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Effect of cyclic loading on elastic–plastic fracture resistance of PHT system piping material of PHWR

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Abstract

The objective of the paper is to study the effect of cyclic loading on the fracture resistance of the SA 333 Gr.6 carbon steel material of the primary heat transport (PHT) system piping of Indian pressurized heavy water reactors (PHWR). Tests have been carried out on compact tension specimens machined from the pipe used in the PHT system. The effect of load ratio, incremental plastic displacement and loading displacement rate on fracture resistance properties of the material has been studied. The cyclic fracture resistance curve has been compared with the monotonic fracture resistance curve and has been found to vary significantly. A negative load ratio with very low incremental plastic displacement between two consecutive loading cycles, significantly affects the fracture resistance of the material.

Keywords: Cyclic load; Fracture resistance; Pipes; Load ratio; Incremental plastic displacement; Loading displacement rate

1. Introduction

The primary heat transport (PHT) system piping in a nuclear power plant (NPP) could be subjected to large cyclic loading during seismic events. A circumferential crack, if present, would experience alternating tensile and compressive stress. The load ratio, R (ratio of minimum to maximum load) may be of the order of -1.0. Several investigators have studied this situation by carrying out fracture tests on compact tension (CT) specimens under reversible cyclic loading [1,2]. Test results clearly indicate that the fracture resistance reduces for a negative load ratio under cyclic loading. The basic reason, as understood, is that the crack tip remains sharp in the case of a ductile material in the presence of the alternating stress. Moreover voids ahead of the crack tip get sharpened [1]. This in turn leads to an apparent reduction in fracture resistance. On the other hand large crack tip blunting is observed in ductile material under monotonic loading. Marschall and Wilkowski, [2] have shown, for 28 in. diameter pipe, that there is a 20% reduction in maximum load carrying capacity and a 30% reduction in crack initiation load. These estimates were based on the cyclic J-resistance curve obtained from CT specimens. The cyclic fracture studies carried out by Kobayashi et al. [3] and Mogami et al. [4] have shown similar conclusions. However, the magnitude of the reduction of maximum load values is different. The most important conclusion from all these studies is that there is a significant reduction in fracture resistance of material under cyclic loading compared to monotonic loading. This reduction is greater at higher crack extensions. This clearly indicates that fracture resistance to tearing reduces significantly. Currently the effect of cyclic loading on the fracture resistance of material is not widely considered in piping integrity assessment. Leak-before-break (LBB) analysis guidelines given in NUREG 1061, [5], also do not account for the effect of cyclic loading on the J–R curve. Most of the LBB assessments performed to date are based on the fracture resistance curve obtained from monotonic loading tests.

A test program was initiated to quantify the fracture resistance under cyclic loading. The significance of cyclic load effects on fracture resistance of material depends on

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the flaw orientation with respect to pipe axis, load ratio, incremental plastic displacement between two consecutive cycles, loading displacement rate and temperature. The basic aim of the program is to determine the fracture properties, which can be used for fracture assessment of primary piping of Indian pressurized heavy water reactors (PHWR) under seismic loads. This test program involves testing and evaluation of the cyclic J–R curve using CT specimens.

Although seismic loads are cyclic and dynamic in nature, in the first phase of testing, cyclic and dynamic effects were separately studied. The cyclic J–R tests were conducted under quasi-static conditions. The dynamic effects were studied to a limited extent under monotonic loading conditions. The loading rate applied was moderate and was limited to the capacity of the testing machine used for the quasi-static tests. It is concluded that the effect of cyclic loading is more significant than the effect of the moderate loading rate under study. The objective of this paper is to bring out the effect of cyclic loading on the fracture resistance of the SA 333 Gr.6 carbon steel material used in the PHT system piping of Indian PHWR. The effects of load ratio and incremental plastic displacement between two consecutive loading and unloading have been brought out. In addition, the observation of a moderate loading rate effect will also be presented.

2. Experimental details

2.1. Material and specimens

The studies were carried out on specimens machined from carbon steel seamless pipes (406 mm outer diameter and 31 mm thick), made of SA333 Gr.6 grade material. The chemical compositions and tensile properties of the material are evaluated from specimens from the same pipe and are given in Tables 1 and 2, [6]. These properties were determined from the samples taken from the same pipe lots as used in Indian PHWR. Table 2 shows that loading rate affects the tensile properties to some extent.

