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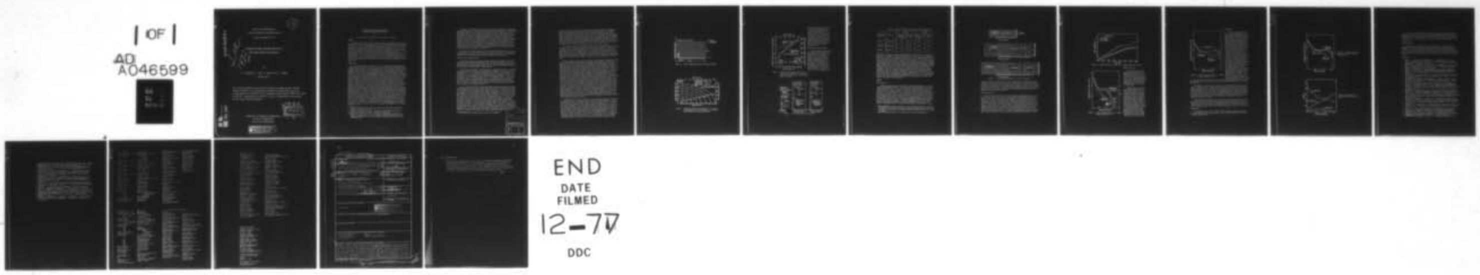

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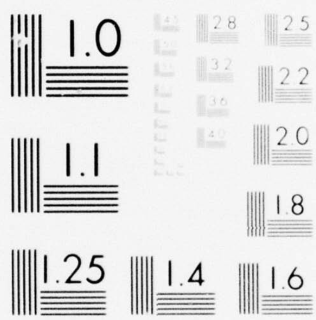

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Technical Report No. 29

A NUMERICAL DYNAMIC FRACTURE ANALYSES OF THREE WEDGE-LOADED DCB SPECIMENS

By

A. S. Kobayashi, S. Mall, Y. Urabe and A. F. Emergy

October 1977

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by

A. S. Kobayashi*, S. Mall**, Y. Urabe*** and A. F. Emery*

SUMMARY

A dynamic finite element code is used to compute the dynamic fracture toughness and crack arrest stress intensity factor from experimentally determined crack velocities in three fracturing wedge-loaded double cantilever beam (DCB) specimens. One experiment involving an Aradite-B DCB specimen by Kalthoff, et al., and two experiments involving Homalite-100 DCB specimens by Kobayashi, et al. and Irwin, et al. were analyzed by this hybrid numerical and experimental technique. Despite minor discrepancies, the computed dynamic fracture toughness and crack arrest stress intensity factors were in reasonable agreement with those determined experimentally. This comparative study between different experimental setups also indicates that the apparent differences in fracture dynamic responses could be attributed mainly to the differences in material properties, bluntness of the initial crack and specimen sizes and not to the differences in experimental techniques used.

INTRODUCTION

Over the past several years, Hahn et al. [1,2,3] have been developing wedge-loaded single/duplex double cantilever beam (DCB) specimens for determining the relation between dynamic fracture toughness, K_{ID}, and crack velocity and for measuring a crack arrest stress intensity factor, K_{Ia}. This specimen development was accompanied by Kanninen et al.'s comprehensive one and two-dimensional dynamic elastic analyses of the wedge-loaded DCB specimen [4,5] with fixed grip loading condition. Later analytical developments by Kanninen, et al. included the addition of a test machine compliance in the loading train for studying the effects of machine compliance on the dynamic response of a fracturing DCB specimen [6]. The dynamic responses of wedge-loaded DCB specimens have also been studied experimentally by dynamic photoelasticity [7,8] and the method of dynamic caustics [9]. It is not surprising that the three series of experiments resulted in somewhat different conclusions regarding the dynamic responses of these DCB specimens. The results of Reference [7], for example, casts doubts on the existence of a unique relation between dynamic fracture toughness and crack velocity and hence of a crack arrest stress intensity factor in the Homalite-100 plates used for fracture testing. On the other hand, a unique relation between dynamic fracture toughness and crack velocity is shown in Reference [8] for the same Homalite-100 material of larger thickness. The crack arrest stress intensity factor, K_{Ia}, was also found to be 95 percent of the static fracture toughness, K_{Ic}. Post arrest stress intensity factor was also observed to be slightly lower than K_{I_a} in agreement with the concept of K_{Ia} based on a static analysis sometime after crack arrest [10]. Recent fracture testings of Aradite-B specimens tend to confirm the above results where the crack arrest stress intensity factor, K_{Ia}, was found to be about equal to the fracture toughness. In these experiments, the dynamic stress intensity factors after crack arrest oscillated about the corresponding static value which varied with the crack velocity history [9] in apparent disagreement with findings of Reference [9].

