EFFECT OF BIAXIALITY ON FRACTURE BEHAVIOR: TESTING AND ANALYSIS OF CRUCIFORM SPECIMEN

A. K. Pawar¹, M. K. Sahu¹, J. Chattopadhyay¹, B. K. Dutta¹, K.K. Vaze¹, P. Gandhi², and G. Raghava²
¹ Reactor Safety Division, Bhabha Atomic Research Centre, Mumbai, INDIA-400085
² Structural Engineering Research Center-CSIR Taramani Chennai, INDIA-600113
E-mail of corresponding author: akpawar@barc.gov.in

ABSTRACT
This paper presents the details of experimental and numerical studies carried out on the cruciform specimens. Cruciform specimens are widely used to study the effect of biaxial loading on the fracture process. Reactor Safety Division, BARC has embarked upon the fracture tests on cruciform specimens to study this effect. Six numbers of cruciform specimens with part through crack at the core have been tested at room temperature and at –70°C under bending with biaxiality ratio of 1:0, 2:1 and 1:1 at CSIR-SERC, Chennai. Three dimensional elastic-plastic finite element (FE) analyses have been carried out for all the specimens. Results obtained from the FE analyses have been found to be in good agreement with the test data. Crack initiation loads have also been predicted numerically based on the initiation toughness \( J_{zhw} \). Effect of multiaxiality on various fracture parameters and load bearing capacity of structures has also been discussed.

INTRODUCTION
In the analysis of the structural integrity of Reactor Pressure Vessel (RPV) containing flaws, one of the important issues is the estimation of biaxial loading effect on fracture toughness of the material. This problem arises in connection with the the normal operation of RPV as well as under the pressurized thermal shock loading. Figure 1 shows the typical flaw in a pressure vessel and the type of loading the flaw experiences. Figure 2 depicts the components of far field stress distribution in a RPV wall during a PTS transient [1].

![Figure 1(a) Loading of pressure vessel (b) crack tip subjected to loading (c) typical specimen for fracture toughness](image)

In the structural integrity analysis of RPV containing the flaws, the fracture toughness values obtained from standard laboratory specimens such as Compact Tension (CT), Three Point Bend Bar (TPBB) are normally used. These specimens are tested under in-plane opening mode (the load acts perpendicular to the crack front \( P_T \neq 0, P_L = 0 \), as in Figure 1 (c)). The out-of-plane loading \( (P_L) \) is not represented in these specimens. Therefore two questions arise:

- Whether it is correct to use fracture toughness data obtained from standard specimen tested under uniaxial loading in order to analyze the onset of crack growth under biaxial loading.
- How fracture toughness depends on biaxiality ratio, \( \beta \) (\( \beta = \) Remote transverse stress acting perpendicular to the crack plane / Remote longitudinal stress acting along the crack front).
There is growing interest worldwide to design a specimen, which can be tested to estimate the effect of biaxial loading on fracture toughness. The majority of the experiments on fracture toughness under biaxial loading have been performed on a plate subjected to biaxial bending moments [1-3]. The configuration of the biaxial bend specimen having cruciform shaped geometry is depicted in Figure 3. The specimen design is capable of reproducing a linear approximation of the non-linear biaxial stress distribution in a RPV wall during a PTS transient [1].

**TESTING OF CRUCIFORM BEND SPECIMENS**

**General Specimen Geometry**

Cruciform specimen consists of a core and arms. Details of the cruciform specimen have been depicted in Figures 3-5. A solid model of the cruciform specimen is shown in Figure 3. Specimen core is made of the same material as the reactor pressure vessel i.e. 20MnMoNi55. Dimension of the core is 300x300x135mm. Arms are simply supported at the ends. Boiler Quality Carbon steel (ASTM-A-516 Grade 70) has been used to make the arms of the specimen. Specimen is loaded by a square load block at the center of the Core of the specimen opposite to the cracked face such that load opens the crack. Dimension of the load block is 90x90 mm. A clearance/margin of 150mm (overhang beyond the supports) on each side of the arms has been provided to account for the lateral displacement. Figure 5 shows the crack geometry in the core. It is a part through crack with a straight crack-front. It is to be noted that the length of the crack is 320mm for cruciform specimen and 430 for uniaxial specimen which are more than the width of the core (300mm). Six number of cruciform bend specimens with different arm-lengths have been tested at different temperatures. A cooling chamber has been prepared to carry out the low temperature tests. A photograph of the actual experimental setup is shown in Figure 6. Arrangement for strain gauges and CMOD gauges on the core has been shown in Figure 7. Specimen for the uniaxial testing has only two arms. A schematic of uniaxial cruciform specimen has been shown in Figure 8.
Figure 6 A photograph of experimental setup for biaxial testing.

