FAILURE ASSESSMENT DIAGRAMS FOR MIXED MODE LOADING AND CRACKED TUBULAR JOINTS

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ABSTRACT

Finite element analyses of two geometries of double T tubular joints under axial loading have been carried out for models in the uncracked condition and with three different crack sizes. The cracked joints experience mixed mode loading and two methods have been used to derive total J values for these mixed mode conditions and then used to construct failure assessment diagrams. The failure assessment diagrams derived using J values direct from ABAQUS show good agreement with those derived using area under the load displacement curves and both cases show that safe assessments of cracked tubular joints can be made using standard PD 6493/R6 assessment diagrams provided appropriate lower bound estimates of plastic collapse load of the cracked geometry are used. Methods for deriving this collapse load and the applied stress intensity factor for cracked tubular joints are described.

KEYWORDS

Cracked tubular joints, mixed mode fracture, failure assessment diagrams.

INTRODUCTION

The BSI Document PD 6493 (BSI 1980,1991) was one of the first codified approaches to assessing the significance of weld defects on a fitness for purpose basis and has been extensively used by industry, particularly the offshore industry. When the first version of the document was issued in 1980 it gave guidance particularly on the effects on fracture and fatigue based on fracture mechanics methods. Two parameters were used to evaluating the fracture behaviour, the first being K-the stress intensity factor for linear elastic fracture mechanics and the second being the CTOD design curve for checking on plastic collapse. The CTOD approach has been used particularly in the offshore industry for fracture toughness requirements for parent material, weld metals and heat affected zones.

The R6 procedure (Milne et.al.1986) was developed using the failure assessment diagram (FAD) concept for the power generation industry. The FAD accounts for the interaction between fracture and plastic collapse, i.e. a fracture axis based on the stress intensity factor K, and a plastic collapse axis based on either flow strength S_r or yield strength L_r. The effects of plasticity on the crack tip severity parameter K are taken into account by the shape of the assessment diagram, which forces the user automatically to consider plastic collapse at the same time.

The 1991 version of PD 6493 (BSI 1991) kept the assessment of the effect of defects on fracture, fatigue and other modes of failure of the 1980 version of the document and sought to bring together a common approach for defect assessment based on use of the failure assessment diagram method originated in the CEGB R6 procedures and to try to extend the approach to any form of structure, including offshore structures. A further revision published in late 1996/early 1997 refines the details of the approaches of the 1991 edition but retain the same principles.

Further research work has been carried out to determine the crack driving force and to confirm the application of the FAD approach in PD 6493 to ultimate strength and fracture assessment of cracked tubular joints.

BASIC ASPECTS OF PD 6493/R6 TREATMENTS

It is important to recognise that the K_r parameter of the assessment diagram uses the linear elastic stress intensity factor with no allowance for the effects of plasticity on the crack tip driving force. As the S_r or L_r value increases so plasticity also increases the effective crack tip driving force. If it is considered that fracture actually occurs when the total effective crack tip driving force, J_{ep} (elastic plastic value) reaches a critical value equivalent to the fracture toughness, then this will occur at $\sqrt{(EJp)} = K_{Ic}$. Since the applied linear elastic stress intensity factor K_I is equivalent to $\sqrt{(EJ_{el})}$, where J_{el} =G in the linear elastic case, then

$$K_r = \frac{K_I}{K_{Ic}} = \sqrt{\frac{J_{el}}{J_{ep}}} \qquad (1)$$

As plasticity increases so the ratio $\sqrt{J_{el}/J_{ep}}$ reduces and this defines the shape of the assessment diagram with increasing S_r or L_r. The standard assessment diagrams in R6/PD6493 were originally derived to represent $\sqrt{J_{el}/J_{ep}}$ plotted against $\sigma_{net}/\sigma_{flow}$ for the case of a large plate under tension loading with a central crack. They have been shown to represent a lower bound to curves derived for other common simple geometries.