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Inherent in the above widely varing conclusions of each series of experiments was the supposition that each result would be generally applicable to any other two dimensional dynamic fracture problems regardless of sizes, compliances of the loading systems and static and dynamic material properties thus each precluding the existence of the other two seemingly contradictory conclusions. Before assessing the possible variability in dynamic responses due to these test parameters, a standard DCB specimen of common geometry and loading system would have to be analyzed by the three groups of experimentalists in order to first assess the experimental accuracies of the techniques used. An alternate procedure would be to analyze the three different wedge-loaded DCB specimens with a common and reliable analytical technique. The agreement or disagreement between the analytical and experimental results could then provide some insight into the effects of specimen size and material properties on the dynamic responses of three different DCB specimens considered in References [7,8 and 9].

The objective of this paper is to use such analytical procedure for a comparative study of the dynamic responses of one typical fracture test results in each of References [7,8 and 9] for the purpose of deducing the effects of specimen geometries and material properties in these three separate test procedures.

DYNAMIC FINITE ELEMENT ANALYSIS

The procedure used is a two-dimensional, dynamic finite element code, HONDO [11], which was updated and modified for fracture dynamic analysis.* The basic modifications consisted of algorithms for startup and for computing dynamic stress intensity factor, dynamic energy release rate, fracture energy, kinetic energy and strain energy at each increment of crack advance.

In the startup procedure, the initial static stress distribution in a preloaded structure prior to dynamic crack propagation is computed. This initial stress distribution must be in complete static equilibrium prior to the initiation of a dynamic event. The finite element breakdown and hence the initial stiffness matrix used in this preliminary static analysis should be identical to those at the initiation or at the instant of time $t = 0+$ in the dynamic analysis. Close attention must be given to computational details, such as matching the 2x2 Gaussian integration points in the preliminary static and subsequent dynamic analyses in order to avoid any small differences between the finite element algorithms which will be sensed as unbalanced residual stresses and thus set off parasitic stress wave propagation in the HONDO II analysis.

In our past dynamic finite element analyses of fracturing Homalite-100 plates, considerable oscillations in the calculated dynamic energy release rates and hence in the dynamic stress intensity factors were noted [12,13]. Although the lack of such oscillations in the corresponding dynamic photoelasticity results are in part attributable to viscous damping in photoelastic polymers, much of the oscillations were thought to be generated through the instant release of crack-tip, finite element nodes during the process of discrete crack-tip advances. In order to reduce the impulse stress waves generated by such instantaneous release of a crack-tip node, the nodal force was reduced in equal increments which were determined by dividing the inter-nodal crack-tip transit time with the built-in finite time-increment in *HONDO II*. This procedure physically models a more gradual transit of the crack-tip between two adjacent finite element nodes. This nodal force release mechanism is similar to that developed by Keegstra [14-17] with the exception that the restraining nodal force is completely eliminated when the crack-tip reaches the adjacent node. The dissipated energy during such crack extension will be governed by the variations in nodal forces versus nodal displacement relation during crack extension. In general this nodal force versus nodal displacement relation is

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* The updated finite element code is referred to as HONDO II.

non-linear and will be governed by the dynamic state surrounding the propagating crack tip thus requiring monitoring of nodal displacement at each incremental time if the dissipated energy is used for calculating dynamic energy release rates. The dynamic stress intensity factor can then be computed from the dynamic energy release rate using Freund's relation [17]. The generality of this relation in the presence of reflected stress waves in finite geometry was shown by Nilsson [18]. Alternatively, the near field dynamic stress field as derived by King et al. [19] can be used to calculate the dynamic stress intensity factor directly from the numerically obtained stresses either at the closest Gaussian integration point or at the center of a finite element which shares the crack tip node.

