CHAPTER 3

MIXED-MODE FRACTURE OF ALUMINUM ALLOYS
USING BEND SPECIMENS

3.1 INTRODUCTION

Modern engineering design has led to the recognition of the importance of fracture problems in many technological fields. The two dimensional plate problems in mechanics with an initial crack when the load is located at an eccentric position from the crack are unique, for which precise analytical solutions do not exist. Although the specimen in this study has simple geometry and loading, the eccentric position of the load gives rise to mixed-mode deformation on the crack lips.

For mixed mode loading, the techniques to use the $J$ -integral and $J_c$ concepts for analyzing the fracture behavior of ductile materials become important and frequently have been discussed. The $J$ -integral of a mixed crack was separated into $J_I$ of the mode I loading component and $J_{II}$ of the mode II loading component by Ishikawa (1979) and Bui (1983) by mathematical analysis. Tohgo and Ishii (1992), Lee and Donovan (1987), Shi et al (1994), Kamat and Hirth (1996a) and Sha Jiangbo et al (2000) Some results on this separation of $J$ integral into mode I component and mode II component were presented. Tohgo and Ishii (1992) developed a method of estimating the $J$ -integral for a mixed crack and discussed the elastic-plastic fracture behavior of the aluminum alloy 605-TS1 by using a four-point-bend
type specimen. Lee and Donovan (1987) showed the $J$-integral relation by describing the fracture under mixed mode loading using a three-point-bend-specimen with a single edge inclined crack. The contribution of the mode II component to the mixed-mode fracture toughness, $J_{Mc}$, was also supported by Shi et al (1987), Kamat and Hirth (1996a), Sha Jiangbo et al (2000).

Conventional testing programs (Zhu and Joyce 2007, Cravero and Ruggieri 2007) to measure crack growth resistance ($J$– $\Delta a$) curves (also termed R-curves) routinely employ three-point bend, SE (B), or compact tension, C(T), specimens in pure mode I. But, very little work (Kamat and Hirth 1996a) has been done in mixed mode category.

Based on the above literature, this work analyses the case of bend specimen subjected to eccentric load and provides an estimation procedure to determine Mixed-mode $J$-resistance curves for SE (B) fracture specimens using the unloading compliance technique. A summary of the methodology upon which $J$ and $\Delta a$ are derived sets the necessary framework to determine crack resistance data from the measured load vs. displacement curves. Laboratory testing of SE(B) specimens of 5083 and 7075 grade aluminum alloys at room temperature provides the load–displacement data needed to verify the estimation procedure for measuring the crack growth resistance curve of the material. The results presented here produce a representative set of solutions which lend strong support to develop new standard test procedures for constraint-designed SE(B) specimens with eccentric load, applicable in measurements of crack growth resistance for pipelines.

The chemical composition of the two alloys used in this thesis are given in Table 3.1.
Table 3.1 Composition of aluminum alloys used

<table>
<thead>
<tr>
<th>Material</th>
<th>Si</th>
<th>Cu</th>
<th>Fe</th>
<th>Mn</th>
<th>Mg</th>
<th>Zn</th>
<th>Cr</th>
<th>Ti</th>
<th>Al</th>
</tr>
</thead>
<tbody>
<tr>
<td>Balanced</td>
<td>0.35</td>
<td>0.10</td>
<td>0.25</td>
<td>0.4</td>
<td>4.2</td>
<td>0.25</td>
<td>0.05</td>
<td>0.15</td>
<td>Balance</td>
</tr>
<tr>
<td>Al 5083</td>
<td>0.42</td>
<td>1.8</td>
<td>0.3</td>
<td>0.1</td>
<td>1.25</td>
<td>5.25</td>
<td>0.2</td>
<td>0.1</td>
<td>Balance</td>
</tr>
</tbody>
</table>

3.2 EXPERIMENTATION

3.2.1 Unloading Compliance Method

Analytical efforts to support the development of laboratory measurements for fracture toughness resistance data have focused primarily on the unloading compliance method (ASTM E1820, 2001) based upon the testing of a single specimen. Compliance is the ratio of displacement to the load applied in a particular loading or unloading cycle. The values of the compliance at each unloading step are determined and these values are used for the computation of corresponding crack length at each loading-unloading cycle. The specimen response is defined in terms of load-load-line displacement (LLD) data or load-crack mouth opening displacement (CMOD) as in Figure 3.3. The technique then enables accurate estimations of J and Δa at several locations on the load-displacement records from which the J-R curve can be developed.

