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THE LOAD SEPARATION TECHNIQUE IN THE ELASTIC-PLASTIC FRACTURE ANALYSIS OF TWO- AND THREE-DIMENSIONAL GEOMETRIES

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SUMMARY

Load separation is the representation of the load in the test records of geometries containing cracks as a multiplication of two separate functions; a crack geometry function and a material deformation function. In this paper, load separation is demonstrated in the test records of several two-dimensional geometries such as: compact tension geometry, single edge notched bend geometry, and center cracked tension geometry and three-dimensional geometries such as semi-elliptical surface crack. The role of load separation in the evaluation of the fracture parameter J-Integral and the associated factor η for two-dimensional geometries is discussed. The paper also discusses the theoretical basis and the procedure for using load separation as a simplified, yet accurate approach for plastic J evaluation in semi-elliptical surface crack which is a three-dimensional geometry. The experimental evaluation of J, and particularly J_{pl}, for three-dimensional geometries is very challenging. A few approaches have been developed in this regard and they are either complex or very approximate. The paper also presents the load separation as a mean to identify the blunting and crack growth regions in the experimental test records of precracked specimens. Finally, load separation as a methodology in Elastic-Plastic Fracture Mechanics is presented.

INTRODUCTION

The path independent J-integral was first introduced by Rice (1) as a crack tip parameter for two-dimensional geometries made of linear or non-linear elastic materials. This line integral form can be written as:

$$\int_{\Gamma} \left(W dy - T \frac{\partial u}{\partial x} ds \right) \qquad [1]$$

where Γ is a contour around the crack as shown in figure 1, W is the strain energy per unit volume, T is the tension vector perpendicular to Γ, u is the displacement in the x-direction and ds is an element of the contour. The experimental evaluation of J using the line integral can be done by placing strain gauges on the outside surface of the specimen along a contour in a plane perpendicular to the crack front. By defining the strain, external traction, and displacement in the x-direction along this contour, J can be evaluated. However, this technique is usually inaccurate

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and impractical. An equivalent, yet more practical J expression was introduced by Rice (1) as:

$$J = -\frac{1}{B}\left[\frac{\partial U}{\partial a}\right]_v \qquad [2]$$

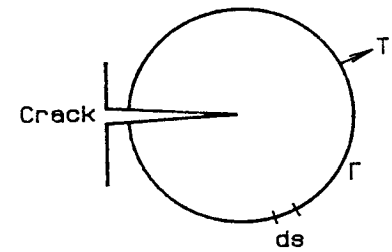

Figure 1 The J-integral contour.

where U is the potential energy and can be measured as the area under the load-line displacement record, a is the crack length, B is the specimen thickness and v is the load-line displacement. This J expression allowed Landes and Begley (2) to develop their multispecimen technique to evaluate J. Their approach requires the testing of many identical blunt notched specimens with different crack lengths in order to develop the U versus a relationship, from which J can be evaluated. Despite the accuracy and reliability of this technique, the high cost of specimens preparation and testing made it impractical. A single specimen technique was later developed for special geometries and crack ranges where the load can be represented in a particular form as will be discussed next.

Rice reduced the energy rate interpretation J form given in eq [2], for deeply cracked bend specimens (3), into:

$$J = \frac{2}{B}\frac{U}{b} \qquad [3]$$

where b is the uncracked ligament. This J expression was based on representing the applied bending moment M versus the angle of rotation due to the crack presence θ as:

$$\theta = f(M/b^2) \qquad [4]$$

The J expression in eq [3] can be obtained from the test record of a single bend specimen. Merkle and Corten (4) also developed a single specimen J expression for compact specimen. They represented the load using limit load analysis as:

$$P = [\sigma_y B (b/2)(2\alpha)]\, g(\theta_p) \qquad [5]$$

where σ_y is the yield strength, θ_p is the plastic rotation due to the crack and α is a function of a and b. Using this form, they developed J as:

$$J = \frac{2(1+\alpha)}{1+\alpha^2}\frac{U}{Bb} \qquad [6]$$

This J expression can be also evaluated by testing a single compact tension specimen.

The load expressions in eqs [4] and [5] can be described as separable forms. This means that the load is represented as a multiplication of two separate functions: a crack geometry

function and a material deformation function and can be written as:

$$P \text{ or } M = G(b \text{ or } a) \,.\, H(\theta \text{ or } v) \qquad [7]$$

Also, the single specimen J form can be generally written as:

$$J = \eta \frac{U}{Bb} \qquad [8]$$

where the modification factor η is a function of the crack length and the geometry. Ernst and Paris (5) proved that the single specimen J form and η-factor only exist if the load can be represented by a separable form.

Further studies suggested representing J as the sum of two parts; J_{el} and J_{pl}. The elastic part, J_{el}, can be evaluated using Linear Elastic Fracture Mechanics as $[K^2/E']$ where K is the stress intensity factor and E' is the effective Young's Modulus. The plastic part, J_{pl}, can be written, according to the ASTM standard test method (6), as:

$$J_{pl} = \eta_{pl} \frac{A_{pl}}{Bb} \qquad [9]$$

where A_{pl} is the area under the load versus plastic displacement test record and the η_{pl}-factor is considered as:

$$\eta_{pl} = 2 \qquad \textit{for bend specimen and}$$

$$\eta_{pl} = 2 + 0.522 \frac{b}{W} \qquad \textit{for compact specimen} \qquad [10]$$

The latter was the linear approximation of Merkle-Corten expression as shown in eq [6]. The single specimen J_{pl} form in eq [9] is based on the load separable form given as:

$$P = G(b/W)\, H(v_{pl}/W) \qquad [11]$$

where W is the specimen width and $G\,(b/W)$ and $H(v_{pl}/W)$ are the geometry and deformation functions.

J-integral was first considered as a stationary crack parameter because it is based on the deformation theory of plasticity. However, it was later applied to extended cracks (7) if the crack growth is of the order of the non-proportional plastic region at the crack tip. This allowed Ernst et al (8) to develop a technique to evaluate a J-R curve for precracked specimen with J updated for the crack growth. This technique is also based on the single specimen J form. Thus, load separation must also exist during crack growth.

The available load separation expressions which are based on limit load analysis have been mainly developed for two-dimensional bending geometries such as bend and compact

tension specimens. This limited the single specimen J form to this geometry only. In this paper, load separation will be demonstrated in bending as well as tension geometries, in stationary as well as growing crack test records, and in two- as well as three-dimensional geometries. It will be also presented as a mean to define crack blunting and growth regions. It will be also used in a new η_{pl} method and to develop a key curve that can provide predicted load-displacement records. By extending load separation to three-dimensional geometries, an equivalent single specimen J form can be developed. Very few techniques are currently available for the experimental evaluation of J for these complex geometries and they are either impractical or inaccurate. Finally, the load separation as a methodology in Elastic-Plastic Fracture Mechanics will be presented.

LOAD SEPARATION IN TWO-DIMENSIONAL GEOMETRIES

Stationary Cracks

In order to study load separation in stationary crack test records, a separation parameter S_{ij} is introduced. This separation parameter represents the ratio of the loads $P(a_i)$ and $P(a_j)$ in the test records of two identical blunt notched specimens with crack lengths a_i and a_j at the same plastic displacement v_{pl}. Thus S_{ij} can be written as:

$$S_{ij} = \left[\frac{P(a_i)}{P(a_j)}\right]_{v_{pl}} \qquad [12]$$

If the load is separable, eq [12] can be rewritten as:

$$S_{ij} = \left[\frac{G(b_i/W)\,H(v_{pl}/W)}{G(b_j/W)\,H(v_{pl}/W)}\right]_{v_{pl}} = \frac{G(b_i/W)}{G(b_j/W)} \qquad [13]$$

For stationary cracks, S_{ij} should maintain a constant value over all of the plastic region. Figure 2 shows the test records of ten identical bend specimen made of HY130 steel with different crack lengths. The specimens are 0.9 inch thick and 2.0 inch wide and have span to width ratio of 4.0. They were originally reported in Ref. (9). When the loads in the different test records were divided by that of the specimen with $a_f/W=0.75$ at the same plastic displacement, the load ratios maintained constant values over all of the plastic region except for a small part at the early plastic behavior, see figure 3. Figure 4 shows the test records of ten HY130 center cracked tension specimens with different crack lengths and figure 5 shows the separation parameter for this set of test records. These specimens (9) were also 0.9 inch thick and 2.0 inch wide. It is clear that load separation exists in tension geometry such as the center cracked tension as well as

