FEA simulation and geometric calibration of Arcan fixture for butterfly specimen of RP material

M Afzal Bhat, A A Shaikh

***Abstract*— The mixed mode fracture parameters are investigated for photopolymer used in 3D printer rapid prototyping system based on modified Arcan fixture and butterfly specimen test. FEA simulation is performed in Abaqus to obtain stress intensity factors for mode I, mode II and mix mode loading and to get geometric calibration factors for arcan fixture. The butterfly specimen and Arcan fixture are modelled by finite element method and analysed at various loading angles to simulate pure mode I, mode II and mix mode fracture for various crack lengths. The objective for the simulation is to evaluate the geometric calibration factors for modified Arcan test in order to obtain fracture toughness under mix mode loading conditions.**

***Index Terms*— Arcan, Calibration, Mix – mode, Rapid Prototyping, Stress intensity factor.**

I. Introduction

The products been produced by Rapid prototyping systems are been directly used for functional end products in recent times. The properties of such product are important regarding the sustenance with respect to working load conditions. Fracture properties are important in such products where inherent cracks are unavoidably present. While applying a load the crack surfaces may open and displace normal to each other, or slide in plane or tear action may take place. These three loading conditions are known as mode I, mode II and mode III as shown in figure 1 [1]. Complex behavior is reported for mixed mode conditions, previous work for mode-I and mode-III fields under small-scale yielding conditions, with the in-plane stresses having a different asymptotic functional form than the out-of-plane stresses [2]. Pure mode-I, II and mixed-mode-I/II are mostly possible in engineering problems.

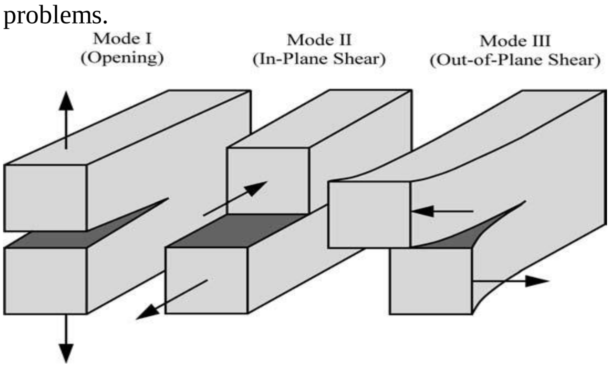

Figure 2.3: The three modes of loading that can be applied to a crack.

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The material deformation behavior can be characterized as being linear elastic, nonlinear elastic, or elasticplastic. In general, the deformation behavior of a material determines which fracture parameter to be used for describing fracture toughness and which fracture test method to be adopted for measuring the toughness value for the material. The first fracture toughness test standard ASTM E399 [3] was developed to determine the point value of plane strain fracture toughness at or near to the onset of crack initiation, K_{IC}. For ductile fracture, the plastic deformation dominates at the crack tip and the material resistance against fracture increases as the crack grows, and thus the toughness is often described in a resistance curve format using the J-integral or crack tip opening displacement (CTOD).

Crack configurations subjected to a general (mixed mode) loading show a crack growth direction which generally is not in agreement with the direction of the cracks. In some studies has been approximately calculated an energy release rate for mixed mode loading, for instance, [4, 5]. A second possibility is the use of suitable field variables of the theory of elasticity as characteristic parameters for crack judgment. In the case of unidirectional loading and mode I loading, respectively, the strength calculation demands, for instance, that the existing normal stress should not exceed a critical value [6]. Various aspects of the failure behaviour initiated from mode - II loaded cracks are discussed in [7] like validity criteria and minimum size specimen requirements for measuring the fracture toughness K_{II}; energy balance of the process of initiation of kinked cracks including compressive notch tip stress concentrations; failure mode transition from tensile cracks to adiabatic shear bands at high loading rates; loading rate dependence of the dynamic fracture toughness K_{IId} in the regime of failure mode transition.