The original developments of the assessment diagram approach in the R6/PD6493 procedures were based on simple geometries under mode I loading only. Work carried out on mixed mode loading (Budden and Jones 1989) has led to recommendations in an Appendix to the R6 procedure for such loading. The basis of these recommendations is to use the standard assessment diagrams as derived for mode I loading but to take account of mixed mode loading in the following way. For the fracture (K_r) axis, the applied stress intensity factor should combine the different loads as follows:

$$K_{eq} = \sqrt{K_I^2 + K_{II}^2 + K_{III}^2/(1-\nu)} \qquad (2)$$

It should be noted that this is essentially equivalent to adding the J components for elastic loading for the different loading modes as scalar quantities and converting to a K value. It is recommended that the fracture toughness for the denominator of K_r should either be determined under mixed mode loading or taken as the mode I toughness if it has been established that this gives the lowest toughness conditions for the type of material concerned.

For the plastic collapse (S_r or L_r) axis the collapse load should be taken as that for the cracked section under the relevant combination of modes of loading.

For application to the mixed mode loading which occurs in tubular joints, it is necessary to be able to estimate the equivalent linear elastic stress intensity factor, the relevant fracture toughness and the collapse load under the appropriate loading.

ANALYSIS OF FAILURE LOADS OF CRACKED TUBULAR JOINTS

The situation is complicated in tubular joints by the nature of the yielding/collapse mechanism for such joints. Although yielding may occur initially at the hot spot stress concentration region at relatively low loads, this yielding is contained by the surrounding elastic material, but progressively increasing displacements occur as global collapse is approached. There is therefore a significant effect of the assumptions made about the collapse load in determining the parameters S_r or L_r on the assessment of cracked tubular joints in general. As noted above the collapse load must take account of the mixed mode loading conditions in tubular joints.

The normal recommendations of the R6/PD 6493 Failure Assessment Diagram are based on local crack tip plasticity increasing as net section yield is approached in statically determinate structural situations and hence on local collapse loads of an uncracked ligament. But for more complex redundant structures, such as tubular joints, the initial yielding is restricted by the remaining surrounding material so the redundant structure can carry more load until final global collapse occurs. Furthermore, because the initial plasticity is contained in redundant structures, the rate of increase of the J value when the cracked ligament first reaches yield will be significantly less than for the simple statically determinate structure. The 1996/97 revision of PD6493 permits the possible use of either local or global collapse loads if the user can demonstrate that the resultant assessment diagram is safe.

As part of the conventional design of tubular joints in offshore structures, it is common practice to use the design equations published for example in the HSE Guidance Notes (HSE 1990) or in the API RP2A Design Codes (API 1993). These give formulae for the characteristic strength of the basic uncracked geometry. In previous work at UMIST (Cheaitani and Burdekin 1994) on the strength of cracked tubular joints and use of assessment diagrams for such joints it was proposed that the collapse load for use in assessment diagrams should be obtained by modifying the HSE characteristic uncracked strength by a load reduction factor based on the net cross sectional area due to the crack and on the geometry modifier Q_β as follows.

$$\text{Axial Load Reduction Factor} = \left[1 - \frac{\text{cracked area}}{(\text{intersection length} \times T)}\right]\left(\frac{1}{Q_\beta}\right) \qquad (3)$$

where, $Q_\beta = 1$ for $\beta \le 0.6$

$$Q_\beta = \frac{0.3}{\beta(1-0.833\beta)} \quad \text{for} \quad \beta > 0.6 \qquad (4)$$

The modified characteristic strength is a global collapse load which is higher than or equal to the local collapse load. It has been found in a series of investigations that the modified HSE characteristic strength is less than the load corresponding to twice the elastic compliance limit in FE analyses which demonstrates that overall plasticity is being well contained. It is important to recognise that the use of a lower bound estimate for plastic collapse load in this way is effectively limiting the plastic deformation at the joint to match the standard assessment diagrams and that it provides a convenient simple approach for practical designers. Furthermore the use of the modified HSE characteristic strength equations automatically takes account of the effect of mixed mode loading on plastic collapse behaviour. This conservative estimate of ultimate strength will now be used to construct the FAD for tubular joints to demonstrate the principles outlined above.