Figure 7 A photograph of Instrumentation on the test section.

Figure 8 Specimen for the uniaxial testing.

Description of test specimens

The brief description of the specimens prepared for the test is given in Table 1.

<table>
<thead>
<tr>
<th>Specimen Name</th>
<th>Length of transverse arm (mm)</th>
<th>Loading Span (mm)</th>
<th>Length of longitudinal arm (mm)</th>
<th>Loading Span (mm)</th>
<th>Test temperature</th>
<th>Biaxiality ratio</th>
<th>Crack length (mm)</th>
<th>Crack depth (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CRRT10</td>
<td>-</td>
<td>-</td>
<td>1930</td>
<td>1720</td>
<td>Room temperature</td>
<td>1:0</td>
<td>425</td>
<td>19.8</td>
</tr>
<tr>
<td>CRSZ10</td>
<td>-</td>
<td>-</td>
<td>1925</td>
<td>1720</td>
<td>-70°C</td>
<td>1:0</td>
<td>430</td>
<td>20.5</td>
</tr>
<tr>
<td>CRRT11</td>
<td>1950</td>
<td>1650</td>
<td>1950</td>
<td>1650</td>
<td>Room temperature</td>
<td>1:1</td>
<td>320</td>
<td>35.2</td>
</tr>
<tr>
<td>CRSZ11</td>
<td>1950</td>
<td>1650</td>
<td>1950</td>
<td>1650</td>
<td>-70°C</td>
<td>1:1</td>
<td>320</td>
<td>36.0</td>
</tr>
<tr>
<td>CRSZ21-A</td>
<td>3150</td>
<td>2850</td>
<td>1990</td>
<td>1690</td>
<td>-70°C</td>
<td>2:1</td>
<td>320</td>
<td>35.0</td>
</tr>
<tr>
<td>CRSZ21-B</td>
<td>3100</td>
<td>2800</td>
<td>1900</td>
<td>1600</td>
<td>-70°C</td>
<td>2:1</td>
<td>320</td>
<td>36.0</td>
</tr>
</tbody>
</table>

SUMMARY OF TESTS RESULTS

Six numbers of tests have been done and summery of these tests is tabulated in Table 2 in the chronological sequence.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Maximum load applied (kN)</th>
<th>Maximum load line displacement (mm)</th>
<th>Maximum CMOD (mm)</th>
<th>Maximum Crack-growth in depth direction (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CRRT10</td>
<td>2715</td>
<td>170.1</td>
<td>1.90</td>
<td>0.7</td>
</tr>
<tr>
<td>CRSZ10</td>
<td>2730</td>
<td>105.8</td>
<td>1.77</td>
<td>0.1</td>
</tr>
<tr>
<td>CRSZ11</td>
<td>3007</td>
<td>28.4</td>
<td>0.55</td>
<td>0.0</td>
</tr>
<tr>
<td>CRRT11</td>
<td>3037</td>
<td>27.8</td>
<td>0.71</td>
<td>0.0</td>
</tr>
<tr>
<td>CRSZ21-A</td>
<td>2766</td>
<td>38.6</td>
<td>1.04</td>
<td>1.2</td>
</tr>
<tr>
<td>CRSZ21-B</td>
<td>2805</td>
<td>40.6</td>
<td>0.9</td>
<td>0.2</td>
</tr>
</tbody>
</table>
FINITE ELEMENT MODELING
One forth of the cruciform bend specimen has been modeled using the symmetry across two planes. Three dimensional elastoplastic finite element analyses have been performed on the cruciform specimens. Symmetry boundary conditions have been applied on Face A and Face B as shown in the Figure 9. Figure 10(a) shows the mesh of the finite element model. Figure 10(b) and Figure 10(c) show zoomed picture of the mesh near the crack. Twenty-node iso-parametric brick element has been used for the analysis. A blunted crack-front has been modeled with a small radius of 0.2 mm. Reduced integration has been employed to eliminate the shear locking in the elements. The cruciform specimen is assumed to be supported at the ends of its four arms by constraining y direction movement of nodes falling on the support line. Load is applied on the specimen using a load block over the test section (i.e. area defined by -45 ≤ Z ≤ 0, 0 ≤ X ≤ 45). A uniform pressure is applied on the top of the load block.

