QUASI-CYCLIC FRACTURE STUDIES ON NARROW GAP WELDED STAINLESS STEEL STRAIGHT PIPES

S. Vishnuvardhan[1], P. Gandhi[1], G. Raghava[1], M. Saravanan[1], DM. Pukazhendhi[1], Sumit Goyal[2], Sunil Satpute[2], Suneel K. Gupta[2], Vivek Bhasin[2] and K. K. Vaze[2]
[1]CSIR - Structural Engineering Research Centre, Taramani, Chennai, INDIA - 600 113
[2]Reactor Safety Division, Bhabha Atomic Research Centre, Mumbai, INDIA - 400 085
E-mail of corresponding author: svvardhan@sercm.org

ABSTRACT

In order to study the crack growth and cyclic tearing instability, which are required for realistic assessment of Leak Before Break applicability, experimental investigations were carried out on five numbers of narrow gap welded stainless steel straight pipes under quasi-cyclic loading. This paper gives details of the test set-up arrangement and test procedure and discusses the test results. All the pipes had circumferential through-wall notch in the weld. The material used in the studies was SA 312 Gr. TP 304LN stainless steel conforming to ASTM A 312/ A 312 M - 09 standard. The specimens were initially fatigue pre-cracked under four point bending in order to produce a sharp crack front. Subsequently, fracture tests were conducted under quasi-cyclic loading. Out of the five specimens, one specimen was tested under a combination of load- and displacement-controlled loading and the remaining four specimens were tested under load-control. During the fracture tests, load, load-line displacement, crack mouth opening displacement, deflection of the pipe (at five locations), and the surface crack growth were continuously monitored. Based on the load-controlled experimental results, material specific plot between cyclic load amplitude (as a percentage of maximum load carrying capacity of a specimen under monotonic fracture) and number of cycles to failure was obtained. The test results indicate that the piping components subjected to quasi-cyclic loading may fail in very less number of loading cycles even when the load amplitude is sufficiently below the monotonic fracture/collapse load. These studies will be helpful in realistic assessment of Leak Before Break applicability in NPP piping components subjected to cyclic loading.

Keywords: Quasi-cyclic fracture; straight pipe; TP 304LN stainless steel; narrow gap weld; through-wall notch; four point bending; Leak Before Break assessment; crack growth; tearing instability

INTRODUCTION

Piping components of Primary Heat Transport (PHT) system of Nuclear Power Plants (NPPs) are expected to experience dynamic cyclic loads during an earthquake event. Fully reversible cyclic loading is known to significantly reduce the fracture resistance and hence the load carrying capacity of cracked components. The instability of the component under cyclic loading depends on the load history and parameters such as load ratio, load range and number of load cycles. Adequate protection of piping components from the effects of earthquake requires detailed knowledge of strength and deformation characteristics of the components under cyclic loads. Available analytical methods based on the principles of mechanics are often inadequate to provide reliable information on these characteristics. The current Leak Before Break (LBB) assessment of piping components is based primarily on the monotonic fracture tearing instability and the effect of cyclic loading on fracture resistance of components is not considered. For realistic assessment of LBB applicability, experimental investigations under cyclic loads are essential. Cyclic experiments are useful to provide basic information on component behaviour, including data on strength and stiffness characteristics, deformation capacities, cyclic hardening or softening effects and deterioration behaviour at large deformation. However, very few experimental results are available in literature on ductile tearing of straight pipes under quasi-cyclic loading. Miura et al. [1] conducted 12 tests on carbon steel pipes with through-wall circumferential crack under cyclic loading in load-controlled mode at room temperature. Rudland et al. [2] carried out two tests on carbon steel pipes with through-wall circumferential crack under cyclic loading in displacement-controlled mode. The *J-R* curve under cyclic loading was found to show dramatic reduction in toughness when compared to monotonic fracture. Venu Kumar et al. [3] conducted cyclic tearing and crack growth studies on 15 carbon steel and eight stainless steel pipes with through-wall circumferential crack, under load and displacement-control modes. The objective of the study was to understand the fracture tearing instability and to evaluate crack growth rate (*da*/*dN*) and crack growth resistance (*J-R*) under low-cycle fatigue with ductile tearing. Vishnuvardhan et al. [4] reported fracture studies on 170 mm nominal outer diametre (OD) Shielded Metal Arc

(SMA) and Narrow Gap (NG) welded stainless steel straight pipes having circumferential through-wall crack in the weld. The crack growth and tearing instability behaviour of the pipes was studied under load-, displacement- and combination of load- and displacement-control loading.