FINITE ELEMENT ANALYSES

The Double T (DT) type tubular joint was chosen for the FE analyses because this type of joint eliminates possible complications due to chord length effects and is convenient for experimental testing which was carried out in a separate industry project. Two different joint geometries (β ratios) were analysed under axial tension. The geometries were identified as series M1 for β =0.5 and series M2 for β =0.95. The dimensions of the DT joints are summarised in Table 1.

For each load case the following crack conditions were analysed using ABAQUS.

1). Uncracked Joint;
2). 15% through thickness crack, crack length = 15% of brace circumference;
3). 30% through thickness crack, crack length = 30% of brace circumference;
4). surface crack,
    (β =0.5), crack length = 30% of brace circumference, crack depth = 75% of chord thickness
    (β =0.95) crack length = 15% of brace circumference, crack depth = 75% of chord thickness

The following material properties were used: Modulus of Elasticity = 210,000 MPa
Possion's Ratio = 0.3
Yield Stress = 327 MPa

An isotropic work hardening rule, Von Mises yield criterion and incremental plasticity were used in the analyses. The properties of the weld metal and HAZ were assumed to be the same as those of the parent metal. For the elastic analyses the midside nodes on the crack tip elements were moved to the 1/4 points in order to model the $1/\sqrt{r}$ singularity. For the elastic-plastic analyses the midside nodes on the crack tip elements were left at the 1/2 points. For both the elastic and elastic-plastic analyses the crack tip elements were quadrilaterals collapsed to triangular prismatic shape. An array of 6 crack tip collapsed quadrilateral elements with tied tip nodes was used, i.e. the coincident nodes at the crack tip were constrained as a single node. Attempts to analyse some FE cracked meshes with independently moving crack tip nodes (untied tip nodes), in order to obtain the crack tip opening displacements (CTOD) were made. This was found to be impossible because of errors encountered due to both extreme element distortions (crack tip elements turning inside out) and non-convergence problems.

All joints were modelled with 20 noded brick elements C3D20 (with 27 integration points in each element) including the effect of the weld profile. In order to model the stress distribution across the thickness and to get better the values of J-integral, three layers of elements across the thickness around the crack region were produced automatically by the mesh generation program PRETUBE. The other parts had one layer of elements across the thickness. The weld profile was modelled by PRETUBE automatically according to the recommendations for the AWS Standard Flat Welds Profile.

FAILURE ASSESSMENT DIAGRAMS FOR CRACKED DT TUBULAR JOINTS

In this study, all FADs for the tubular DT joints have been constructed using HSE characteristic failure collapse loads modified according to equation 3.

The J-integral values calculated directly from ABAQUS have been used to construct the FAD for cracked tubular joints. These J values include mixed mode effects and from a series of other studies to be reported separately are considered reliable under mixed mode loading. The FADs are compared with the standard Level 2 FAD given in PD 6493.

The fracture axis is given by:

$$K_r = \frac{K_I}{K_{Ic}} = \sqrt{\frac{J_{el}}{J_{ep}}} \qquad (5)$$

where values of J_{el} were obtained from a linear elastic FE analysis with the mid-side nodes on the crack tip elements were moved to the 1/4 points to give the stress singularity at the crack tip. The values of J_{ep} were calculated from large displacement elastic-plastic FE analysis. The J_{el} was calculated under the same load values as J_{ep} in the elastic-plastic analysis.

The FADs derived from the ABAQUS J values for the M1 and M2 geometries are shown in Figs. 1 and 2. In these FADs, the values of J_{el} and J_{ep} were taken from the second node (J2) closest to the outer surface of the chord for the through thickness cracked joints. For the surface cracked joints the values of J-integral at the deepest point of crack were used to construct the FADs because these J values were found to be the maximum J values along the crack front. In each of the FADs, the standard FAD is plotted to compare with the FADs for the different cracked joints in each series. It can be seen that because conservative plastic collapse loads were used to construct the FADs, all the FAD curves for these tubular joints lie outside the standard Level 2 FAD given in PD 6493. This demonstrates that using standard FADs is safe for assessment of cracked tubular joints providing the input data takes account of the lower bound collapse load and of mixed mode loading as is done by use of the FE analysis results in these cases.