Before deriving the quantities and parameters needed to determine the crack growth resistance curves for the SE(B) specimens, this section first provides an overview of the nature of the procedure.

The procedure to estimate crack growth resistance data begins by invoking the energy release rate interpretation of the J-integral. Upon
consideration of the elastic and plastic contributions to the strain energy for a cracked body under Mode I deformation, \( J \) can be conveniently defined in terms of its elastic component, \( J_{\text{el}} \), and plastic component, as

\[
J = J_{\text{el}} - J_{\text{pl}} \tag{3.1}
\]

where the elastic component, \( J_{\text{el}} \), is given by

\[
J_{\text{el}} = \frac{K_I^2}{E'} \tag{3.2}
\]

\[E' = E / (1 - \nu^2) \text{ - for plane strain case}\]

and \( E' = E \) for plane stress case

Here, \( K_I \) denotes the (Mode I) elastic stress intensity factor for the cracked configuration where \( E \) and \( \nu \) are the elastic modulus and Poisson’s ratio respectively.

The plastic component, \( J_{\text{pl}} \), is derived from adopting the approach proposed by Sumpter and Turner (1976) building upon earlier work of Rice (1973) to relate the J-integral to the area under the load vs. load-line displacement. The approach simply relates the plastic contribution to the strain energy (due to the crack) and \( J \) in the form

\[
J_{\text{pl}} = \frac{2A_{\text{pl}}}{B_N b_0} \tag{3.3}
\]

where \( A_{\text{pl}} \) is the plastic area under the load vs. load-line displacement, \( B_N \) is the net specimen thickness, \( b_0 \) is the initial uncracked ligament \( (b_0 = (W - a_0)) \) where \( W \) is the width for the cracked configuration and \( a_0 \) is the initial crack length). Here, we also note that \( A_{\text{pl}} \) can be defined in terms of LLD data or CMOD data. The previous expressions, Equations (3.2) and (3.3), define the
key quantities driving the evaluation procedure for $J$ as a function of applied (remote) loading and crack size. Further, the previous solution for $J_{pl}$ retains strong contact with the deformation plasticity definition of $J$ and thus assumes nonlinear elastic material response. However, the area under the actual load–displacement curve for a growing crack differs significantly from the corresponding area for a stationary crack (which the deformation definition of $J$ is based on) (Zhu and Joyce 2007). Consequently, the measured load–displacement records must be corrected for crack extension to obtain an accurate estimate of $J$-values with increased crack growth. A widely used approach (which forms the basis of current standards such as ASTM E1820 (2001)) to evaluate $J$ with crack extension follows from an incremental procedure which updates $J_{el}$ and $J_{pl}$ at each partial unloading point, denoted by $k$, during the measurement of the load vs. displacement curve (Figure 3.3) in the form

$$J_k = J_{el}^k + J_{pl}^k$$

(3.4)

For the SE(B) specimen, parameter stress intensity factor, $K_i$ is evaluated at the current load, $P_i$, as

$$K_{i} = \left[ \frac{P_i S}{B W^2} \right] f\left(\frac{a_i}{W}\right)$$

(3.5)

where $f\left(\frac{a_i}{W}\right)$ defines a nondimensional stress intensity factor dependent upon specimen geometry, crack size and loading condition (pin-loaded vs. clamped ends). For the SE(B) specimens analyzed here, ASTM E1820 (2001) provides analytical expressions for the nondimensional stress intensity factors $f\left(\frac{a_i}{W}\right)$.
Another key step in the experimental evaluation of crack growth resistance response involves the accurate estimation of the instantaneous crack length as testing progresses. The unloading compliance technique provides a convenient and yet simple procedure to correlate crack extension with the specimen compliance for increased crack growth. The slope of the load–displacement curve during the k-th unloading defines the instantaneous specimen compliance, denoted by $C_k$, which depends on specimen geometry and crack length.

The summarized procedure needs exact calculation of $J$, specimen compliance, $C$ and other parameters through Equations (3.6) to (3.11). These quantities thus play a crucial role in defining the $J$–$R$ curve from laboratory measurements of load vs. displacement for the tested specimen. Current test standards (such as ASTM E1820 (2001)) provide appropriate forms for calculation of compliance $C$, applicable to SE (B) specimens with deep cracks ($a/W \geq 0.45$).

