contour provided the energy dissipated behind the crack tip plus the energy release rate at the tip per unit crack extension. The elongating contour accounts for unloading behind the crack tip, as well as deformation close to, and in front of the crack tip. Values of T^*_ε calculated using the moving contour dropped to zero soon after crack initiation as they represent the energy release rate at the crack tip. Thus, the elongating contour should be used in calculating T^*_ε which is the energy dissipated in the extending crack wake, per unit crack extension as well as the energy release rate in process zone ahead of the crack tip.

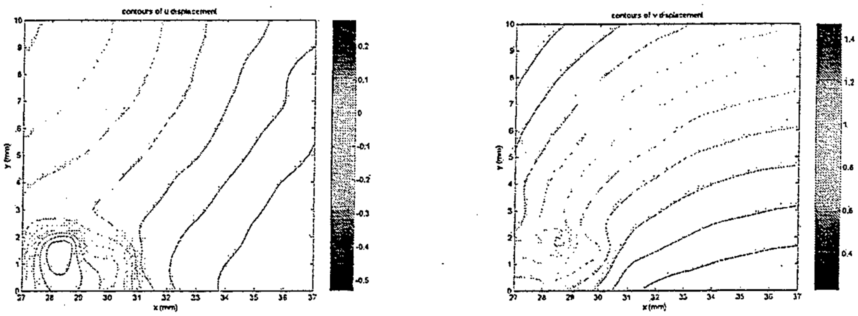
Okada et al [7] simplified the integration procedure by neglecting the contour behind the crack tip. This led to a calculation method involving the truncation of the integral contour from an empirically determined distance behind the crack tip. Since the region ahead of the crack tip is in the loading phase and has not undergone significant plastic deformation, the deformation theory of plasticity can be used to compute the stresses from the measured strains. He showed that the T^*_ε value calculated using the cut-off integration contour method with the deformation theory of plasticity agreed well with the T^*_ε value obtained using the incremental theory of plasticity and an elongating contour. Omori et al used the Okada method to measure T^*_ε experimentally in A606 HSLA steel [8], and 2024-T3 aluminum [9].

Pre-processing of Displacement Data

In this study, the Okada method, as used by Omori et al, was used to determine experimentally T^*_ε associated with stable crack growth in a particulate composite SEN specimen. The finite displacement field surrounding the extending crack was recorded by the Digital Image Correlation (DIC) method. A program was written in Matlab to allow interpolation of displacements from scattered points in the DIC images to node points in a regular array, on the surface of the specimen. Despite the symmetry about the crack plane, the data was split into the upper and the lower halves (with respect to the plane of the crack) due to the un-symmetric displacement (or strain) field with respect to the crack in a particulate composite, the displacement fields and hence the T^*_ε integral for each half were computed separately and then summed for the final T^*_ε value. For this work, a grid resolution of 0.25 millimeters for the re-interpreted displacement field was chosen. This allowed relatively accurate correspondence of the crack tip to a node, and optimized the accuracy of the interpolation scheme. Displacements were calculated over a fixed interval, which spanned from 2 millimeters behind the crack tip to 8 millimeters in front of, and 10 mm above the crack tip (total window size of 10 x 10 mm).

The first step in the analysis was interpolation of the displacement data from the provided points to a regularly spaced grid surrounding the crack tip. After resetting the coordinate system, the data sets were split into top and bottom halves with respect to the crack plane. A "window" of data is being extracted for the area spanning from 2.0 mm behind the current crack tip, 8 mm in front of it, and 10 mm above it for a 10 mm x 10 mm window of displacement data. A grid size of 0.25 mm is used. Displacement contour plots were used to locate abnormal displacement points, or non-convergent points. These points were then removed from the original data set and the displacement field was re-interpolated and subsequent displacement contours were observed. This process was repeated until the displacement contours appeared sufficiently smooth. Normally, this procedure only required one to two iterations. Figure 1 shows the *u* and *v* displacement fields before removal of discontinuous points from the original data.