Several tests have been used for measuring mixed-mode fracture toughness in the mode-I/II range. These tests include: the edge-delamination tension [8] the crack-lap shear [9], the mixed-mode bending (MMB) test [10], the asymmetric double cantilever beam [11], the mixed-mode flexure [12], and the variable mixed-mode [13] test. However, all of these tests have one or more problems which limit their usefulness. The modified Arcan test [14] seems to solve many of these problems. The Arcan test can be used with the simple and similar specimens for all in-plane mixed mode tests and can be used to separate the mode-I and mode-II components. In other mixed-mode fracture tests, several different types of specimens are often needed to measured fracture toughness over a desired range of mixed-mode combinations. The use of different test configurations can involve different test variables and analysis procedures that can influence test results in ways that are difficult to predict. The Modified Arcan test can be used to measure fracture toughness over a wide range of mixed mode I/II ratios including pure mode I and pure mode II.

In this study geometric calibration factors of Arcan fixture for butterfly specimen of rapid prototyping material are calculated through the Arcan apparatus modeling using finite element method and also the influence of crack length ratio on stress intensity factors and energy released rates for different loading angles are investigated.

II. Finite Element Modelling

Arcan fixture is fabricated to facilitate application of load at various load-angles with respect to axis passing through the mid plane of butterfly specimen. The dimensions for the arcan fixture is given in figure 1.

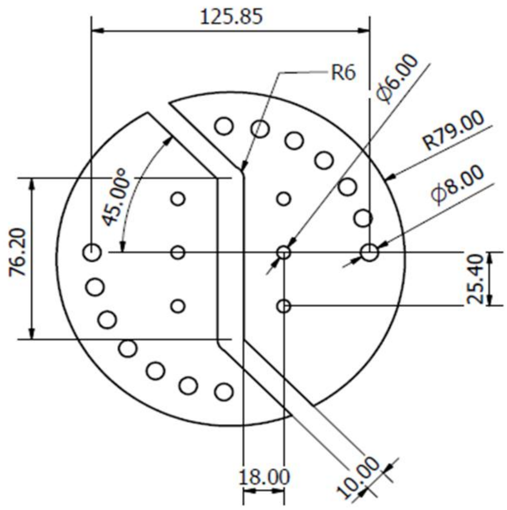

Figure 1. Dimensions in mm of Arcan fixture.

Numerical analyses are carried out using the interaction J-integral method in Abaqus/CAE. Figures 2 and 3 show example of the mesh pattern of the specimen. The analysis are performed with ABAQUS under a constant load of 500 N applied at pin location.

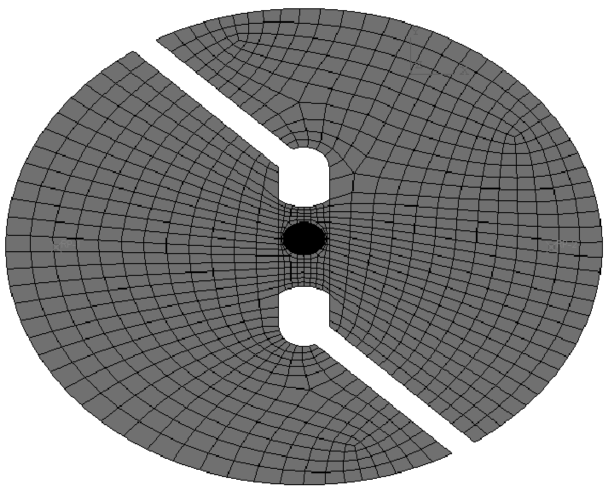

Figure 2. Mesh of the Arcan fixture used for the analysis.

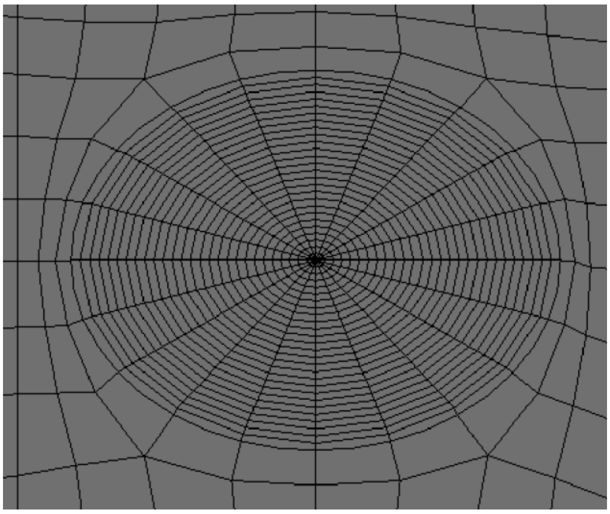

Figure 3. Focused mesh around crack tip.

