



Fracture strength evaluation of AA 2219-T87 weldment using SINTAP and modified IFM procedures

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Abstract: Fracture data of parent and weld metals obtained from tensile surface cracked AA2219-T87 plates are correlated using a modified inherent flaw model. Fracture parameters are evaluated to generate the failure assessment diagram of the material useful in failure assessment of cracked components. Failure assessment diagrams are generated employing SINTAP Level-3 defect assessment procedure. A comparative study is made on the tensile fracture strength evaluation of AA2219-T87 cracked configurations utilizing both the approaches.

Keywords: Centre through crack, centre surface crack, Equivalent through crack, Failure assessment diagram, Fracture strength.

Nomenclature

a	Crack depth	Lr	Ratio of applied stress to yield stress
a_{ci}	Damage zone size	M	Mismatch factor at yield stress
c	Half crack length	t	Specimen thickness
$2c_{eq}$	Equivalent through crack length for surface crack	W	Specimen width
E	Young's modulus	Y	Finite width correction factor
F	Applied force	σ	Applied far field stress
F_{YB}	Yield load of base material	σ_f	Failure stress
F_{YM}	Yield load of mismatch configuration	σ_{NC}^{∞}	Fracture strength of a wide specimen
$2h$	Total width of weld	σ_{NC}	Fracture strength of finite width specimen
K_c	Critical Stress Intensity Factor	σ_0	Ultimate tensile strength (unnotched strength)
K_{IC}	Plane strain fracture toughness	ψ	Normalized remaining ligament
K_{IFM}, δ_{aci}	Fracture parameters in equation (1)		
$K_Q (\equiv \sigma_{NC}^{\infty} \sqrt{\pi c})$	Parameter in Failure assessment diagram		
K_{mat}	Material constant		
Kr	Ratio of the applied linear elastic stress intensity factor to Material constant K_{mat}		

I. Introduction

Fracture and yielding are the two types of failure criteria recognized in aerospace applications. Failure due to yielding is applied to a criterion in which some functional of the stress or strain is exceeded and fracture is applied to a criterion in which an already existing crack extends according to an energy balance hypothesis. Experimentation with a variety of materials would show that the theory works well for certain materials but not for others. The safety assessment of structures without a fracture mechanics analysis is insufficient and may cause an unexpected reduction in the load carrying capacity of an actual structure due to the presence of unavoidable crack-like defects not being taken into consideration. The extraordinary success of fracture mechanics lies in its ability to combine a theoretical framework with experimentally measured critical quantities.

When dealing with a specific material for a particular application, it is not clearly established whether K_{IC} (plane strain fracture toughness) or K_c (fracture toughness when plane strain conditions are not met) values should be used. The values of K_{IC} seem to be relevant in heavy sections like forgings or thick plates. Design based on K_{IC} requires unreasonably thick panels in normally thin-sectioned structural members as in aerospace industry.

In such circumstances it is necessary to carry out what is called K_c tests as per ASTM-E561 standards, corresponding to the thickness of the members in the intended structural applications. The geometry dependent values of K_c can be determined from the point of tangency between the crack growth resistance curve (R-curve) and the crack driving force curve of a through-cracked configuration. For part through cracked configuration, fracture strength estimations are not possible directly from the R-curve of the material because the part through crack has two dimensions namely, crack length and its depth. Though the concept of R-curves has been adopted to characterize stable crack extension and predict residual strength of thin-walled structures particularly in the aircraft industry, ASTM E561 yields R-curves in terms of the stress intensity factor as a function of the “effective” crack length. The new ASTM E2472 addresses the determination of resistance to stable crack extension under low constraint conditions in terms of crack-tip opening displacement (CTOD) and crack-tip opening angle (CTOA).

II. Modified Inherent Flaw Model

The significant parameters affecting the size of a critical crack in a structure are the applied stress levels, the fracture toughness of the material, the location of the crack and its orientations. Since the intensity of the stress at the crack tip, K is a function of load, geometry and crack size, it is more appropriate to have a relationship between the critical stress intensity factor at failure and the failure stress from the fracture data of cracked specimens for the estimation/prediction of the fracture strength to any cracked configuration. For cracked configurations, a relation between the critical stress intensity factor (K_Q) and the corresponding stress (σ_{NC}^∞) at failure is obtained from modified inherent flaw model (IFM) as [1]-[2]:

$$K_Q = K_{IFM} \left\{ 1 - \delta_{aci} \frac{\sigma_{NC}^\infty}{\sigma_0} \right\} \sqrt{1 - \left(\frac{\sigma_{NC}^\infty}{\sigma_0} \right)^2} \quad (1)$$

Where, σ_{NC}^∞ is the failure stress normal to the direction of the crack in a wide specimen and σ_0 is the ultimate stress of the material. Equation (1) represents a failure assessment diagram useful for fracture strength evaluation of different cracked configurations. The fracture Strength (σ_{NC}^∞) of the center crack wide tensile specimen is obtained from that of a finite width specimen (σ_{NC}) as

$$\sigma_{NC}^\infty = \sigma_{NC} Y \quad (2)$$

Where the finite width correction factor [3] is,

$$Y = \sqrt{\sec\left(\frac{\pi c}{W}\right)} \quad (3)$$

Where ‘c’ is half the crack length and W is the specimen width.

