DRAFT NOTE

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Subject : CTOD versus J-Integral as a fracture parameter

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Summary

A BRITE-EURAM project has been set up with the objective of providing a unified structural integrity evaluation method for European industry (SINTAP). The project has been split up into five tasks with the final deliverable being a procedure to assess structural integrity. Arising out of this project is the question whether the procedure should be based on the J-integral or CTOD fracture parameters. The purpose of this note is to discuss the viewpoints of SRTCA on this matter.

To evaluate whether the J-Integral or CTOD is more appropriate as a fracture parameter the parameters were reviewed from the following perspectives;

- history,
- fracture toughness,
- crack driving force,
- and codes

In terms of fracture toughness parameters, the J-integral and CTOD approaches are equivalent within acceptable limits through the empirically derived plastic constraint factor, m. If the ASTM draft fracture toughness procedure is adopted, J and CTOD will be explicitly linked via a prescribed m factor.

For most structural assessments the crack driving force will be determined numerically. The best way to calculate the crack driving force is by the J-Integral due to its robust nature, theoretically sound development and ease of calculation.

The brief review of the codes show that the crack driving force calculated by CTOD either use semi-empirical relationships or a strip yield model that may be suspect. Crack driving force calculations in the J based codes are based on actual J-Integral solutions.

Historically CTOD and J are used quite extensively. It is recommended, based on the above arguments, to calculate in terms of the J-Integral for the structural assessment procedure and convert the input/output of the structural assessment to CTOD where required. This will maintain continuity with past data and methodologies.

Historical Perspective

The evolution of the J-Integral and CTOD fracture toughness parameters are linked closely to specific industries and geography. In the United Kingdom, Well's CTOD parameter was applied extensively to fracture analysis of welded structures, beginning in the late 1960's. While fracture research in the U.S. was driven primarily by the nuclear power industry during the 1970's, fracture research in the U.K. was motivated by the development of oil resources in the North Sea. In 1971, Burdekin and Dawes applied several ideas proposed by Wells several years earlier and developed the CTOD design curve, a semi-empirical fracture mechanics methodology for welded steel structures. The nuclear power industry in the UK developed their own fracture design analysis based on the strip yield model of Dugdale and Barenblatt. The J-Integral based methodology of the U.K. and U.S. nuclear power industry and the U.K. CTOD methodology have begun to merge in recent years (Fracture Mechanics: Fundamentals and Applications).

In Germany GKSS has independently proposed a δ_5 CTOD parameter. The parameter is probably quite extensively used in Germany but the author has no knowledge about the use of the method outside of Germany.

Both fracture toughness parameters have been used quite extensively and have a deep historical basis. From a pragmatic standpoint it should be realised that in the oil and gas industry (also U.K. industry in general) has a lot of past data expressed in terms of CTOD. Further material engineers in the industry are familiar with CTOD. Likewise can be said about the nuclear industry (also U.S. industry in general) except the fracture toughness data is expressed in terms of the J-Integral. Thus to eliminate one parameter will be met with resistance from engineers favouring the other parameter.

Fracture Toughness

J-Integral fracture toughness and CTOD fracture toughness are related to each other through the following equation;

$$J = m\sigma_y CTOD \tag{1}$$

where m is the plastic constraint factor and σ_y is the yield stress. The plastic constraint factor is an empirical parameter. The plastic constraint factor m has been defined by ASTM based on crack depth (a) to thickness (W) ratio and the ratio of yield to ultimate strengths (σ_u) as follows;

$$m = -0.111 + 0.817\frac{a}{W} + 1.36\frac{\sigma_u}{\sigma_y} \tag{2}$$

In the U.S. the new draft ASTM standard calculates CTOD from J based on the above defined m factor. Thus the ASTM standard now explicitly makes J and CTOD equivalent. It should also be realised that the BSI and ASTM definitions of CTOD differ by at least 10%.

The relationship between J and CTOD is empirical but the empirical relationship is such that transferability between J and CTOD is within acceptable bounds.

Crack Driving Force

Depending on the level of the assessment, elastic components of the crack driving force are required or the full crack driving force comprising the elastic and plastic components are required. If the more simplified approach is used, i.e. only the elastic component is required, the elastic driving force is obtained from handbooks or can also be calculated numerically. The handbook solutions are usually expressed in terms of K_I with CTOD and the J-Integral inferred from the following equations;

$$CTOD = \frac{K_I^2}{\sigma_y E'} \text{ or } J = \frac{K_I^2}{E'} \qquad (3)$$

If the crack driving force is calculated numerically it is usually calculated using the J-Integral approach (be it the domain integral approach or the De Lorenzi approach, the two being equivalent in the authors opinion). The J-Integral approach is robust, the definition is well established, and does not require very detailed mesh refinement. The CTOD approach requires detailed mesh refinement in the vicinity of the crack tip and a definition of CTOD must be established. Figure 1 illustrates two possible definitions of CTOD with the right hand side being the more common definition. Shih has shown that the right hand side definition of CTOD can be analytically derived from J assuming HRR stress fields (Ramberg-Osgood stress-strain response assumed) in the vicinity of the crack tip and a small strain analysis. Although the small strain analysis is a major detraction to Shih's analysis finite element results show that his analysis is correct even for a large strain analysis.