CT specimens, of thickness 25 mm (80% of pipe thickness) and other dimensions conforming to the ASTM standard E1820 [7], were machined from the pipes. The specimens for the material study were machined in the L–C orientation with respect to the pipe axis. The L–C orientation means loading is in the longitudinal direction and the notch length is along the circumferential direction. This simulates the real condition in which circumferential cracks, in pipes, are subjected to axial stress induced by earthquake.

Table 1
Chemical composition in wt%

Material	C	Mn	Si	P	S	Al	Cr	Ni	N
SA333 Gr.6	0.14	0.9	0.25	0.016	0.018	<0.1	0.08	0.05	0.01

Table 2
Tensile properties of SA333 Gr.6 material

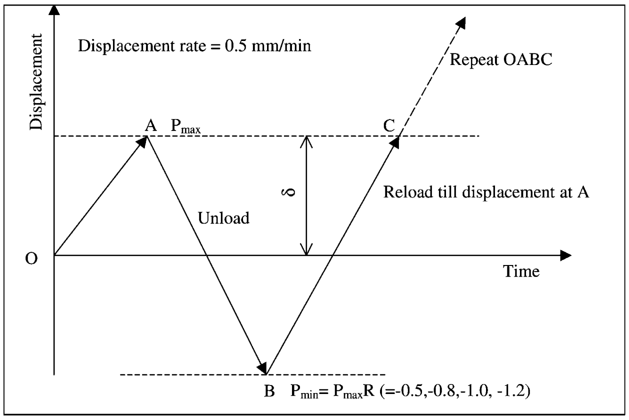
Strain rate (per s)	σ_y (MPa)	σ_u (MPa)	El (%)
3×10^{-3}	302	450	36.7
2×10^{-2}	370	490	36

2.2. Experimental procedure

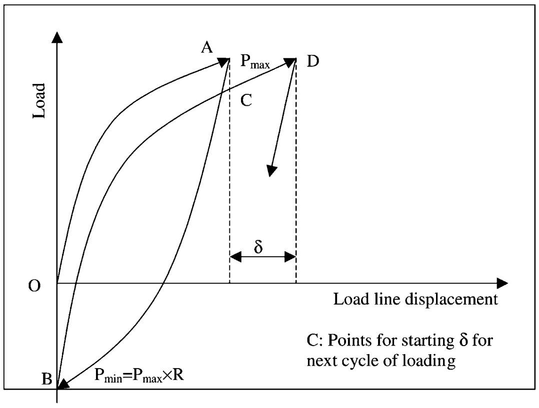
There is no testing standard currently available for cyclic J-integral testing. The tests were carried out as per the intent of ASTM E1820 and E1152 [7,8] with some modifications. The single specimen technique was followed for the determination of the cyclic J–R curve. The specimens were pre-cracked to a crack length-to-width ratio of $(a/W) \sim 0.6$ on a servo-hydraulic testing machine using the software-controlled stress intensity factor range (ΔK) decreasing test method. The ΔK after pre-cracking was maintained as 12–15 MPa$\sqrt{\text{m}}$.

The cyclic J-integral tests were carried out on the servo-electric machine. Each specimen after pre-cracking was subjected to loading to some pre-determined load line displacement (LLD) and unloading to a point such that the required load ratio could be maintained. In the next cycle, the loading was carried out to an increased LLD (called incremental plastic displacement) from the previous cycle and unloading to such a point to maintain the required load ratio. This cycle was repeated for 30–40 cycles to get sufficient data points for the determination of the cyclic J–R curve. The schematic sketch of the sequence of cyclic loading is shown in Fig. 1. Load versus LLD was recorded for each test. A typical Load–LLD curve obtained during a test is shown in Fig. 2. The areas under the upper half of the LLD-axis of the Load–LLD plot are used for evaluating the cyclic J–R curve.

One of the quantities of interest is the initiation fracture toughness (J_i). The value of J_i for ductile material is usually determined from the J–R curve using a blunting line or stretch zone width (SZW) approach. For determination of the blunting line several criteria are available, for example, ASTM, EGF recommendations, etc. For a very ductile material like SA333 Gr.6, the value of J_i strongly depends on the choice of the blunting line equation given by various investigators. Since critical SZW is known as a material property, therefore, for very ductile material SZW approach is appropriate. SZW can be explained as when the material is subjected to continuously increasing load, the material ahead of the crack tip deforms plastically thereby leading to the blunting of the sharp crack. The blunting ahead of the crack tip depends on the ductility of the material. The blunting of the crack tip increases with increasing load or displacement until tearing of the material starts. There is an



