J-integral evaluation and structural integrity assessment using FAD for SA 312 Type 304 LN steel welded pipes with notch under monotonic loading

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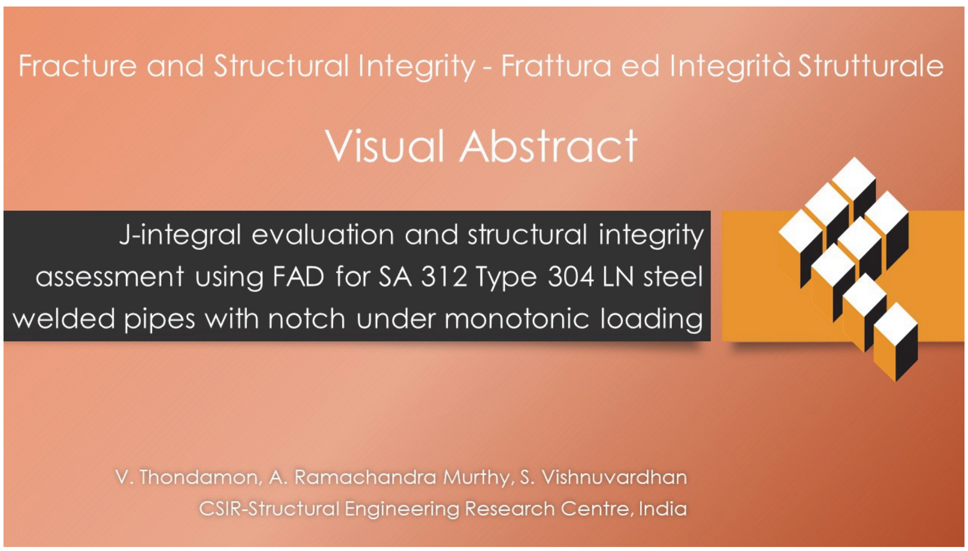

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INTRODUCTION

Failure assessment diagram (FAD) is used for assessing the structural integrity of a component containing defect subjected to a specified loading. It provides a means to study the interaction between plastic capacity utilization and fracture resistance of the structural component under study. Failure assessment diagram approach requires construction of a plot between fracture ratio (K_r) and load ratio (L_r). Fig. 1 shows a typical FAD. Load ratio is the ratio of the applied bending moment to the capacity i.e., the limit load moment of the structural component. Fracture ratio is the ratio of the applied stress intensity factor to the initiation fracture toughness of the material or fracture resistance. The comparison of the crack tip driving force with the fracture toughness of the material or fracture resistance and the applied load with the limit load moment are performed simultaneously. Assessment points of coordinates (L_r, K_r) are determined for the loading conditions (for particular load, material properties and crack size), and these assessment points are then plotted in the FAD and compared with the failure assessment line. If the plotted point lies within the region between the failure assessment line and both the axes of the FAD, then the component is considered as acceptable under given assessment conditions.

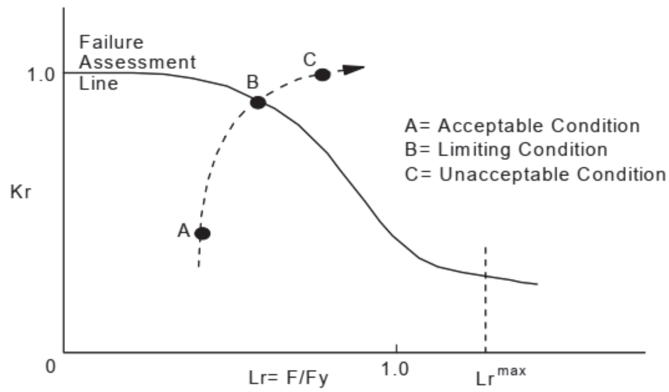

Figure 1: Typical Failure Assessment Diagram (FAD) [1].

Piping components of the nuclear power plant are generally made of high toughness low alloy steels such as stainless steels that are resistant to unstable defect growth. Stainless steel SA312 Type 304 LN is the most commonly used material in the nuclear power plant industry. Weld being a low ductile material, contribute significantly to the fracture process and higher stresses at crack tip as well due to residual stress. FAD is a standardized process for structural assessment which considers the possibility of failure by combination of plastic collapse as well as fracture. The stability of through-wall crack can be determined by use of FAD which does not involve rigorous non-linear fracture mechanics approach. The primary modes of failure associated with defects on a structural component are plastic collapse and brittle failure. Parameters such as geometry of the structural component, crack size and orientation and material properties govern the FAD. For assessing the safety and integrity of cracked and damaged metallic structures, FAD is widely used. Failure assessment diagram represents an interaction between plastic-collapse failure and fracture mechanics. The assessment point inside the failure assessment line indicate that the crack is acceptable, and the assessment point above the failure assessment line is an unacceptable crack that indicates a predicted structural failure. Assessment point located on the failure assessment line indicates a critical crack length for a given load or critical load for a stationary crack [2-11]. For the evaluation of assessment points, Ainsworth et al. [12] utilized the initiation fracture toughness of the material for fracture resistance and considered the load value at the crack initiation point. Effective fracture toughness values obtained from the J-R curves and the limit load moment, representing the resistance to fracture and notch driving force respectively were derived and used for assessment on the FAD [13].