In the above section, FADs were constructed by the values of J-integral directly from ABAQUS. One of the methods used to calculate the J-integral values with experimental results is the energy method (work done) from load-displacement curves using the area under the load-displacement curve up to a given total deflection. This same energy method will now be used to derive a new method for construction of FADs to confirm their general applicability to joints subject to mixed mode effects as follows:

As a general equation,

$$J_{el} = \frac{\eta_{el} A_{el}}{C} \qquad (6)$$

$$J_{ep} = \frac{\eta_{ep} A_{ep}}{C} \qquad (7)$$

where,

$$A_{el} = \sum_{i=0}^{n} P_i \delta_{el\,i} \qquad (8)$$

$$A_{ep} = \sum_{i=0}^{n} P_i \delta_{ep\,i} \qquad (9)$$

and η_{el}, η_{ep} are coefficients for elastic and elastic-plastic analysis respectively, C is a coefficient dependent on the geometry of the cracked specimen.

Clarke and Landes (1979) concluded from CT specimen experimental tests, and it has been generally found for other cases that

$$\eta_{el} \approx \eta_{ep} \quad \text{for } a/w>0.5 \tag{10}$$

Hence J can be expressed as:

$$J = \frac{\eta A}{C} \tag{11}$$

Substituting Eqns., (6) to (9) into Eqn. (5), then

$$K_r = \sqrt{J_r} = \sqrt{\frac{J_{el}}{J_{ep}}} = \sqrt{\frac{\eta_{el}A_{el}/C}{\eta_{ep}A_{ep}/C}} = \sqrt{\frac{A_{el}}{A_{ep}}} \tag{12}$$

$$\text{when } i=1,\ \frac{A_{el}}{A_{ep}} = \frac{P_1 \times \delta_{el\,1}}{P_1 \times \delta_{ep\,1}} = \frac{\delta_{el\,1}}{\delta_{ep\,1}} \tag{13}$$

where the values of load for each increment are the same for elastic analysis and elastic -plastic analysis.

$$\text{when } i=n,\ \text{Limit} \frac{A_{el}}{A_{ep}} \rightarrow 0.$$

Hence the fracture axis K_r is converted to solve $A_r = \frac{A_{el}}{A_{ep}}$, which is the ratio of elastic area of work to elastic-plastic area of work. This is easy to calculate because A_r is only relevant to the load and displacement values and these pairs of values can be obtained from either FE analysis or experimental test. A large number of FE analysis results have shown that with good modelling load-displacement results from FE analysis are very reliable up to the stage of tearing.

Although A_r is equivalent to the ratio J_r because A_r is derived from J_r, A_r is much simpler than J_r in both definition and calculation method and is automatically relevant to any mixed mode loading which may be present. When the load is very low, $\delta_{el} \approx \delta_{ep}$ and $A_r \approx 1$. When the load increases, the effects of plasticity increase also. For these higher loads, $\delta_{el} < \delta_{ep}$ and $A_r < 1$. As A_r reduces from 1 to 0, the effect of plasticity is reflected in the shape of the FAD. The collapse axis, S_r is retained as described previously because this is essentially controlling the amount of plasticity at the crack. A typical load-load point displacement curve is plotted in Fig 3. In this figure, the relationship between A_{el} and A_{ep} (δ_{el} and δ_{ep}) is clear.