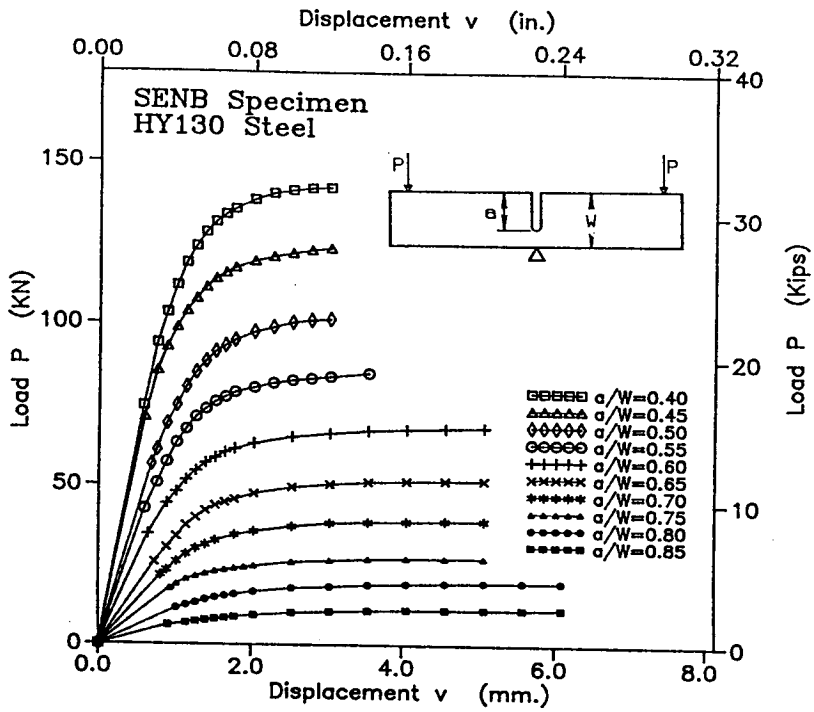

Figure 2. The test records of ten single edge notched bend specimens.

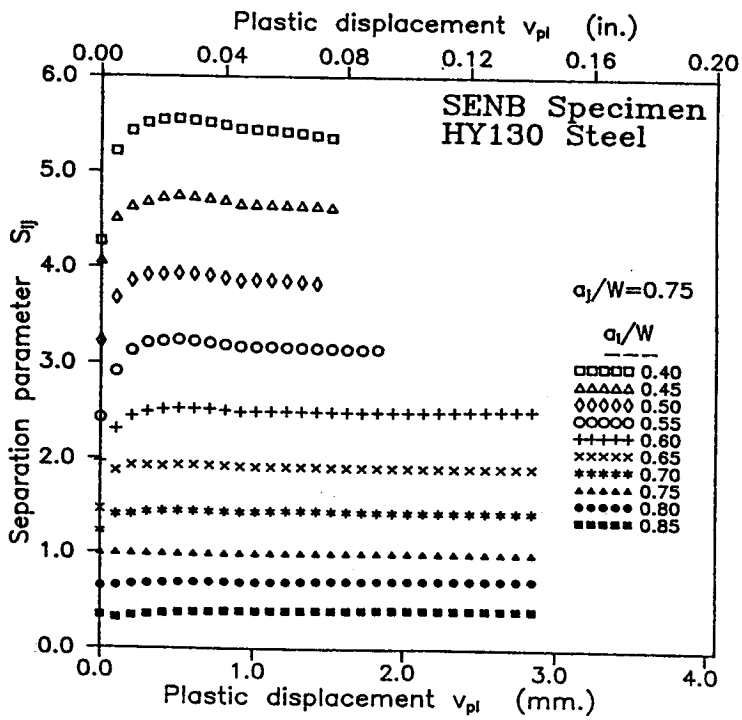

Figure 3. Load separation in the experimental test records of bend specimens.

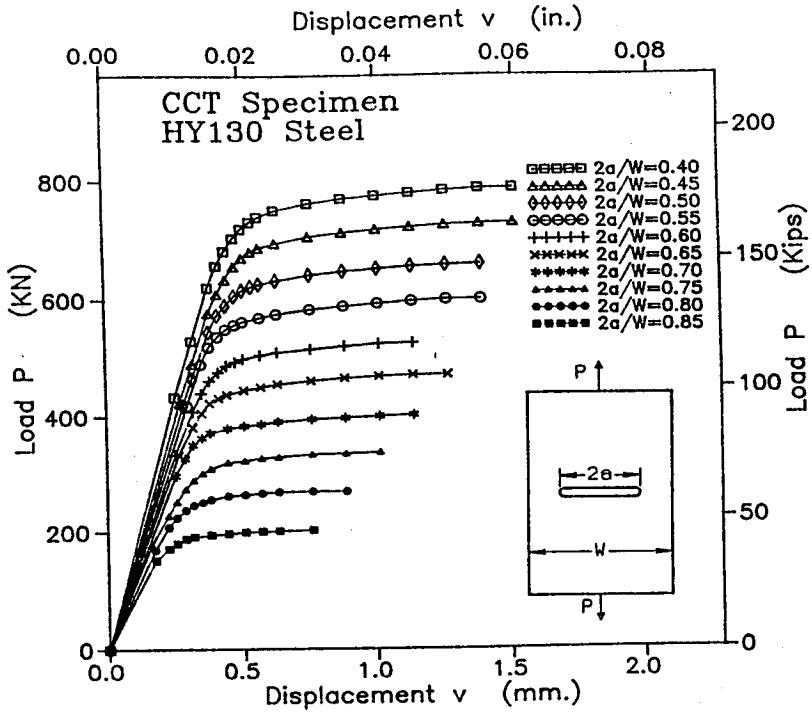

Figure 4. The test records of ten center cracked tension specimens.

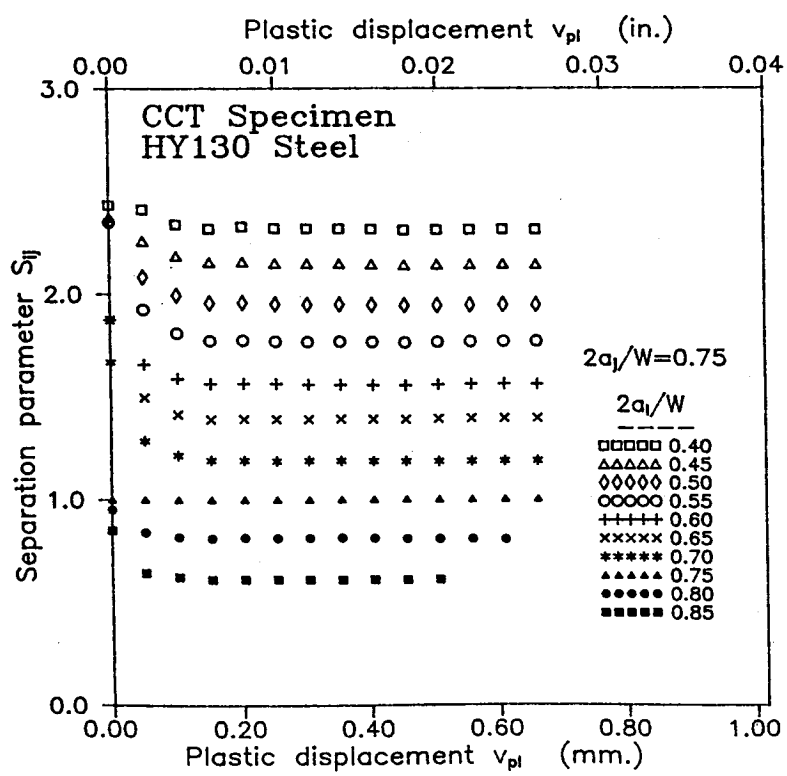

Figure 5. Load separation in the experimental test records of center cracked tension specimens.

bending geometry such as the bend specimen. Sharobeam and Landes (10,11) studied load separation in 12 sets of test records and found that load separation is dominant in all of the studied cases. Their study included different work hardening materials, different bending and tension geometries and wide range of crack length and geometrical proportions.