The entire specimen is modeled using eight node collapsed quadrilateral element and the mesh is refined around crack tip, so that the smallest element size found in the crack tip elements is approximately 0.02 mm. A linear elastic finite element analysis is performed under a plain strain condition using root square stress field singularity. To obtain a root square singularity term of the crack tip stress field, the elements around the crack tip were focused on the crack tip and the mid side nodes were moved to a quarter point of each element side. The calibration factors are calculated through equation:

$$K = \frac{P}{B\sqrt{w}} f(x)$$

Where, P is the applied load, *W* is specimen width, *B* is specimen thickness and *f(x)* is geometric calibration factor.

III. Results and Discussions

A. Mode-I & II Geometric Calibration Factors

In order to assess geometrical factors or non-dimensional stress intensity factors $f_I(a/w)$ and $f_{II}(a/w)$ to determine fracture toughness for specimens, the a/w ratio is varied between 0.1 and 0.9 at 0.1 intervals and a fourth order polynomial is fitted through finite element analysis for plane strain conditions as (figure 4):

$$f_I\left(\frac{a}{W}\right) = 0.859301 - 5.0861x + 27.9190x^2 - 50.8327x^3 + 33.2327x^4$$

$$f_{II}\left(\frac{a}{W}\right) = 0.308186 + 0.515746x + 15.2351x^2 - 37.8640x^3 + 29.5620x^4$$

Here *a/W* is the crack length ratio, where *a* is the crack length and *W* is the specimen length.

The relationship between the non-dimensional stress intensity factor and the loading angle is shown in figure 5 for crack length ratio of 0.5. It can be seen that for loading angles less than 60 degree, the mode-I fracture is dominant and as the mode-II loading contribution increases, the mode-I stress intensity factor decreases and the mode-II stress intensity factor increases. For loading angles greater than 60 degree mode-II fracture becomes dominant.

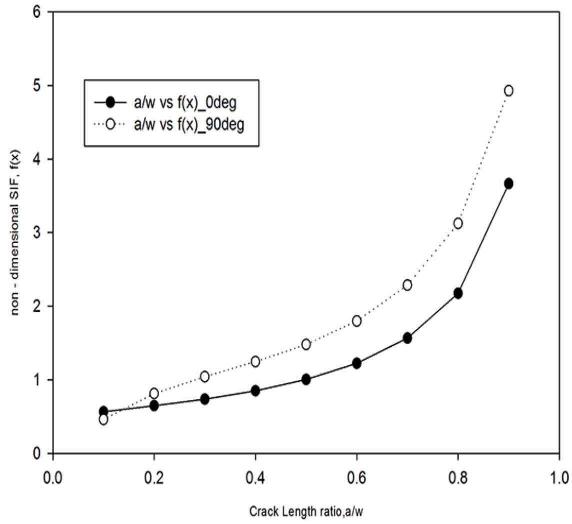

Figure 4. Calibration factors with the variation of crack length ratios.

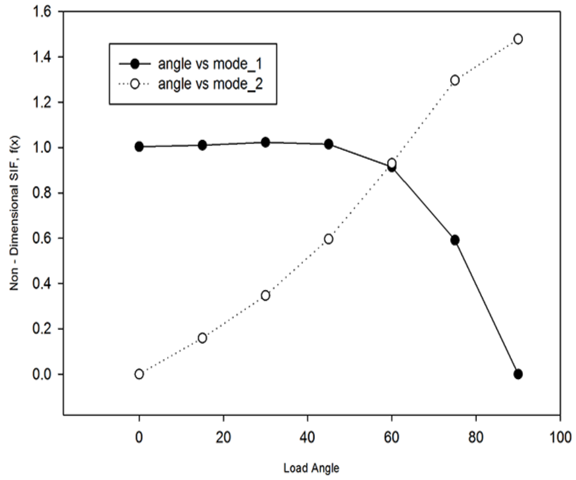

Figure 5. Calibration factors with the variation of load angles for crack lengthratio of 0.5.

B. Mix Mode-I & II Geometric Calibration Factors

In order to assess geometrical factors or non-dimensional stress intensity factors for mixed-mode conditions to determine specimens fracture toughness, the a/w ratio is varied between 0.1 and 0.9 at 0.1 intervals in plane strain conditions. The variation of the mode I and mode II geometric calibration factors with crack length ratios for different load angles are shown in figures 6 & 7 and Tables I & II respectively.