For the determination of two fracture parameters (K_{IFM} and δ_{aci}), test results of simple laboratory specimens like compact tension specimens, center crack specimens etc. can be utilized. For fracture strength evaluation of any other structural configuration, the stress intensity factor corresponding to that geometry is to be used in (1) to develop the necessary fracture strength equation. If the values of applied stress and corresponding stress intensity factor for the specified crack size in a structure lie below the $K_Q - \sigma_{NC}^\infty$ curve of the failure assessment diagram, the structure for that loading condition is safe. This article considers fracture data of AA2219-T87 useful in aircraft applications [4] and demonstrates the adequacy of the modified IFM approach as well as the SINTAP Level-3 defect assessment procedure in the tensile fracture strength evaluation of cracked configurations. The modified IFM approach is found to be simple and includes mismatch effect (if any) in the fracture parameters (K_{IFM} and δ_{aci}).

III. Equivalent through crack

Equivalent through crack size for the given part-through crack size can be evaluated, by equating stress intensity factors of both the specimens using Newman’s finite element solutions [5]-[6].

$$K_c = \sigma_f (\pi a)^{\frac{1}{2}} \frac{M_0}{\phi} \quad (4)$$

Where,

$$M_0 = \left[M_1 + \left\{ \phi \sqrt{\frac{c}{a}} - M_1 \right\} \left(\frac{a}{t} \right)^{\sqrt{\pi}} + \phi \sqrt{\frac{c}{a}} (M_2 - 1) \left(\frac{a}{t} \right)^{2\sqrt{\pi}} \right] f_w$$

$$\phi^2 = 1 + 1.464(a/c)^{1.65} \quad \text{for } a \leq c$$

$$\phi^2 = 1 + 1.464(c/a)^{1.65} \quad \text{for } a > c$$

$$M_1 = 1.13 - 0.1(a/c) \quad \text{for } a \leq c$$

$$M_1 = \{1 + 0.03(c/a)\}(c/a)^{1/2} \quad \text{for } a > c$$

$$M_2 = (\pi/4)^{1/2} \quad \text{for } a \leq c$$

$$M_2 = 1 + (c/a)\{(\pi/4)^{1/2} - 1\} \quad \text{for } a > c$$

$$f_w = \sqrt{\sec \left\{ \left(\frac{\pi c}{W} \right) \left(\frac{a}{t} \right)^{1/2} \right\}}$$

Here a is the depth and c is half the crack length of a surface crack and W is the width of the plate. When $a = t$, the expression holds well for through crack. The Nomo gram [7] shown in Fig.1 is useful to find out $2c_{eq}$ from $2c$.

IV. Application of SINTAP

The SINTAP provides different Levels of complexity, which can be used depending upon the quality and detail of the input data available. Level 3 assessment is applicable to strength mismatched structures. Strength mismatch factor M , is defined as the ratio of the yield strength of the weld metal to that of the base material.

In the present SINTAP Level 3 analysis, two cases are considered. In case (a) 'Crack in Base Metal only' is considered. In case (b) 'Crack in Weld Metal only' is considered. In both the cases, Mismatch factor is assumed as 0.95 since the material under consideration, Aluminium 2219-T87 alloy is a homogeneous material. The Material Properties and Input Data for SINTAP are given in the table (1) and (2) for case (a) and case (b) respectively. The results are shown in table 3 and table 4 respectively. The SINTAP Level-3 analysis is performed using the equations described in SINTAP procedures [9]. SINTAP Level 3 analysis requires full stress-strain data to determine the stress-strain curve for the equivalent material. When full stress-strain data for both materials available, $f(L_r)$ is defined as

$$f(L_r) = \left(\frac{E \varepsilon_e}{\sigma_e} + \frac{L_r^2 \sigma_e}{2E \varepsilon_e} \right)^{-\frac{1}{2}} \quad (5)$$