### 3.2.2 Mixed Mode Fracture Testing on SE(B) Specimens

In the present research the three-point bend specimen with an unsymmetrical crack is introduced and investigated as suggested by Gdoutos and Zacharapoulos (1987) for the study of mixed-mode crack growth. The symmetrical three-point bend cracked specimen has been used extensively in fracture-mechanics studies. It is one of the standard specimens used in the ASTM codes for determining the fracture toughness $J_{lc}$. The mixed-mode bend specimen has not been studied as much as the symmetrical case i.e. a centre loaded specimen in the literature.

The specimen taken for this case was of dimensions 114.2 x 25.4 x 12.7 mm and all specimens were notched for mounting clip gauge. The
specimen drawing is shown in Figure 3.1. Then all the specimens were precracked for a/W=0.5. Then all the specimens were loaded with loading unloading cycles to get a load-displacement plot as shown in Figure 3.3. The list of specimens with loading conditions is given in Table 3.2.

Table 3.2 Specimen loading conditions and critical stress intensity factors, $K_c$

<table>
<thead>
<tr>
<th>Specimen No.</th>
<th>Eccentricity, $e$</th>
<th>Maximum Load, $P_{max}$</th>
<th>Crack length to specimen width ratio a/W</th>
<th>Critical stress intensity factor $K_c$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>mm</td>
<td>kN</td>
<td></td>
<td>MPa-$\sqrt{\text{m}}$</td>
</tr>
<tr>
<td>A1</td>
<td>0</td>
<td>4.23</td>
<td>0.51</td>
<td>22.97</td>
</tr>
<tr>
<td>A2</td>
<td>10</td>
<td>4.89</td>
<td>0.52</td>
<td>27.18</td>
</tr>
<tr>
<td>A3</td>
<td>20</td>
<td>7.61</td>
<td>0.53</td>
<td>43.47</td>
</tr>
<tr>
<td>A4</td>
<td>30</td>
<td>8.87</td>
<td>0.54</td>
<td>52.81</td>
</tr>
<tr>
<td>B1</td>
<td>0</td>
<td>4.83</td>
<td>0.51</td>
<td>25.52</td>
</tr>
<tr>
<td>B3</td>
<td>10</td>
<td>4.99</td>
<td>0.51</td>
<td>26.79</td>
</tr>
<tr>
<td>B4</td>
<td>20</td>
<td>5.08</td>
<td>0.52</td>
<td>27.60</td>
</tr>
<tr>
<td>B6</td>
<td>30</td>
<td>6.48</td>
<td>0.51</td>
<td>34.38</td>
</tr>
</tbody>
</table>

Figure 3.1 SE(B) specimen with mixed mode loading
A purpose of this study is to determine the critical fracture toughness $J_c$ and J–R curve under mixed mode. After precracking, the specimens were tested under eccentric load as shown in Figure 3.1. The photograph of a sample specimen along with the experimental setup is shown in Figure 3.2. The dimensions are: span between the supports, $S=100$ mm, width, $W=25.4$ mm, thickness, $B=12.54$ mm and the precracked $a/W$ ratio is kept at 0.5 for all specimens. The eccentricity, $e$ is kept at 0, 10, 20 and 30 mm.

The $J_c$ tests are carried out with loading unloading cycles. The obtained load-displacement record is useful for finding the $J-\Delta a$ curves as stated in Cravero and Ruggieri (2007).

Here an issue of negative crack length arises. That is, initially some crack lengths are obtained in negative due to compressive residual stress present during the unloading cycles. This has to be corrected. This issue is addressed by offsetting all the crack lengths to the amount of most negative value as suggested by Chang-Sung Seok (2000).