In the present study, structural integrity assessment of three welded pipe specimens of SA 312 Type 304 LN steel containing circumferential through-wall notch under monotonic loading has been carried out using FAD. For evaluating limit load moment, analytical expressions proposed by Zahoor [14] and Takahashi [15] were considered. Stress intensity factor was calculated using the expressions proposed by Ainsworth et al. [16]. Fracture resistance was considered in terms of initiation fracture toughness and J-integral was evaluated using load-CMOD method proposed by Kamaya [17]. The evaluated assessment points were plotted on the FAD containing failure assessment lines constructed as per SINTAP procedure and BS 7910 standard 2A and 2B levels of assessment.

Experimental studies

Vishnuvardhan et al. [18–19] conducted experimental investigations on straight pipes containing circumferential through-wall notch located at the weld. The test specimens were made of SA312 Type 304LN stainless steel and welded together using nickel-based alloy, Inconel-82 (ERNiCR-3), as filler. The material properties of weld material are reported by Suranjit et al. [20]. The tensile tests were carried at room temperature. The weld material exhibits a yield strength of 386.6 MPa and an ultimate tensile strength of 666 MPa. Additionally, the Young's modulus was 220 GPa and the percentage elongation was 40.8%. The stress-strain curve of weld material is shown in Fig. 2 [20].

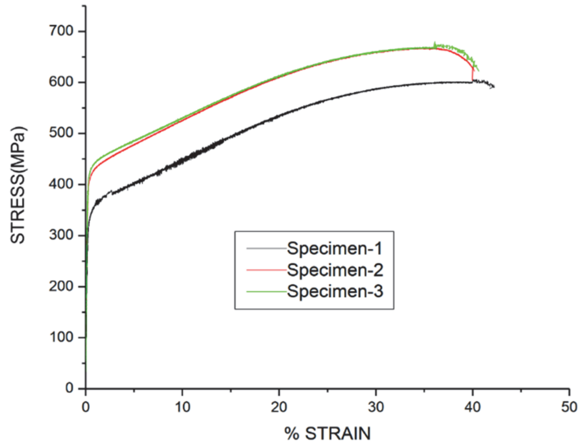

Figure 2: Stress-strain curve of weld material.

The geometric specifications of the pipe specimens are presented in Tab. 1 [18–19]. A schematic diagram of a straight pipe containing a circumferential through-wall notch in the weld is shown in Fig. 3. The specimens were loaded under four-point bending under monotonic loading. Each of the three pipes featured a circumferential through-wall notch in the weld. The nominal outer diameters of the pipes were 168 mm, 171 mm, and 325 mm. Their lengths ranged from 1996 mm to 4960 mm. The average wall thicknesses varied between 14.6 mm and 25.7 mm, and the notch lengths after fatigue pre-cracking were approximately between 90 mm and 170 mm. All notches had an angle of approximately 60°. The pipe specimens considered in the present study were Post Weld Heat Treated (PWHT) to remove the residual stresses. Hence, residual stresses are not considered in the structural integrity assessment.

Specimen No.	Pipe diameter (mm)	Pipe thickness (mm)	Pipe length (mm)	Notch length 2c (mm)	Notch angle 2θ (°)
SP6-60-TWC-SSW-M1	168	14.79	2022	92	62.8
SSPW6-25	171	14.6	1996	90	59.9
SSPW12-27	325	25.7	4960	170	59.8

Table 1: Geometric specifications of the pipe specimens.

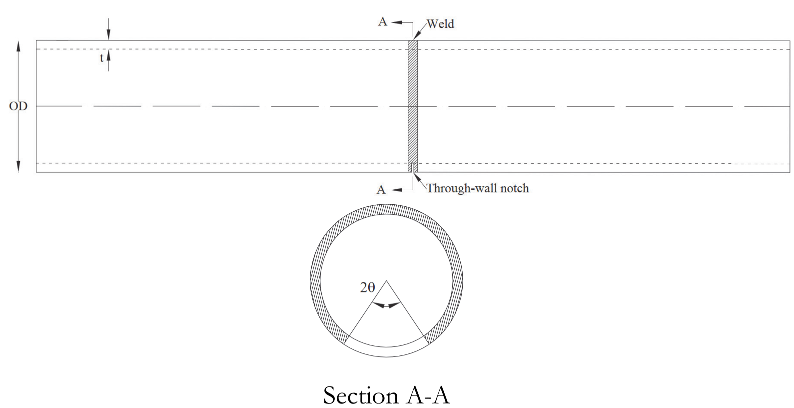

Figure 3: Schematic diagram of a straight pipe containing a circumferential through-wall notch in the weld.

Before conducting the fracture experiments, all pipe specimens were subjected to fatigue pre-cracking to generate a sharp crack front. Fig. 4 shows the experimental set-up used for this pre-cracking. Fatigue pre-cracking was performed using a ±1000 kN capacity actuator under four-point bending and constant amplitude sinusoidal loading was applied until at least 2 mm of crack growth was achieved at both notch tips along the circumferential direction. Fig. 5 shows a schematic of the fracture test set-up. Fig. 6 shows a close-up view of the experimental set-up. The specimens were subjected to displacement-controlled loading using servo-hydraulic actuators with capacities of ±1000 kN and ±2000 kN. During the fracture tests, applied load, load-line displacement (LLD), crack mouth opening displacement (CMOD), pipe deflection, and crack growth were measured.

Figure 4: Experimental set-up for fatigue pre-cracking.