Based on PD6493 Level 2, the FADs have been constructed as A_r vs. S_r for the tubular joint models M1 and M2 using the FE analysis results and these FADs are plotted in Figs. 4 and 5. From a comparison of the two sets of FADs, it can be seen that both sets of FADs agree very closely when the collapse axis is defined by the same method. This new method (energy-area method) only uses the global behaviour parameters (load values and displacements) and hence is unrelated to the local mesh at the crack tip region. Furthermore it is the ratio of the work done for elastic and elastic-plastic analyses and so the effect of the mesh for the whole model is relatively small provided a similar mesh is used in both cases. The energy-area method has also been applied to the surface crack joint cases. All FADs show generally good agreement between the two sets of FADs produced from ABAQUS direct values of J or the area under the load displacement curve for the different crack and geometry cases. There is a small difference between the curves for the M2 surface crack cases where the area method gives results slightly higher than the direct J method.

DISCUSSION

On the basic assumption that failure will occur when a driving force parameter reaches a critical value of a resistance parameter, under mixed mode loading both the driving force and resistance parameters should be those for the mixed mode conditions. Under mixed mode loading the total J value is the sum of the contributions from each of the modes present, although a major effects of mixed mode loading is to increase the mode I contribution itself because of the additional plasticity under combined loading. If a finite element analysis of the cracked structure is available estimates of the total J value may be obtained directly from ABAQUS, from the area under the load displacement curve or in other work to be reported separately by conversion from the crack tip displacements. The crack tip displacement method has the advantage that it enables the relative contributions from the different modes to be established although account must be taken of the different constraint factors for the different modes at different load levels.

Other related work at UMIST has also shown that the fracture toughness under mixed mode loading conditions may be different from that under the conventional test conditions of mode I only. For tests carried out on thin samples of steel from model tubular joints tested, it appears that the toughness results for mixed mode I/III in which the ratio of mode III to mode I components of J was about 40% showed a reduction in fracture toughness expressed as total J of about 25% compared to the mode I only case. Since the mode III loading is by shear and the yield strength in shear is significantly lower than the yield strength in tension, it is not surprising that the effect of mode III on ductile tearing is to cause a reduction in overall toughness.

It has been shown in the present work that the standard R6/PD 6493 assessment diagrams can be used satisfactorily for assessment of cracked tubular joints provided total J values for mixed mode loading are used for the K_r fracture axis and a lower bound estimate used for collapse load to limit plasticity at the cracked section to match the behaviour underlying the standard cases. For practical assessment purposes it is necessary to have methods available to estimate the equivalent applied stress intensity factor and fracture toughness for the degree of mixed mode loading present, and to have a method available to estimate the lower bound collapse load.

It has previously been suggested by UMIST that a simple way to provide an upper bound estimate of the equivalent K value for cracked tubular joints is as follows:

$$K_{eq} = \alpha\, \sigma_{HS} \sqrt{\pi a} \tag{14}$$

where σ_{HS} is the local stress in the uncracked joint at the position corresponding to the ends of the crack, 2a is the total crack length around the perimeter of the weld toe region and α is a coefficient. This result was derived by taking the total J values from a series of elastic analyses of DT and K joints with β ratios in the range 0.3 to 0.95. The results are presented in Table 1 for the present analyses where it can be seen that the ratio K/K_{eq} is typically about 0.3 to 0.5 for these cases. In other geometries somewhat higher values closer to 1 have been obtained and hence the use of $\alpha=1$ in equation 14 is recommended to give safe results.

CONCLUSIONS

Mixed mode loading is important in cracked tubular joints and studies have been carried out to develop procedures to estimate crack tip driving forces under such conditions.

The use of global collapse strength for cracked tubular joints is a satisfactory basis to construct the Failure Assessment Diagram because this provides a simple means of matching the amount of plasticity at the crack to that underlying the standard assessment diagrams. This global collapse strength has been defined by modifying the uncracked HSE characteristic strength by a reduction factor based on loss of cross sectional area due to the crack and on the geometric modifier Q_β.

Failure Assessment Diagrams have been constructed using J-integral results directly from FE analyses and from an energy/area method including mixed mode loading cases. All FADs fall outside the standard PD 6493 Level 2 FAD hence use of the standard FAD to assess cracked tubular joints is safe in conjunction with the modified global collapse load.