The objective of the present studies is to understand the crack growth and cyclic tearing instability of 324 mm OD TP 304LN stainless steel pipes used in PHT system of Advanced Heavy Water Reactors (AHWR). Detailed experimental investigations were carried out on six NG welded pipes having circumferential through-wall crack in the weld. The studies were carried out under quasi-cyclic loading, i.e., at slow rates of loading which has substantial effect on the fracture resistance of the component. It has been reported that the slow cyclic testing, compared to dynamic testing, results in a small decrease in strength and increase in rate of deterioration; thus, the results from these studies can be considered as conservative for the purpose of assessment [5]. The investigations have been carried out either under load-control or under a combination of load- and displacement-controls. The details of fracture tests and the results are presented in this paper.

EXPERIMENTAL STUDIES

Material Properties

The pipe specimens used in the present studies were made of TP 304LN stainless steel conforming to ASTM A 312/A 312 M - 09 standard [6]. Actual composition of the material and the specified values as per ASTM A 312/A 312 M - 09 standard are given in Table 1. The yield strength and ultimate tensile strength are 345 MPa and 521 MPa respectively. The percentage elongation is 65 and the Young's modulus is 195 GPa.

Table 1: Chemical composition of TP 304LN stainless steel

Element	C	Mn	P	S	Si	Ni	Cr	N
% weight	0.03	1.78	0.024	0.007	0.38	9.11	18.26	0.06
ASTM A 312 / A 312M - 09 (max.)	0.03	2.00	0.045	0.030	1.00	8 - 12	18 - 20	0.10 - 0.16

Specimen Details

The dimensional details of test specimens are given in Table 2. Figure 1 shows the schematic of a typical straight pipe with circumferential through-wall notch in the NG weld. Totally five specimens were tested under cyclic loading under four point bending. All the pipes had circumferential through-wall notch in the weld. The length of the pipes varied from 4856 mm to 5090 mm. The average thickness of the pipes varied from 23.3 mm to 26.1 mm. The initial length, width and angle of notch were approximately 170 mm, 3.0 mm and 60° respectively.

Table 2: Details of test specimens

Specimen No.	Diameter of pipe (mm)	Thickness of pipe (mm)	Length of pipe (mm)	Notch dimensions				
				A (mm)	$2C$ (mm)	R (mm)	W (mm)	2θ (°)
QCSP-12-60-TWC-NGW-C1	324	25.6	4866	TW	169	0.1	3.0	59.8
QCSP-12-60-TWC-NGW-L2	324	26.1	5090	TW	168	0.1	3.0	59.4
QCSP-12-60-TWC-NGW-L3	324	25.0	4943	TW	167	0.1	3.0	59.1
QCSP-12-60-TWC-NGW-L4	324	25.1	4856	TW	168	0.1	3.0	59.4
QCSP-12-60-TWC-NGW-L5	324	23.3	4940	TW	170	0.1	3.0	60.1

TW: Through-wall; a: Notch depth; $2C$: Notch length; R: Tip radius; W: Notch width; 2θ: Initial notch angle

Fatigue Pre-cracking

Prior to the fracture experiments, all the specimens were fatigue pre-cracked under four point bending using a ±1000 kN capacity servo-hydraulic actuator. The inner and outer spans during fatigue pre-cracking were 1200 mm and 4000 mm respectively. The fatigue pre-cracking was carried out by applying sinusoidal constant

amplitude cyclic loading at a frequency of 0.9 Hz. The minimum and maximum load values were 16 kN and 160 kN respectively. The maximum load was kept within 20% of the Theoretical Plastic Collapse Load (TPCL) of the pipe. The TPCL was calculated using the following equation.

$$P_L = \frac{16\sigma_f {R_m}^2 t}{Z-L}\left(cos\frac{\theta}{4} - \frac{1}{2}sin\frac{\theta}{2}\right) \quad (1)$$

Where R_m is the mean radius of the pipe, t is the thickness of the pipe, σ_f is the flow stress of the material which is defined as the mean of yield and ultimate strengths, Z and L are outer and inner spans, θ is the half crack angle. The purpose of fatigue pre-cracking was to produce a sharp crack front. Fatigue pre-cracking was carried out till a crack growth of at least 2 mm was reached at both the notch tips. Video Microscope was used to monitor the surface crack growth during fatigue pre-cracking at regular intervals of fatigue cycles. Figure 2 shows the test set-up for fatigue pre-cracking on a stainless steel pipe. Table 3 gives details of fatigue pre-cracking.