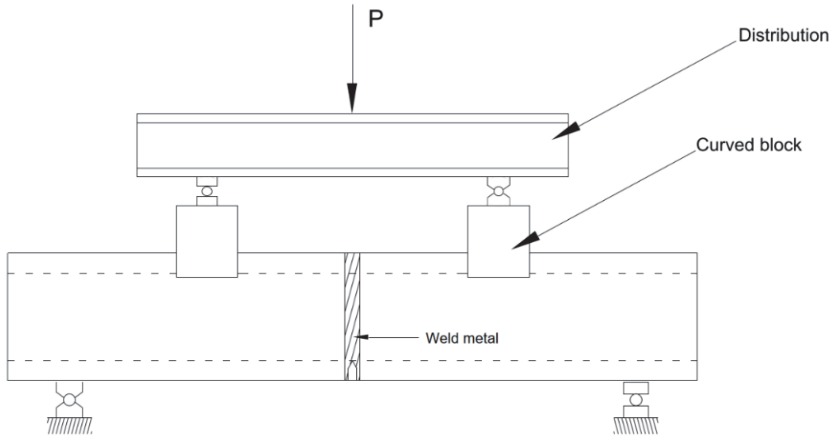

Figure 5: Schematic of the fracture test set-up.

Figure 6: Closeup view of experimental set-up.

Parameters for FAD

Failure assessment of a structural component is carried out using load ratio and fracture ratio. To evaluate these ratios, applied moment, limit load moment, stress intensity factor and fracture resistance are required.

Limit load moment

Limit load moment is the cross-sectional capacity of a component. For evaluating the limit load moment of pipes with circumferential through-wall notch under bending, analytical expressions were proposed by Zahoor [14] and Takahashi [15].

Expression proposed by Zahoor [14]

Limit load moment solution of pipe with circumferential through-wall notch under bending is given by

$$M_L = 4R_m^2 t\sigma_f \left[\cos\left(\tfrac{\theta}{2}\right) - \left(\tfrac{1}{2}\right)\sin(\theta)\right] \quad (1)$$

where, flow stress, $\sigma_f = \dfrac{\sigma_y + \sigma_u}{2}$

The expression proposed by Zahoor accounts for the strain hardening of the material by incorporating flow stress. Flow stress is the stress required for continuing plastic deformation of material.

Expression proposed by Takahashi [15]

Limit load moment solution of pipe with circumferential through-wall notch under bending is given by

$$M_L = 4R_m^2 t\sigma_y \left[\cos\left(\tfrac{\theta}{2}\right) - \left(\tfrac{1}{2}\right)\sin(\theta)\right] \quad (2)$$

Stress intensity factor by Ainsworth et al. [16]

The stress intensity factor represents the state of stress near the crack tip when a load is applied, and it is used to predict crack growth in structural components. To evaluate the stress intensity factor for a pipe with a circumferential through-wall notch under bending, the expressions proposed by Ainsworth et al. (2016) are as follows.

$$K_b = F_b \sigma_b \sqrt{\pi a} \quad (3)$$

$$\sigma_b = M_b / \pi R_m^2 t \quad (4)$$

$$F_b = 1 + A\left[4.5967\left(\tfrac{\theta}{\pi}\right)^{1.5} + 2.6422\left(\tfrac{\theta}{\pi}\right)^{4.24}\right] \quad (5)$$

$$A = \left[0.125\left(R_m/t\right) - 0.25\right]^{0.25} \quad (6)$$

The above expressions are valid for $5 \le R_m/t \le 10$.

Fracture resistance

There are several methods available in the literature for evaluation of fracture resistance under monotonic loading, viz, Leak Before Break approach, η factor method, ENGC method, limit load method, crack mouth opening displacement method (CMOD), HRR method and load - crack mouth opening displacement method. Among these methods, load-CMOD method considers large plastic deformation around the crack tip opening in terms of area under load-CMOD plot and yields the highest J-integral values. Hence, in the present study, load-CMOD method was used to evaluate J-integral.

Initiation fracture toughness [20]

Initiation fracture toughness refers to the stress intensity factor value at which a crack begins to initiate and propagate from an existing notch. It is a material property and independent of the specimen geometry and the nature of loading. The fracture tests were carried at room temperature. Initiation fracture toughness in terms of J_{Ic} for weld material was 266 kJ/m².

$$K_{Ic} = \sqrt{J_{Ic} E'} = 254 \text{ MPa}\sqrt{\text{m}}$$

J-integral using load-CMOD method by Kamaya [17]

This method considers the overall plastic deformation energy of the crack. The initial crack length (a0), the applied load (P), and crack mouth opening displacement (CMOD) are the major governing parameters. To evaluate J-integral under monotonic loading using this method, the governing equation is:

$$J = J_{EL} + J_{PL} \quad (7)$$

Elastic component of the J-integral is expressed as:

$$J_{EL} = \frac{K^2}{E'} \tag{8}$$

$$E' = \frac{E}{\left(1-\mu^2\right)} \tag{9}$$

Plastic component of the J-integral is expressed as:

$$J_{PL} = \frac{\left(\eta_{CMOD} * A_p\right)}{t*\left(W-a_0\right)} \tag{10}$$

$$\eta_{CMOD} = 1.040 - 0.687\left(\frac{a}{W}\right) \tag{11}$$

where, t is thickness of the pipe specimen, W is width of the pipe specimen, a_0 is initial crack length, η_{CMOD} is dimensionless function of geometry of the pipe, A_p is area under plastic part of load-CMOD curve.
The above expressions are valid for $0.1 \le a/W \le 0.7$.