In Equation (5), ε_e is the true strain obtained from the uniaxial stress-strain curve for the equivalent material at a true stress σ_e . The stress-strain curve for the equivalent material can be determined from the tensile data of the base and weld material as

$$\sigma_e(\varepsilon^p) = \frac{(F_{YM}/F_{YB} - 1)\sigma_w(\varepsilon^p) + (M - F_{YM}/F_{YB})\sigma_B(\varepsilon^p)}{(M - 1)} \quad (6)$$

It should be noted that the strength mismatch M , in Equation (6) is defined not only at the yield stress (0.2% plastic strain) but also at a number of different plastic strain values ε^p

$$M(\varepsilon^p) = \frac{\sigma_w(\varepsilon^p)}{\sigma_B(\varepsilon^p)} \quad (7)$$

and $\frac{F_{YM}}{F_{YB}}$ should be found for those values of M . This gives a contrast to the SINTAP Level 2 equations where the values of M and $\frac{F_{YM}}{F_{YB}}$ are defined at the yield stress. The equivalent yield stress σ_{Ye} , the flow stress $\bar{\sigma}_e$ and the cut off $L_r^{\max}$ are defined as

$$\sigma_{Ye} = \frac{F_{YM}}{F_{YB}} \sigma_{YB}, \quad \bar{\sigma}_e = \frac{F_{YM}(\bar{\epsilon}^p)}{F_{YB}} \sigma_B(\bar{\epsilon}^p), \quad L_r^{\max} = \frac{\bar{\sigma}_e}{\sigma_{Ye}} \quad (8)$$

V. Material curve generation

The True stress – strain curves of AA 2219-T87 base metal and weld metal are essential to draw the stress-strain curve of the equivalent material. Hence they are drawn using inverse of Ram berg Osgood relation [8] given by the Equation (9).

$$\sigma = \frac{E\epsilon}{\left\{1 + \left(\frac{\epsilon}{\epsilon_0}\right)^n\right\}^{1/n}} \quad (9)$$

Where $\epsilon_0 = \frac{\sigma_0}{E}$ and $n = 2.76$ for base metal and 3.3 for weld metal respectively. The material constant ‘n’ is a parameter defining the shape of the non-linear stress-strain relationship. Once the material parameters n and ϵ_0 are available, a continuous smooth material curve can be generated by substituting in Equation (9). The stress-strain curve of the equivalent material is drawn using Equation (6). Fig.2 shows the True stress – strain curves generated for AA2219-T87 with crack in base metal only. Similarly Fig.3 shows the True stress – strain curves generated for AA2219-T87 with crack in weld metal only.

A. Evaluation of the material constant (K_{mat})

The material constant K_{mat} is required to plot the test results in the SINTAP failure assessment diagram and to evaluate the stress intensity factor K_I for any applied load from the SINTAP failure assessment diagram. The equation to evaluate material constant K_{mat} is derived as follows. The ordinate of any SINTAP failure assessment diagram is given by

$$\frac{K_I}{K_{mat}} = f(L_r) \quad (10)$$

For the failure load of the cracked configurations, the K_I in the above relation becomes the critical stress intensity factor (K_c). When $K_I = K_c$, the above Equation (10) becomes $\frac{K_c}{K_{mat}} = f(L_r)$ and

$$\text{Let the error } E = \sum_{i=1}^n \{K_{ci} - K_{mat} f(L_r)_i\}^2$$

Where n = number of test specimens. Partially differentiating the error equation with respect to K_{mat} and equating to zero in order to minimize error, we get

$$K_{mat} = \frac{\sum_{i=1}^n f(L_r)_i K_{ci}}{\sum_{i=1}^n f(L_r)_i^2} \quad (11)$$

Where $L_r = \frac{F}{F_{YM}}$ and K_c = Critical Stress Intensity Factor calculated from experimental data [4]. The

critical stress intensity factor K_c for centre surface crack tension (SCT) specimens is calculated from equation (4).

B. Evaluation of mismatch yield load

The mismatch yield load F_{YM} is calculated from expressions suggested [10] - [11]. Under Plane stress condition, for crack in the centre line of the weld metal

Under matching ($M < 1$)

Under Plane stress condition, for crack in the centre line of the weld metal

$$\frac{F_{YM}}{F_{YB}} = M \quad \text{for } 0 \leq \psi \leq 1.43 \quad (12)$$

$$\frac{F_{YM}}{F_{YB}} = \min\left\{\frac{F_{YM}^{(1)}}{F_{YB}}, \frac{F_{YM}^{(2)}}{F_{YB}}\right\} \quad \text{for } 1.43 \leq \psi \quad (13)$$

$$\frac{F_{YM}^{(1)}}{F_{YB}} = M \left[\frac{2}{\sqrt{3}} - \left(\frac{2 - \sqrt{3}}{\sqrt{3}} \right) \frac{1.43}{\psi} \right] \quad (14)$$

$$\frac{F_{YM}^{(2)}}{F_{YB}} = 1 - (1 - M) \frac{1.43}{\psi} \quad \text{Where } \psi = (W - 2c) / 2h \quad (15)$$