The J-Integral approach is the preferred route for calculating the crack driving force numerically as it is well established in major FEM codes, it is robust and does not require intensive mesh refinement in the vicinity of the crack tip.

To determine the crack driving force experimentally is problematic. The J-Integral approach using the line integral is difficult and is not very reliable. The CTOD method inferred from the CMOD is more suited for this approach and has been extensively employed in wide plate testing. The relationship between CMOD and CTOD from wide plate testing in the author's opinion is not well established. The J-Integral can be derived experimentally from interferometric methods such as moiré but this is also numerically intensive in the interpretation of the results. The δ_5 parameter seems to be the only parameter that can give the crack driving force experimentally with relative ease. As will be discussed this can be related to the J-Integral through the HRR fields and as such can be thought of as a unique way of experimentally measuring the J-Integral.

The crack driving force will usually be determined numerically and as such the J-Integral method is the best method.

Codes

The most popular codes, in terms of fracture parameters, can be delineated into two groups;

- **J-Integral** - EPRI, R6, PD-6493:1991 and ETM
- **CTOD** - ETM, JWES 2805:1980, PD 6493:1980, PD6493:1991

PD6493:1980 and JWES 2805:1980 are based on a CTOD design curve approach. The CTOD design curves for the two different codes are different. The PD6493 CTOD design curve is quadratic in form for low strains and linear thereafter whereas the Japanese code is linear for all ranges of applied strain. The Japanese code over predicts CTOD at low strains and under predicts at higher strains compared to PD6493:1980. Level 1 of PD6493:1991 is based on the CTOD design curve of PD6493:1980, level 2 is based on the Dugdale model whereas level 3 is J-Integal based with a conservative conversion to CTOD. ETM is based on δ_5 and EPRI and R6 are J based. Thus in terms of codes the J-Integral and CTOD are evenly split.

Level 3 of PD6493 and the R6 failure assessment diagram approach and the EPRI approach are based on numerically or analytically J based crack driving force solutions. Appropriate assumptions for material properties and plastic components of J are made dependent of the level of sophistication of the failure assessment diagram. The J based crack driving force is then compared to J fracture toughness results.

The Level 2 failure assessment diagram (PD6493) is based on the strip yield model but has been modified to account for other geometries but still assumes a long narrow plastic zone shape and a plane stress structure. It should be emphasised that the failure assessment curve is more liberal than the level 3 curves and only coincide in the elastic perfectly-plastic limit.

The CTOD design curve approaches of JWES:1980, PD64993:1980, and PD6493:1991 level 1 determine the crack driving force semi-empirically (CTOD design curve) and then relate it to CTOD fracture toughness.

Thus the crack driving force for the J based codes are determined from actual J crack driving force solutions whereas the crack driving force of CTOD based codes are derived semi-empirically (CTOD design curve) or through the potentially non-conservative strip yield model.

The ETM method uses the δ_5 parameter. The δ_5 parameter is related to the J-Integral. Schwalbe states that for a given material δ_5 is uniquely related to J can be explained if one assumes that the gauge points over which δ_5 is measured are located within the HRR field. The rest of the derivation follows similar lines to that explained in the crack driving force section (about Shih's findings relating J and CTOD). The main difference being that δ_5 will be outside of the zone of finite strains as opposed to CTOD. The drawback to the δ_5 approach is that under small scale yielding conditions it overpredicts δ_5 because the HRR fields are so small that it does not encompass the δ_5 gauge points. δ_5 has been shown to be also related to the CTOD design curve.

Conclusions

In terms of fracture toughness parameters, the J-integral and CTOD approaches are equivalent within acceptable limits through the empirically derived m factor. If the ASTM draft fracture toughness procedure is adopted, J and CTOD will be explicitly linked via a prescribed m factor.

For most structural assessments the crack driving force will be determined numerically. The best way to calculate the crack driving force is by the J-Integral due to its robust nature, theoretically sound development and ease of calculation.

The brief review of the codes show that the crack driving force calculated by CTOD either use semi-empirical relationships or a strip yield model that may be suspect. Crack driving force calculations in the J based codes are based on actual J-Integral solutions.

Historically CTOD and J are used quite extensively. It is recommended, based on the above arguments, to calculate in terms of the J-Integral for the structural assessment procedure and convert the input/output of the structural assessment to CTOD where required. This will maintain continuity with past data and methodologies.

A summary of the pros and cons of J-Integral and CTOD parameters are tabulated in Table 1.

Table 1 *Comparison of J-Intergral and CTOD fracture parameters*

	CTOD	J-Integral
History	U.K. - welded structures in the oil and gas industry	U.S. - nuclear industry U.K. - nuclear industry
Fracture Toughness	- equivalent through empirical m factor - ASTM enforces equality between parameters by determining CTOD from J and using a prescribed m factor	
Crack Driving Force (numerical)	- requires detailed meshing - CTOD definition needs to be established	- robust - theoretically sound - minimum mesh refinement
Crack Driving Force (experimental)	- easy to visualise - relationship between CMOD and CTOD not well established - δ_5 parameter well established	- difficult - possible with moiré method but post processing is numerically intensive
Codes	- PD6493:1980, PD6493:1991, JWES-2805, ETM - crack driving force calculation is semi-empirical if based on CTOD design curve - strip yield model approach is potentially non-conservative	- R6, PD6493:1991, EPRI, ETM - J based crack driving force solutions

Figure 1 *CTOD definitions*