Precracked Specimens

Initially, we will assume that load separation also exists in the precracked test records but with different geometry and deformation functions than those for stationary cracks test records. Thus, the load in precracked specimen and blunt notched specimen test records can be written as:

$$P_p = G_p(b_p/W)\, H_p(v_{pl}/W) \qquad \textit{for precracked specimen and} \qquad [14]$$

$$P_b = G_b(b_b/W)\, H_b(v_{pl}/W) \qquad \textit{for blunt notched specimen} \qquad [15]$$

where the subscript p denotes precracked specimen while b denotes blunt notched specimen. The separation parameter can be then written as:

$$S_{pb} = \left[\frac{P_p}{P_b}\right]_{v_{pl}} = \left[\frac{G_p(b_p/W)\, H_p(v_{pl}/W)}{G_b(b_b/W)\, H_b(v_{pl}/W)}\right]_{v_{pl}} \qquad [16]$$

S_{pb} represents the ratio of the load in precracked specimen test record to the load in the test record of an identical specimen but with a stationary crack. Since $G_b(b_b/W)$ is constant because the crack is stationary, S_{pb} can be rewritten as:

$$S_{pb} = A\, G_p(b_p/W)\, h_{pb}(v_{pl}/W) \qquad [17]$$

where A is a constant and $h_{pb}(v_{pl}/W)$ is the ratio between the two deformation functions at the same plastic displacement. If several precracked test records are used with the same blunt notched record, one gets S_{pb} for each precracked specimen test record as:

$$S_{pb}^{i} = A\, G_p^{i}(b_p/W)\, h_{pb}^{i}(v_{pl}/W) \qquad [18]$$

where i denotes the different precracked specimen test records. If the different S_{pb}'s were plotted together versus b_p/W and collapsed into one record, then S_{pb} would be independent of v_{pl} and all the records would have the same geometry function $G_p(b_p/W)$. Thus, S_{pb} can be written as:

$$S_{pb} = A\, G_p(b_p/W) \qquad [19]$$

This would also indicate that the load is separable for precracked test records and can be represented as a multiplication of geometry and deformation functions. Figure 6 shows the test

records of three precracked specimens (E71, E75, E76) and a blunt notched specimen (E73). The specimens are compact tension and made of A533B steel with 1.0 inch thickness, 2.0 inch width and 20% side grooving. They were originally used in Ref. (12). The initial crack to width ratios for the precracked specimens are 0.608, 0.607 and 0.607 and the final crack to width ratios are 0.656, 0.7115, and 0.794 respectively. Figure 7 shows S_{pb} versus b_p/W for the different precracked specimen test records on a log-log graph. All of the records collapsed together into one which proves the assumption of load separation. Sharobeam and Landes (13) studied load separation in four sets of precracked specimen test records of different materials and with large crack growth. They indicated that load separation existed in all of the studied cases.

In precracked test records, load separation can be also used to define both the blunting and growing crack regions. Figure 8 shows both b_p/W and S_{pb} versus v_{pl} for one of the A533B precracked specimens. There are three regions for S_{pb} versus v_{pl}. The first region is very small at the early plastic behavior and is usually called the non-separable region. Then there is a second region where both S_{pb} and b_p/W almost maintain constant values. This is the blunting region. In the third region, both S_{pb} and b_p/W decrease indicating crack growth. The blunting and crack growth regions can be also identified in figure 7. The blunting region looks like a vertical line while the crack growth region looks like an inclined line.

Plastic η Development

Based on eqs [2] and [11], η_{pl} can be written as:

$$\eta_{pl} = \frac{b/W}{G(b/W)} \frac{\partial G(b/W)}{\partial (b/W)} \qquad [20]$$

The geometry function $G(b/W)$ can be obtained using the separation parameter S_{ij} or S_{pb}. The stationary crack separation parameter S_{ij} maintains constant value over all of the plastic region for specific a_i and a_j values. If S_{ij} is developed for different a_i values with respect to a single a_j value, one can construct the relationship S_{ij} versus a_i/W (or b_i/W) as:

$$S_{ij} = \left[\frac{G(b_i/W)}{G(b_j/W)}\right]_{vary\ b_i} = A\, G(b_i/W) \qquad [21]$$

where A is a constant equal to the inverse of $G(b_j/W)$. The S_{ij} expression in eq [21] can be then used directly in eq [20] instead of $G(b/W)$ to evaluate η_{pl}. Figures 9 and 10 show the variations of S_{ij} versus b/W on log-log graphs for both the bend and center cracked tension sets of test records shown before in figures 2 and 4. The power law function fits well the S_{ij}-b_i/W relationship in both cases. Thus, S_{ij} can be written as:

$$S_{ij} = A_1 (b/W)^m \qquad [22]$$

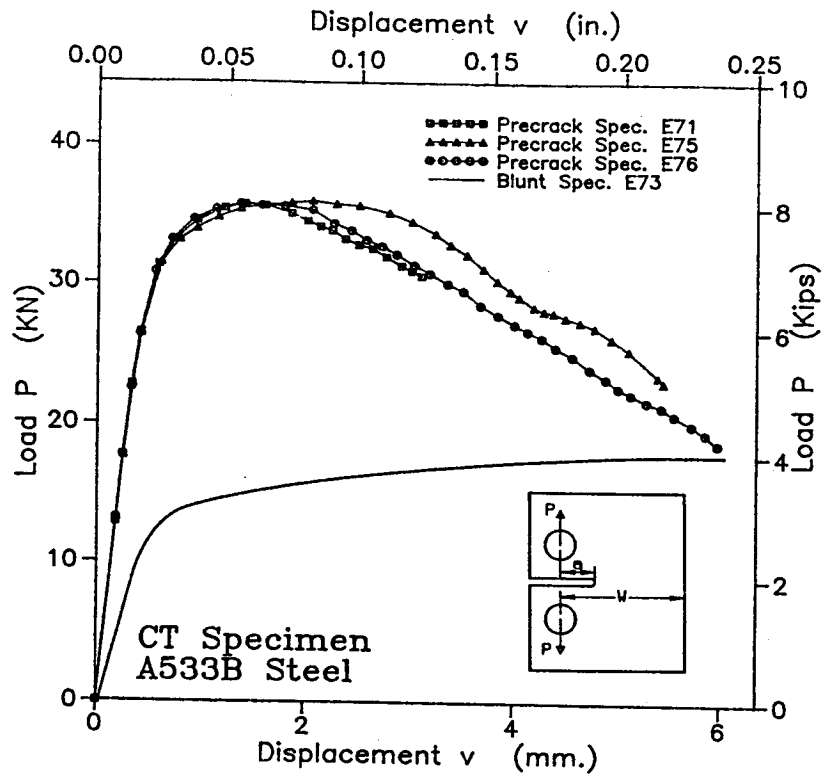

Figure 6. The test records of three precracked and one blunt notched compact tension specimens.

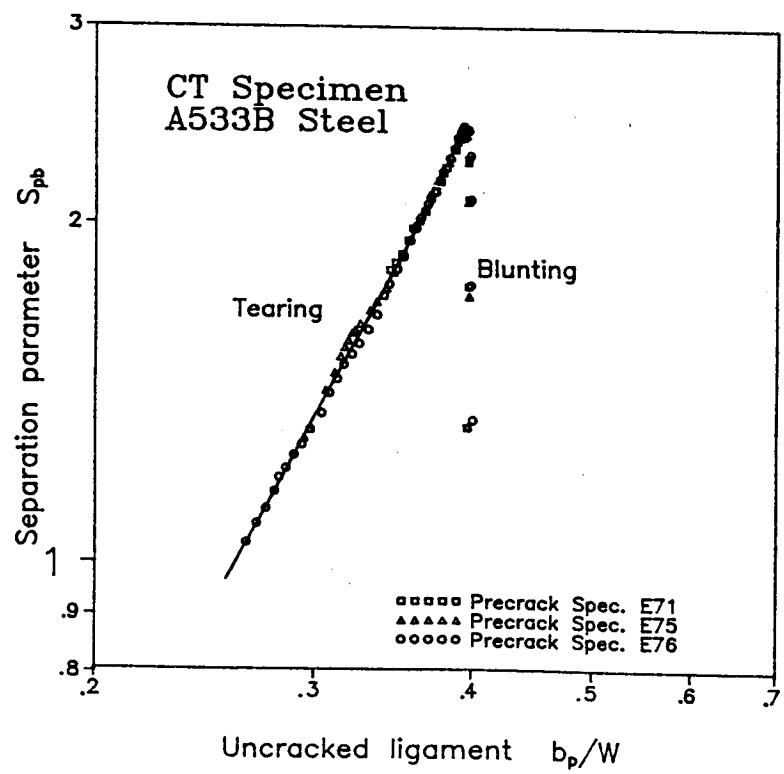

Figure 7. Load separation in the precracked compact tension specimens test records.

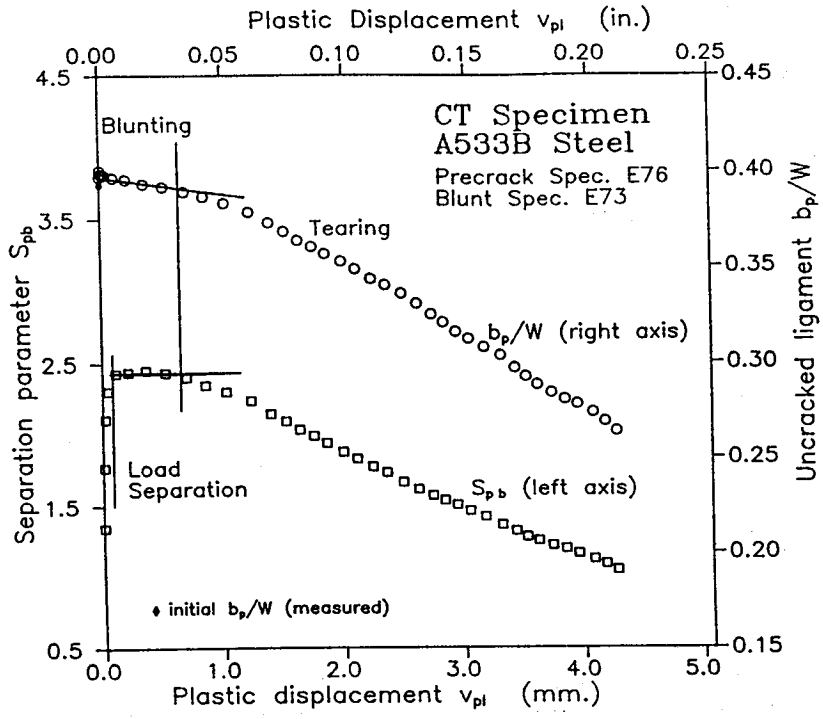

Figure 8. The blunting and tearing regions in the precracked specimen test record.

