



Determination of Maximum Load of TWC Straight Pipes: Comparative Study of Estimation Schemes

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ABSTRACT

The present paper describes the evaluation of Maximum Load Carrying Capacity of Through Wall Cracked pipes of Primary Heat Transport (PHT) System of 500 MWe Pressurised Heavy Water Reactor (PHWR) being constructed at Tarapur, India. Three different widely used, estimation schemes namely GE/EPRI, A16 : Guide and R-6, were studied. It was concluded that although crack driving forces, determined by above methods, differ significantly, however the maximum failure load is nearly same. It was also concluded that if slope of crack driving force v/s crack growth resistance is approximated by $(\sim\sigma_f^2 a/E)$, the error in estimation of Maximum Failure Load is marginal.

1.0 INTRODUCTION

Prediction of maximum failure load is one of the important steps in Leak - Before - Break (LBB) assessment of high energy piping. The Through Wall Cracks (TWC) are postulated in the straight pipe at the highest stress locations or at poorest material property locations like weld etc. The cracks are generally assumed to be circumferential at the girth welds. The flaw should be large enough so that the leak from this postulated TWC is assured of detection when pipe is subjected to normal operational loads. It should be demonstrated that there is a factor of at least 10 between the leakage from the Leakage Size Flaw (LSC) and the plant's installed leak detection capability, [2]. The calculated maximum failure load is compared with the maximum Design Basis Accident (DBA) load. It is required to be demonstrated that maximum failure load is greater than DBA load. It should also meet "Safety Margin" as specified by USNRC and IAEA documents, IAEA-TECDOC-710, [1] and SRP No.3.6.3 [2]. The ratio of Maximum Failure Load to the DBA load should be at least equal to or greater than 1.4. However, this factor can be reduced to 1.0 if normal and seismic loads are summed absolutely.

The straight pipes are primarily subjected to Bending Moments. It can either fail by Non-Ductile Fracture, Ductile Tearing or Plastic Collapse. It is easy to determine Maximum Failure Load (MFL) if the governing failure mechanism is Plastic Collapse or Non - Ductile fracture. In case of plastic collapse, it has been widely shown that MFL can be determined with reasonable

accuracy using limit load or modified limit load formulae, [10] & [11]. If non-ductile fracture is governing failure mode then MFL can be simply determined by comparing Material Fracture Toughness (K_{IC}) and Applied Stress Intensity Factor (SIF). SIF expressions for circumferential TWC pipes are well documented in A-16 Guide, [3] & Ductile Fracture Handbook [4].

If ductile tearing is the governing failure mode then evaluation of MFL involves determination of elastic-plastic Crack Driving Force (CDF) which is also known as applied J-integral. The ductile tearing takes place in two steps, first the initiation of crack growth occurs which is either followed by stable crack growth called Ductile Tearing or the unstable crack propagation (called Tearing Instability). The load corresponding to unstable crack growth is termed as MFL. This is determined by following conditions:

$$\begin{aligned} \text{Initiation of Crack will occur if } & J_{app} = J_i \\ \text{Unstable Crack Growth will occur if } & J_{app} \geq J_R(\Delta a) \quad \text{and} \quad - \text{ (necessary condition)} \\ & T_{app} \geq T_{mat} ; \text{ for the given } \Delta a, - \text{ (sufficient condition)} \end{aligned}$$

where

$$\begin{aligned} J_{app} &= \text{Crack Driving Force} \\ J_i &= \text{Initiation Toughness or Material J at initiation} \\ J_R(\Delta a) &= \text{Material J after } \Delta a \text{ amount of crack extension} \\ T_{app} &= (E / \sigma_f^2) (dJ_{app}/da) \\ T_{mat} &= (E / \sigma_f^2) [dJ_R(\Delta a) / da] \end{aligned}$$

J v/s Applied Bending Moment (M) and J v/s Tearing Modulus curves are plotted side by side. The unstable Tearing Moment or MFL can be evaluated by determining the intersection point of J_{app} v/s T_{app} and J_{mat} v/s T_{mat} curve (as shown in Fig.1) and projecting it to J v/s Bending Moment curve. The crack driving force (J_{app}) can be evaluated by non linear Finite Element (FE) Analysis. However, several approximate techniques are commonly used to determine J_{app} . These approximate techniques are also called "Estimation Schemes" and are preferred over FE Analysis since former are less computational intensive.