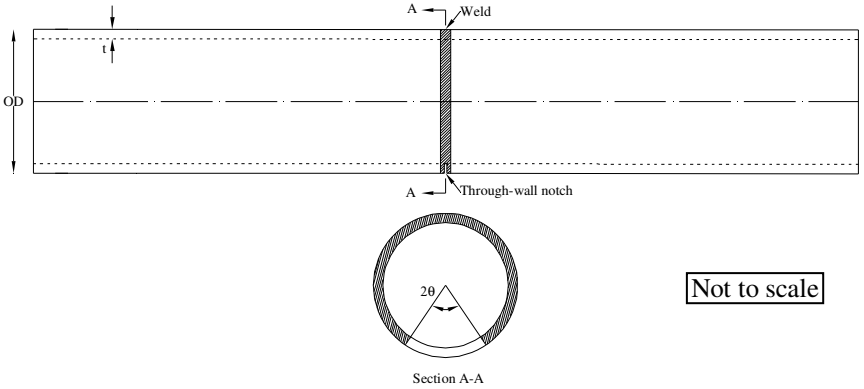

Fig. 1: Typical straight pipe with circumferential through-wall notch in the weld

Fig. 2: Test set-up for fatigue pre-cracking on a stainless steel pipe

Fracture Experiments

Fracture experiments were conducted, subsequent to fatigue pre-cracking, using a ±2000 kN capacity servo-hydraulic actuator. The pipes were supported on pedestals over a hinge support on one side and a roller support on the other. At the two support points, the upward movement of ends of pipes was arrested by placing a stiffened plate over the pipes and holding it down using high strength steel tie rods which were in turn connected to the supporting pedestal. Roller support was provided between the pipe and the top stiffened plate at one support point and hinge support was provided at the other support point, as shown in Fig. 3, such a way that a roller support on the top of the pipe coincides with a hinge support at the bottom at one end and vice versa at the other end. A

rigid steel distribution beam was fixed to the actuator and the same was used to apply two point loading. The distribution beam was supported on steel curved blocks at the two loading points to transfer the load smoothly without causing local denting of the pipes. The pipes were held to the load distribution beam using rigid plates at the top of distribution beam and below the pipes and connecting them using high strength tie rods. This arrangement was required to ensure proper application of reverse cyclic loading. The servo-hydraulic actuator was fixed to a steel reaction frame, which was connected to the strong floor of the laboratory. Figure 3 shows a schematic view of the cyclic fracture experimental set-up. Figure 4 shows a close-up view of cyclic fracture experiment on a straight pipe.

Table 3: Details of fatigue pre-cracking

Specimen No.	Span (mm)		Frequency (Hz)	Number of cycles	Crack length at the end of fatigue pre-cracking (mm)		Crack angle at the end of fatigue pre-cracking (°)
	Inner	Outer			Tip A	Tip B	
QCSP-12-60-TWC-NGW-C1	1200	4000	0.9	14000	2.15	3.38	61.7
QCSP-12-60-TWC-NGW-L2	1200	4000	0.9	18000	3.50	2.50	61.5
QCSP-12-60-TWC-NGW-L3	1200	4000	0.9	17000	2.65	3.00	61.1
QCSP-12-60-TWC-NGW-L4	1200	4000	0.9	16305	2.00	3.00	61.2
QCSP-12-60-TWC-NGW-L5	1200	4000	0.9	15000	2.75	2.60	62.0
Cyclic load: Minimum = 16 kN, Maximum = 160 kN							