The crack length can be determined from the following Equation (3.6)

$$a_i/W = \left[ 0.999748 - 3.9504u + 2.9821u^2 - 3.21418u^3 + 51.51564u^4 - 113.031u^5 \right]$$

(3.6)

where

$$u = \frac{1}{\sqrt{\frac{\text{BWEC}_i}{S/4}} + 1}$$

(3.7)

$C_i = (\Delta V/\Delta P)$ on an unloading compliance

$V$ = crack opening displacement at notched edge,

$B$ = specimen thickness
The crack lengths found from Equations (3.6) and (3.7) are suitable only for symmetric loading cases. For the unsymmetrical loading cases, a new effective modulus is found as used by Chandra Kishen and Saouma (2004).

\[ E_{\text{eff}} = \frac{C_0^{\text{EXP}}}{C_0^{\text{FEM}}} \]  (3.8)

where \( E_{\text{eff}} \) = Effective modulus of elasticity, N/mm\(^2\)
\( C_0^{\text{EXP}} \) = Experimental Compliance of the first or initial loading cycle, mm/N
\( C_0^{\text{FEM}} \) = Compliance of the zeroth loading cycle found from Finite Element Analysis (FEA), mm/N.

The effective compliance for all other unloading cycles can be found using the following equation,

\[ C_i^c = E_{\text{eff}} \cdot C_i^{\text{EXP}} \]  (3.9)

where \( C_i^{\text{EXP}} \) = Experimental compliance of the \( i^{th} \) loading cycle, mm/N
\( C_i^c \) = Corrected compliance of the \( i^{th} \) loading cycle, mm/N.

Substituting \( C_i^c \) in the place of \( C_i \) in Equation (3.7) and using Equation (3.6), the required instantaneous crack lengths are found. The same procedure is followed to determine the corrected crack length for all specimens which are loaded eccentrically.

3.3 RESULTS

The precracked specimens were first tested under static loading and unloading cycles. The load displacement data were taken and shown in Figures 3.3 and 3.4. From the unloading compliance data, the crack lengths are determined. And from Equations (3.1) to (3.4), the J is calculated.
Figure 3.2 Photo showing the eccentric load application on specimen No. A3 of Al 5083

Figure 3.3 Typical load vs displacement plot of Al 5083 for the specimen A3 with load eccentricity distance, e=20 mm
Figure 3.4  Typical load vs. displacement plot of Al 7075 for for specimen B4 with load eccentricity distances, e=20mm

Substituting the maximum pop in load which is determined from the load displacement plot, in Equation (3.5), the critical stress intensity factors are found. The critical stress intensity factors determined for the two alloys are plotted as shown in Figure 3.5. The J-Δa curves of specimens with various load eccentricity distances (e) are shown in Figures 3.6 and 3.7 for the two aluminum alloys 5083 and 7075.

The Δa values are determined from the Equations (3.6) to (3.9). The J-Δa curves are plotted as follows for Al 5083 and Al 7075 for different load eccentricity e.
Figure 3.5 Critical stress intensity factor values versus eccentricity distance, $e$

Figure 3.6 $J$-$\Delta a$ curve of Al 5083 bend specimen for different load eccentricity distances($e$)
3.3.1 Determination of J-Δa Curve

The property $J_c$ which is determined by the method as stated by Cravero and Ruggieri (2007), characterizes the toughness of a material near the onset of crack extension from a preexisting fatigue crack. The beginning of the unstable crack growth is marked by $J_c$ parameter. A curve is plotted as in Figure 3.8, using the J and Δa data points obtained already, from the Equation (3.10).

$$J = M \sigma_Y \Delta a$$  (3.10)

Here $M=2$ is taken from the standard ASTM E1820 (2001). $\sigma_Y$ is the average of 0.2% offset yield strength $\sigma_{YS}$, and ultimate yield strength $\sigma_{TS}$ as given below:

$$\sigma_Y = \frac{\sigma_{YS} + \sigma_{TS}}{2}$$  (3.11)

A regression line is plotted as shown in Figure 3.8 using the expression

$$\ln J = \ln C_1 + C_2 \ln \frac{\Delta a}{k}$$  (3.12)

where $k=1.0$mm

Here $C_1$ and $C_2$ are calculated using the data pairs which confirm within the 0.15 mm slope exclusion line and 1.5 mm slope exclusion line.
Figure 3.7 J-\(\Delta a\) curve of Al 7075 bend specimen for different load eccentricity(e) distances

Figure 3.8 Regression line to evaluate \(J_c\) from J - \(\Delta a\) points
\( \Delta a \) in Equation (3.10) is calculated as given below:

\[
\Delta a_{(i)} = \frac{J_{Q(i)}}{M \sigma_y} + 0.2 \text{mm} \tag{3.13}
\]