In this paper, fracture assessment of PHT pipes of 500 MWe PHWR, being constructed at Tarapur, India, have been determined by three different estimation schemes. The evaluation of MFL is based on Ductile Tearing. The normal and seismic loads have been added using SRSS rule.

2.0 NOMENCLATURE

h = function of R/t , θ , n and λ
 θ = half the crack angle subtended at the centre
 n = strain hardening parameter
 P = Applied axial Load
 M = Applied Bending Moment
 P_o = Reference Limit Load for tension
 M_o = Reference Limit Load for bending
 R_o = Outer radius of Pipe
 R_i = Inner radius of Pipe

$R = (R_o + R_i)/2 =$ mean radius of pipe

$J_t = J_e$ for tensile load

$J_b = J_e$ for bending moment

$J_e = J$ -elastic

$J_p = J$ -plastic

f_t, f_b are modified geometry factor for tensile and bending moment respectively

F_t, F_b are geometry factor for tensile and bending moment respectively

$t =$ wall thickness of pipe

$E =$ Young's Modulus of material

MFL = Maximum Failure Load

LSC = Leakage Size Crack

NOC = Normal Operating Condition

3.0 ESTIMATION OF APPLIED J-INTEGRAL (J_{app}) & TEARING MODULUS (T_{app})

Three different estimation schemes have been used for the evaluation of J_{app} . These are discussed below :

3.1 Estimation Of J_{app}

(a) GE/EPR1 Estimation Scheme, [4] & [5]

J-integral for pipe with TWC is written in the following form :

$$J_{app} = f_t P^2 / 4Rt^2 E + f_b M^2 / R^3 t^2 E + \alpha \sigma_o \epsilon_o R(\pi - \theta)(\theta / \pi) h(P/P_o)^{(n+1)}$$

where,

$$f_b = (\theta_o / \pi) [1 + A \{4.5967(\theta_o / \pi)^{1.5} + 2.6422(\theta_o / \pi)^{4.24}\}]^2$$

$$f_t = (\theta_o / \pi) [1 + A \{5.3303(\theta_o / \pi)^{1.5} + 18.773(\theta_o / \pi)^{4.24}\}]^2$$

$$\theta_o = \theta [1 + (1/\beta) \{(n-1)/(n+1)\} \{(\sigma_t F_t + \sigma_b F_b)^2 / \sigma_b^2\} / \{1 + (P/P_o)^2\}]$$

$$A = [0.125(R/t) - 0.25]^{0.25}$$

$$P_o = 0.5 [-\lambda R P_o^2 / M_o + \{(\lambda R P_o^2 / M_o)^2 + 4 P_o^2\}^{0.5}]$$

$$\lambda = M/PR$$

(b) R-6 Estimation Scheme, [6]

J-integral can be written as

$$J_{R-6} = \chi_{R-6} \times J_e$$

$$\chi_{R-6} = \psi_{R-6} + \epsilon_r / (L_r \sigma_o / E)$$

$$\psi_{R-6} = L^3 \sigma_o / 2E\epsilon_r$$

where,

$\psi_{R-6} =$ the plastic zone correction

$\epsilon_r =$ the reference strain (from stress- strain curve)