The appropriateness of the above procedures for computing a dynamic stress intensity factor was checked by analyzing the Broberg problem [20]. Figure 1 shows the coarse finite element breakdown used in analyzing a crack propagating at a high speed of $C/C_1 = 0.33$ where C and C_1 are the crack velocity and dilatational wave velocity in a steel, respectively. The large square finite element of 150 mm x 150 mm as well as the relatively high crack velocity used in this study simulated the extreme conditions experienced in another paper presented at this Symposium and thus served as an estimate of numerical errors involved in the latter [21].

Figure 2 shows the theoretical and computed crack opening displacements (COD) as the central crack starts to extend from zero crack length at constant rate. Despite the coarseness of the mesh, remarkable agreement between the computed and analytical CODs at even the first few increments of crack extension is noted. The coarseness of the finite element mesh at the initial phase of crack extension suggests that the near field COD equations from Reference [19] cannot be used effectively for computing the dynamic stress intensity factor, K_I^{dyn}. Since the adjacent Gaussian integration points and the center of the element was closer to the crack tip, an attempt was made to compute the dynamic stress intensity factor, K_I^{dyn} by using the near field, dynamic state of stresses as described in Reference [19]. The dynamic stress intensity factors computed from the normal and deviatoric stresses at the nearest Gaussian integration point, however, varied as much as 40 percent from the theoretical values and thus this procedure was abandoned. The dynamic stress intensity factor computed from the normal stress, σ_{yy}, at the center of the element as defined in Figure 3 were more stable and thus this K_I^{dyn} was compared against the theoretical solution as shown in Figure 3. Note that much of the spurious oscillations in the calculated dynamic stress intensity factors observed in previous analyses [12,13] were eliminated by the linearly increasing release of nodal force while the crack tip advanced from one finite element node to another. The initial large overestimation of K_I^{dyn}, as shown in Figure 3, could be attributed to the inappropriateness in using a one-term representation of the near field dynamic state of stress when the crack extended from zero crack length to 3 to 4 finite element lengths. However, remarkable agreements between computed and theoretical K_I^{dyn} are noted for longer crack length where the one-term representation of the near field dynamic state of stress becomes increasingly valid.

Although the above results indicate the need for finer element breakdown at the initial phase of the Broberg problem, such fine element breakdown for calculating K_I^{dyn} from the mid-element stress may not be always practical, since the time increment in dynamic finite element analysis is governed by the size of its smallest element. The strain energy release rate procedure of calculating static stress intensity factors from the results of finite element analysis, on the other hand, consistently provided accurate static stress intensity factors with relatively coarse meshes and thus the related dynamic energy release rate procedure was used to compute K_I^{dyn} for the same Broberg problem. As shown in Figure 3, notable improvement in the accuracy of K_I^{dyn} at the time of the first increment of crack propagation was made but the K_I^{dyn} after 3 to 4 incremental crack extensions was not as accurate as the K_I^{dyn} computed directly from the mid-element stress. Nevertheless, the proven accuracy of the energy release

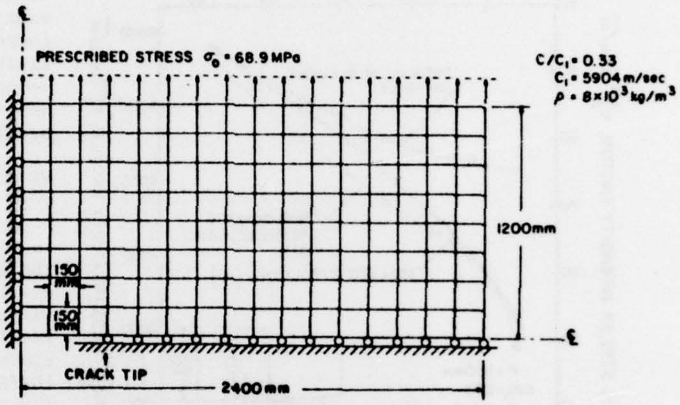

Figure 1. Finite Element Breakdown for Broberg's Problem.