Under Plane stress condition, for crack in the base metal

$$\frac{F_{YM}}{F_{YB}} = M \left[1.095 - 0.095 \exp\left\{-\frac{1 - M}{0.0108M}\right\} \right] \quad \text{for } M < 1 \quad (16)$$

VI. Results and Discussion

Fracture analysis has been carried out considering the ultimate tensile strength values and the fracture data of AA2219-T87 (base metal and weld metal) generated from center-crack tensile specimens having different thicknesses. Table 3 gives the comparison of fracture strength estimations with the test results, using SINTAP, for AA2219-T87 base metal at temperature 295 K for $t=16$ mm. Similarly Table 4 gives the comparison of fracture strength estimations with the test results, for AA2219-T87 weld metal at temperature 77 K for $t=25$ mm. Table 5 gives the comparison of fracture strength estimations with the test results, using modified IFM approach, for AA 2219-T87 base metal at temperature 295 K for $t=16$ mm. Similarly Table 6 gives the comparison of fracture strength estimations with the test results, for AA 2219-T87 weld metal at temperature 77 K for $t=25$ mm. The standard error is found to be less than 0.1 following modified IFM and SINTAP approaches. This trend indicates that these approaches provide the fracture strength estimations within $\pm 10\%$ of the test results. Fig. 4 and 5 indicate the closeness with which the fracture data have been correlated using the modified Inherent Flaw Model. Failure assessment diagrams are used as a ready reference chart to verify whether the design point is in safe region or not. Fig. 6 shows the failure assessment diagram using SINTAP, including the fracture data [4] of the material for Aluminium 2219-T87 base metal at temperature 295K for $t=16$ mm. Fig. 7 shows the failure assessment diagram using SINTAP, including the fracture data [4] of the material for Aluminium 2219-T87 weld metal at temperature 77 K for $t = 25$ mm. It can be seen from Fig.8 and Fig.9 that most of the fracture strength estimations are below $\pm 10\%$ of the test results. There is no appreciable difference in standard errors in the fracture strength estimations utilizing the SINTAP and the modified IFM. However, the modified IFM approach is quite simple to use.

VII. Concluding Remarks

In this paper, SINTAP Level 3 assessment procedure has been used to evaluate fracture strength of AA 2219-T87 base metal and weld metal which are homogeneous metals with the assumption of $M = 0.95$, and failure assessment diagrams are drawn. Similarly FAD is drawn using the modified inherent flaw model. There is no need to consider separately the mismatch effect in the modified IFM approach because the two fracture parameters (K_{IFM} and δ_{aci}) take into account such mismatch effects of the weld (if any). The procedure is validated considering the fracture data of AA2219-T87 center surface crack tension specimens. Failure assessment diagrams showed that the fracture data were closer to the failure boundary. On comparing both failure assessment diagrams, it is found that the standard error (percentage) in SINTAP and the modified IFM approach is almost equal. Hence, the modified IFM approach provides reasonably accurate fracture strength predictions for homogeneous metals.

References

- [1] A.Subhananda Rao, G. Venkata Rao, and B.Nageswara Rao, "Generation and validation of failure assessment diagrams for notched strength prediction of solid propellant tensile specimens", Mater. Sci. Technol., Vol.21, No. 4, 2005, pp. 488-494.
- [2] S.Rajakumar . and Christopher, T. "Generation and Validation of Failure Assessment Diagrams for High Strength Alloys Utilizing the Inherent Flaw Model" Material Science Research Journal, Vol. 4, 2010, pp.01-14.

- [3] Y.Murakami , Stress intensity factors handbook, New York, Pergamon, 1987.
- [4] G.C.Sih , Handbook of Stress Intensity Factors. Lehigh University, Pennsylvania, 1973.
- [5] J.C.Newman Jr and I.S.Raju , “Analysis of surface cracks under tension or bending loads”.1979; NASA-TP-1578.
- [6] Newman Jr JC. Fracture analysis of surface and through cracks in cylindrical pressure vessels.1976; NASA-TND-8325.
- [7] S.Rajakumar and T.Christopher,. “Fracture strength of centre surface cracked tensile specimens made of Aluminium 2219-T87 alloy welding “Transactions of Nonferrous Metals”, Society of China, Vol.21, 2011, pp.2568-2575.
- [8] A.P.Beena , M.K. Sundaresan , and B. Nageswara Rao, “Destructive tests of 15CDV6 steel rocket motor cases and their application in light weight design”, International Journal of Pressure Vessels and Piping, 1995;62: 313-320.
- [9] Yun-Jae Kim et.al. SINTAP defect assessment procedure for strength mismatched structures.Engng.Frac.Mech.2000; 67:529-546
- [10] SINTAP: Structural Integrity Assessment Procedure for European Industry. Final Procedure, 1999, Brite-Euram Project No. BE95- 1426, British Steel.
- [11] S.AL.Laham, Stress intensity factor and limit load factor Hand book. Issue 2, British Energy Generation Ltd, 1998.