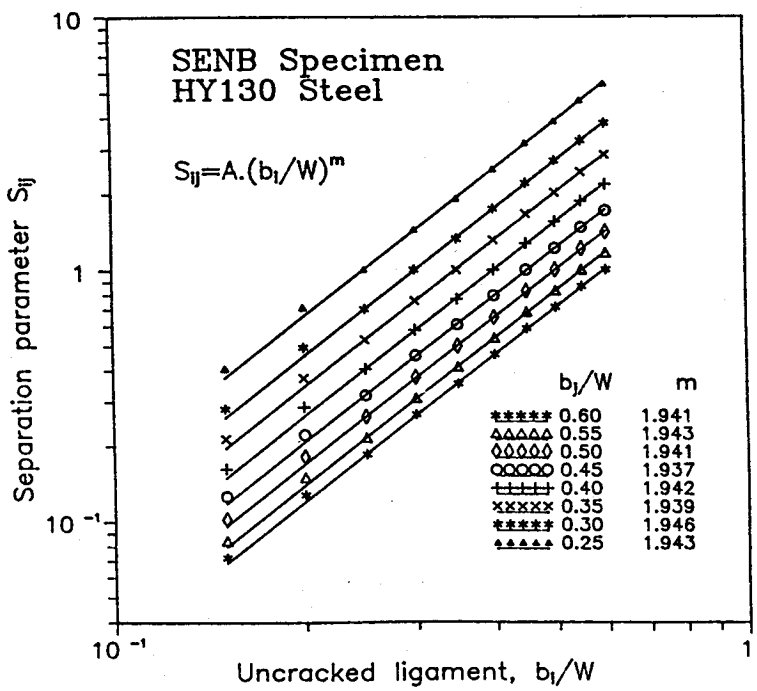

Figure 9. The separation parameter S_{ij} versus b_l/W in the bend specimen test records.

where A_1 is a constant and m is the power law exponent. From eqs [20], [21] and [22], η_{pl} is equal to the power law exponent m. For the given set of bend specimens, η_{pl} has an average value of 1.96 and for the center cracked specimens, it is equal to 0.96. The evaluation of η_{pl} using the load separation technique is discussed in detail in Ref. (13).

For the precracked specimens, the separation parameter S_{pb} is equal to the geometry function times a constant as shown in eq [19]. Thus by constructing the relationship S_{pb} versus b_p/W, the geometry function can be developed. Figure 7 shows the variation of S_{pb} with respect to b_p/W on a log-log graph for the A533B compact tension set. The relationship can be well fitted by a power law function with a power law exponent of 2.12 which is also the value of η_{pl} for this set as discussed early. When identical A533B compact tension specimens but with stationary cracks used to evaluate η_{pl} using the stationary crack separation parameter S_{ij}, a value of 2.17 was obtained which is very consistent with the precracked specimens results.

Thus, η_{pl} can be obtained using either test records of a set of identical blunt notched specimens with different crack sizes or a precracked specimen test record together with a test record of an identical blunt notched specimen.

The Key Curve

As the geometry function is developed, an expression for the normalized load, P_N, can be written as:

$$P_N = \frac{P}{G(b/W)} = H(v_{pl}/W) \qquad [23]$$

The normalized load is a function of the plastic displacement only and is independent of the crack length. The P_N versus v_{pl} relationship is commonly called the key curve. Figures 11 and 12 show the key curves for both the bend and center cracked tension sets. Figure 13 shows the key curve for the A533B precracked specimen test records together with three test records of identical blunt notched specimens. Our studies showed that the geometry and deformation functions are the same for both stationary and growing crack test records of same material and geometry. The key curve can be used to construct the load-displacement test record of any specimen of same material and geometry with any crack length within the range of the key curve.

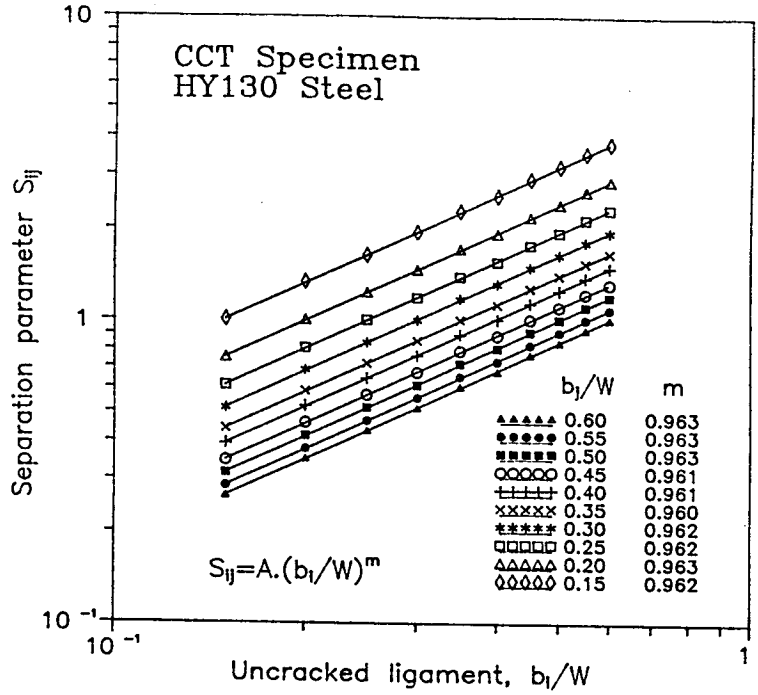

Figure 10. The separation parameter S_{ij} versus b_l/W in the center cracked tension specimen test records.

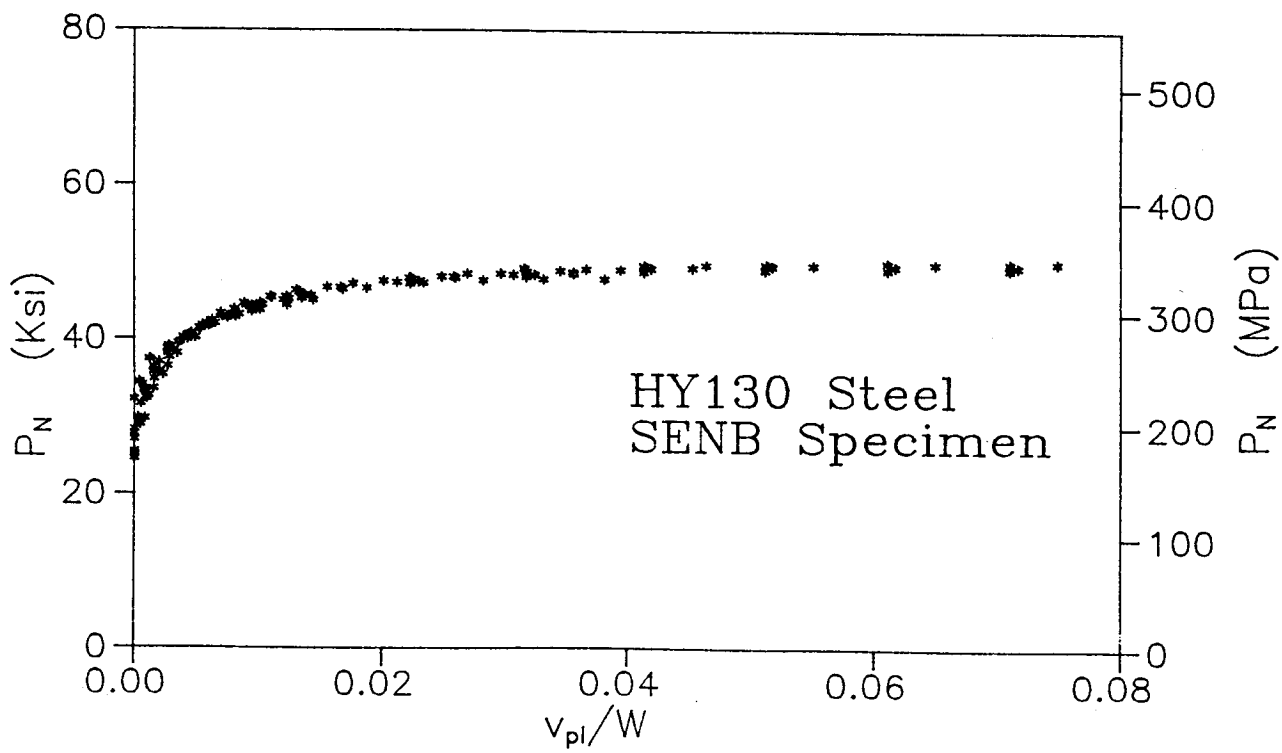

Figure 11. The key curve for the HY130 bend specimens.