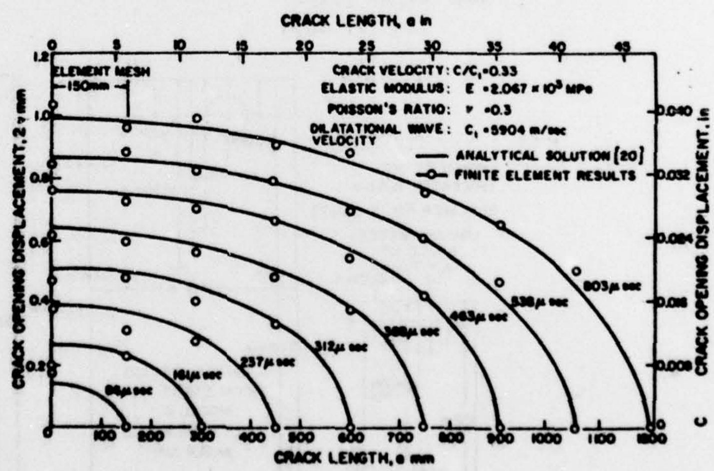

Figure 2. Computed Crack Opening Displacement of a Central Crack Expanding at a Constant Rate in a Uniaxial Stress Field of 68.9 MPa (10,000 psi).

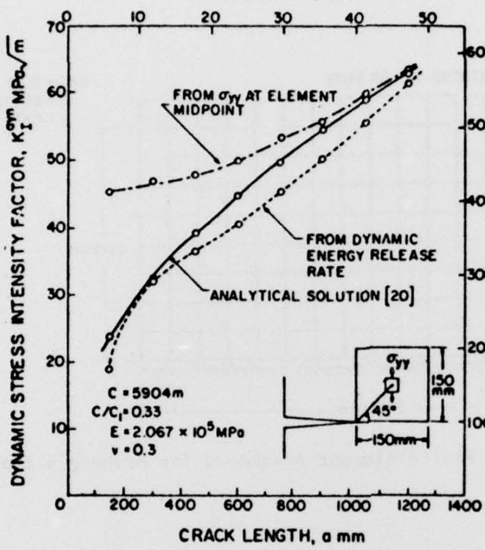

Figure 3. Dynamic Stress Intensity Factors of a Central Crack Expanding at a Constant Rate in a Uniaxial Stress Field of 68.9 MPa (10,000 psi).

rate procedure in static analysis and its reasonable accuracy in computing K_I^{dyn} with such coarse mesh of Figure 1, i.e. 150 mm square, at a high crack velocity of $C/C_1 = 0.33$ lead us to choose the procedure of dynamic energy release rate for computing K_I^{dyn} in our dynamic finite element analyses of the wedge-loaded DCB specimens as well as the crack arrest test specimens [21].

WEDGE-LOADED DCB SPECIMENS

The three wedge-loaded DCB specimens which were analyzed by the dynamic finite element code described above are shown in Figure 4. For convenience in identification, the three specimens are designated as KML, IDKFE and KBW specimens, respectively. The static and dynamic material properties as determined by the three groups of investigators [7,8,9] are shown in Table 1. Although the static material properties were