(a)



(b)

Fig. 1. Loading scheme for cyclic J tests: (a) loading sequence for cyclic J test at negative load ratio; (b) sketch showing load versus load line displacement.

apparent increase in the crack length due to blunting. This apparent increase in crack length is called SZW. The maximum blunting just prior to initiation of tearing is termed as the critical SZW. The initiation fracture toughness (J_i), for cyclic load tests was evaluated at the crack growth

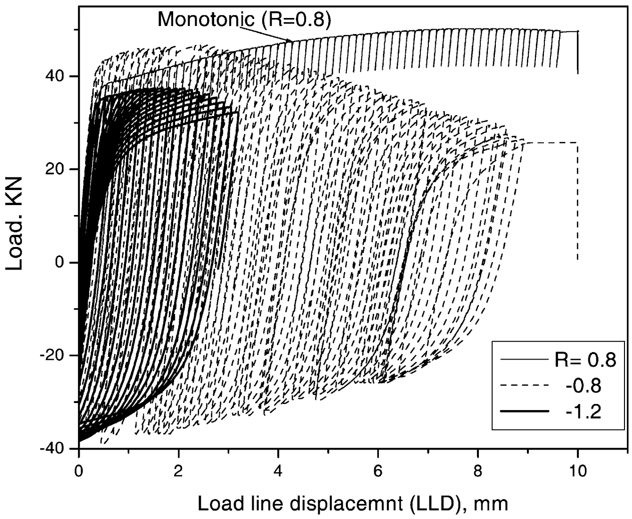


Fig. 2. Typical load–load line displacement curve at various load ratio.

corresponding to the critical SZW. The SZW value used was in turn determined from the quasi-static monotonic fracture tests on the same material. This SZW will be denoted as SZW_m. Thus the value of J_i evaluated cannot be really called an initiation fracture toughness for cyclic tests. However, this helps to quantify the relative effects in and around the real initiation fracture toughness. Moreover, in cyclic tests features like blunting and stretching are difficult to identify because they get destroyed due to repeated alternating loading. The J_i value is evaluated from the intersection of the cyclic J–R curve and the offset line at a crack extension equal to the critical SZW_m of the material.

The tests were carried out at room temperature and air environment. In cyclic tests, the effects of the following parameters were studied.

1. Load ratio (R) = 0, −0.5, −0.8, −1.0, and −1.2
2. Incremental plastic displacement (δ) = 0.15, 0.3 and 0.5 mm

In the monotonic dynamic tests, the effects of loading displacement rate were limited to 2 and 0.2 mm/min.

3. Test results

The test observations are presented here, with respect to parameters such as load ratio, incremental plastic displacement, and loading displacement rate. The effect of load ratio and incremental plastic displacement were studied under cyclic loading and loading displacement rate under monotonic loading.

3.1. Effect of load ratio (R)

Tests were conducted for different load ratio (the ratio of minimum to maximum load per cycle). The selected load ratios were 0, −0.5, −0.8, −1.0 and −1.2. Load–LLD plots for various load ratio are shown in Fig. 2. For comparison, the curve for a standard monotonic fracture test is also added. This is usually at a load ratio of 0.8. It is observed that the specimens tested at load ratios of 0.8 and 0 show almost identical fracture resistance behaviour (Fig. 3). Specimens tested for load ratios of −0.5, −0.8, −1.0 and −1.2 attain maximum loads at lower LLD than that of the specimens tested for $R = 0$. It is also observed that the load bearing capacity of the specimens tested at negative load ratio drops at a faster rate after attainment of maximum load. In other words it can be inferred that the increase in compressive loads during alternating stress decreases the load sustaining ability of the material as tearing progresses and hence results in a significant reduction in energy absorption capacity.