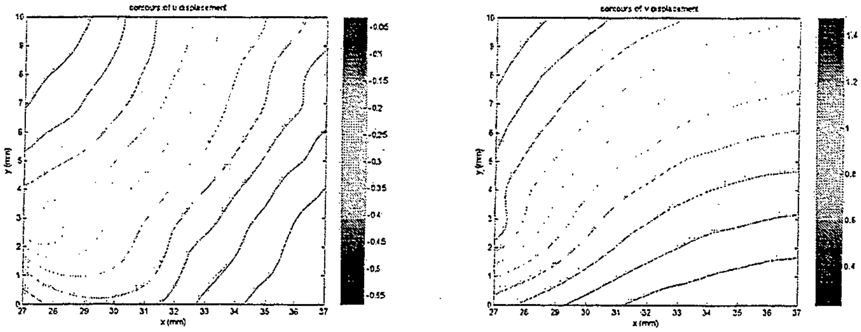
Discontinuous displacement points were very evident in the original data file. For example, a *u*-displacement of say 3.0 mm should not exist if neighboring points show displacements of something like 0.2 mm. In Figure 1, a few obviously discontinuous points are obvious in the vicinity of the coordinates x = 28.5 mm and y = 1.5 mm. These points were removed, and the interpolation program was then rerun with the fixed data and results are shown in Figure 2. In this case, removal of two non-convergent points smoothed the data sufficiently.



u-field (unfixed)

v-field (unfixed)

Figure 1: u and v-fields before removal of discontinuities.



u-field

v-field

Figure 2: Corrected displacement fields.

Two output files for each half, one containing x-y coordinates of nodes and corresponding *u*-displacements and the other containing x-y coordinates of nodes and corresponding *v*-displacements, were then used to create input files containing nodal displacement and connectivity information for the main T^*_ε calculation program which is based on isoparametric formulation and naturally compatible with grid data.

T^*_ε Calculation

For each calculation of T^*_ε, an initial crack tip is specified, along with an integration contour size, and the EDI region size. Displacement data is then used by the program to calculate strains from which stresses are calculated using the equivalent stress-strain relation. Finally, T^*_ε is calculated using the stresses and strains with Okada's truncated EDI method, and a deformation theory of plasticity as suggested in [7]. T^*_ε for each image and several inner contour sizes ranging between 2.0 and 5.0 mm with domain sizes of 0.25, 0.50, and 0.75 mm were determined. T^*_ε has been shown to be independent of domain size [7], but was nonetheless calculated for different sizes to provide insight into possible data abnormalities.

T^*_ε and *J*-integral Results

T^*_ε was calculated for all provided data sets (images 04, 06, 08, 09, 10, 12) on integration contours ranging from 2.00 to 5.00 mm, in 0.50 mm increments. The results were then compared to *J*-integral results. The values of near field T^*_ε and the values of *J*-integral were generally close in magnitude with T^*_ε on the conservative side. Hence, the *J*-integral and T^*_ε integral should be similar in magnitude, and both relatively path independent prior to crack extension. Just prior to stable crack growth, enough nonlinearity was present to incur the path dependency. After the onset of crack growth, the far field *J*-integral continued rising with crack extension for contour sizes of approximately 4.0 mm and larger. Figures 3, 4 and 5 show this trend for integration contours of 3.0, 3.5, and 4.0 mm. Near field (within approximately a 3.0 mm radius or less) *J*-integral is expected to drop to near zero, but far-field *J*-integral should continue to rise as the specimen is monotonically loaded with crack extension. Far field *J*-integral would be comparable to *J*-integral calculated in any variety of ways utilizing the strain energy, or area under the load-load line displacement curve. The value for J_{el} is calculated as $J_{el} = 4.26$ *psi-in.* The total *J*-integral value would normally be evaluated as the summation of J_{el} and J_{pl}, assuming a Ramberg-Osgood material. The summation of the two gives a value, $J_{tot} = 7.26$ *psi-in* that compares well with far-field *J*-integral calculated via contour integration and serves as a validation for their method.