Figure 9  3D schematic of quarter of the cruciform specimen.
Figure 10 (a) Finite element mesh of quarter of the cruciform specimen.
Figure 10 (b) Zoomed view of the cruciform specimen core.
Figure 10 (c) Fine mesh at the crack front.

Material properties
The material properties used for the material of the core include Young’s modulus E = 210000 MPa, Poisson’s ratio ν = 0.3. The material used for the core of the cruciform specimen is 20MnMoNi55. The yield strength for this material at room temperature is 490MPa and at -70°C is 547 MPa. The true stress vs. true strain curves are shown in Figure 11. Material properties used for the arm material include Young’s modulus E = 203000 MPa, Poisson’s ratio ν = 0.3. The material used for the arms of cruciform specimen is Boiler Quality Carbon steel conforming to ASTM SA 516 Gr-70. The true stress vs. true strain curve for the material is shown in Figure 12.
FINITE ELEMENT ANALYSES RESULTS

In finite element analyses it has been observed that the area of the load application has a significant effect on the results obtained. During the uniaxial room temperature test, a metal plate of dimension 300x300x40, i.e. of the size of the core had been placed between the specimens and load ram. For all other tests the loading ram directly kept over the specimen. This metal block has been incorporated in the finite element modeling for CRRT10.

Test data for the crack initiation load are not available hence they cannot be compared with the analysis data directly. However, Crack initiation loads from analyses can be compared in an indirect way. The crack initiation load can be compared with the maximum load applied during the test. If the crack growth observed in the test then crack initiation load should below the maximum load and vice versa. It is found that analyses result are consistent.
for all but one case. For specimen CRRT11 crack initial load predicted less than the maximum load and no crack growth found in this case.

**Cruciform bend Specimen at room temperature and biaxiality ratio unity (CRRT11)**

The results of the FE analysis for specimen CRRT11 have been compared with the test data. Figure 13, Figure 14 and Figure 15 show the crack mouth opening displacement (CMOD) vs. load curves from three different locations along the crack length. There were three CMOD gauges had been placed along the length of the crack during the experiment, one at the center and one each at either side 80mm from the center. The finite element analysis data have also been plotted along with the test data. It is clear from Figures 25-27 that the analysis results are matching extremely well with the test data. CMOD measurements are independent of machine compliance behavior. Figure 16 shows the variation of the crack driving force (applied $J$-integral) with load. $J_{IC}$ value for 20MnMoNi55 is 250 kJ/m$^2$ at room temperature. It is clear from the figure that load corresponding to the $J_{IC}$ is 3380 kN, which is more than the maximum load (3037 kN) applied during the test. It has been found that there is no crack growth during the experiment. Figure 17 and Figure 18 depict the variation of the load with the maximum principal strain along the transverse and longitudinal directions respectively. Two strain gauges had been placed along each arm of the cruciform specimen in the space between the load diffusion control slots.

**Machine compliance correction**

Figure 19 shows load line displacement vs. Load curves. Predicted crack initiation load has been shown by horizontal line. This line does not cross the test line. The data from FE analysis deviate excessively from the test data. This deviation can be attributed to the machine compliance, which is included in load line displacement measurement. The difference in values of load line displacement in test data and in FE result can be stated as machine compliance. The machine compliance can be determined from the test data and FEA data of the specimen CRRT11. A correction can be applied to the load line displacement measurements of other remaining tests, since all the tests have been carried out on the same machine. Kalidindi, Abusafieh and El-Denah [4] have discussed various techniques to determine the machine compliance and their shortcomings and suggested some improvements. Although the correction used in the paper is for compression test yet it has been applied to the specimens subjected to bending, since ultimate effect on the testing machine in both the case is similar. In this paper, second method described in [4] has been incorporated. In this technique, the measured load-displacement relationship for a given specimen (test data) is subtracted from its FE analysis load-displacement relationship to obtain the machine compliance relationship. The machine compliance has been plotted against the load in Figure 20 and a polynomial of order five has been fitted. Machine compliance correction a function of the load $P$ is in kN,

$$\delta = A_5 P^5 + A_4 P^4 + A_3 P^3 + A_2 P^2 + A_1 P + A_0$$

$$A_5 = 0.23093, A_4 = 0.022348, A_3 = -0.0000226,$$

$$A_2 = 1.2886 \times 10^{-3}, A_1 = -3.6018 \times 10^{-6}, A_0 = 3.9869 \times 10^{-16}$$