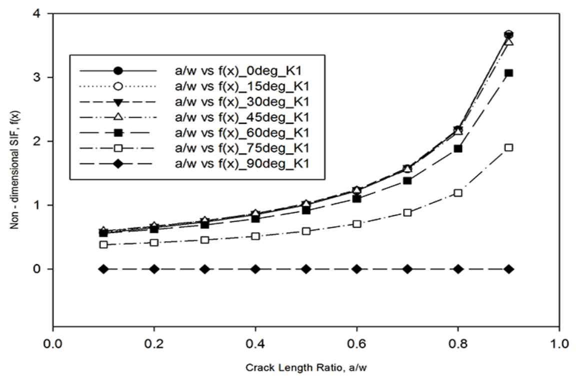

Figure 6. Mode I calibration factors with the variation of crack length ratios for various load angles.

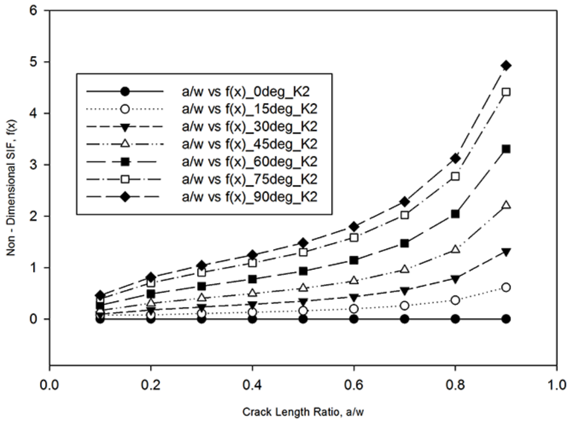

Figure 7. Mode II calibration factors with the variation of crack length ratios for various load angles.

Table I. Mode I calibration factors with the variation of crack length ratios for various load angles.

a/W	0°	15°	30°	45°	60°	75°	90°
0.1000	0.5657	0.5717	0.5865	0.5966	0.5592	0.3801	0.0000
0.2000	0.6473	0.6531	0.6667	0.6715	0.6194	0.4126	0.0000
0.3000	0.7364	0.7422	0.7551	0.7556	0.6899	0.4546	0.0000
0.4000	0.8502	0.8563	0.8690	0.8656	0.7846	0.5118	0.0000
0.5000	1.0039	1.0103	1.0231	1.0150	0.9141	0.5918	0.0000
0.6000	1.2239	1.2309	1.2434	1.2287	1.0994	0.7063	0.0000
0.7000	1.5658	1.5737	1.5851	1.5590	1.3848	0.8826	0.0000
0.8000	2.1742	2.1824	2.1926	2.1428	1.8871	1.1913	0.0000
0.9000	3.6661	3.6736	3.6668	3.5446	3.0694	1.9030	0.0000

Table II. Mode II calibration factors with the variation of crack length ratios for various load angles.

a/w	0°	15°	30°	45°	60°	75°	90°
0.1000	0.0000	0.0798	0.0938	0.1653	0.2684	0.3929	0.4595
0.2000	0.0000	0.0798	0.1754	0.3060	0.4889	0.7017	0.8117
0.3000	0.0000	0.1064	0.2333	0.4044	0.6395	0.9061	1.0420
0.4000	0.0000	0.1307	0.2858	0.4929	0.7740	1.0877	1.2446
0.5000	0.0000	0.1590	0.3469	0.5961	0.9299	1.2966	1.4788
0.6000	0.0000	0.1980	0.4312	0.7377	1.1427	1.5828	1.7971
0.7000	0.0000	0.2587	0.5617	0.9563	1.4719	2.0206	2.2848
0.8000	0.0000	0.3654	0.7912	1.3395	2.0433	2.7775	3.1268
0.9000	0.0000	0.6125	1.3180	2.2050	3.3093	4.4180	4.9302

C. Effect of crack length on mix mode fracture

Energy release rate versus loading angle is demonstrated in figure 8 and table III. An increase of loading angle from 0 degree to 90 degree leads to an addition of strain energy and this causes a reduction of fracture resistance of specimen. Also an increase of crack length ratio leads to a same effect on fracture resistance as shown in the figure 9 and table IV.