Applied elastic stress intensity factors for mixed mode loading in tubular joint geometries for both surface and through thickness cracked cases may be estimated by using crack dimensions together with the stress concentration in the uncracked tubular joint at the crack position.

ACKNOWLEDGEMENT

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Table 1 Geometries of Tubular Joints used in FE Analysis

Identification	Joint geometry	Dimensions
Series M1	β=0.5, τ=0.5	D 572,d 286,T 19,t 9.5
Series M2	β=0.95, τ=1.0	D 572,d 543, T 19,t 19

Table 2 Estimation of Stress Intensity Factor for Cracked DT joints

M1 β=0.5 axial tension	15%T-T-C	30% T-T-C	30% S-C
a-crack length (mm)	69.0	138.5	14.25
K_{TOT}	10.25	13.44	9.9
SCF	11.353	10.3	11.84
$\sigma_H\sqrt{\pi a}$	38.44	49.39	18.22
$K_{TOT}/\sigma_H\sqrt{\pi a}$	0.3	0.3	0.543
M2 β=0.95 axial tension	15% T-T-C	30% T-T-C	15% S-C
a-crack length (mm)	140.0	280.0	14.25
K_{TOT}	5.1	4.58	2.72
SCF	9.45	7.35	10.41
$\sigma_H\sqrt{\pi a}$	25.77	28.39	9.06
$K_{TOT}/\sigma_H\sqrt{\pi a}$	0.36	0.36	0.3

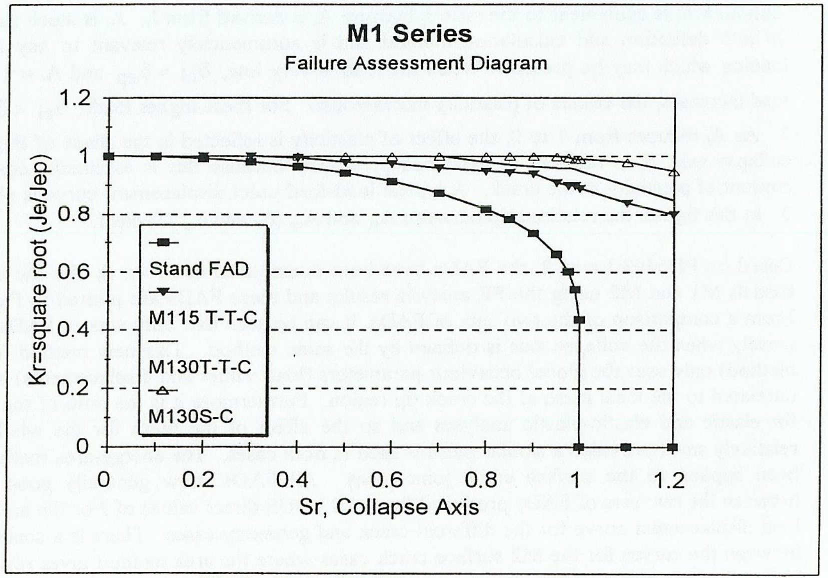

Fig. 1. Series M1 failure assessment diagram

The use of global collapse strength for cracked tubular joints is a satisfactory basis to construct the Failure Assessment Diagram because this provides a simple means of matching the amount of plasticity at the crack to that underlying the standard assessment diagrams. This global collapse strength has been defined by modifying the uncracked HSE characteristic strength by a reduction factor based on loss of cross sectional area due to the crack and on the geometric modifier Q_β.