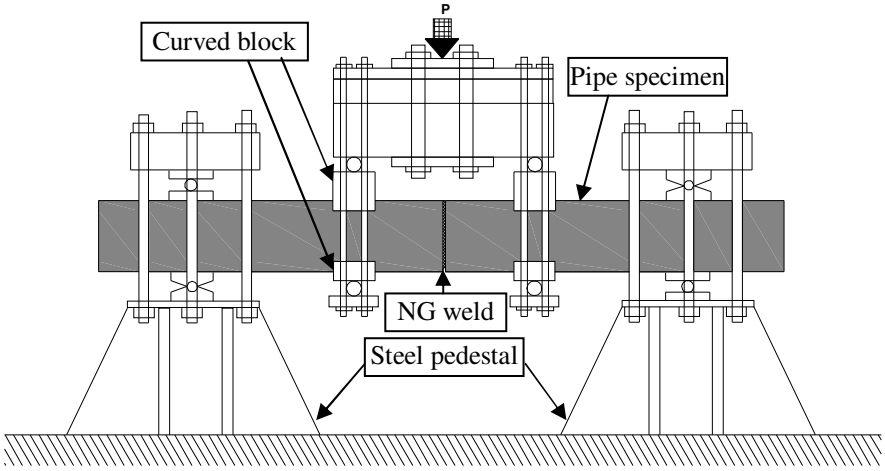

Fig. 3: Schematic view of the cyclic fracture test set-up

During the fracture experiments, the pipe specimens were instrumented to obtain applied load, load-line displacement (LLD), Crack Mouth Opening Displacement (CMOD), crack extension and deflection of pipe. The applied load was measured directly using strain-gauge-based load cell of ±2000 kN dynamic capacity connected to the actuator. The load-line displacement was measured by the in-built LVDT of the actuator. CMOD was measured using specially fabricated clip gauges. Strain-gauge-based clip gauges with opening of 3 - 30 mm and 15 - 80 mm were used and these were calibrated prior to the experiments to the required range of opening. The clip gauges were connected to the data acquisition system and the data was acquired continuously. Image Processing Technique (IPT) was used for online monitoring of surface crack growth. The IPT consisted of three CCD cameras interfaced to a computer system with image acquiring software. Two cameras were focused towards the crack tips to obtain the crack growth images. The third camera was focused towards the digital display of the digital controller of the actuator to record the load and actuator displacement values corresponding to the crack growth at various stages of loading. A grid of 5 mm spacing was made on the pipe near the crack tips to obtain the crack growth data. The deflection of the pipe was measured by means of ± 100 mm and ± 75 mm range LVDTs kept along the span of the pipe. The LVDTs were connected to a high speed data acquisition system interfaced to a computer.

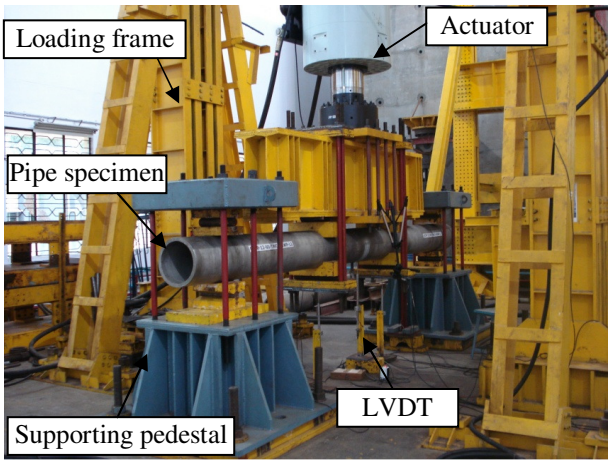

Fig. 4: Close-up view of cyclic fracture experiment on a straight pipe

Out of the five specimens, one specimen was tested under a combination of load- and displacement-controls and the remaining specimens were tested under load-control. In the case of the specimen tested under a combination of load- and displacement-controls, the compression part of the cyclic load was applied under displacement-control and the corresponding load value was noted. Then, tensile load equal in magnitude was applied under load-control, i.e., keeping load ratio (R) equal to -1, thus, completely reversed cyclic loading was achieved. The rate of loading was varied from 0.040 mm/sec to 0.125 mm/sec during displacement-control and from 5 kN/sec to 13 kN/sec during load-control. The applied displacement was increased gradually at the rate of three mm per cycle. The maximum and minimum load values in the four load-controlled fracture tests were ±650 kN, ±560 kN, ±510 kN and ±590 kN corresponding to 90%, 80%, 70% and 85% of the static load carrying capacity of similar specimen respectively. The rate of loading was varied from 3 minutes/cycle to 4 minutes/cycle. Figures 5 (a) and (b) show typical loading history used during the cyclic fracture experiments.

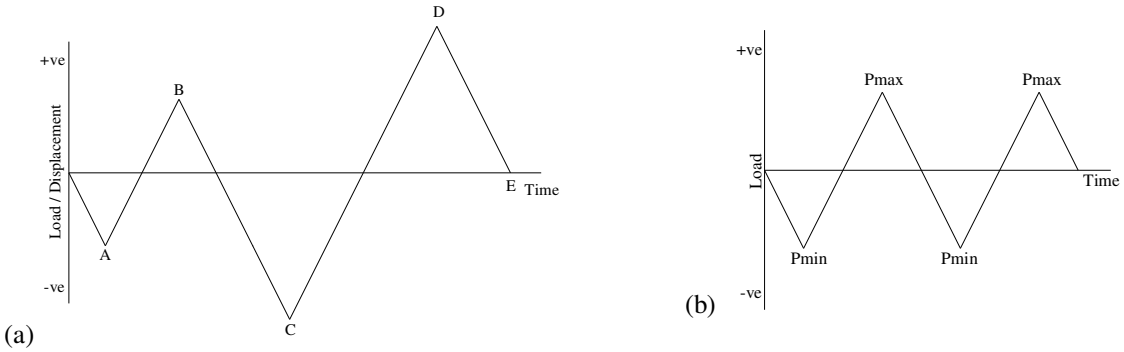

Fig. 5: Loading history used for cyclic fracture experiments under
(a) Combined load- and displacement-control (b) Load-control