The corresponding J–R curves obtained for different load ratios are shown in Figs. 3–5 for $\delta = 0.5$ mm, 0.3 and 0.15 mm, respectively. These figures show that the J–R

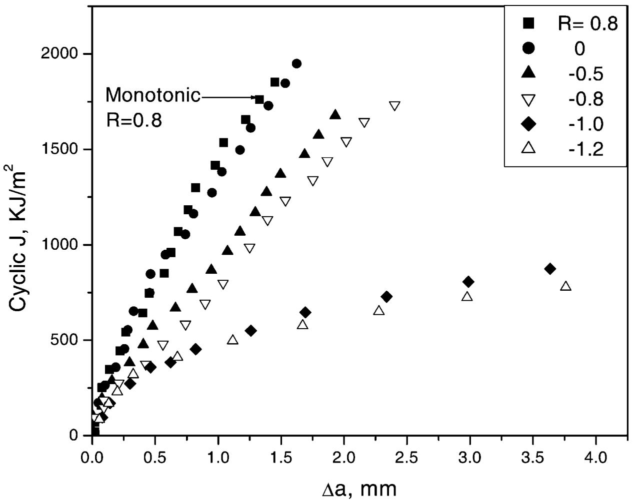


Fig. 3. Effect of load ratio on fracture resistance of material at $\delta = 0.5$ mm.

curves reduces with decrease in load ratio for the given incremental plastic displacement. For the purpose of comparison, let us select the crack growth (Δa) of 1.5 mm. At this Δa, the value of J, for $R = 0$ is 1810 KJ/m^2 and is invariant with change in δ. However, for $R = -1.0$, the values of J are 609, 448 and 393 KJ/m^2 for incremental plastic displacements of 0.5, 0.3, and 0.15 mm, respectively. It is quite apparent that irrespective of the values of δ, there is a significant reduction in J as load ratio becomes more and more negative. On the other hand the change is insignificant if the load ratio remains positive. This can be observed for J–R curves at load ratios of 0 and 0.8 (standard monotonic fracture test).

The initiation fracture toughness (J_i) is evaluated corresponding to $\Delta a = \mathrm{SZW_m}$ as discussed in Section 2.2. The variation of J_i with load ratio is shown in Table 3 and Fig. 6. The significant reduction in fracture resistance as load ratio decreases is observed at a crack extension of 1.5 mm and is shown in Fig. 7.

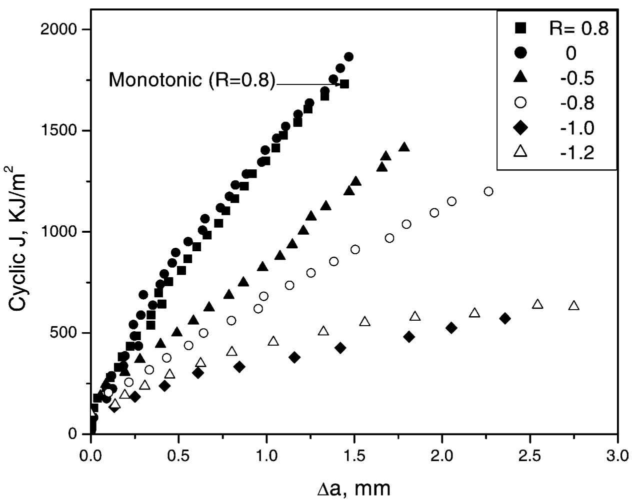


Fig. 4. Effect of load ratio on fracture resistance of material for $\delta = 0.3$ mm.

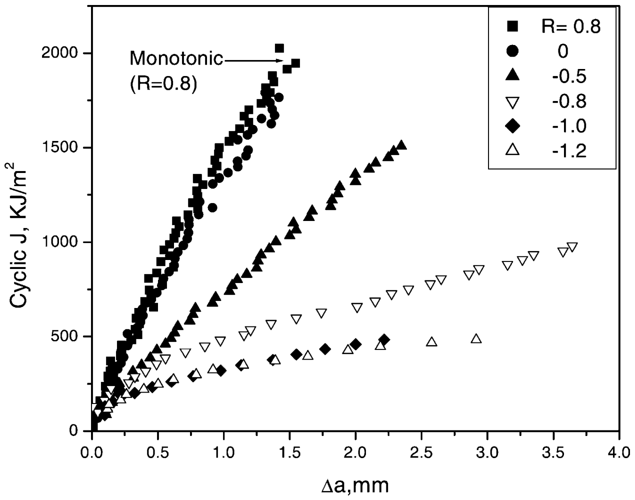


Fig. 5. Effect of load ratio on fracture resistance of material for given $\delta = 0.15$ mm.

3.2. Effect of incremental plastic displacement

The cyclic tests were conducted at three incremental plastic displacement (δ) values of 0.15, 0.3 and 0.5 mm. The Load–LLD plot is shown in Fig. 8. The figure shows the same behaviour for incremental plastic displacements of 0.3 and 0.5 mm in terms of attainment of maximum load for a given LLD. The incremental plastic displacement of 0.15 mm shows attainment of maximum load at a lower LLD compared to that for 0.3 or 0.5 mm.