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$K_{TOT}/\sigma_H\sqrt{\pi a}$	0.3	0.3	0.543
M2 β=0.95 axial tension	15% T-T-C	30% T-T-C	15% S-C
a-crack length (mm)	140.0	280.0	14.25
K_{TOT}	5.1	4.58	2.72
SCF	9.45	7.35	10.41
$\sigma_H\sqrt{\pi a}$	25.77	28.39	9.06
$K_{TOT}/\sigma_H\sqrt{\pi a}$	0.36	0.36	0.3

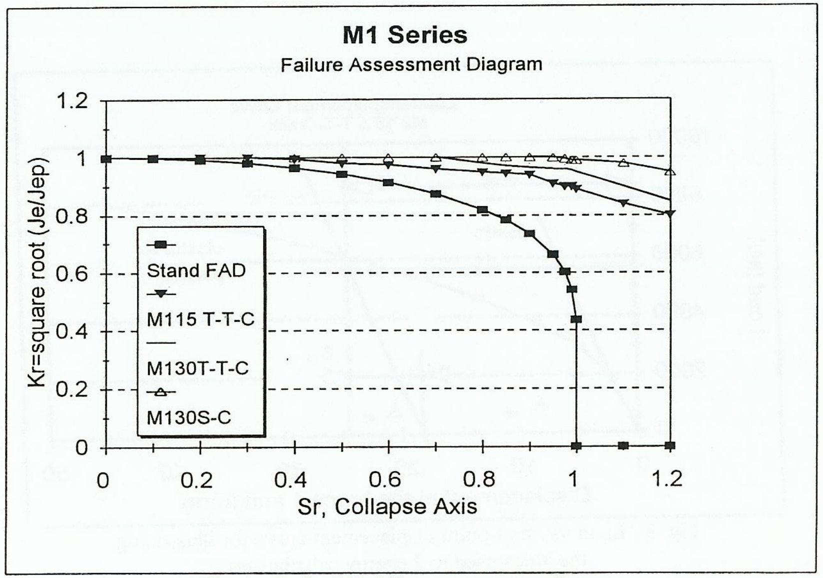

Fig. 1. Series M1 failure assessment diagram