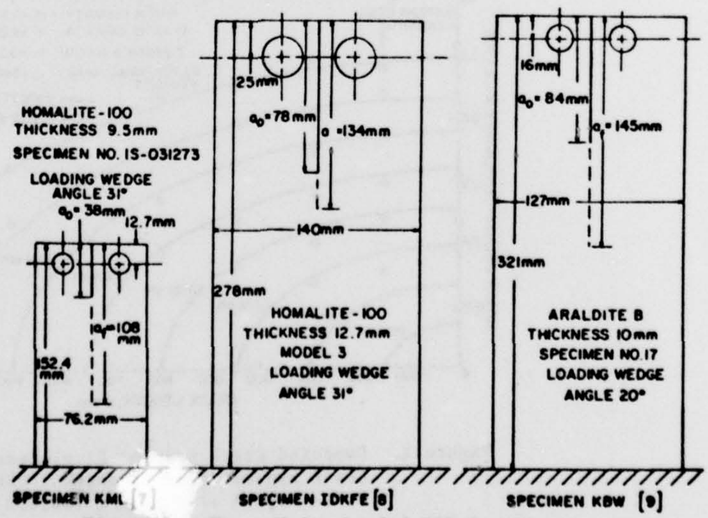

Figure 4. Three Wedge-Loaded DCB Specimens

Table 1 - Elastic Properties of Wedge-Loaded DCB Specimens

Specimen Identifica.	Material	Static		Dynamic	
		Modulus of Elasticity GP_a	Poisson's Ratio	Modulus of Elasticity GP_a	Poisson's Ratio
KML[7]	Homalite-100	3.72	0.345	4.65	0.345
IDKEF[8]	Homalite-100	3.89	0.31	4.82	0.31
KBW[9]	Araldite-B	3.38	0.33	3.66	0.39

comparable, the Araldite-B epoxy showed lesser strain sensitivity and higher static fracture toughness than the two Homalite-100 plates. The 30 to 40 percent differences in static and dynamic elastic moduli in the Homalite-100 plates forced the calculation to be conducted following the procedure [6] developed at Battelle's Columbus Laboratories. Basically, the procedure is to execute all static and dynamic analyses by using the static elastic modulus and then use the dynamic static modulus when computing the dynamic stress intensity factor from the dynamic energy release rate.* Identical fine meshes in the three finite element breakdowns, as shown in Figure 5, were used in analyzing all three specimens in order to minimize the numerical errors due to different fineness in finite element breakdown. The crack positions versus time relations for the three specimens, as shown in Figure 6, were then used to drive the crack at prescribed rates and the dynamic energy release rate, $\mathcal{G}_I^{dyn}$, and dynamic stress intensity factors, K_I^{dyn}, were computed following the procedure described above. It is interesting to note that the crack propagated comparable distances in all three specimens and that the crack velocity in the KML specimen was significantly higher than those in the IDKFE and KBW specimens.

RESULTS

KML Specimen [7]

A state of plane stress was assumed in the numerical analysis of this relatively thin Homalite-100 plate. The calculated and measured dynamic stress intensity factors as well as the calculated static stress intensity factor versus crack position are shown in Figure 7. Since the loading pin displacement at the onset of crack propagation was not measured in this series of experiments, the stress intensity factor for crack initiation, K_Q**; was estimated on the basis of matching the total dynamic energy released with the calculated total static strain energy released in this specimen. The resultant K_Q would thus be underestimated since no estimate of the extraneous dissipated energy in the specimen is included in this calculation. Reasonable agreement existed between the computed and measured K_D throughout the crack propagation except for the initial phase of crack propagation and in the region of momentary crack arrest. The isolated experimental point in the former was ignored in this comparison due to

* The superposition procedure developed in the original dynamic finite element analysis [12,13] handles this strain sensitivity problem by using static elastic modulus in the static calculation and dynamic elastic modulus in the dynamic analysis.