FAD APPROACHES

Failure assessment line provides demarcation between the acceptable zone and unacceptable zone in a FAD. It provides the limiting interaction between the fracture ratio and the load ratio. From the failure assessment line and the position of the assessment point of the specimen, it can be assessed whether the structural component is safe or unsafe, for a given crack length and corresponding applied load. If the assessment point of the specimen falls between the failure assessment line and the axes of the FAD, the structural component is safe for the crack length and corresponding applied load.

SINTAP procedure [1]
The SINTAP procedure was developed to assess the integrity of structures with flaws, for use in European industry. It offers different levels of complexity to provide flexibility for industrial applications and user needs. The failure assessment line equation provided in this procedure is the same as the one provided in R6 procedure. This procedure provides different equations for materials which exhibit a lower yield plateau and materials which does not exhibit a lower yield plateau.

For materials which exhibit a lower yield plateau,

$$K_r = f\left(L_r\right) = \begin{cases} \left[1+0.5\left(L_r\right)^2\right]^{-1/2} & L_r \le 1.0 \\ 0 & L_r > 1.0 \end{cases} \tag{12}$$

For materials which do not exhibit a lower yield plateau,

$$K_r = f\left(L_r\right) = \begin{cases} \left[1+0.5\left(L_r\right)^2\right]^{-1/2}\left[0.3+0.7\exp\left(-0.6L_r^6\right)\right] & L_r \le L_r^{max} \\ 0 & L_r > L_r^{max} \end{cases} \tag{13}$$

$$L_r^{max} = 1+\left(150/R_p\right)^{2.5}$$

where R_p is the material's proof stress in MPa

BS 7910:2005 [21]
BS 7910:2005 standard, guide to methods for assessing the acceptability of flaws in metallic structures addresses the integrity assessment of both new and existing constructions using non-destructive testing methods. The acceptance levels for the

flaws that are detected must be established. The failure assessment line equation provided in this procedure is the same as the ones provided in DNV-RP-108 code, API 579 code and FITNET procedure. This code provides various levels of assessment based on the availability of inputs, i.e., Level 1A, Level 2A and Level 2B.
For Level 1A assessment,

$$K_r = f\left(L_r\right) = \begin{cases} 0.707 & L_r \le 0.8 \\ 0 & L_r > 0.8 \end{cases} \quad (14)$$

For Level 2 assessment,

$$L_r^{\max} = \frac{\sigma_y + \sigma_u}{2\sigma_y} \quad (15)$$

where σ_y is the material's proof stress and σ_u is material's ultimate stress in MPa.

For Level 2A assessment for materials which does not exhibit a lower yield plateau,

$$K_r = f\left(L_r\right) = \begin{cases} \left[1 - 0.14\left(L_r\right)^2\right]\left[0.3 + 0.7\exp\left(-0.65L_r^6\right)\right] & L_r \le L_r^{\max} \\ 0 & L_r > L_r^{\max} \end{cases} \quad (16)$$

For Level 2B assessment,
This level of assessment provides a material specific failure assessment line. This method is suitable for both the parent material as well as the weld metals. It gives more precise results as compared to Level 2A. This method uses material specific stress-strain curve.

$$K_r = f\left(L_r\right) = \begin{cases} \left[\frac{E\varepsilon_{ref}}{L_r\sigma_y} + \frac{L_r^3\sigma_y}{2E\varepsilon_{ref}}\right]^{-1/2} & L_r \le L_r^{\max} \\ 0 & L_r > L_r^{\max} \end{cases} \quad (17)$$

where, ε_{ref} is the true strain obtained from the uniaxial tensile stress-strain curve at a true stress, $L_r\sigma_y$.

INTEGRITY ASSESSMENT USING FAD

For carrying out structural integrity assessment of SA 312 Type 304 LN steel welded pipes with circumferential through-wall notch under monotonic loading, failure assessment diagrams are utilized. For the assessment, fracture ratio and load ratio were evaluated for all the three specimens. For calculating the load ratio, applied bending moment and limit load moment were used. For calculating the fracture ratio, stress intensity factor (SIF) and fracture resistance were used. For evaluating applied moments, experimental data reported by Vishnuvardhan et al. [18-19] was utilized. For evaluating limit load moment, analytical expressions proposed by Zahoor [14] and Takahashi [15] were considered. Stress intensity factor was calculated using the expressions proposed by Ainsworth et al. [16]. Fracture resistance was considered in terms of material's initiation fracture toughness and J-integral value evaluated using load-CMOD method proposed by Kamaya [17]. The evaluated assessment points were plotted on the FAD containing failure assessment lines as per SINTAP procedure and BS 7910 Standard 2A and 2B level of assessment. Sample calculations and details of sensitivity analysis carried out are given in the annexures.
Tab. 2 shows the load and fracture ratios for the welded pipe specimens evaluated using limit load moment proposed by Zahoor and Takahashi and fracture resistance using initiation fracture toughness and J-integral value evaluated using load-CMOD method. For the pipe specimens SP6-60-TWC-SSW-M1, SSPW 6-25 and SSPW 12-27 the load ratios evaluated using the expressions proposed by Zahoor are 0.572, 0.494 and 0.462 respectively. The load ratios evaluated using the expressions proposed by Takahashi are 0.778, 0.672 and 0.628 respectively. The fracture ratios evaluated using initiation

fracture toughness are 0.736, 0.619 and 0.810 respectively. The fracture ratios evaluated using J-integral by load-CMOD method are 0.694, 0.588 and 0.787 respectively.