$L_r = M / M_o =$ Applied Moment / Limit Moment

$$J_e = J_t + J_b + 2 \times (J_t \times J_b)^{1/2}$$

$$J_t = f_t P^2 / 4Rt^2 E$$

$$J_b = f_b M^2 / R^3 t^2 E$$

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

$$F_t = 1 + A [5.3303(\theta / \pi)^{1.5} + 18.773(\theta / \pi)^{4.24}]$$

$$\begin{aligned}
A &= [0.125(R/t)-0.25]^{0.25} \\
M_0 &= 4\sigma_0(R_0)^2 t (1-\zeta - \zeta^2/3)(\cos\alpha-0.5\sin\theta) \\
\zeta &= t/R_0 \\
\alpha &= [0.5\theta(1-\zeta) (1+0.5\zeta/(1-\zeta))]/(1-0.5\zeta) + P/4\sigma_0 R_0 t(1-\zeta) \\
\sigma_t &= P/2\pi R t \\
\sigma_b &= M/\pi R^2 t
\end{aligned}$$

(c) A16 Estimation Scheme, [3]

J-integral can be written as

$$\begin{aligned}
J_{A16} &= \chi_{A16} \times J_e \\
\chi_{A16} &= \psi_{A16} + \varepsilon_t/(\sigma_t/E) \\
\psi_{A16} &= 0.5\sigma_r^2/(\sigma_r^2 + \sigma_0^2)
\end{aligned}$$

where,

$$\begin{aligned}
\psi_{A16} &= \text{the plastic zone correction} \\
\sigma_r &= \pi (\sigma_b + \sigma_t)/4[\cos\alpha-0.5\sin\theta]
\end{aligned}$$

It may be noted that GE/EPRI scheme is based on the stress-strain relation in the form of Ramberg-Osgood curve. It is defined by strain hardening parameter n and α . However, R-6 and A16 are based on actual stress-strain curve and do not require any curve fitting. Therefore, Ramberg-Osgood curve approximately represents true stress-strain curve of the material. Hence, GE/EPRI scheme may result in approximate determination of crack driving force. The Crack Driving Force determined by GE/EPRI and R-6/A16 will therefore differ.

3.2 Determination Of T_{app}

T_{app} (Applied Tearing Modulus), for all the above schemes, is estimated as follows:

(a) GE/EPRI Scheme [4] & [5]

The applied tearing modulus was determined by analytically differentiating the expression of J_{app} given in para. (a) of article 3.1, except for the term $dh/d\theta$, that is, the derivative of h -function with respect to θ . The $dh/d\theta$ is interpolated numerically for the evaluation of T_{app} .

(b) R-6 and A16 scheme

To determine T_{app} for LSC corresponding to crack angle θ , first the J-integral is determined for the crack size $(\theta - 0.3)^0$ and $(\theta + 0.3)^0$. The $dJ/d\theta$ is evaluated by constructing a right angle triangle between these two arbitrary crack sizes. The numerical value of $dJ/d\theta$ is substituted in following expressions -

$$\begin{aligned}
T_{app} \text{ (for R-6 scheme)} &= (E/R\sigma_r^2) (dJ_{R-6}/d\theta) \\
T_{app} \text{ (A-16 scheme)} &= (E/R\sigma_r^2) (dJ_{A-16}/d\theta)
\end{aligned}$$

4.0 PIPING DETAILS AND MATERIAL PROPERTIES

The above estimation schemes were employed for fracture assessment of PHT pipes. The 500 MWe PHWR PHT seamless piping has been divided into three parts, namely Steam

Generator Inlet (SGI) line, Steam Generator Outlet (SGO) line and Pump Discharge Line (PDL). The typical pipe sizes are given in Table 1. In each of these sections, the applied forces, moments and stresses under the Normal Operating Conditions (NOC) and accident conditions are given in Table 1.

NOC loads were used to evaluate the Leakage Size Cracks (LSC). The LSC was based on leak rate of 0.5 Kg/sec which also contains of safety factor 10, as specified by GDC-4 of USNRC, [7]. The LSC values for each of the pipes are given in Table 1.