**(1)**

**Cruciform bend Specimen at subzero temperature and biaxiality ratio unity (CRSZ11)**

The results of the FE analysis for specimen CRSZ11 have been compared with the test data in Figures from 21 to 26. Figure 21 and Figure 22 show the CMOD vs. load curves for test as well as from the FE analysis. CMOD has
been measured at the centre of crack and 80mm left from the center. It is clear from the figure that the FE analysis results slightly differ from the test data. Since test is carried out at very low temperature (-70°C) the data acquired are not smooth. Corrupted CMOD measurement obtained from the CMOD gauges that were not at the center. Loading has been done only up to 3007kN. A correction has been applied to the load line displacement of the test data for the machine compliance as discussed earlier. Figure 23 shows corrected load line displacement vs. Load curves. FE analysis data matches fairly well with the corrected LLD vs. load test data. Figure 24 shows the variation of J-integral with load. \( J_{IC} \) value for 20MnMoNi55 is 100 kJ/m\(^2\) at -70°C. Predicted crack initiation load found to be 2675kN for this case which is lower than the maximum load applied (3007kN). But there is no crack growth detected in this case. Figure 25 and Figure 26 show the variation of load with the maximum principal strain along longitudinal and transverse direction respectively. Finite element analysis data show a good agreement with the test data for these parameters.

![Figure 23 Load line displacement vs. load for specimen CRSZ11.](image)

![Figure 24 J integral vs. load for specimen CRSZ11.](image)

![Figure 25 Maximum principal strain vs. load along the longitudinal arm for specimen CRSZ11.](image)

![Figure 26 Maximum principal strain vs. load along the transverse arm for specimen CRSZ11.](image)

![Figure 27 CMOD vs. Load curves at center for specimen CRSZ21-A.](image)

![Figure 28 CMOD vs. Load curves 80 mm left from the center for specimen CRSZ21-A.](image)

**Cruciform bend Specimen A at subzero temperature and biaxiality ratio two (CRSZ21-A)**

The results of the FE analysis for specimen CRSZ21-A have been compared with the experimental data. Figure 27 and Figure 28 show the CMOD vs. load curves for test as well as from the FE analysis. FE analyses results slightly differ from the test data in Figure 27. Except for gauge at center other two CMOD measurements are very inconsistent. Figure 28 shows one such measurement. Loading has been done only up to 2766 kN. Figure 29 shows corrected load line displacement vs. Load curves. The FE analysis data show a good agreement with the test data. Figure 30 shows the variation of the J-integral with load. Crack initiation load for this case predicted to be 1650kN which is lower than the maximum load. A crack growth of 1.2 mm has been observed in this case. Figure 31 and Figure 32 show the variation of load with the maximum principal strain along longitudinal and transverse direction respectively. Finite element analysis data show a good agreement with the test data for these parameters.
Figure 29 Load line displacement vs. load for specimen CRSZ21-A.

Figure 30 Load vs. J-integral for specimen CRSZ21-A.

Figure 31 Maximum principal strain along longitudinal direction vs. load for CRSZ21-A.

Figure 32 Maximum principal strain along transverse direction vs. load for CRSZ21-A.

Figure 33 CMOD vs. load curves at center for specimen CRSZ21-B.

Figure 34 CMOD vs. load curves at 80mm right from the center for specimen CRSZ21-B.

Figure 35 Load line displacement vs. load curves for specimen CRSZ21-B.

Figure 36 Load vs. \( J \)-integral with load for specimen CRSZ21-B.

Figure 37 Maximum principal strain vs. load for specimen CRSZ21-B.

**Cruciform bend Specimen B at subzero temperature and biaxiality ratio two (CRSZ21-B)**

The results of the FE analysis for specimen CRSZ21-B have been compared with the experimental data. Figure 33 and Figure 34 show the variation of load with CMOD. FE analysis results slightly differ from the test. Except for CMOD measurement at 80mm right from the center all CMOD measurement are inconsistent. Figure 33 shows one such CMOD data. Loading has been done only up to 2805 kN. Figure 35 shows load line displacement vs. load curves. The FE analysis data show a good agreement with the test data. Figure 36 shows the variation of \( J \)-integral with load. Crack initiation load for this case found out to be 1742KN which is less than the maximum load applied (2805kN). A crack growth of 0.2 mm has been observed in this case. Figure 37 and Figure 38 show the variation of load with the maximum principal strain along longitudinal and transverse direction respectively. Finite element analysis data show a good agreement with the test data for these parameters.
Figure 38 CMOD vs. Load curves at center for specimen CRRT10.