Fig. 7 shows the FAD using limit load moment proposed by Zahoor and fracture resistance in terms of initiation fracture toughness. Fig. 8 shows the FAD using limit load moment proposed by Zahoor [14] and fracture resistance in terms of J-integral using load-CMOD method. Fig. 9 shows the FAD using limit load moment proposed by Takahashi and fracture resistance in terms of initiation fracture toughness. Fig. 10 shows the FAD using limit load moment proposed by Takahashi [15] and fracture resistance in terms of J-integral using load-CMOD method.

	Load ratio, Lr		Fracture ratio, Kr	
Specimen No.	Zahoor [14]	Takahashi [15]	Initiation fracture toughness method	Load-CMOD method
SP6-60-TWC-SSW-M1	0.572	0.778	0.736	0.694
SSPW 6-25	0.494	0.672	0.619	0.588
SSPW 12-27	0.462	0.628	0.810	0.787

Table 2: Load and fracture ratios for the welded pipe specimens.

For SP6-60-TWC-SSW-M1, the load ratio using expression proposed by Takahashi is 0.778 and the fracture ratio using initiation fracture toughness method is 0.736. For SSPW 6-25, the load ratio using expression proposed by Takahashi is 0.672 and the fracture ratio using initiation fracture toughness method is 0.619. For SSPW 12-27, the load ratio using expression proposed by Takahashi is 0.628 and the fracture ratio using initiation fracture toughness method is 0.810. From Fig. 8, it can be observed that the assessment point for SSPW 6-25 lies within the failure assessment line and the assessment point for SSPW 12-27 and SP6-60-TWC-SSW-M1 lies marginally inside the failure assessment line. Therefore, specimen SSPW 6-25 is considered to be safe and the specimens SSPW 12-27 and SP6-60-TWC-SSW-M1 is considered to be critical. Similar assessment has been carried out for all the specimens using expressions proposed by Zahoor and Takahashi for evaluating load ratio. The initiation fracture toughness and J-integral using load-CMOD method were used for evaluating fracture ratio. All the specimens lie within the stable region for all the assessments. For limit load moment proposed by Takahashi, specimens SSPW 12-27 and SP6-60-TWC-SSW-M1, is closer to the failure assessment line indicating that for the given notch length and applied load, the specimens are in a critical condition.

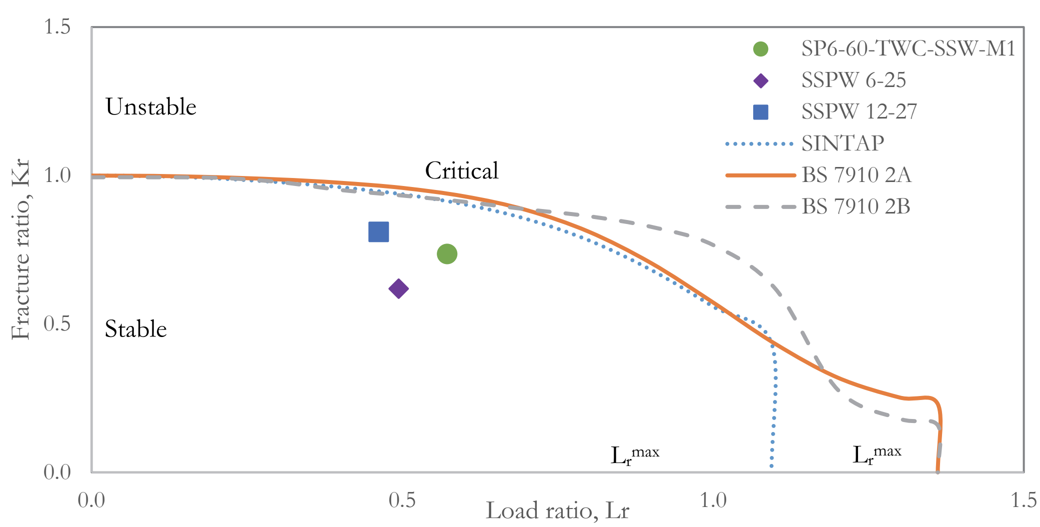

Figure 7: FAD using limit load moment by Zahoor and initiation fracture toughness.