Design Basis Accident loads were determined from seismic analysis of piping system. The loads considered in the analysis are - (a) Dead Weight, (b) Internal Pressure, (c) Safe Shut Down Earthquake (SSE) – Inertia + SAM + Missing Mass Correction, (d) Load and Moments due to Thermal Expansion. For each of these pipes the Design Basis Accident load are given in Table 1. Net Bending Moment is arrived at after combing Bending Moments about three different directions.

Table 1: Pipe sizes, Accident Loads & LSC

Quantity	SGI Pipe	SGO Pipe	PDL Pipe
Outer Diameter (Do)	508 mm	610 mm	457 mm
Outer Radius (Ro)	254 mm	305 mm	228.5 mm
Thickness (t)	40 mm	50 mm	35 mm
Leakage Size Crack (2θ)	34.6 ⁰	32.4 ⁰	35 ⁰
Axial Load	0.158 MN	0.628 MN	0.131 MN
Applied Bending Moment (SRSS Combination)	640 KN-m	917 KNm	314 KN-m

4.1 Material Properties

The pipes are made of carbon steel conforming to specifications of SA 333 Gr 6 of ASME Boiler and Pressure Vessel Code Section II. The operating temperature is about 300⁰ C. The properties were measured by carrying out specimen testing from pipe material. Specimens of both base metal and weld metal were tested. The testing was done at different temperatures viz. Room Temperature, 200⁰C, 250⁰C, 300⁰C, [8]. It was observed that the mechanical properties and fracture toughness are lower at 250⁰C compared to 300⁰C. Hence fracture properties at 250⁰C were used. It was also observed that mechanical properties are lower for base metal than that for weld metal. However, the toughness is lower for weld metal as compared to base metal. Therefore, it was decided to use mechanical properties of base metal and toughness of weld metals. The important properties at 250⁰C are given below:

- (a) Young's Modulus (E) = 179000 MPa
- (b) Poisson's Ratio (ν) = 0.3
- (c) Yield Strength (σ_y) = 240 MPa (Base Metal)
- (d) Ultimate Tensile Strength (σ_u) = 458 MPa (Base Metal)
- (e) Flow Stress [σ_f = (σ_y + σ_u)/2] = 349 MPa (Base Metal)
- (f) Ramberg Osgood stress-strain curve Parameters

- (i) $\epsilon_0 = \sigma_0/E$
- (ii) $\sigma_0 = \sigma_y$
- (iii) $\alpha = 8.1505$ (Base Metal)
- (iv) $n = 3.273$ (Base Metal)

(g) J_i (defined at 0.2 mm of Δa) = 412 KJ/m² for Weld Metal

(h) J_{mat} v/s T_{mat} curve : is shown in Fig. 1 for Weld Metal . The maximum stable crack growth was found to be 9 mm in C-T specimen and corresponding J_{mat} ($\Delta a = 9$ mm) was 1564 KJ/m²; [8]. The relation between J_{mat} v/s T_{mat} is given below :

$$T_{mat} = 17.29 \times 10^5 (J_{mat})^{-1.312}; \quad \text{for } J_{mat} < 1564 \text{ KJ/m}^2$$

The crack growth in piping will be much more than 9 mm therefore, material J v/s T curve needs extrapolation. The equation of extrapolated curve is given below and shown in Fig.1 , [12].

$$J_{mat} = 2759 - 10.73(T_{mat})$$

5.0 RESULTS

The Maximum Failure Load (MFL) as determined by three estimation schemes for SGI, SGO and PDL pipe are shown in Table 2.