Figures 10 & 11 and tables V & VI show the effect of increasing of loading angle and crack length ratio on stress intensity factors of mode-I and mode-II stress intensity factors. It is observed that the values of stress intensity factors for mode I and mode II increases with load angle and crack length.

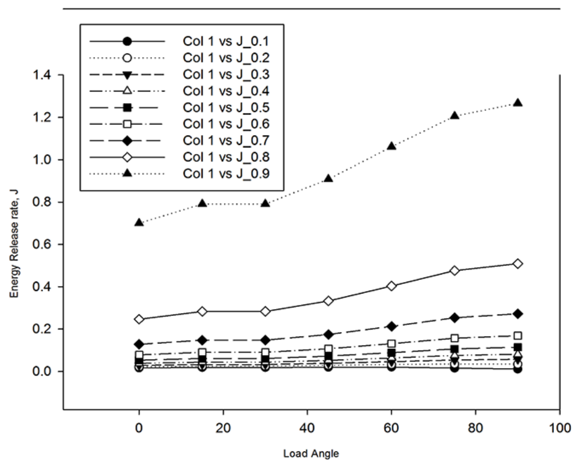

Figure 8. J - integral values with the variation of load angles for various crack length ratios.

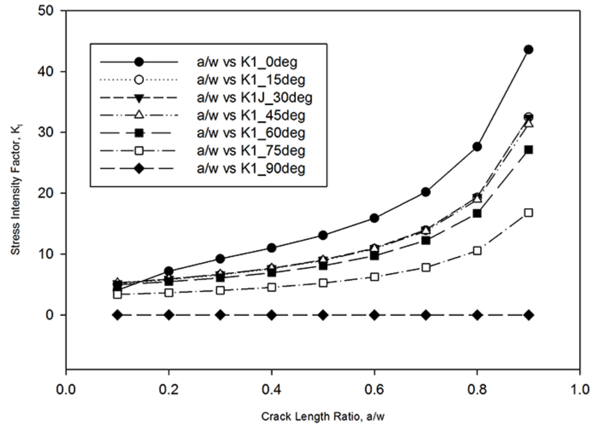

Figure 10. Mode I stress intensity factor values with the variation of crack length ratios for various load angles.

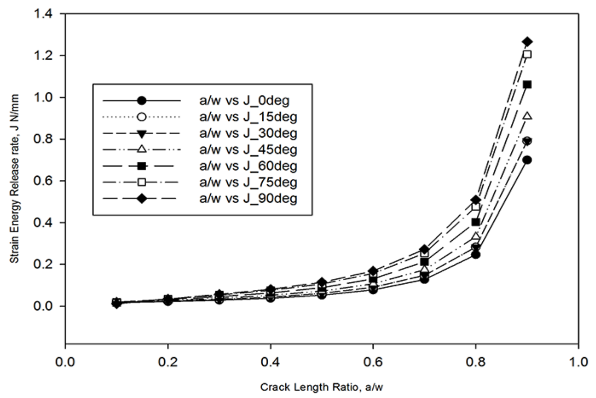

Figure 9. J - integral values with the variation of crack length ratios for various load angles.

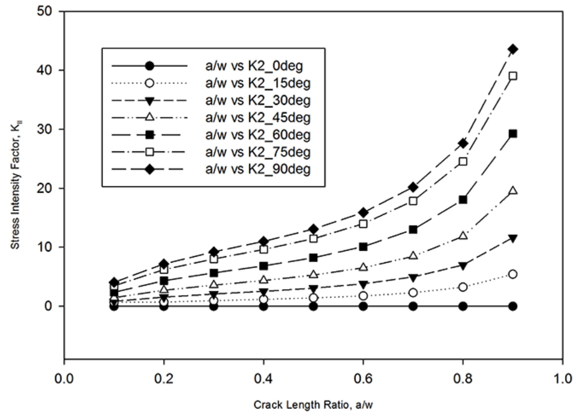

Figure 11. Mode II stress intensity factor values with the variation of crack length ratios for various load angles.