Table-1: The Material Properties and Input Data for SINTAP Level 3 Case (a): Crack in Base Metal only

Aluminium2219-T87 alloy
Ultimate strength = 477.1 MPa Yield strength = 386.81 MPa Young's Modulus = 66900MPa The mismatch yield load = 380.95MPa Material constant, <i>Kmat</i> = 68.32 MPa√m Temperature = 295 K Inverse Ram berg Osgood Relation Exponent <i>n</i> = 2.76

Table-2: The Material Properties and Input Data for SINTAP Level 3Case (b): Crack in Weld Metal only

Aluminium2219-T87 alloy
Ultimate strength = 379.2 MPa Yield strength = 224.09 MPa Young's Modulus = 6760 MPa The mismatch yield load = 234.90MPa Material constant, <i>Kmat</i> = 57.55 MPa√m Temperature = 77 K Total width of weld = 20 mm Inverse Ram berg Osgood Relation Exponent <i>n</i> = 3.3

Table-3: Comparison between experimental and SINTAP fracture strength for Aluminium 2219-T87 base metal

$$\sigma_y = 386.81 \text{ MPa, } t = 16 \text{ mm. } M = 0.95, \text{ Level 3}$$

Specimen Dimensions (mm)				Fracture Strength, σ_{NC} , MPa		
Width, W	Thickness t	Crack Depth a	Crack length, 2c	Test [4]	SINTAP Analysis	Relative Error (%)
Temperature: 295K						
228.5	16.3	7.52	61.00	291.0	268.21	7.8
558.9	16.3	15.24	145.41	148.9	147.00	1.3
139.8	15.9	6.88	16.61	373.0	399.88	-7.2
171.4	16.3	6.07	15.27	379.2	419.26	-10.6
139.7	16.3	8.61	23.42	331.0	346.07	-4.6
139.8	15.9	9.19	24.41	335.1	332.15	0.9
171.4	15.9	9.91	29.21	323.4	303.23	6.2
Standard error = 0.06						

Table-4: Comparison between experimental and SINTAP fracture strength for Aluminium 2219-T87 weld metal
 $\sigma_y = 224.09$ MPa, $t = 25$ mm. $M=0.95$, Level 3

Specimen Dimensions (mm)				Fracture Strength, σ_{NC} , MPa		Relative Error (%)
Width, W	Thickness t	Crack Depth a	Crack length, 2c	Test [4]	SINTAP Analysis	
Temperature: 77 K						
507.3	25.6	11.86	84.58	169.6	173.22	-2.1
609.7	25.9	18.03	107.82	136.5	148.85	-9.1
342.6	25.6	17.86	60.30	174.4	163.62	6.2
406.7	20.0	19.99	65.63	148.9	159.01	-6.8
406.4	25.6	21.36	71.93	168.2	147.50	12.3
Standard error = 0.08						

Table-5: Comparison between experimental and analytical fracture strength for Aluminium 2219-T87 base metal $\sigma_0 = 477.1$ MPa, $t = 16$ mm. ($K_{IFM} = 79.28$ MPa $\sqrt{m}$, $\delta_{aci} = 0.00$)

Specimen Dimensions (mm)					Fracture Strength, σ_{NC} , MPa		Relative Error (%)
Width, W	Thickness t	Crack Depth a	Crack length, 2c	Eq.Crack length, 2c _{eq}	Test [4]	IFM Analysis	
Temperature: 295K							
228.5	16.3	7.52	61.00	30.5	291.0	285.2	2.0
558.9	16.3	15.24	145.41	133.3	148.9	156.9	-5.4
139.8	15.9	6.88	16.61	11.1	373.0	371.6	0.4
171.4	16.3	6.07	15.27	9.8	379.2	380.9	-0.5
139.7	16.3	8.61	23.42	16.7	331.0	338.4	-2.2
139.8	15.9	9.19	24.41	18.0	335.1	331.5	1.1
171.4	15.9	9.91	29.21	22.2	323.4	313.6	3.0
Standard error = 0.03							

Table-6: Comparison between experimental and analytical fracture strength for Aluminium 2219-T87 weld metal