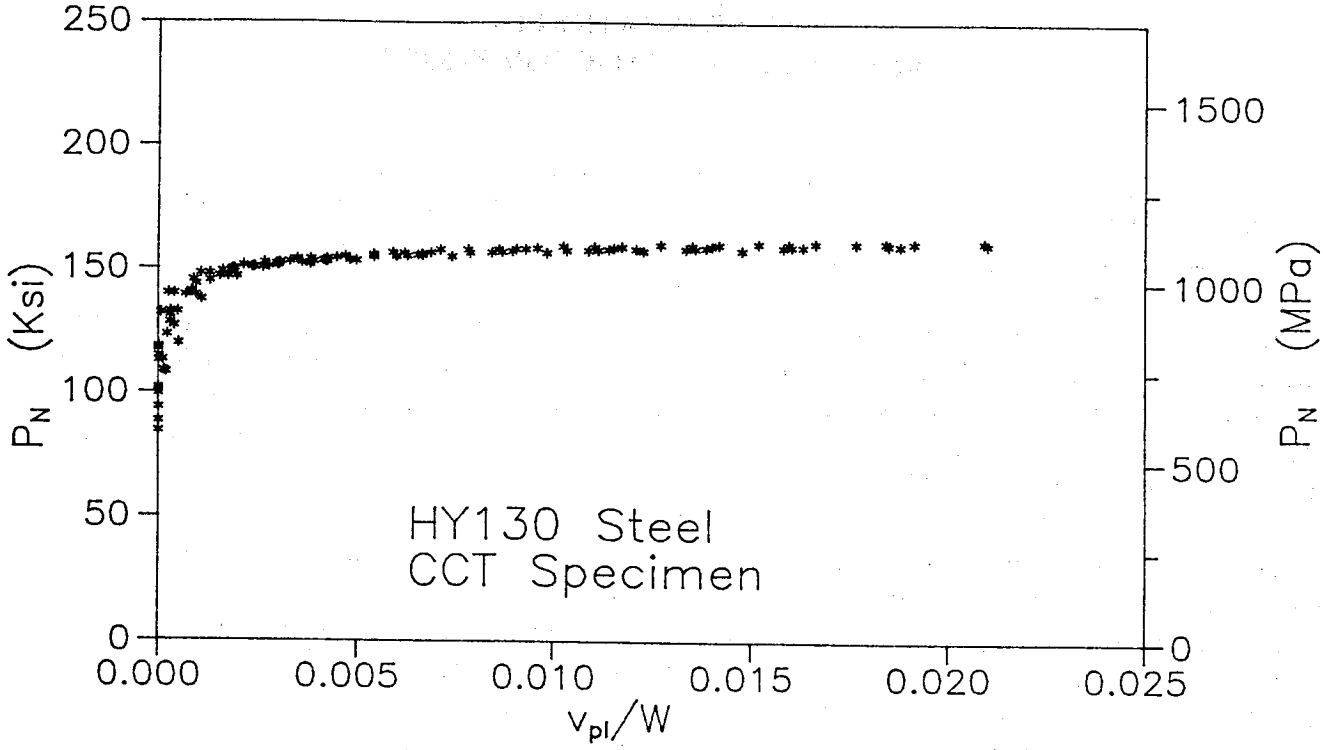

Figure 12. The key curve for the HY130 center cracked tension specimens.

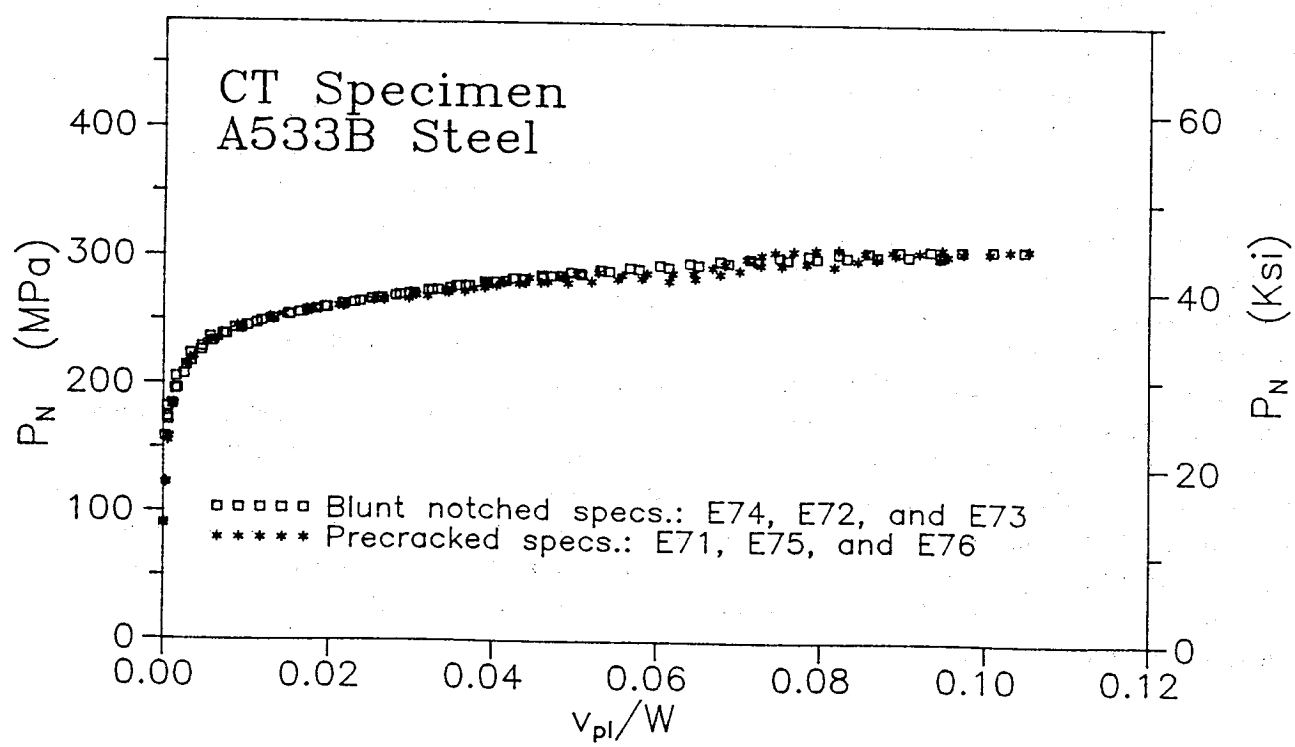

Figure 13. The key curve for the A533 precracked and blunt notched compact tension specimens.

LOAD SEPARATION IN THREE-DIMENSIONAL GEOMETRIES

The experimental evaluation of J in three-dimensional geometries is usually very challenging. The single specimen J form given in eqs [8] and [9] is not directly applicable to three-dimensional geometries because of different reasons. The single specimen J form can be used only for single valued J as in two-dimensional geometries. J in three-dimensional geometries is not single valued but it varies along the crack front. The single specimen J form requires load separation which is not fully studied yet in three-dimensional geometries. The area under the test record in the single specimen J form is based on the Load-Line Displacement (LLD). In some three-dimensional geometries such as surface cracks, the LLD is insensitive to the crack size and the Crack Mouth Opening Displacement (CMOD) is the displacement that is commonly measured. The crack in the single specimen J form is defined by one parameter, its length, while in three-dimensional geometries, it is defined by two parameters, its depth and width. Thus, in order to simplify J evaluation in three-dimensional geometries and develop a form equivalent to the single specimen J form in two-dimensional geometries, these issues need to be addressed. Load separation in three-dimensional geometries need to be studied. The variable J needs to be replaced by an equivalent single-valued J. The two-parameter crack may need to be represented by an equivalent single parameter crack. A factor equivalent to η_{pl} in the two-dimensional analysis needs to be developed. Finally, the relationship between the LLD and CMOD needs to be studied.