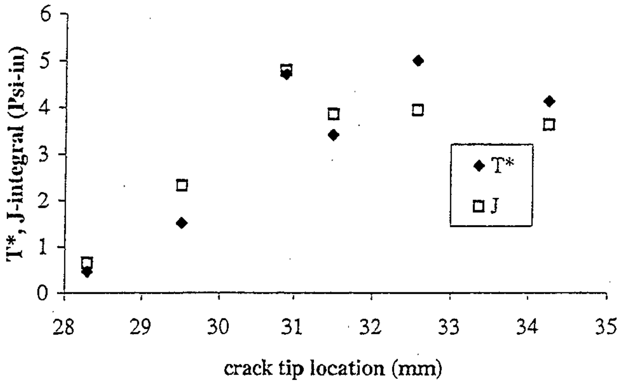


Figure 3: Comparison of T^*_ε and J-integral for a 3.0 mm contour.

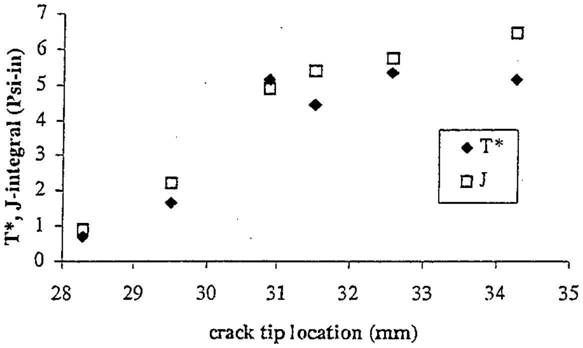


Figure 4: Comparison of T^*_ε and J-integral for a 3.5 mm contour.

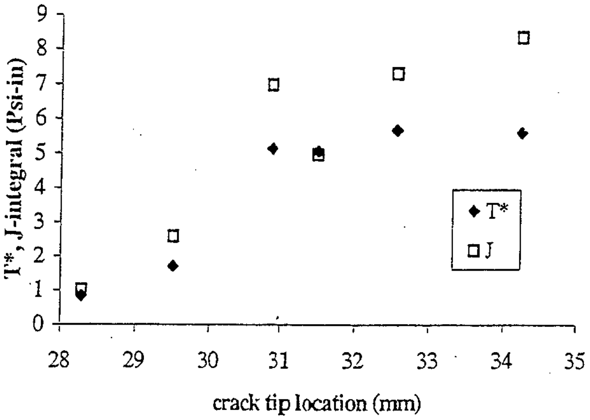


Figure 5: Comparison of T^*_ε and J-integral for a 4.0 mm contour.

The assumption that this material behaves as a Ramberg-Osgood material may be reasonable provided testing conditions are well controlled. It is obvious from inspection of the load-load line displacement record that the material is time dependent. In this case, the constitutive relationship is much more complicated. The stability of the obtained T^*_ε values for data sets beyond the crack initiation provides a glimmer of hope that the Ramberg-Osgood assumption can be made, at least for these small amounts of crack extension. However, validation of these results should be made by using the T^*_ε curve as a fracture criterion in FE analyses.

Conclusion

For the provided displacement data, the T^*_ε calculation procedure utilizing the T^*_ε program provided reasonable results. Values compare reasonably well to the *J*-integral values provided by Oklahoma State University and both integral quantities seem to follow expected trends. The post-crack initiation values are within reason considering a comparison with far field *J*-integral calculated via the EPRI *J*-estimation scheme. From this analysis, the steady state T^*_ε value is between 5.0 and 6.0 Psi-in and the critical *J*-integral value is similar at approximately 7.0 Psi-in.

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