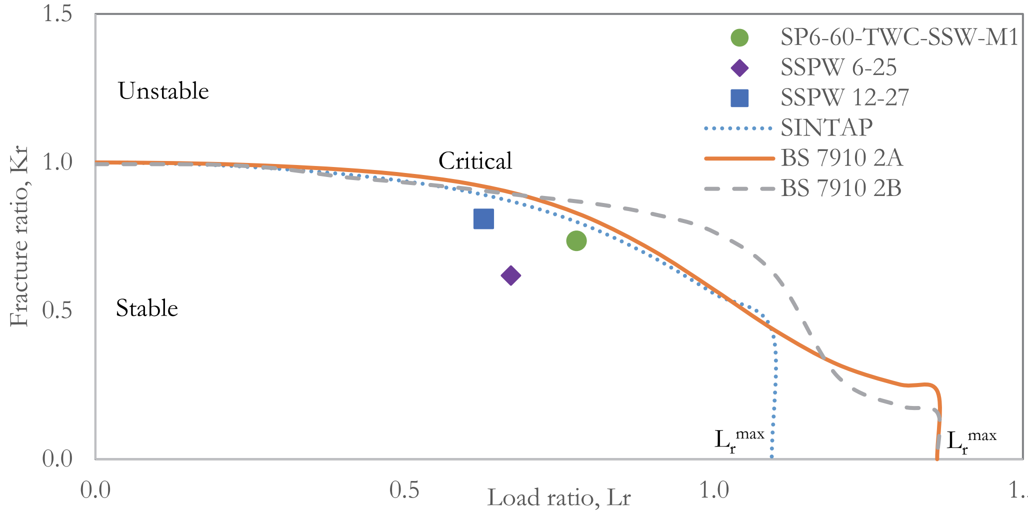

Figure 8: FAD using limit load moment by Takahashi and initiation fracture toughness.

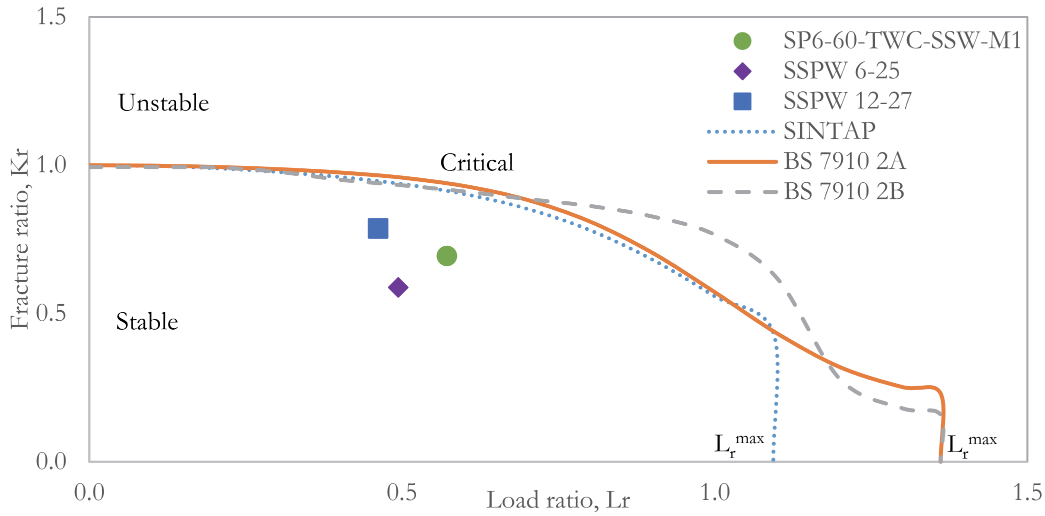

Figure 9: FAD using limit load moment by Zahoor and J-integral using load-CMOD method.

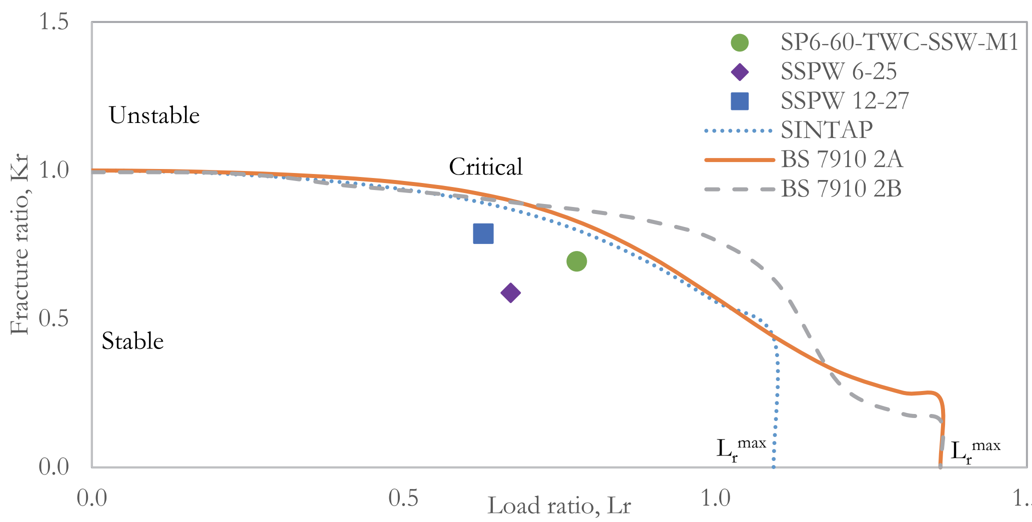

Figure 10: FAD using limit load moment by Takahashi and J-integral using load-CMOD method.

Sensitivity analysis

The input parameters used for structural integrity assessment using FAD is obtained using different instruments during the fracture tests. These measurements are quite often accompanied by variability due to various practical reasons such as sensitivity of the instrument, calibration of the instrument, access of the structural component, noise in data, etc. Hence, a sensitivity analysis of the assessment procedure has been performed to understand the variability in results due to the variation in the input parameters. Sensitivity analysis has been carried out for specimen SSPW 6-25. The crack length and pipe thickness have been varied by ± 0.5 mm and ± 0.25 mm respectively. Flow stress and initiation fracture toughness of the weld material have been varied by ± 25 MPa and ± 25 MPa√m respectively.