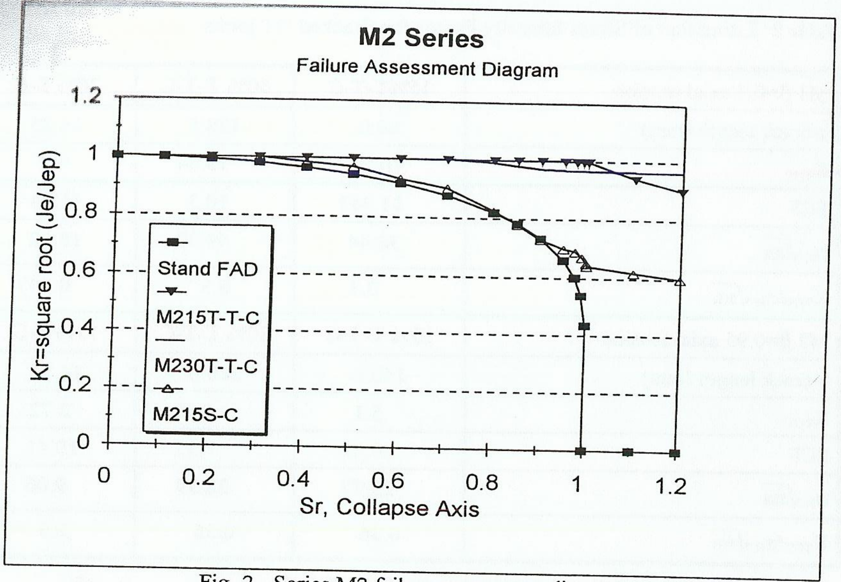

Fig. 2. Series M2 failure assessment diagram

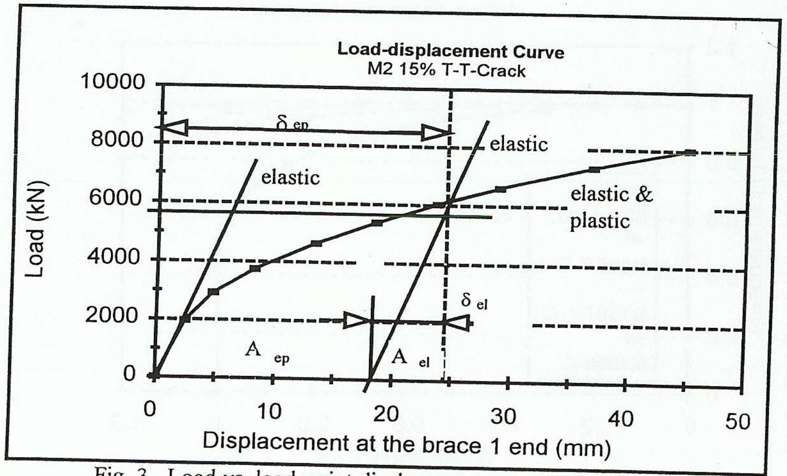

Fig. 3. Load vs. load-point displacement curve for illustrating the areas used to J energy calculations

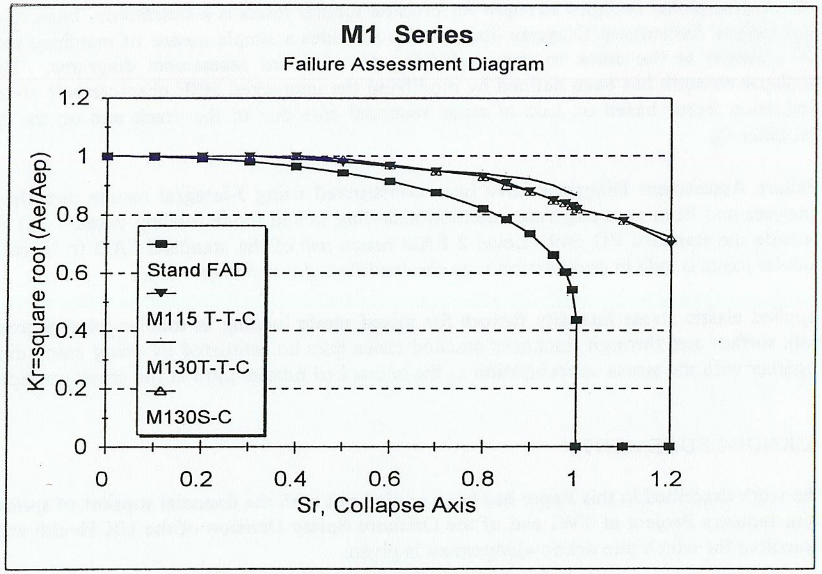

Fig. 4. M1 series FADs by energy method

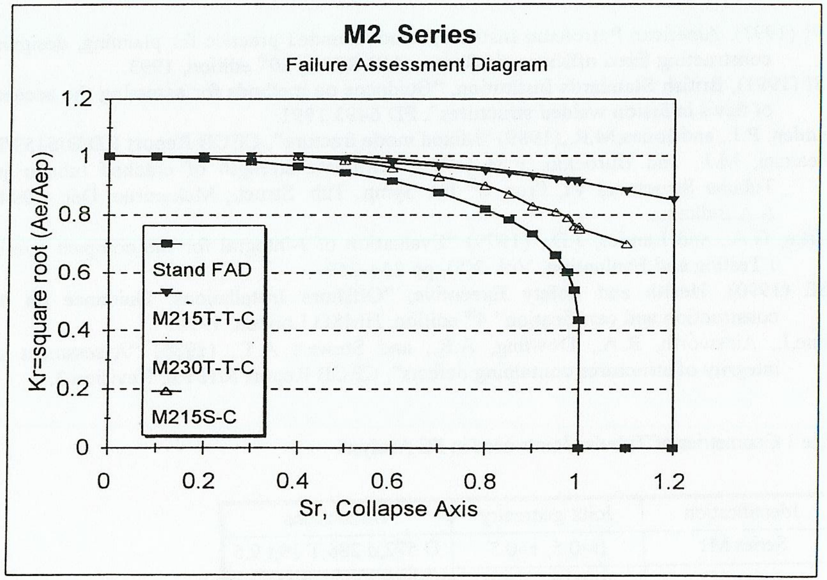

Fig. 5. M2 series FADs by energy method