** Note that the subscript of I is dropped for all plane stress results.

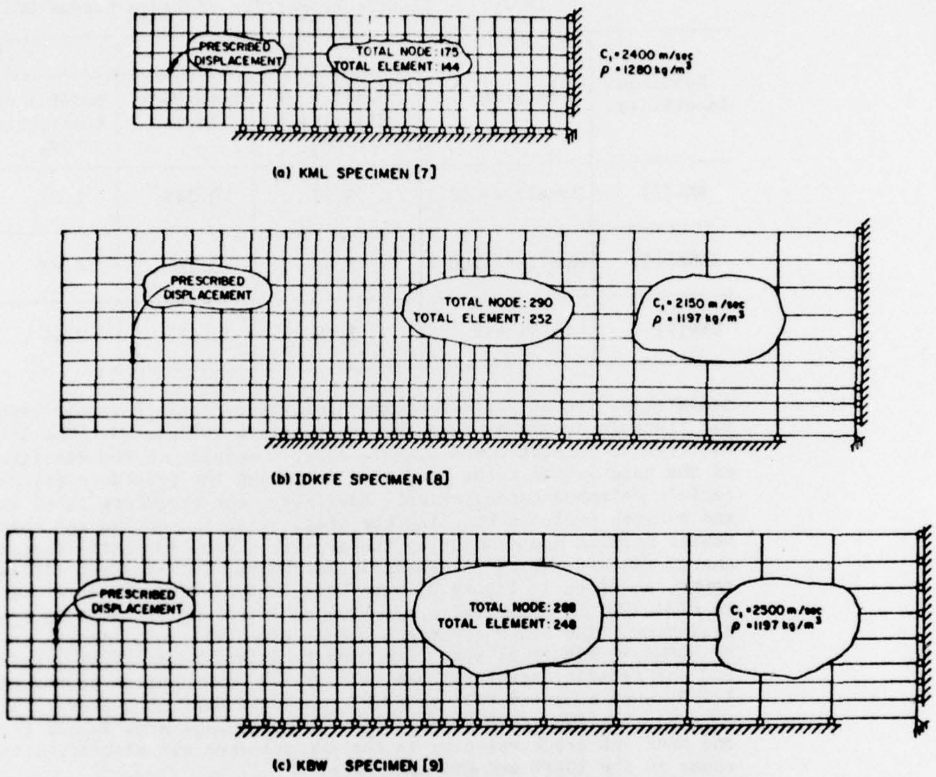

Figure 5. Finite Element Breakdowns of Three DCB Specimens

the blurriness in the dynamic isochromatic fringes and crack tip position which could have introduced large errors in K_D determination. The minor discrepancies between the experimental and calculated K_D in the region of crack arrest can be attributed to the dynamic finite element analysis which is sensitive to the variations in crack velocities. Crack velocities measurements in this region were not accurate due to the discrete recording of the crack which apparently arrested momentarily before starting up again.

IDKFE Specimen [8]

Figure 8 shows the variations in the calculated and measured dynamic stress intensity factors as well as the calculated static stress intensity factors. Note that the state of plane strain was assumed in the static and dynamic analyses of this specimen, not because this Homalite-100 specimen was thicker (13 mm versus 10 mm), but because the plane stress results yielded a lower K_D and increased the already existing discrepancies between measured and calculated results. Further study of the data in Table 2.14 and Figure 2.9 in Reference [8] indicated that perhaps the recorded wedge-pin-opening displacement in this experiment could be low thus providing a low K_{IQ} on which the entire static and dynamic calculations were based. If K_{IQ} was underestimated by say twenty percent, then the calculated static and dynamic stress intensity factor curves will shift upward and almost match the experimental dynamic stress intensity factors.

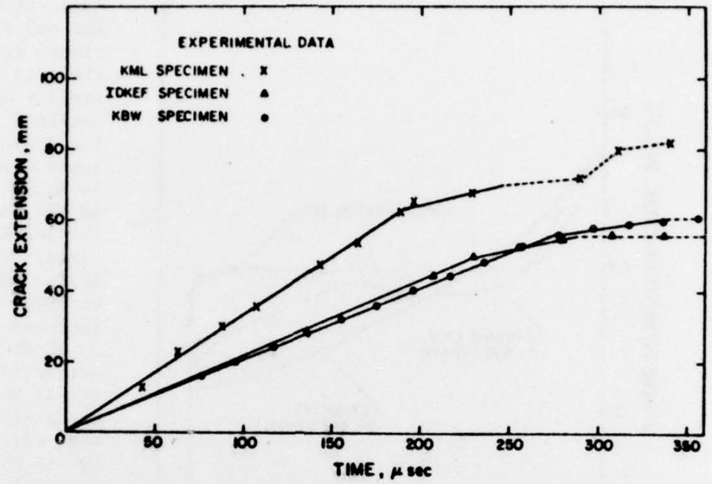

Figure 6. Crack Tip Position Versus Time in Wedge-Loaded DCB Specimens.