Figure 39 Load line displacement vs. Load curves for specimen CRRT10.

Figure 40 Variation load with maximum principal strain for specimen CRRT10.

Figure 41 Variation J integral with load for specimen CRRT10.

Figure 42 CMOD vs. Load curves at center for specimen CRSZ10.

Figure 43 Load line displacement vs. load curves for specimen CRSZ10.

Figure 44 Variation load with maximum principal strain for specimen CRSZ10.

Figure 45 Variation J-integral with load for specimen CRSZ10.

Figure 46 variation of biaxiality ratio with J-integral.

Figure 47 Variation of q ahead of the center of crack-front.

Figure 48 variation of $A_{eq}$ with J-integral.

Figure 49 variation of $A_{eq}$ with in-plane Bending moment.
Biaxiality ratio is ratio of the component of stress along longitudinal direction ($\sigma_{xx}$) to the component of stress along transverse direction ($\sigma_{yy}$). Stresses have been found out by finite element analysis. For cruciform specimens CRRT11 and CRSZ11, biaxiality ratio remains around unity throughout the loading. For cruciform specimens CRSZ21-A and CRSZ21-B, biaxial ratio changes with the load value. The biaxiality ratio remains around two at smaller load. At higher loads, the arms of the cruciform specimen start yielding. The smaller arms (longitudinal direction) takes more load hence they start to yield first and transfer some of the load to the longer arms (transverse arms). On further loading the longer arms also start yielding and biaxiality ratio tend to become unity. The variation of the biaxiality ratio with the $J$-integral is shown in Figure 46 for cruciform specimen CRSZ21-A. Biaxiality ratio remains around two up to $J$-integral value 100 kJ/m$^2$ then it sharply falls and tends to unity. Value of $J_{IC}$ is 100 kJ/m$^2$ at -70°C. A biaxiality ratio of two has been maintained till the onset of the crack-growth for cruciform specimens for the -70°C tests. A biaxiality ratio of two is very difficult to maintain till the onset of crack-growth in a cruciform specimen at room temperature because the value of $J_{IC}$ is very high at room temperature (250 kJ/m$^2$) hence both the specimens for biaxiality ratio two (CRSZ21-A and CRSZ21-B) have been tested at -70°C.

FE analyses for multiaxiality effect comparisons

Cruciform specimens, which have been tested, do not have exactly identical core geometry. The uniaxial specimens do not have the weld joints and they are made up of single material (20MnMoNi55). Its core is also different from the core of cruciform specimen for biaxial testing. It has longer crack length (430mm) and shallower crack depth (20mm) and do not have the slots in transverse direction. There is small difference in crack depth even among cores of the cruciform specimens for biaxial testing. Comparison of results of FE analyses for these specimens will be inconclusive. The FE models have already shown good agreement with the test data, which validates the FE model. To have a meaningful comparison, FE analyses have been performed on specimens having identical core geometry and material properties. Three FE models of cruciform specimens with identical cores (i.e. thickness of cores, crack lengths, crack depths and slot configuration are kept the same) have been analyzed. Material of arms is also kept the same for all models. First model, CRFE21 (FE stands for Finite Element), has the arm lengths similar to the specimen CRSZ21-A to get a biaxiality ratio 2:1. Second model, CRFE11, has the arm lengths similar to CRSZ11 to get a biaxiality ratio 1:1. Third model, CRFE10 has arm lengths similar to CRSZ10 to get the uniaxial state of stress across the crack front. All the models of cruciform specimen (i.e. CRFE21, CRFE11 and CRFE10) have identical cores containing crack 320mm of length and 20mm of depth.