$\sigma_0 = 379.2$ MPa, $t = 25$ mm. ($K_{IFM} = 54.08$ MPa $\sqrt{m}$, $\delta_{aci} = 0.00$)

Specimen Dimensions (mm)					Fracture Strength, σ_{NC} , MPa		Relative Error (%)
Width, W	Thickness t	Crack Depth a	Crack length, 2c	Eq.Crack length, 2c _{eq}	Test [4]	IFM Analysis	
Temperature: 77K							
507.3	25.6	11.86	84.58	44.4	169.6	179.1	-5.6
609.7	25.9	18.03	107.82	78.0	136.5	141.4	-3.6
342.6	25.6	17.86	60.3	47.9	174.4	172.6	1.1
406.7	20.0	19.99	65.63	65.6	148.9	151.3	-1.6
406.4	25.6	21.36	71.93	63.5	168.2	153.5	8.8
Standard error = 0.05							

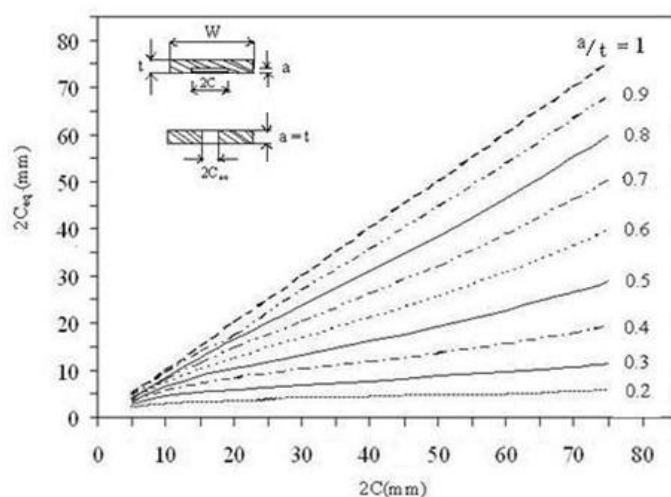


Fig.1: Nomo gram for equivalent through crack

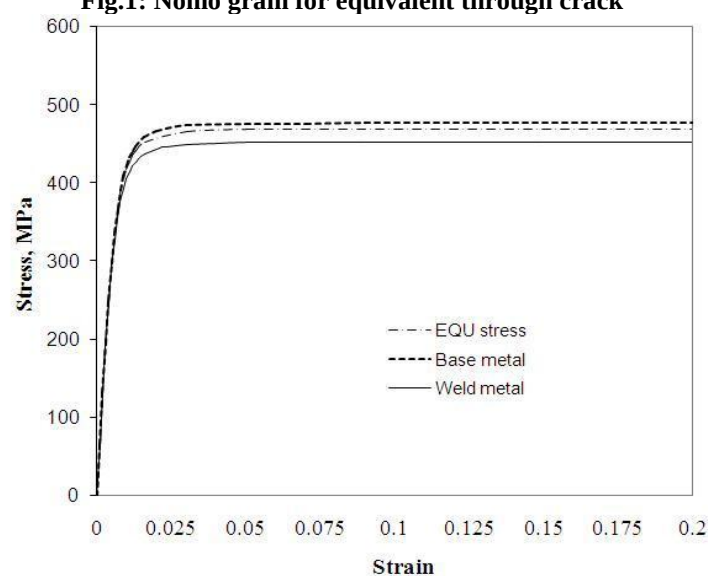


Fig. 2: True stress –True strain curves for Aluminium 2219-T87 alloy (crack in base metal) used in SINTAP Level 3

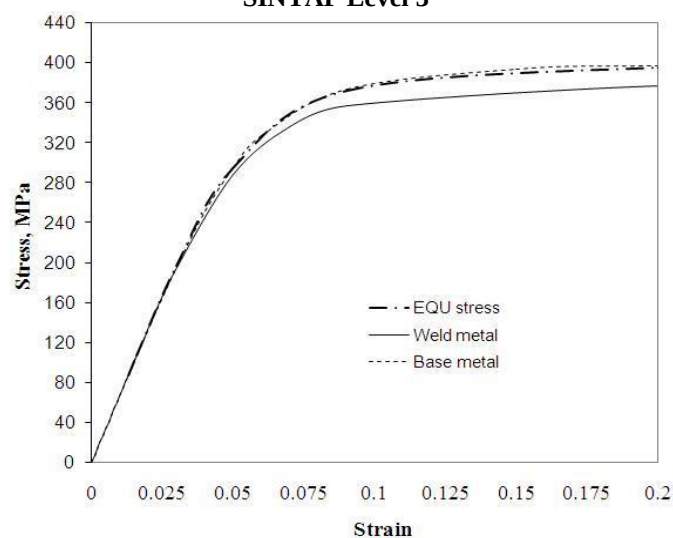


Fig. 3: True stress –True strain curves for Aluminium 2219-T87 alloy (crack in weld metal) used in SINTAP Level 3