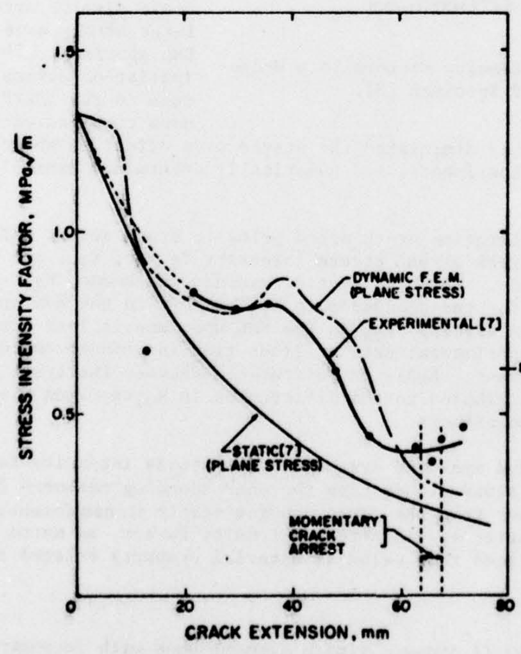

Figure 7. Stress Intensity Factors in a Wedge-Loaded DCB Specimen [7]

KWB Specimen [9]

Figure 9 shows the variations in the calculated and measured dynamic stress intensity factors as well as the calculated static stress intensity factors. Reasonable agreement in the calculated and measured K_D are seen, with minor differences in calculated and measured values in the region of crack arrest.

Figure 10 shows the calculated variations in energies with crack extension. These energy variations follow the characteristic rapid decrease in strain energy, an increase followed by a drop in kinetic energy and gradual increase in dissipated fracture energy [1-6]. The actual values differ with those in Figure 2.11 of Reference [6], particularly in the former two energies. Part of these discrepancies could be attributed to the one-dimensional analysis used in the Battelle code which would underestimate the strain energy and hence the fracture energy computed from energy balance.

DISCUSSIONS

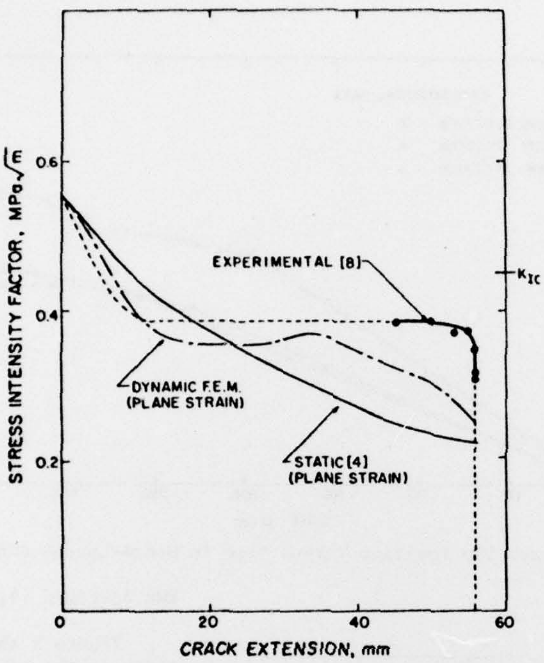

Figure 8. Stress Intensity Factors in a Wedge-Loaded DCB Specimen [8].

Calculated and measured dynamic stress intensity factors in KML and KBW wedge-loaded DCB specimens agreed reasonably well and there is reason to speculate that similar agreement would have been obtained in the IDKFE specimen. The dynamic finite element analysis reproduced the oscillations in K_D in the KML specimen as well as the relatively uniform K_{ID} in the IDKFE and K_D in the KBW specimen. The oscillations in K_D in the KML specimen could be attributed to the smallness in specimen size, as shown in Figure 4, which would generate higher interaction between the reflected stress waves and the propagating crack tip. This large stress wave effect was further augmented by the high K_Q value necessary to drive the crack approximately the same distance as in the other two IDKFE and KBW specimens. The computed overshoot in K_D immediately after crack propagation could also be attributed to the large stress wave effect in the KML specimen. The lower crack initiation stress intensity factors in the IDKFE and KBW specimens combined with the much longer specimen sizes obviously diminished the stress wave effect as shown by the lack of oscillations in the experimental and numerically determined dynamic stress intensity factors.

The gradual deceleration crack speed prior to crack arrest and thus the existence of a distinct crack arrest stress intensity factor, K_{Ia}, are noted in the IDKFE and KBW specimens. The high static fracture toughness, K_{Ic}, of Araldite-B could be responsible for the closeness in K_{Ia} and K_{Ic} in the KBW specimen as the crack slows down to an arrest. K_{Ia} in the KML specimen is less distinct, possibly due to the lack of experimental data at finer time increments during the period of momentary crack arrest. Again the difference between the crack arrest characteristics could be attributed to the differences in K_Q, specimen sizes and the associated stress wave effects.