Table 2: MFL & Safety Margin for SGI, SGO and PDL Pipes (Load or Moment in MN-m)

Pipe Line	Maxi. Accident Load (a)	GE/EPRI		R-6		A-16	
		MFL (b)	Safety Margin (b/a)	MFL (c)	Safety Margin (c/a)	MFL (d)	Safety Margin (d/a)
SGI	0.64	1.89	2.953	2.01	3.14	2.01	3.14
SGO	0.917	3.329	3.63	3.49	3.806	3.48	3.795
PDL	0.314	1.37	4.363	1.47	4.681	1.47	4.681

The Table 2 shows that the safety margin available against the Maximum Applied Load is greater than 1.4. It is also observed that the estimated J_{app} v/s Moment values of A16 and R-6 matches closely, however, the J_{app} v/s Moment values are different from GE-EPRI scheme specially in the zone when applied load causes initiation of gross section yielding. The important fact noted from Table 2, is that the MFL obtained by different schemes do not differ significantly although there are large apparent differences in J_{app} v/s Moment curves.

Sommer, [9], have proposed that approximate value of slope of J_{app} v/s T_{app} curve is given by $\sigma_f^2(\theta R)/E$. If this approximation is used, then equation of J_{app} v/s T_{app} curve can be written as

$$J_{app} = [\sigma_f^2(\theta R)/E] T_{app} \quad (1)$$

Using equation Eq. 1 and J_{app} - T_{app} curve, the approximate value of MFL can be evaluated straight away. The approximate value of MFL for above piping is given in Table 3.

Table 3: Approximate MFL values for SGI, SGO & PDL pipes

PIPE	SGI	SGO	PDL
Maxi. Failure Load (MN-m)	2.04	3.56	1.49

Comparing the value of MFL in Table 2 and Table 3, it is observed that these are fairly close. Therefore, it is recommended that preliminary calculation of maximum load of through wall cracked pipe can be made using the approximate equation given above.

6.0 REFERENCES

- [1] "Applicability of the Leak Before Break Concept" Report No.: IAEA-TECDOC-710, 1993.
- [2] "Leak Before Break Evaluation Procedures", Standard Review Plan (SRP) 3.6.3, Federal Register, Volume 52, No. 167, Friday, August,28,1987, notices pp. 32626 to 32633.
- [3] "A16 : Guide for defect assessment and Leak Before Break Analysis", CEA Report, 1995.
- [4] Zahoor, A., "Ductile Fracture Handbook", Volume 1-3, 1990.
- [5] Kumar, V.,German,M.D.,Sih,C.F.,et al, "Advances in elastic-plastic fracture analysis". Report No. EPRI-NP-3607, 1984.
- [6] Milne, I.S.; Ainsworth, R.A.; Dowling, A.P.; Stewart, A.T.; " Assessment of the integrity of structures containing defects". Report No. CEGB/R/H/R6-Rev.3.
- [7] "Nuclear Regulatory Commission Modification of General Design Criteria (GDC)-4: Requirements for protection Against Dynamic Effects of Postulated Pipe Ruptures", Federal Register, Volume 52, No. 201,1987.
- [8] "Investigations on Elevated Temperature J-R Behaviour of Nuclear Grade Steel", Report No.: F&F/BARC/JR/SA333 June 1996, National Metallurgical Laboratory, Jamshedpur, India.
- [9] Sommer, E, "On the relevance of ductile fracture concepts for the assessment of large scale specimens of the German Research Program integrity of components (FKS)", Nuclear Engineering and Design, 72(1982),35-41.
- [10] Kanninen, M.F.; Broek,D.; Marschall, C.W.; Rybicki, E.F.; Sampath, S.G.; Simonen,F.A.; and Wilkowslei,G.M.; Mechanical Fracture Predictions for Sensitized stainless steel piping with circumferential cracks, Final Report, EPRI-NP-192, Sep. 1976.
- [11] Maricchiolo,C.; and Milella,P.P.; Fracture behaviour of Carbon Steel Pipes containing circumferential cracks at room temperature and 300 °C, Nuclear Engineering and Design, Vol. 111, 1989, Pp 35-46
- [12] Singh, P.K., Chattopadhyay, J, Kushwaha, H.S., "Tensile and fracture properties of primary heat transport system piping material", BARC External Report No. BARC/1997/E/018, 1997.