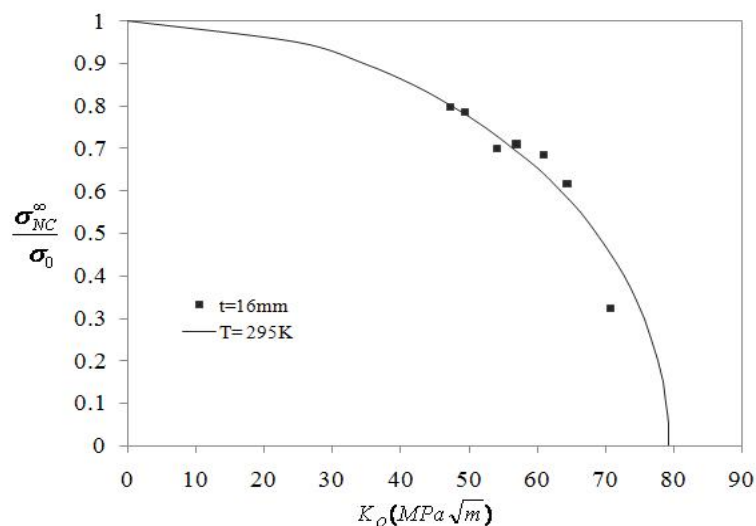


**Fig. 4: Failure assessment diagram for Aluminium 2219-T87 base metal with Test data[4] . $K_{IFM}= 79.28M$
 $Pa\sqrt{m}$, $\delta_{aci}=0.00$**

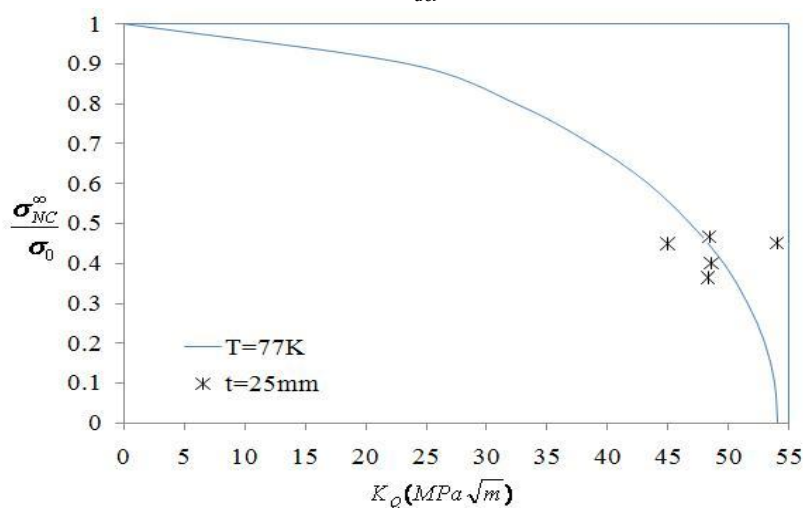


**Fig. 5: Failure assessment diagrams for Aluminium 2219-T87 weld metal with Test data[4] . $K_{IFM}= 54.08$
 $M Pa\sqrt{m}$, $\delta_{aci}=0.00$**

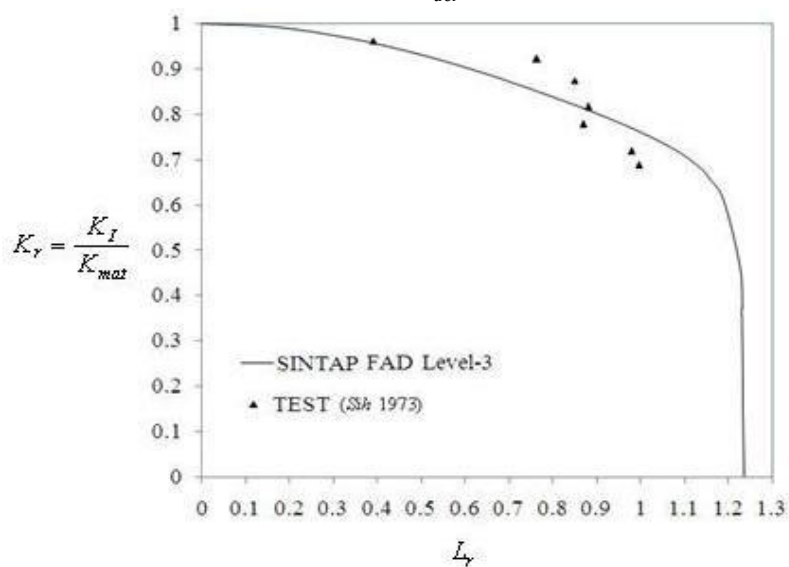


**Fig. 6: Failure assessment diagram for Aluminium 2219-T87 base metal with Test data[4] using SINTAP
Level 3. $M = 0.95$**