The corresponding J–R curves for different incremental plastic displacements are shown in Figs. 9–13 for different R ratios. Fig. 9 shows the J–R curve for $R = 0$; it is observed that the effect of δ is insignificant and the minor differences are within the experimental scatter.

Fig. 10 shows that the J–R curve decreases with the decrease in incremental plastic displacement for a given load ratio, $R = -0.5$. For negative R ratio, the effect of δ becomes more pre-dominant. The values of J are compared in Table 3 for two salient points viz. $\Delta a = \mathrm{SZW_m}$ (J_i) and $\Delta a = 1.5$ mm.

Initiation fracture toughness (J_i) is evaluated corresponding $\Delta a = \mathrm{SZW_m}$ as discussed in Section 2.2.

3.3. Effect of loading displacement rate

The tests were carried out under monotonic conditions with loading displacement rates of 0.2 and 2.0 mm per minute and a load ratio 0.8 (i.e. 20% unloading). Load–LLD curves obtained during the tests are shown in Fig. 14. This figure shows that the specimen tested at the higher loading displacement rate (2 mm/min) attains a maximum load at a lower LLD, compared to the one tested at a lower loading displacement rate (0.2 mm/min). Maximum load is attained at LLD of 7.5 and 5.5 mm for displacement rates of 0.2 and 2 mm/min, respectively. The corresponding J–R curves are given in Fig. 15. The figure shows that the effect

Table 3
Effect of R and δ, on J_i corresponding to SZW_m and J corresponding to $\Delta a = 1.5$ mm

Load ratio (R)	Values of J in KJ/m^2					
	$\delta = 0.5$ mm		$\delta = 0.3$ mm		$\delta = 0.15$ mm	
	$\Delta a = SZW_m$	$\Delta a = 1.5$ mm	$\Delta a = SZW_m$	$\Delta a = 1.5$ mm	$\Delta a = SZW_m$	$\Delta a = 1.5$ mm
0.8	295	1895	312	1787	286	1958
0	309	1809	325	1820	254	1811
−0.5	258	1337	258	1127	213	1049
−0.8	195	1164	222	901	178	586
−1.0	192	609	160	449	139	407
−1.2	198	559	173	553	153	393

$SZW_m = 0.15$ mm, determined from specimens of monotonic fracture test (see Section 2.2).

of loading displacement rate on the $J-R$ curve is more pronounced at higher crack extension (Δa). Tensile properties also do not vary significantly for a similar range of displacement rate.

4. Discussion

The common observation from all the cyclic test results is that as R-ratio becomes negative, the difference between the energy absorption capacity reduces, which is manifested directly in a lowering of fracture resistance ($J-R$). The more negative is the R-ratio, the more is the reduction in fracture resistance. This observation is consistent with other investigators, Rudland et al. [1], Marschall et al. [2], Joyce James et al. [9] and Soek et al. [11]. The magnitude of the reduction increases as crack tearing progresses. One of the apparent observations is that, during the entire course of a test, the crack tip remains very sharp because of compressive loading. This is unlike the observations under quasi-static monotonic tests on the material, where there was large blunting of the crack tip. The sharpened crack tip leads to high constraint to plastic zone growth and hence high normal stress at the crack tip. This in turn implies that there would be an apparent reduction in the fracture resistance since a larger fraction of the input energy is going towards tearing of a surface rather than plastification.

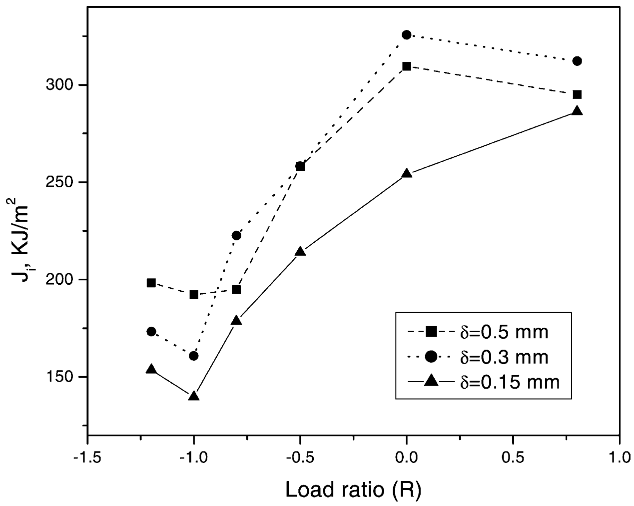


Fig. 6. Effect of load ratio on initiation fracture toughness.