We will focus our discussion here on semi-elliptical surface crack as an example of three-dimensional geometries, see figure 14a. Both experimental and numerical data will be analyzed. The experimental data are for panels made of 2219-T87 aluminum as a base metal with tungsten arc-weld seam that is blunt notched with semi-elliptical surface crack. The panels are 1.0 inch thick and 4.0 inch wide. These data were originally used by McCabe et al (15) in a study on developing J-integral for surface cracks using the equivalent energy approach. The numerical data were developed using a finite element model with 2927 nodes and 387 20-nodes hybrid brick elements. The mesh in the crack vicinity includes several rings of focused elements as shown in figure 14b. The crack tip sides of the first ring elements were collapsed to capture the $1/r$ singularity and the mid-side nodes in the first three rings elements were moved to the quarter point to capture the $1/r^{1/2}$ singularity. The adequacy of the mesh and accuracy of the model results were verified by comparing the results with Newman-Raju elastic solutions and also some experimental test records, see Ref. (16). The model is used to provide load-LLD records, load-CMOD records, and J-integral at different locations on the crack front for different combinations of material, crack depth, crack width, and panel size. These numerical data together with the experimental data will be used here to address the conditions listed above to develop a single specimen J form for surface cracks equivalent to the single specimen J form in two-dimensional geometries.

Load Separation

Figure 15 shows three experimental test records for different crack sizes and figure 16 shows the separation results for this set of records. Also, figure 17 shows several numerical records for several combinations of crack depth and width and figure 18 shows the separation results for this set. σ in the numerical test records represents the remote tensile stress and is equal to the load per unit area. It is clear that load separation also exists in the test records of semi-elliptical surface cracks and the load can be then written as:

$$\sigma = G(a,c)\, H(v_{pl}) \qquad [24]$$

where a is the crack depth, c is the crack width and v_{pl} here is the plastic CMOD.

Effective Crack Length

Sharobeam and Landes (16,17) studied several expressions for effective crack length and concluded that the expression suggested by the R6 method works well for short surface cracks. This expression can be written as:

$$a_e = \frac{\pi a}{2\left[2 + \dfrac{a/c}{a/t}\right]} \qquad [25]$$

where a_e is the effective crack length and t is the specimen thickness. For deeper cracks, this expression may need to be modified.

The Single Specimen Form

They also developed an energy rate interpretation form for surface crack as:

$$J_{pl,av} = -\frac{1}{S}\left[\frac{\partial U_{pl}}{\partial a_e}\right]_{v_{pl}} \qquad [26]$$

where S is the crack front length and $J_{pl,av}$ is the average J_{pl} over the crack front and can be written as:

$$J_{pl,av} = \frac{1}{S}\int_S J_{pl}(s)\, dS \qquad [27]$$

where s is any point along the crack front. From load separation, eq [24], and the energy rate interpretation form, eq [26], a single specimen J form can be written as:

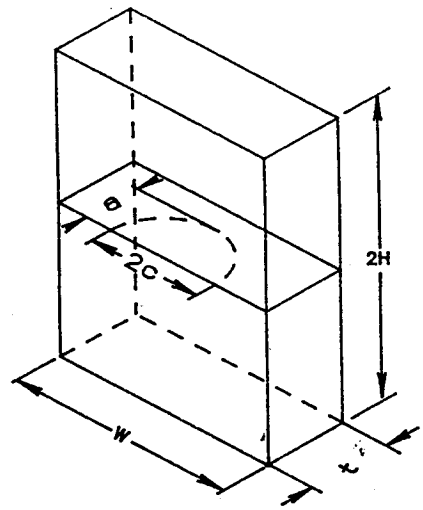

Figure 14a. The semi-elliptical surface crack.

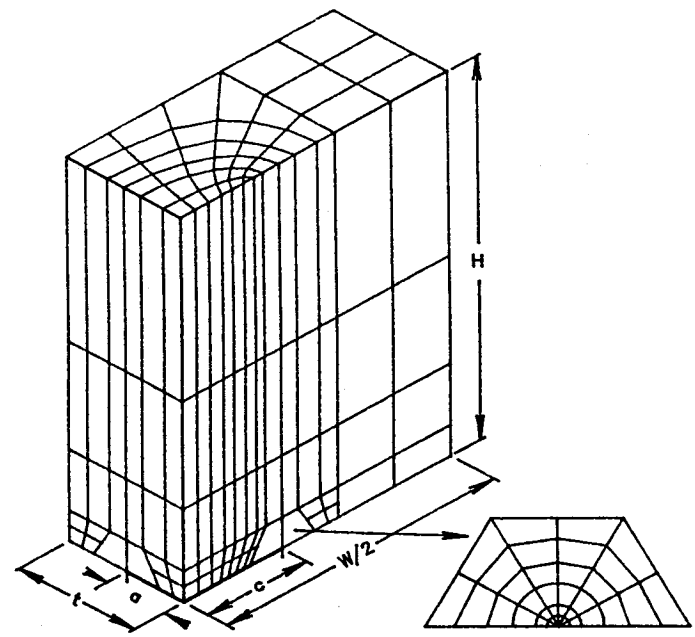

Figure 14b. The finite element model.

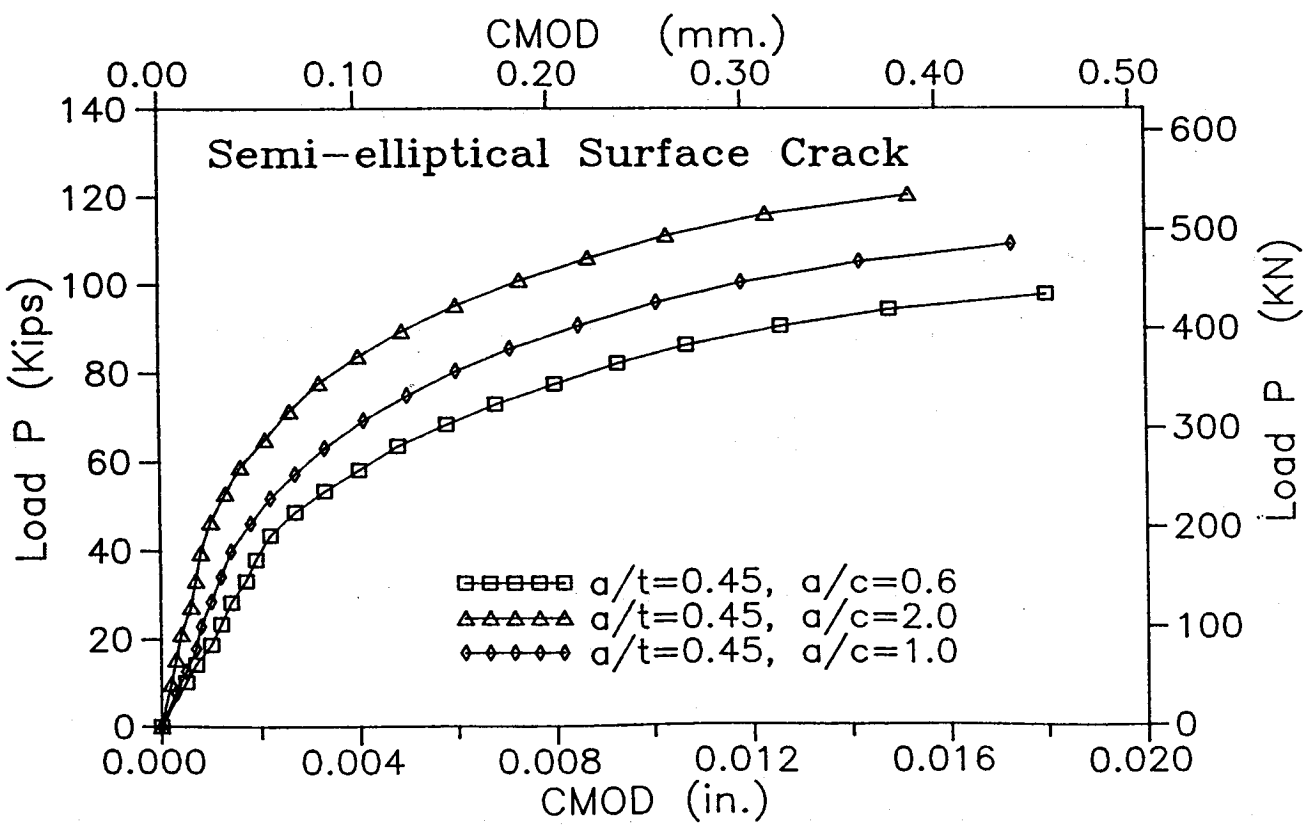

Figure 15. Experimental test records of three surface cracks.