Here an interim \( J_{Q(i+1)} \) is evaluated using the expression,

\[
J_{Q(i+1)} = C_1 \left( \frac{\Delta a_{(i)}}{k} \right)^{C_2}
\]

(3.14)

where \( k=1.0 \text{ mm } (0.0394 \text{ in.}) \)

By incrementing \( i \) and returning to Equations (3.13) and (3.14), the iteration is repeated until the interim \( J_Q \) converges to within \( \pm 2\% \). Using the steps shown from Equations (3.10) to (3.14) the critical fracture toughness is calculated and presented in the Figure 3.9 for the two materials. For Al 5083 alloy, the mixed mode fracture toughness \( J_c \) first increases steadily from when \( e=0 \) to 30 mm. This suggests that the \( J_c \) increases because of the mode II effect upto when \( e=30 \text{ mm} \) and also because of the constraint. The fracture toughness values of the specimens tested are listed in Table 3.3.

**Table 3.3 Fracture toughness values, \( J_c \) for different load eccentricity distances of Al 5083 and Al 7075**

<table>
<thead>
<tr>
<th>Specimen No.</th>
<th>Load Eccentricity, mm</th>
<th>Fracture Toughness, ( J_c, \text{kJ/m}^2 )</th>
<th>Material</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>0</td>
<td>16.5</td>
<td>Al 5083</td>
</tr>
<tr>
<td>A2</td>
<td>10</td>
<td>22.5</td>
<td>Al 5083</td>
</tr>
<tr>
<td>A3</td>
<td>20</td>
<td>46</td>
<td>Al 5083</td>
</tr>
<tr>
<td>A4</td>
<td>30</td>
<td>74</td>
<td>Al 5083</td>
</tr>
<tr>
<td>B1</td>
<td>0</td>
<td>17</td>
<td>Al 7075</td>
</tr>
<tr>
<td>B3</td>
<td>10</td>
<td>18.3</td>
<td>Al 7075</td>
</tr>
<tr>
<td>B4</td>
<td>20</td>
<td>22</td>
<td>Al 7075</td>
</tr>
</tbody>
</table>
Figure 3.9 Comparison of mixed mode fracture toughness of Al 5083 and Al 7075 bend specimens vs. the eccentricity distance

To determine a regression line, we use equation (3.12)

\[ \ln J = \ln C_1 + C_2 \ln \left( \frac{\Delta a}{k} \right) \]  

(3.12)

A linear regression line can be obtained using method of least squares. This equation is given by ASTM standard E1820 –01. The regression line helps us to find \( J_{fc} \), by suitably extrapolating this line so as to meet a blunting line with slope \( J/\Delta a = 2\sigma_Y \)

A flowchart is given in APPENDIX 2 to calculate \( J_{fc} \) fracture toughness using \( J \) and \( \Delta a \) datapoints obtained from experiments.

**Significance of the regression line:** The best fitted line through the horizontal points, is called regression line(R-line). The meeting point of
regression line with 0.15mm exclusion line (slope =0.15mm in the J- Δa curve) gives the J_Q. If J_Q value meets all the three requirements of ASTM standard E1820-01, then J_Q is called size independent, fracture toughness J_{lc}.

The three requirements for qualification of J_Q as J_{lc} are:

1. Specimen thickness \( B > 25 \frac{J_Q}{\sigma_y} \),

2. Initial ligament \( b_0 > 25 \frac{J_Q}{\sigma_y} \),

3. Regression line slope (dJ/da) < \( \sigma_Y \)

The k in equation (3.12) is a unit conversion factor to convert between mm to inch. For instance k=1.0 mm or 0.0394 in.

3.3.2 Finite Element Analysis

Finite element analyses (FEA) of the specimens were performed in order to determine the J-integral for different loading conditions, geometries, and material properties. The FEA results are compared to the J-integral determination using the experiments as explained above. 2D finite element models of the SE (B) specimens were constructed using isoparametric 8 noded elements (PLANE 82) using the commercial finite element program ANSYS 10.0.