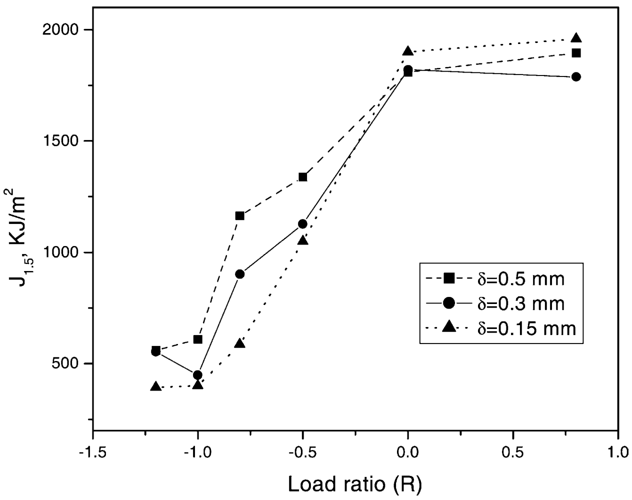


Fig. 7. Effect of load ratio on fracture toughness at crack extension of 1.5 mm.

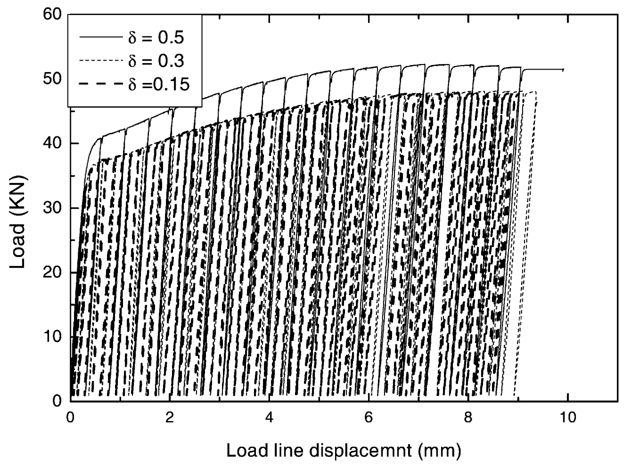


Fig. 8. Load–Load line displacement plot for various incremental plastic displacement δ at given load ration $R = 0$.

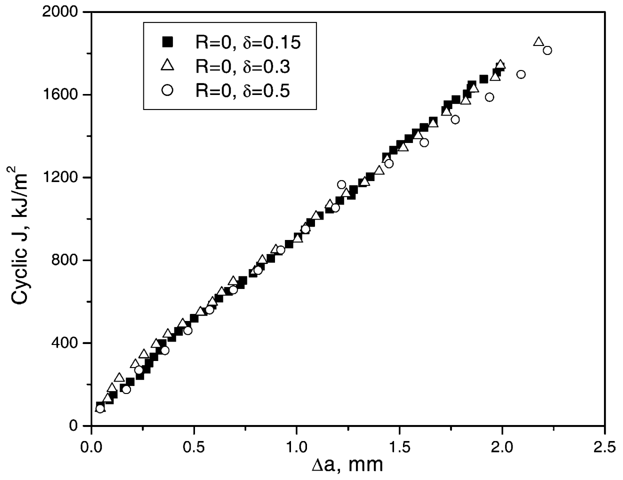


Fig. 9. Effect of incremental plastic displacement δ on fracture resistance of material at load ratio $R = 0$.

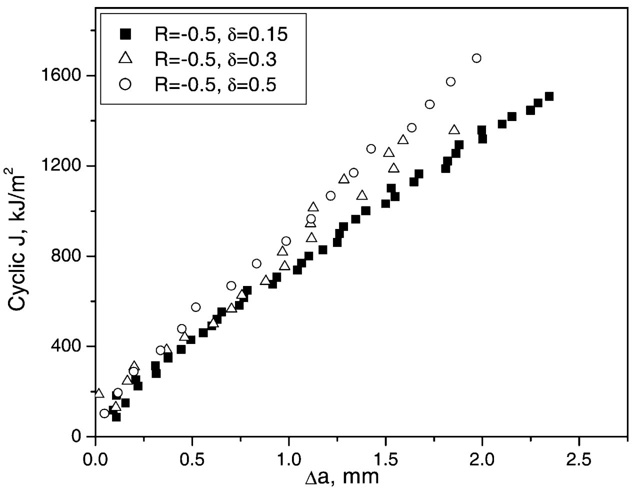


Fig. 10. Effect of incremental plastic displacement δ on fracture resistance of material at load ratio $R = 0.50$.