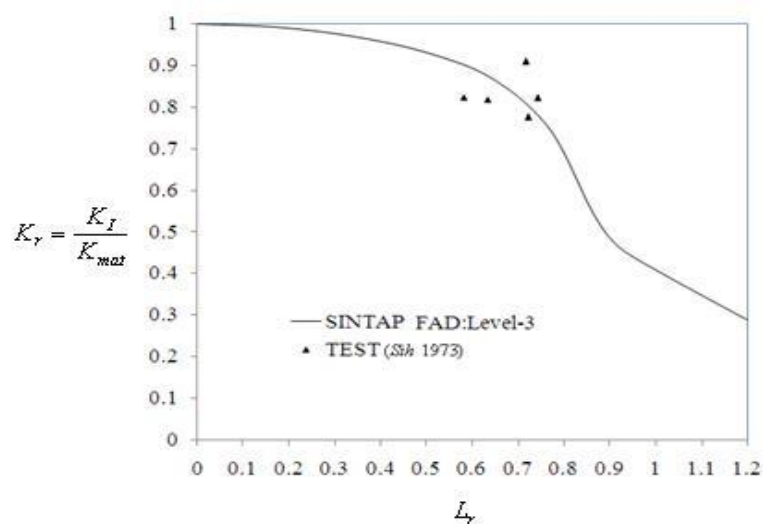


Fig. 7: Failure assessment diagram for Aluminium 2219-T87 weld metal with Test data[4] using SINTAP Level 3, $M = 0.95$.

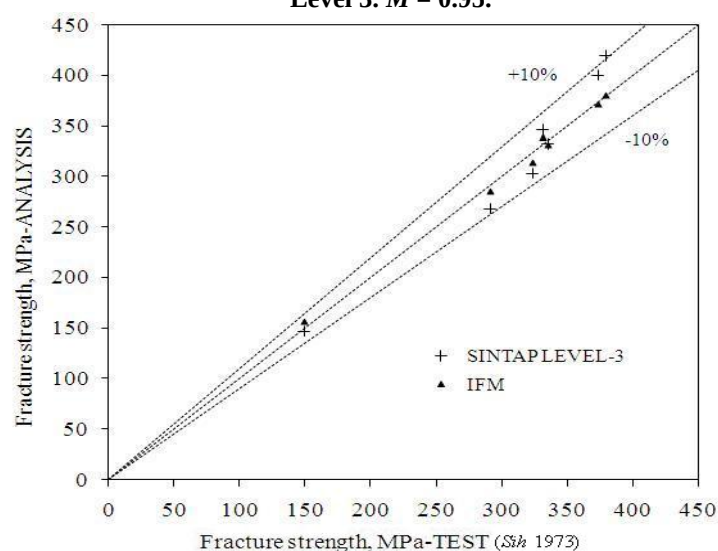


Fig. 8: Comparison of fracture strength of Aluminium 2219-T87 base metal with SINTAP Level 3

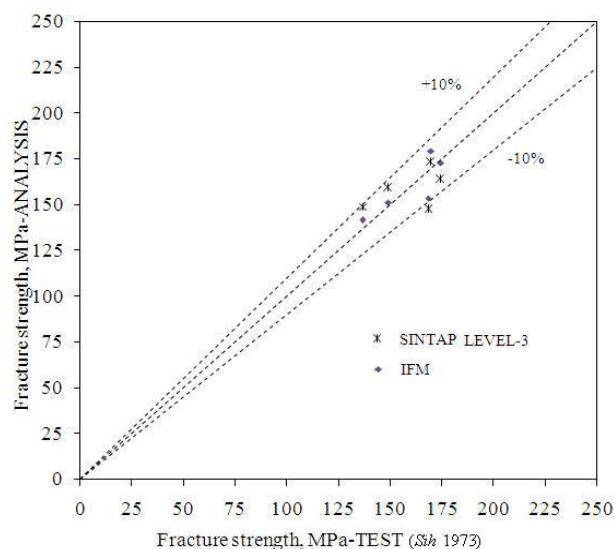


Fig. 9: Comparison of fracture strength of Aluminium 2219-T87 weld metal with SINTAP Level 3