The calculated and measured dynamic arrest stress intensity factors of the three specimens were always lower than the corresponding measured fracture toughnesses, K_{Ic}, and higher than the corresponding static stress intensity factor. The variability in the latter static stress intensity factor, as noted in Figures 7, 8 and 9, probably exclude this value as material property related to crack arrest.

CONCLUSIONS

The updated HONDO II dynamic finite element code with incremental release of crack tip nodal force has been shown to be a reliable procedure in analyzing fracture dynamic problems.

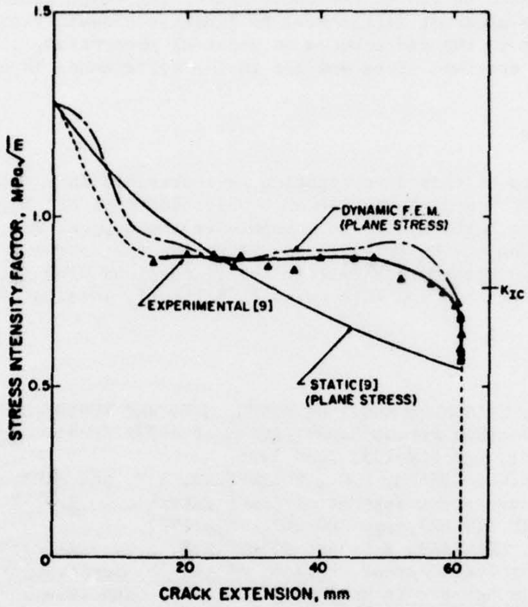

Figure 9. Stress Intensity Factors in a Wedge-Loaded DCB Specimen [9].

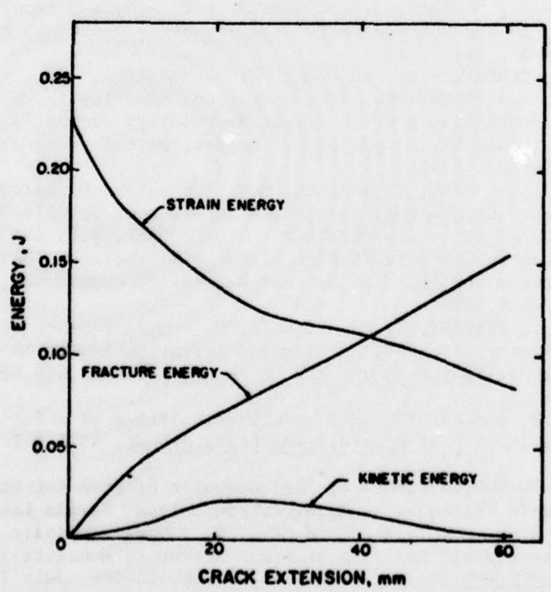

Figure 10. Energies in a Wedge-Loaded DCB Specimen [9].

This code successfully duplicated the experimentally determined dynamic fracture toughness in two of the three fracturing wedge-loaded DCB specimens and showed that the apparent differences in fracture dynamic responses could be attributed mainly to the differences in material properties, bluntness of the initial crack and specimen sizes and not to the differences in experimental techniques used.

ACKNOWLEDGEMENT

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A dynamic finite element code is used to compute the dynamic fracture toughness and crack arrest stress intensity factor from experimentally determined crack velocities in three fracturing wedge-loaded double cantilever beam (DCB) specimens. One experiment involving an Aradite-B DCB specimen by Kalthoff, et al., and two experiments involving Homalite-100 DCB specimens by Kobayashi, et al. and Irwin, et al. were analyzed by this hybrid numerical and experimental technique. Despite minor discrepancies, the computed dynamic fracture toughness and crack (continued on reverse) → over

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arrest stress intensity factors were in reasonable agreement with those determined experimentally. This comparative study between different experimental setups also indicates that the apparent differences in fracture dynamic responses could be attributed mainly to the differences in material properties, bluntness of the initial crack and specimen sizes and not to the differences in experimental techniques used.