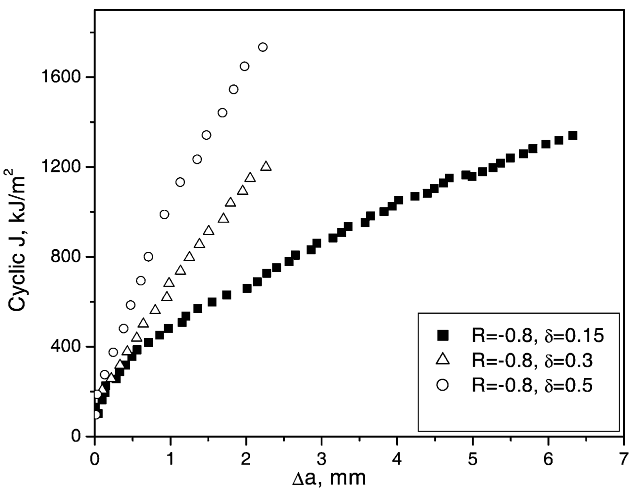


Fig. 11. Effect of incremental plastic displacement δ on fracture resistance of material at load ratio $R = -0.8$.

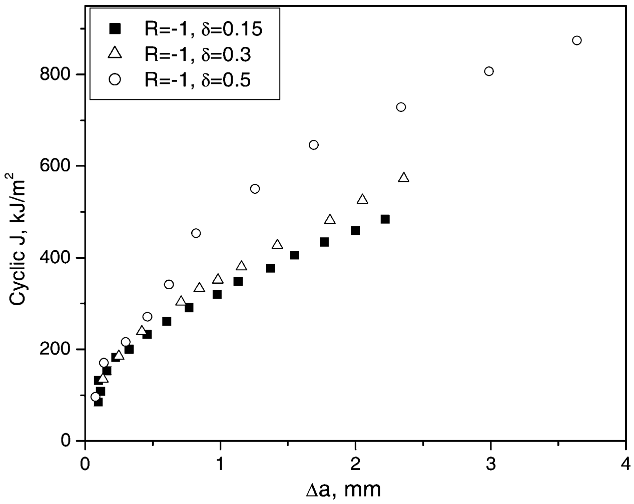


Fig. 12. Effect of incremental plastic displacement δ on fracture resistance of material at load ratio $R = -1.0$.

Apart from this, some other investigators, such as Rudland et al. [1], have also observed that there is considerable sharpening of voids ahead of a crack tip under alternating tensile and compressive stresses. This in turn facilitates void coalescence and hence reduction in fracture resistance.

It was also observed that for $R < -1.0$, the change in J–R curves is insignificant with respect to those at $R = -1.0$. A similar observation is reported by Rudland et al. [1] for SA106 Gr.B carbon steel pipe material. They have reported that lower bound values of J–R curves are achieved at $R = -0.8$.

In cyclic tests apart from R-ratio, another parameter of importance is the incremental plastic displacement (δ). The general observation is that for lower values of δ, at any given negative R-ratio, the reduction in fracture resistance is more whereas for positive R-ratio the effect is insignificant.

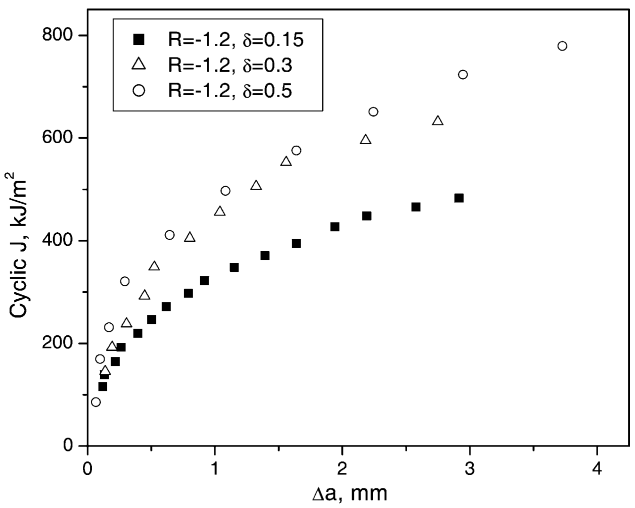


Fig. 13. Effect of incremental plastic displacement δ on fracture resistance of material at load ratio $R = -1.2$.