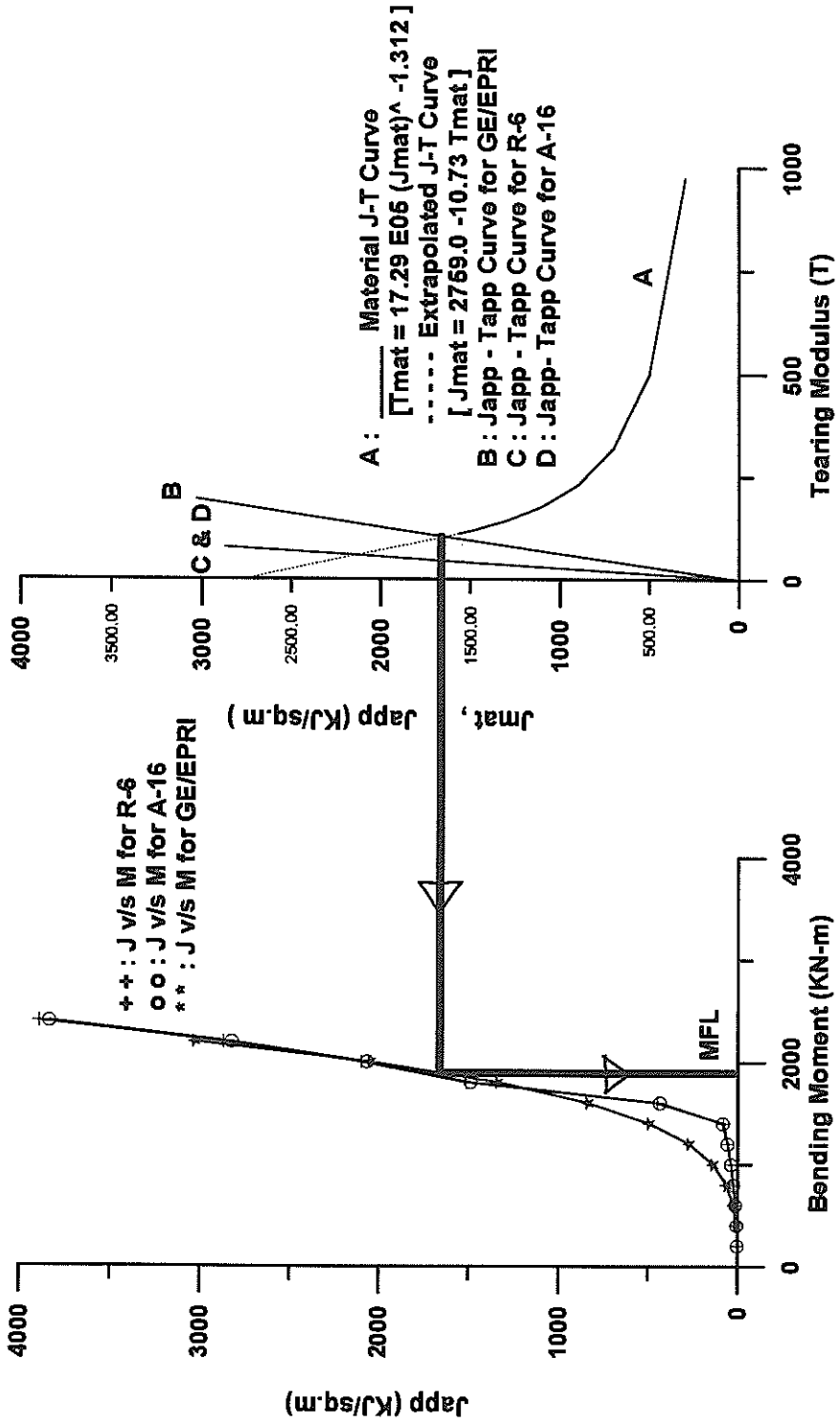


Fig. 1 : Determination of Maximum Failure Load (MFL)