The specimen is modeled as a plane stress element with the thickness input. The model is meshed with quadratic elements. The area near the crack tip is fine-meshed with the element size in the order of 2-3 microns. The meshed model is shown in Figure 3.10. The two zoomed views are shown in the inner Figures. The total number of nodes and elements are 29613 and 9742 respectively. The inner most mesh has an element edge length in the order of 3e-3mm.
Figure 3.10 Model showing finite element mesh created using ANSYS 10.0

The path integral proposed by Rice (1973) is used in the finite element analysis calculations. The procedure to calculate J-integral using the method suggested by Rice has been outlined in a flowchart and the same is given is Annexure 1. The results are compared with the experimental J-Δa curve in Figures 3.11 to 3.14.

In Figure 3.11, the J-Δa curve of mode I of Al 5083 is compared with that of Brocks et al (2010) and finite element (ANSYS) results. The experimental results are found to be close to the ANSYS results and Brocks et al (2010) up to 1 mm increase in crack length. In Figure 3.12, J-Δa curve of specimen A2 with eccentricity, e=10 mm, is compared with finite element results. The experimental results are found to be matching close to the values obtained by ANSYS 10.0. The nature of J-Δa curves of mixed-mode I/II and the mode I, is supported by Tohgo and Ishii (1992). They (Tohgo and Ishii 1992) have obtained similar J-Δa curves where the one corresponding to mode I embraces little area under it and the other corresponding to mixed-mode I/II embrace larger area. Further, the J-Δa curves are compared with that of FEA results for the specimen with e=20 mm and e=30 mm separately and found to be in conformity with that of experimental results. They are shown in Figures 3.13 and 3.14 respectively.
Figure 3.11 Comparison of J-Δa curve estimated experimentally with numerical results for symmetrical loading (Specimen A1)

Figure 3.12 Comparison of J-Δa curve estimated experimentally with numerical results for unsymmetrical loading with eccentricity e=10 mm (Specimen A2)
Figure 3.13 Comparison of J-Δa curve estimated experimentally with numerical results for unsymmetrical loading with eccentricity e=20 mm (Specimen A3)

Figure 3.14 Comparison of J-Δa curve estimated experimentally with numerical results for unsymmetrical loading with eccentricity e=30 mm (Specimen A4)

3.3.3 Fractographic Images

The following Figures show the fractographic images of the fractured specimens of Al 5083 and Al 7075. In Figure 3.15 (i), where pure
mode I loading is applied, a large size spherical voids are observed. The crack growth is occurred by means of coalescence of these voids. So, the void coalescence mechanism dictates the kind of fracture in this type of loading as also stated by Imad S. Barsoum (2003). The SEM images of mixed-mode specimens are shown in Figure 3.15 (ii) to (iv).

The fractographic images of the specimens of Al 7075 are shown in Figures 3.16 (i) to (iv). Here the first Figure 3.16(i) shows the specimen corresponding to mode I and the remaining shown the images of mixed-mode specimens.

![Scanning electron micrograph (SEM) of Al 5083 specimen subjected to different load eccentricities](image)

Figure 3.15 Scanning electron micrograph (SEM) of Al 5083 specimen subjected to different load eccentricities (i) e=0 mm pure mode I, (ii) e=10 mm, (iii) e=20 mm, (iv) e=30 mm
Figure 3.16 Scanning Electron Micrograph (SEM) of Al 7075 specimen subjected to different load eccentricities. (i) e=0 mm pure mode I, (ii) e=10 mm, (iii) e=20 mm, (iv) e=30 mm

3.4 DISCUSSION

For loading near to the crack location (mode I), the deformation ahead of the crack is dominated by mode I field. The type of fracture surface is covered with typical equi-axed dimple patterns (Figure 3.15 (i)).

However, as the eccentricity of loading increases the mode II field also will be produced. Since the effect of mode I is reduced for increasing
eccentricity of loading (Gdoutos and Zacharopoulos 1987), stability is observed in the fracture process for Al 5083. This type of fracture surface has elongated dimple patterns and a number of flat surfaces. The slightly elongated dimple patterns can be seen in Figure 3.15 (ii). The flat surfaces are created by shear slip. These are seen in Figures 3.15 (iii) and 3.15 (iv), which correspond to eccentricity $e=20$ mm and $e=30$ mm respectively. These flat surfaces are shear bands which lead to shear localization and the type of failure corresponds to shearing mechanism.

This shear localization at the forefront of the crack produces incompatible stresses at the interfaces of particles in the trajectory of the crack causing particle fracture which leads to void formation.

The voids, once formed, can further enhance the shear localization process and tend to limit the size of the portion of the plastic zone which is strongly influenced by the mode I loading component.