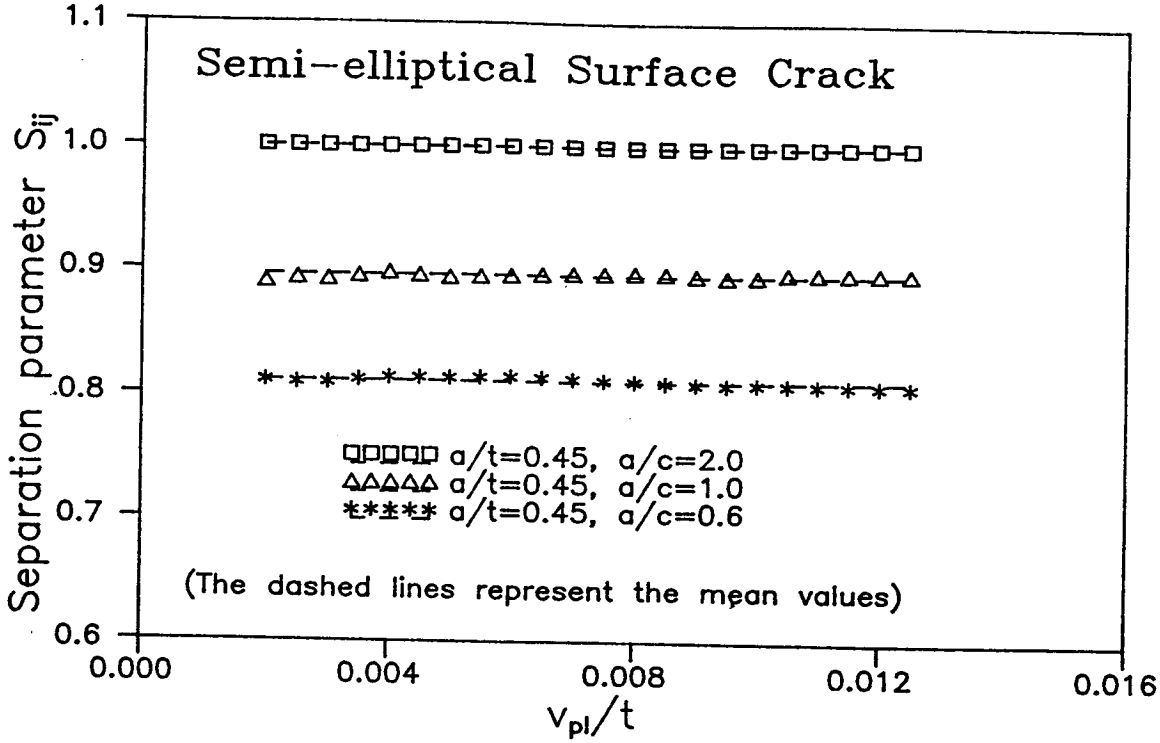

Figure 16. Load separation in the experimental test records of surface cracks.

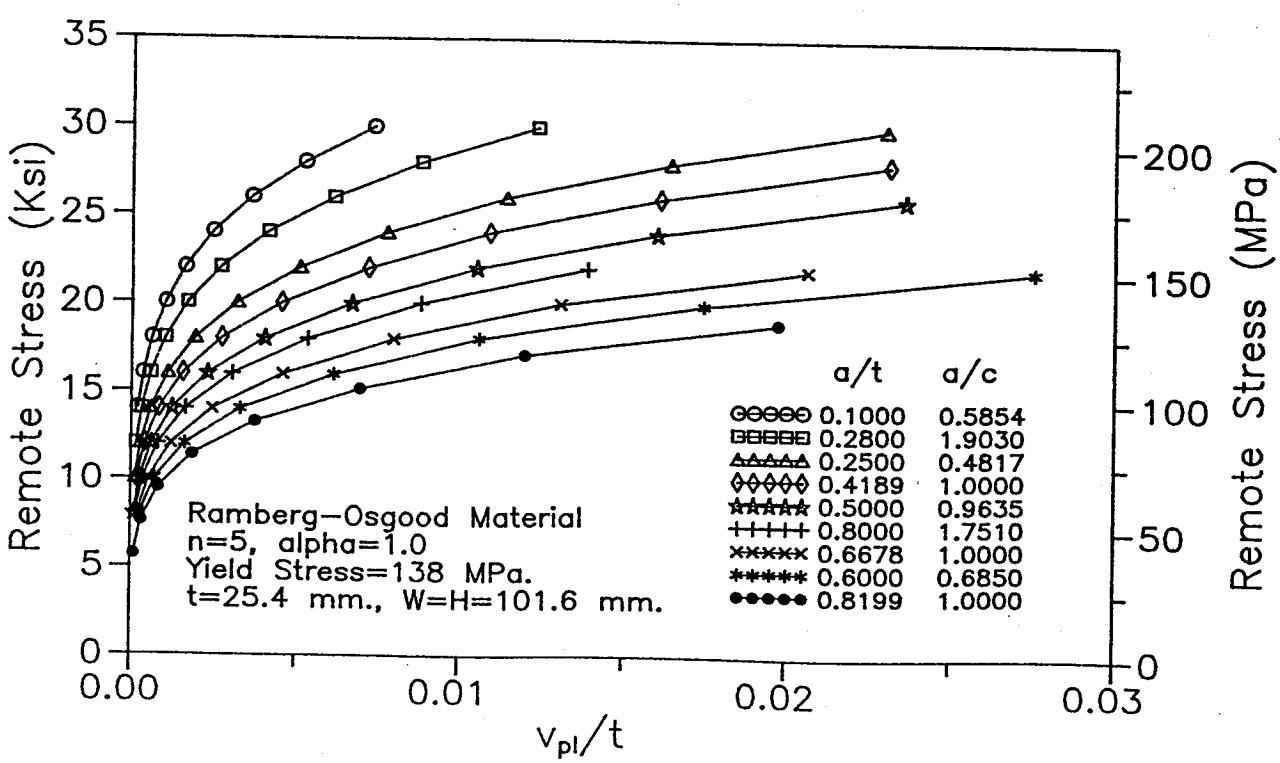

Figure 17. Numerical test records of semi-elliptical surface cracks.

$$J_{pl,av} = -\frac{1}{SG}\frac{\partial G}{\partial a_e}\int \sigma\, dv_{pl} \qquad [28]$$

where G is the geometry function expressed as a function in a_e. The plastic displacement, v_{pl}, in eq [28] could be either plastic LLD or plastic CMOD. It can be shown that the ratio between both plastic displacements is independent of the amount of plasticity for the same crack size and material. Figure 19 shows the ratio between plastic CMOD and plastic LLD at different stages of loading represented by amount of plastic displacement, for different crack sizes. The ratios maintained constant values over most of the plastic region. Thus, each type of plastic displacement can be considered as a constant times the other. Equation [28] can be written in a form similar to the single specimen J form in two-dimensional geometries as:

$$J_{pl,av} = \zeta_{pl}\int \sigma\, dv_{pl} \qquad [29]$$

where:

$$\zeta_{pl} = f\left[\left(\frac{a}{c},\frac{a}{t}\right), geometry, material\right] \qquad [30]$$

The factor ζ_{pl} is equivalent to the η_{pl} factor in two-dimensional geometries. Full description of ζ_{pl} is given in ref. (16). $J_{pl,av}$ in eq [29] can be obtained from the test record of a single specimen. In some cases, the maximum value of J on the crack front and not the average value is required. Sharobeam and Landes (16) developed a relationship between the maximum J and $J_{pl,av}$. They found that this relation is almost independent of the material and specimen size and it can be represented as a function of a/t and a/c only.

THE LOAD SEPARATION METHODOLOGY IN ELASTIC-PLASTIC FRACTURE MECHANICS

Figure 20 shows a schematic flow chart of the load separation methodology in Elastic-Plastic Fracture Mechanics. By testing a set of blunt notched specimens or at least a single blunt notched specimen together with one or more precracked specimens, η_{pl} and the key curve can be developed using load separation. Thus the calibration curves $J(a,P)$ can be obtained. The J-R curve can be developed using a precracked specimen test record and the value of η_{pl} obtained using load separation. The calibration curves $J(a,P)$ together with the J-R curve provide the full elastic-plastic behavior of any structure of same geometry and material as the tested specimen even if it has a different crack size.