The FAD parameters for the actual values of crack length, pipe thickness, flow stress and initiation fracture toughness are given below.

Load ratio, L_r (using Zahoor) = 0.494
Load ratio, L_r (using Takahashi) = 0.672
Fracture ratio, K_r (using initiation fracture toughness) = 0.619
Fracture ratio, K_r (using load-CMOD) = 0.588

Initiation fracture toughness is a material property. The major contribution for fracture ratio (using load-CMOD), K_r is from J_{EL}. Hence there is no variation in fracture ratio (using initiation fracture toughness) and fracture ratio (using load-CMOD) due to change in crack length, thickness or flow stress. Variation in initiation fracture toughness K_{IC} contributes only to the fracture ratio. Hence there is no variation in load ratio due to change in initiation fracture toughness. Therefore, sensitivity analysis has been performed by varying crack length, pipe thickness and flow stress with respect to load ratio. And sensitivity analysis has been performed by varying initiation fracture toughness with respect to fracture ratio. Tabs. 3-6 gives the results of sensitivity analysis carried out by varying crack length, pipe thickness, flow stress and initiation fracture toughness.

(a) Sensitivity analysis by varying crack length
Actual crack length = 1.29 mm
Variation considered = ± 0.5 mm

Crack length, a (mm)	Load ratio, L_r (Zahoor)	% variation	Load ratio, L_r (Takahashi)	% variation
0.79	0.493	-0.202	0.671	-0.149
0.89	0.493	-0.202	0.671	-0.149
0.99	0.493	-0.202	0.671	-0.149
1.09	0.493	-0.202	0.672	0.000
1.19	0.494	0.000	0.672	0.000
1.29	0.494	0.000	0.672	0.000
1.39	0.494	0.000	0.673	0.149
1.49	0.494	0.000	0.673	0.149
1.59	0.495	0.202	0.673	0.149
1.69	0.495	0.202	0.674	0.298
1.79	0.495	0.202	0.674	0.298

Table 3: Results of sensitivity analysis by varying crack length.

(b) Sensitivity analysis by varying pipe thickness
Actual pipe thickness = 14.6 mm
Variation considered = ± 0.25 mm

Pipe thickness, t (mm)	Load ratio, L_r (Zahoor)	% variation	Load ratio, L_r (Takahashi)	% variation
14.35	0.500	1.215	0.681	1.339
14.4	0.499	1.012	0.680	1.190
14.45	0.498	0.810	0.678	0.893
14.5	0.496	0.405	0.676	0.595
14.55	0.495	0.202	0.674	0.298
14.6	0.494	0.000	0.672	0.000
14.65	0.493	-0.202	0.671	-0.149
14.7	0.491	-0.607	0.669	-0.446
14.75	0.490	-0.810	0.667	-0.744
14.8	0.489	-1.012	0.665	-1.042
14.85	0.487	-1.417	0.664	-1.190

Table 4: Results of sensitivity analysis by varying pipe thickness

(c) Sensitivity analysis by varying flow stress
Actual flow stress = 526 MPa
Variation considered = ± 25 MPa

Flow stress, σ_f (MPa)	Load ratio, L_r (Zahoor)	% variation	Load ratio, L_r (Takahashi)	% variation
501	0.518	4.858	0.719	6.994
506	0.513	3.846	0.709	5.506
511	0.508	2.834	0.699	4.018
516	0.503	1.822	0.690	2.679
521	0.499	1.012	0.681	1.339
526	0.494	0.000	0.672	0.000
531	0.489	-1.012	0.664	-1.190
536	0.485	-1.822	0.655	-2.530
541	0.480	-2.834	0.647	-3.720
546	0.476	-3.644	0.639	-4.911
551	0.471	-4.656	0.631	-6.101

Table 5: Results of sensitivity analysis by varying flow stress

(d) Sensitivity analysis by varying initiation fracture toughness
Actual initiation fracture toughness = 254 MPa√m
Variation considered = ± 25 MPa√m

Initiation fracture toughness (MPa√m)	Fracture ratio, Kr (Initiation fracture toughness)	% variation	Fracture ratio, Kr (Load-CMOD)	% variation
229	0.685	10.662	0.644	9.524
234	0.671	8.401	0.632	7.483
239	0.657	6.139	0.620	5.442
244	0.643	3.877	0.609	3.571
249	0.630	1.777	0.598	1.701
254	0.619	0.000	0.588	0.000
259	0.606	-2.100	0.577	-1.871
264	0.594	-4.039	0.567	-3.571
269	0.583	-5.816	0.558	-5.102
274	0.573	-7.431	0.548	-6.803
279	0.562	-9.208	0.539	-8.333

Table 6: Results of sensitivity analysis by varying initiation fracture toughness

From the sensitivity analysis, it was observed that variation in load ratio due to ± 0.5 mm variation in crack length and ± 0.25 mm variation in pipe thickness is negligible. The maximum variation in load ratio due to ± 25 MPa variation in flow stress is 7% and the maximum variation in fracture ratio due to ± 25 MPa√m variation in initiation fracture toughness is around 10%. Hence it can be inferred that the inherent variability in measurement of the input parameters does not alter the assessment results significantly.