Table III. Energy release rate J - integral with the variation of crack length ratios for various load angles.

a/w	0°	15°	30°	45°	60°	75°	90°
0.10000	0.01667	0.01838	0.01838	0.01996	0.02004	0.01557	0.01100
0.20000	0.02182	0.02475	0.02475	0.02836	0.03243	0.03451	0.03432
0.30000	0.02825	0.03253	0.03253	0.03825	0.04609	0.05353	0.05655
0.40000	0.03765	0.04359	0.04359	0.05168	0.06327	0.07527	0.08068
0.50000	0.05249	0.06079	0.06079	0.07216	0.08856	0.10590	0.11390
0.60000	0.07802	0.09025	0.09025	0.10690	0.13100	0.15640	0.16820
0.70000	0.12770	0.14740	0.14740	0.17420	0.21270	0.25320	0.27190
0.80000	0.24620	0.28300	0.28300	0.33270	0.40290	0.47580	0.50920
0.90000	0.70000	0.79090	0.79090	0.90760	1.06100	1.20500	1.26600

Table IV. Energy release rate J - integral with the variation of load angles for various crack length ratios.

Load angle	0.1 a/w	0.2 a/w	0.3 a/w	0.4 a/w	0.5 a/w	0.6 a/w	0.7 a/w	0.8 a/w	0.9 a/w
0	0.01667	0.02182	0.02825	0.03765	0.05249	0.07802	0.12770	0.24620	0.70000
15	0.01838	0.02475	0.03253	0.04359	0.06079	0.09025	0.14740	0.28300	0.79090
30	0.01838	0.02475	0.03253	0.04359	0.06079	0.09025	0.14740	0.28300	0.79090
45	0.01996	0.02836	0.03825	0.05168	0.07216	0.10690	0.17420	0.33270	0.90760
60	0.02004	0.03243	0.04609	0.06327	0.08856	0.13100	0.21270	0.40290	1.06100
75	0.01557	0.03451	0.05353	0.07527	0.10590	0.15640	0.25320	0.47580	1.20500
90	0.01100	0.03432	0.05655	0.08068	0.11390	0.16820	0.27190	0.50920	1.26600

Table V. Mode I stress intensity factor with the variation of crack length ratios for various load angles

a/w	0°	15°	30°	45°	60°	75°	90°
0.10000	4.06128	5.05300	5.18400	5.27300	4.94300	3.36000	0.00000
0.20000	7.17485	5.77300	5.89300	5.93500	5.47500	3.64700	0.00000
0.30000	9.21029	6.56000	6.67400	6.67900	6.09800	4.01800	0.00000
0.40000	11.00098	7.56900	7.68100	7.65100	6.93500	4.52400	0.00000
0.50000	13.07096	8.93000	9.04300	8.97100	8.08000	5.23100	0.00000
0.60000	15.88395	10.88000	10.99000	10.86000	9.71700	6.24300	0.00000
0.70000	20.19530	13.91000	14.01000	13.78000	12.24000	7.80100	0.00000
0.80000	27.63693	19.29000	19.38000	18.94000	16.68000	10.53000	0.00000
0.90000	43.57752	32.47000	32.41000	31.33000	27.13000	16.82000	0.00000

Table VI. Mode II stress intensity factor with the variation of crack length ratios for various load angles

a/w	0°	15°	30°	45°	60°	75°	90°
0.1000	0.00000	0.7049	0.8291	1.4610	2.3720	3.4730	4.0613
0.2000	0.00000	0.7049	1.5500	2.7050	4.3210	6.2020	7.1749
0.3000	0.00000	0.9401	2.0620	3.5740	5.6520	8.0090	9.2103
0.4000	0.00000	1.1550	2.5260	4.3570	6.8410	9.6140	11.0010
0.5000	0.00000	1.4050	3.0660	5.2690	8.2190	11.4600	13.0710
0.6000	0.00000	1.7500	3.8110	6.5200	10.1000	13.9900	15.8840
0.7000	0.00000	2.2870	4.9650	8.4530	13.0100	17.8600	20.1953
0.8000	0.00000	3.2300	6.9930	11.8400	18.0600	24.5500	27.6369
0.9000	0.00000	5.4140	11.6500	19.4900	29.2500	39.0500	43.5775

IV. CONCLUSION

The mixed mode fracture mechanics parameters are investigated for RP material for modified Arcan test specimen and finite element analysis is used to evaluate the effect of crack length on fracture criterion. The geometric calibration factors is given for both plane stress and plane strain conditions and different mixed-mode loading conditions of modified Arcan specimen. The results of this study will be used in future investigations on mixed mode fracture of RP material through experimental analysis.

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