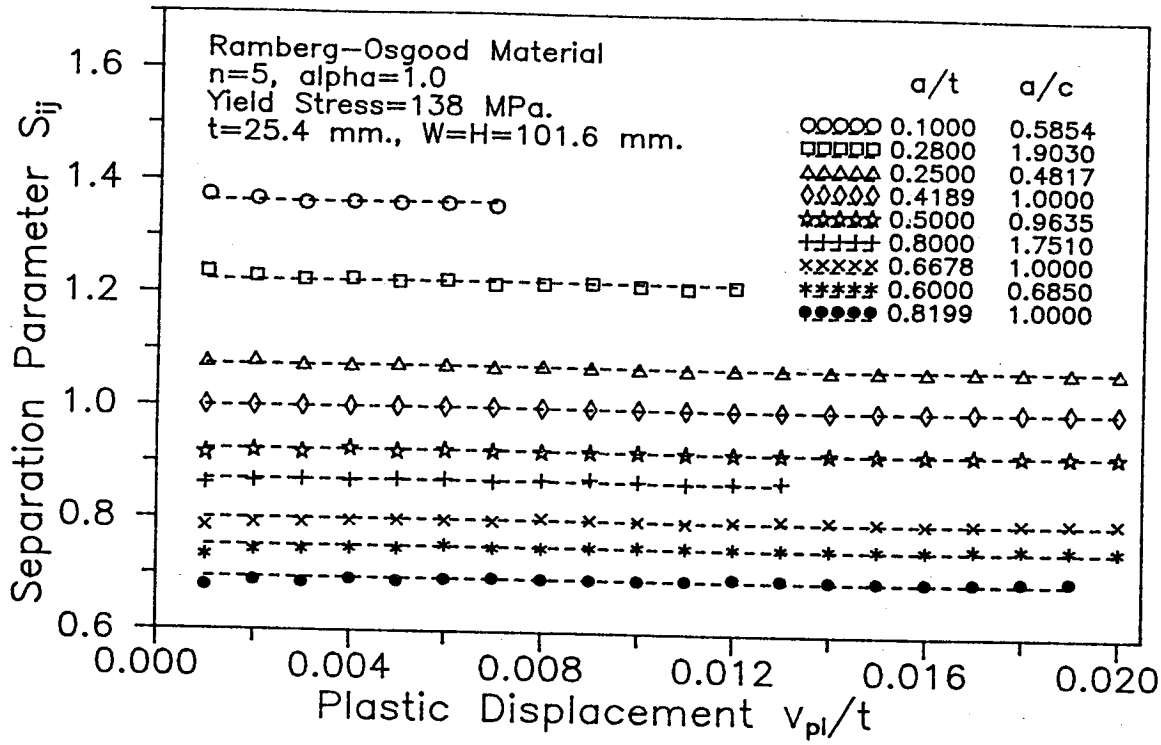

Figure 18. Load separation in the numerical test records of surface cracks.

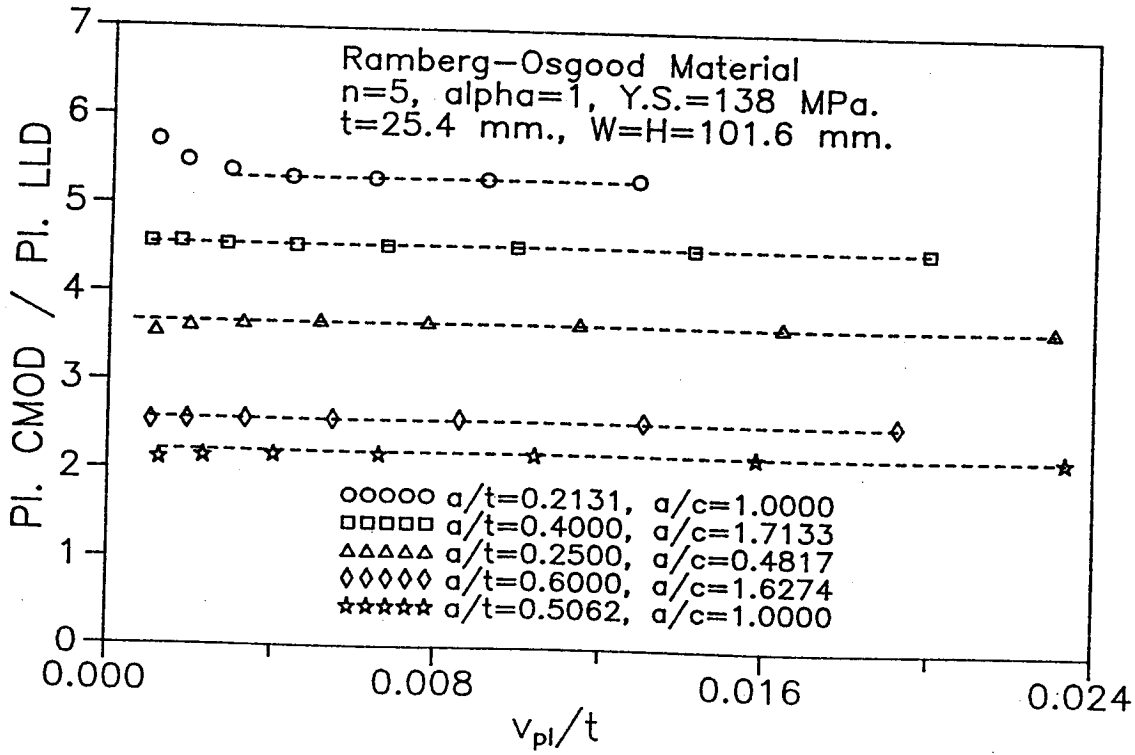

Figure 19. The ratio [plastic CMOD/plastic LLD] versus [plastic CMOD/thickness].

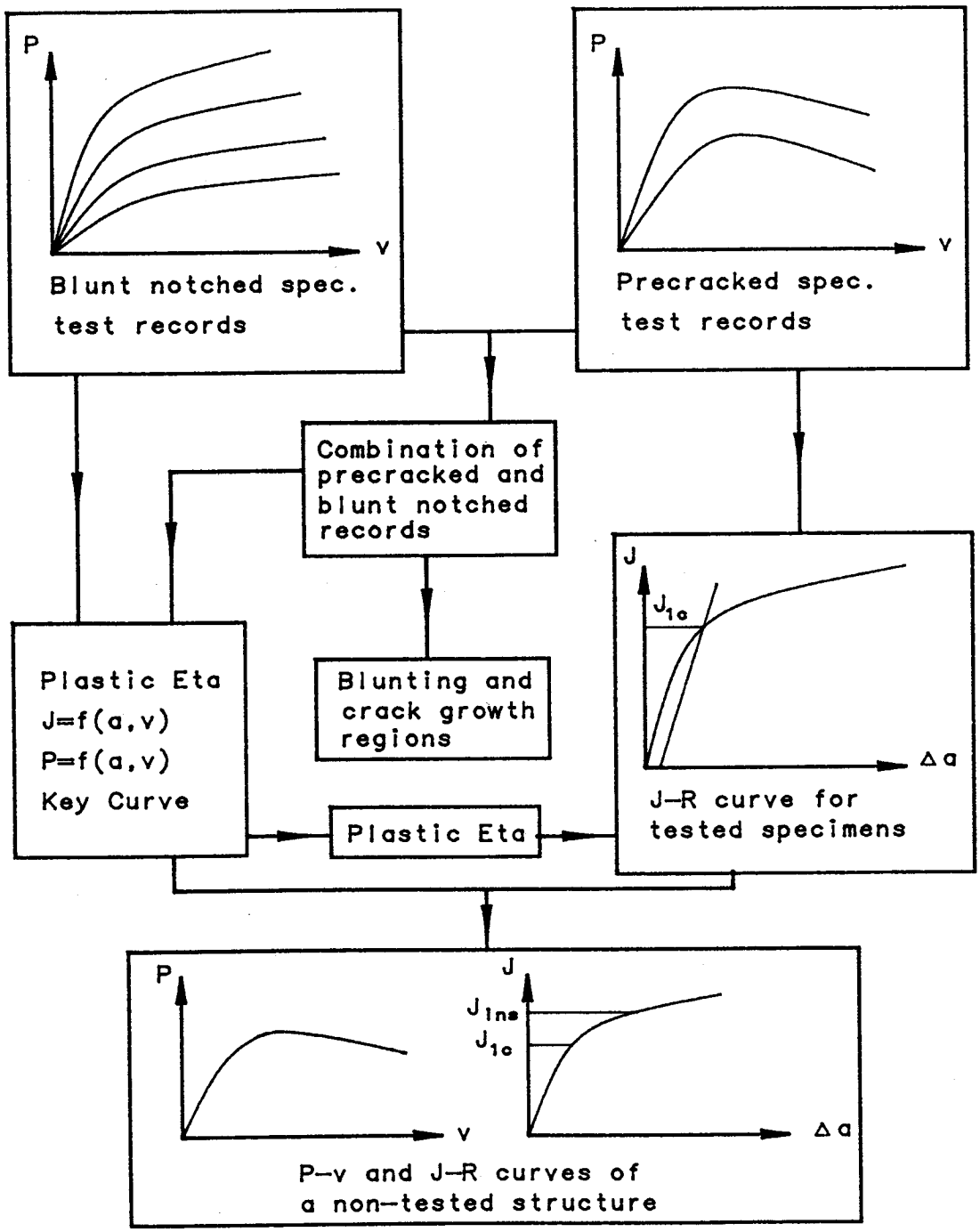

Figure 20. The load separation methodology in Elastic-Plastic Fracture Mechanics.

CONCLUSIONS

Load separation is dominant in both tension and bending two-dimensional geometries. It can be also extended to three-dimensional geometries such as surface cracks. This allows the development of an equivalent single specimen J expression for surface cracks. Load separation exists in both stationary and growing crack test records. It can be used to identify both the blunting and growing crack regions. The η_{pl} factor can be developed using the separation parameters obtained from load separation. Generally, load separation yielded a new simplified approach in Elastic-Plastic Fracture. This approach can be applied to any geometry as long as its test records are showing load separation.

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