SUMMARY AND CONCLUSION

Failure assessment diagram (FAD) is used for structural integrity assessment of a component containing defect subjected to loading. Structural integrity assessment has been carried out for the three welded pipe specimens made of SA312 Type 304 LN with through-wall notch under monotonic loading. For carrying out structural integrity assessment, failure assessment diagrams were utilized. For evaluating applied moments, experimental data reported by Vishnuvardhan et al. [18-19] was utilized. For evaluating limit load moment, expressions proposed by Zahoor [14] and Takahashi [15] were considered. Expression proposed by Zahoor incorporates flow stress which is higher than the yield strength, results in higher limit load moment values. Stress intensity factor was calculated using the expressions proposed by Ainsworth et al. [16]. Fracture resistance was considered in terms of material's initiation fracture toughness and J-integral evaluated using load-CMOD method proposed by Kamaya [17]. The load-CMOD method accounts for a plastic deformation as well. The evaluated assessment points were plotted on the FAD containing failure assessment lines as per SINTAP procedure and BS 7910 standard 2A and 2B level of assessment. The failure assessment line as per BS 7910 2B level assessment is material specific whereas, SINTAP and BS 7910 2A level assessment are not material specific. Structural integrity assessment using FAD was carried out by comparing the load ratio and fracture ratio with failure assessment line. From the sensitivity analysis, it was observed that the inherent variability in measurement of the input parameters does not alter the assessment results significantly.

The limit load moments evaluated from the expressions proposed by Zahoor resulted in higher values because they account for the strain hardening of the material by incorporating flow stress. Fracture resistance considered in terms of J-integral evaluated using load-CMOD method proposed by Kamaya [17] was higher due to inclusion of plastic deformation in terms of area under load-CMOD plot. The failure assessment lines from SINTAP procedure and BS 7910 standard Level 2A and 2B (for SA312 Type 304 LN steel) yielded similar failure assessment lines.

From the above assessment, it was observed that

- In all the assessments, all the three specimens were in the stable region.
- For limit load moment proposed by Takahashi, specimens SSPW 12-27 and SP6-60-TWC-SSW-M1 were in stable region but it was marginally below the failure assessment line indicating that for the given notch length and applied load, the specimens are in a critical condition.

This structural integrity assessment is very significant in deciding the safety of operation of the piping components.

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NOMENCLATURE

2c	Notch length
2θ	Notch angle
R_m	Mean radius
t	Thickness
σ_y	Yield strength
σ_u	Ultimate strength
K_b	Stress intensity factor
M_b	Applied bending moment
a	Crack length
J	J-integral
E	Young's modulus

ANNEXURE

Sample calculation for evaluation of FAD parameters

Sample calculation for evaluation of FAD parameters for specimen SSPW 6-25 are given below.

a. Inputs for specimen SSPW 6-25:

Mean radius, R_m = 78.2 mm
Thickness, t = 14.6 mm

Crack length, $a = a_0 + \Delta a = 91.26$ mm
Half crack angle, $\theta = 0.58$ rad
Applied moment, $M_b = 63$ kNm

Yield stress, $\sigma_y = 386.6$ MPa
Ultimate stress, $\sigma_u = 666$ MPa
Young's modulus, E = 220 GPa
Poisson's ratio, $\mu = 0.3$
Initiation J-integral, $J_{Ic} = 266$ kJ/m2

b. Limit load moment:

b.1. Zahoor 1989:
Expression:

$$M_L = 4R_m^2 t\sigma_f \left[\cos\left(\tfrac{\theta}{2}\right) - \left(\tfrac{1}{2}\right)\sin(\theta)\right]$$

where, flow stress, $\sigma_f = \dfrac{\sigma_y + \sigma_u}{2}$

Result:
$M_L = 128$ kNm

b.2. Takahashi:
Expression:

$$M_L = 4R_m^2 t\sigma_y \left[\cos\left(\tfrac{\theta}{2}\right) - \left(\tfrac{1}{2}\right)\sin(\theta)\right]$$

Result:
$M_L = 94$ kNm

c. Stress intensity factor Ainsworth et al. 2016:
Expression:

$$K_b = F_b \sigma_b \sqrt{\pi a}$$

$$\sigma_b = M_b / \pi R_m^2 t$$

$$F_b = 1 + A\left[4.5967\left(\tfrac{\theta}{\pi}\right)^{1.5} + 2.6422\left(\tfrac{\theta}{\pi}\right)^{4.24}\right]$$

$$A = \left[0.125\left(R_m/t\right) - 0.25\right]^{0.25}$$

Result:
$K_b = 157$ MPa√m

d. Fracture resistance:

d.1. Initiation fracture toughness (Suranjit et al. 2014):
Expression:

$$K_{Ic} = \sqrt{J_{Ic}E'}$$

$$E' = \tfrac{E}{\left(1-\mu^2\right)}$$

Result:
$K_{Ic} = 254$ MPa√m

d. 2. J-integral using load-CMOD method by Kamaya 2018:
Expression:
A_p = Area under plastic part of load-CMOD curve

$$W = 2\pi R$$

$$J = J_{EL} + J_{PL}$$

$$J_{PL} = \frac{\left(\eta_{CMOD} * A_p\right)}{t*\left(W - a_0\right)}$$

$$\eta_{CMOD} = 1.040 - 0.687\left(\frac{a}{W}\right)$$

$$K = \sqrt{JE'}$$

Result:

K = 267 MPa√m