There are several parameters to quantify the crack tip constraint/stress triaxiality, such as the $T$-stress [7], $Q$-parameter [8], the multi-axiality quotient ($q$) [5], $A_2$ parameter [9], etc. In this paper, the multi-axiality quotient ($q$) is used as a measure of stress triaxiality. Multi-axiality quotient $q$ [5] is defined as ratio of equivalent stress to $\sqrt{3}$ times the hydrostatic stress as in Equation 2.
Where \( q \) is the multiaxiality quotient, \( \sigma_n \) is the hydrostatic stress and \( \sigma_1, \sigma_2 \) and \( \sigma_3 \) are the principal stresses. Multi-axiality quotient \( q \) defines the level of constraints ahead the crack tip. Small values of \( q \) calculated from this definition indicate high degree of multiaxiality. For \( q \) values at constant low level \( (q \sim 0.27) \) only very little or no stable crack extension can be expected [6]. Values of \( q \) can be calculated from finite element analysis results. The variation of \( q \) along the remaining ligament ahead of the center of crack front has been plotted at the onset of the crack growth for all three FE models in Figure 47. These calculations for \( q \) have been carried out when the value of applied \( J \)-integral is near \( J_{IC} \) (100 kJ/m\(^2\)) for all the cases. It can be seen that the values of \( q \) corresponding to the CRFE11 are minimum among the three while the values of \( q \) corresponding to the uniaxial case CRFE10 are maximum throughout the length. Values of \( q \) corresponding model CRFE21 are falling in between. It can be concluded that the crack front of CRFE11 (biaxiality ratio is 1:1) is the most constrain and crack front of CRFE10 is the least constrained. Microstructurally significant distance is the region between \( \frac{(\sigma_1-\sigma_2)^2+(\sigma_2-\sigma_3)^2+(\sigma_3-\sigma_1)^2}{\sigma_1+\sigma_2+\sigma_3} \) and \( \frac{(\sigma_1-\sigma_2)^2+(\sigma_2-\sigma_3)^2+(\sigma_3-\sigma_1)^2}{5\sigma_1+5\sigma_2+5\sigma_3} \) to \( \frac{(\sigma_1-\sigma_2)^2+(\sigma_2-\sigma_3)^2+(\sigma_3-\sigma_1)^2}{5\sigma_1+5\sigma_2+5\sigma_3} \).

\[
q = \frac{\sigma}{\sqrt{3}\sigma_n}
\]

\[
\sigma_n = \frac{\sigma_1 + \sigma_2 + \sigma_3}{3}
\]

\[
\sigma = \frac{1}{\sqrt{2}} \sqrt{(\sigma_1-\sigma_2)^2+(\sigma_2-\sigma_3)^2+(\sigma_3-\sigma_1)^2}
\]

Figure 50 Variation of in-plane bending moment CMOD.

A similar trend can be seen for values of \( A_{nq} \) corresponding to the three models as seen in the previous Figure. The line corresponding to \( J \)-integral value of 100N/mm intersects the curve for CRFE11 (biaxiality ratio 1:1) then it intersects the curve for CRFE21 (biaxiality ratio 2:1) and at last it intersects the curve for CRFE10 (biaxiality ratio 1:0). So it can be concluded that the in-plane bending moment required to start crack extension is lowest (661.3kN.m) in the least constrained specimen (CRFE11) and it is highest (693.3kN.m) for the most constrained specimen (CRFE11). Figure 50 shows the variation of the in-plane bending moment with CMOD. Values of the in-plane bending moment is the lowest for the most constrained specimen CRFE11 (biaxiality ratio 1:1) and it is highest for the least constrained specimen CRFE10 (biaxiality ratio 1:0) for all the values of CMOD. Curve for in-plane bending moment for CRFE21 (biaxiality ratio 2:1) lie in between the two curves. Initially its nature is similar to a uniaxial specimen but after a certain value of CMOD (~ 0.7) its nature starts to differ and the curve shifts towards the curve for CRFE11 (biaxiality ratio 1:1).
CONCLUSIONS

Six numbers of cruciform specimens have been tested at -70°C and room temperature with a biaxiality ratio 1:0, 2:1 and 1:1. Detailed 3D finite element analyses have been carried out for all the cases and various data such as CMOD, LLD, J-integral, strains along various directions have been computed. Finite element analyses results show a good agreement with the test data for most of the cases. It has been shown clearly by the FE analyses performed on three models CRFE11, CRFE21 and CRFE10 (with identical core geometry and similar arm lengths as in specimens CRSZ11, CRSZ21A, and CRSZ10) that crack-front is most constrained in model CRFE11 with the biaxiality ratio 1:1 and the crack-front is least constrained for uniaxial model CRFE10 with help of multiaxiality quotient $q$ and $A_{nr}$.

Constraint level across the crack-front of the model CRFE21 with biaxiality ratio 2:1 is found to lie between the two extremes. It has also been shown that the in-plane bending moment required for extension of crack is lowest for most constrained model (CRFE11) with biaxiality ratio 1:1 and it is highest for least constrained model (CRFE10) with biaxiality ratio 1:0.

REFERENCES