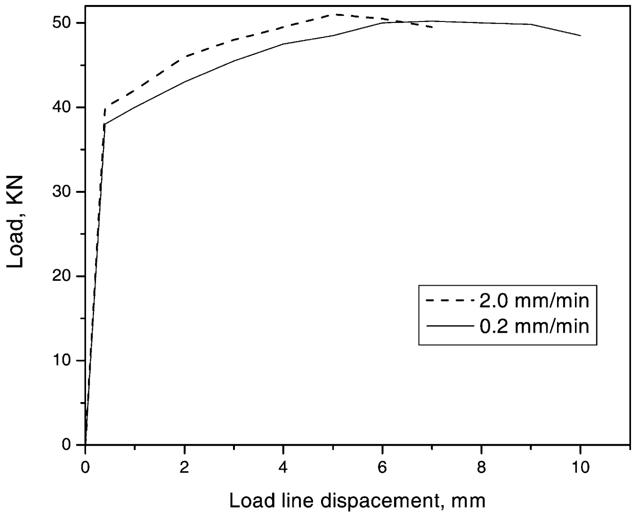


Fig. 14. Load–load line displacement for different loading rate.

This observation can be partly explained by considering the fact that during cyclic loading, two mechanisms are concurrently taking place; one is cyclic degradation and the other is fatigue crack growth. At the lower δ values, the numbers of cycles to reach any LLD values are more and hence this leads to more contribution from fatigue crack growth and therefore a higher effective crack growth for the same LLD. However, gross observation shows that there is a strong synergy between the cyclic fracture degradation and fatigue crack growth. This is so because at $R = 0$, the effect of δ is not observed at all. Therefore analytical predictions based on superposition of ductile tearing growth alone and fatigue crack growth alone are not likely to be accurate. Marshall et al. [2], Mc Clung et al. [10] and Soek et al. [11] have also shown the degradation in fracture toughness of a material for a negative load ratio and decrease in values of incremental plastic displacement.

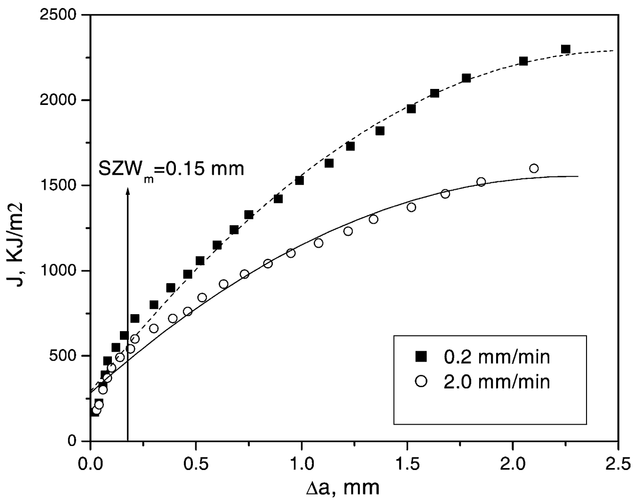


Fig. 15. Effect of loading displacement rate on fracture resistance of material.

In the current testing program only two loading rates were studied. It is quite apparent that the effect of loading displacement rate is not very significant on fracture resistance behaviour of the material compared to cyclic effects. Similar, observations have been reported by Rudland et al. [1] for carbon steel materials. It can be concluded that for fracture assessment of piping components due to seismic loads, the important factor to be considered is the degradation in fracture toughness of material due to cyclic loading.

5. Conclusions

The results of the study on the effect of cyclic loading on the fracture resistance of the material can be summarized as:

1. There is a significant difference between the fracture resistance of the material under monotonic and cyclic loading.
2. Negative load ratio has a significant effect on the cyclic $J-R$ curve of the material. The reduction in cyclic $J-R$ curve becomes more pronounced for load ratio $(R) < 0$. During seismic events, the likely value of R is approximately -1.0. It can also be concluded that the lower bound $J-R$ curve for SA333 Gr.6 corresponds to $R = -1.0$.
3. Incremental plastic displacement also significantly affects fracture resistance behaviour of the material. The incremental plastic displacement signifies the effect of number of cycles during an earthquake for a given load ratio.
4. Higher loading displacement rate degrades the fracture resistance behaviour of the material.

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