In the case of alloy Al 7075, the mode I fracture is very similar compared to that of Al 5083 (Figure 3.16 (i)). The equiaxed voids are present in both the alloys when they are loaded at the centre of the span (eccentricity, $e=0$), which corresponds to mode I.

But when the eccentricity is increased from 0 to 10, 20 and 30 mm, the behavior of Al 7075 is quite different from Al 5083. In alloy Al 7075 when loaded with eccentrically, the number of shear bands is less compared to that of alloy Al 5083. So, the major mechanism causing the failure is still mode I only. Hence, the material behaves relatively brittle when compared to Al 5083 subjected to mixed-mode loading in bend specimens.

In Figure 3.8, the J values are plotted against the crack growth for different load eccentricity distances. When the load eccentricity is zero, mode
I is alone produced. This gives a lowest J-R curve and the curve becomes higher for higher values of load eccentricity distances. The J-R curves of load eccentricity values 0 and 10 mm are found to be closer, but the 10 mm curve is higher than 0 mm curve. The curves of 20 mm and 30 mm curves are higher and higher. This is because of mixture of mode I and mode II are produced when the load is deviated from the mid-span and just above the crack. The inference is when the load eccentricity increases and approach near one of the supports, the resistance to bending is also increased, this causes the crack to experience an inclined loading but little bending. This causes the material to possess more toughness when loaded near to the supports.

The same trend is observed in Al 7075 (Figure 3.7) and also experienced by Tohgo and Ishii (1992) in the case of Al 6061. The J-R curve of Al 7075 with load eccentricity e=0, 10 and 20 mm are closer. But the J-R curve corresponding to e=30 mm, is far higher. This is because, when the load eccentricity is near to the center, the resistance to bending is less, so it got lower J-R curve. Gdoutos and Zacharopoulos (1987), had found that when the eccentricity was increasing, mode I fracture toughness decreased and mode II fracture toughness increased. The net result is the reduction in fracture toughness. But, because of resistance to bending though small, the J-R curve of e=10 mm is higher than that of e=0.

The estimated fracture toughness values, \( J_c \) for different load eccentricity are compared for the two alloys Al 5083 and Al 7075. The \( J_c \) of Al 5083 alloy is found to start from 16.5 kJ/m\(^2\) at e=0 mm and rises to 22.5 kJ/m\(^2\) at e= 10 mm. Then it rises steeply for the rest of the load eccentricity (e) distances (Figure 3.9).
But, for Al 7075, the $J_c$ is steadily increasing for the increase in eccentricity distance. This material exhibits a fracture toughness of 17 kJ/m$^2$ at $e=0$ mm and 18.3-28.25 kJ/m$^2$ for the remaining load eccentricity ($e$) distances. This is because of its resistance to the bending. But, at the same time, this material is observed to be so brittle and does not bend gradually. Though, the bending moment is same in both the alloys, the nature of the material characteristic of Al 7075, tends it to offer relatively a little energy release for unit increase in crack length as the eccentricity is moving towards one of the supports. The reason for this behavior is that the plasticity formed is relatively lesser because of the brittle nature of the material Al 7075.

### 3.5 CONCLUDING REMARKS

This method of estimating mixed mode fracture toughness $J_c$ is a novel and viable method to create a mixed mode by applying load at eccentric point on a three point bend specimen. The following conclusions are made from this work:

1. The compliance based approach is used to determine the $J$ – Resistance curve for mixed-mode fracture using bend specimens.

2. The fracture toughness, $J_c$ in mixed-mode I/II is found to be maximum at load eccentricity $e= 30$ mm for both the alloys (Al 5083 and Al 7075). The fracture toughness Al 5083 increases considerably from mode I to mixed-mode I/II as load eccentricity increases. But, fracture toughness $J_c$ of Al 7075 is found to increase marginally for the increase in load eccentricity.

3. The mode I fracture occurs because of void coalescence mechanism, whereas the mixed mode fracture toughness occurs mainly because of shear localization mechanism.
It appears that this approach described in this chapter, provides a powerful and general tool that can be used to compute numerically the fracture toughness of SE (B) specimens.

Under mixed mode loading by load eccentricity technique, the mode decoupling method along with force analysis can be used to separate the material fracture toughness values in mode I and mode II.