RESULTS AND DISCUSSION

Table 4 gives details of test parameters and results of fracture experiments [7]. During the fracture experiments, load, LLD, CMOD, deflection of the pipe (at five locations), and the surface crack growth were continuously monitored. Figures 6 and 7 show typical load versus LLD curves for specimens tested under combined load- and displacement-control loading and load-control respectively. The relation between applied load and load-line displacement forms a hysteresis loop during each cycle. The area of the loop increased gradually with the number of loading cycles and it increased very rapidly at a few cycles before failure in the case of specimens tested under load-controlled loading. Figure 8 shows typical variation of load with number of cycles for the specimen subjected to combined load- and displacement-control loading and Fig. 9 shows typical variation of LLD with number of cycles for the specimen subjected to load-controlled loading. Figures 10 and 11 show typical load versus CMOD curves for the specimens tested under combined load- and displacement-control loading and load-control respectively. The variation of CMOD was also similar to the LLD.

Table 4: Test parameters and results of fracture experiments

Specimen No.	Type of loading	Mode of control	Applied load/LLD	Number of cycles to failure	Final crack angle (°)
QCSP-12-60-TWC-NGW-C1	Quasi-cyclic	Combined	Incremental	28	114.2
QCSP-12-60-TWC-NGW-L2		Load	±650	21	94.0
QCSP-12-60-TWC-NGW-L3		Load	±560	72	110.6
QCSP-12-60-TWC-NGW-L4		Load	±510	121	126.0
QCSP-12-60-TWC-NGW-L5		Load	±590	41	106.0

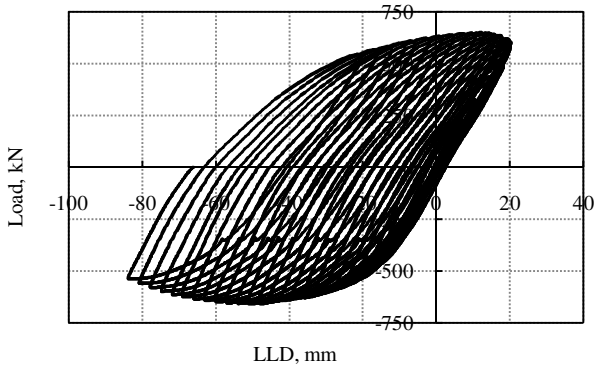

Fig. 6: Load versus LLD curve for the specimen QCSP-12-60-TWC-NGW-C1

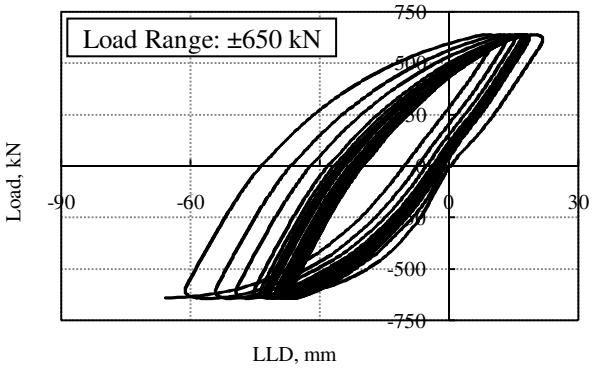

Fig. 7: Load versus LLD Curve for the specimen QCSP-12-60-TWC-NGW-L2

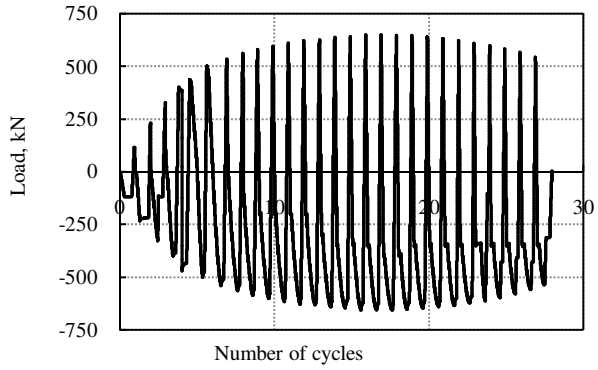

Fig. 8: Variation of load with number of cycles for the specimen QCSP-12-60-TWC-NGW-C1

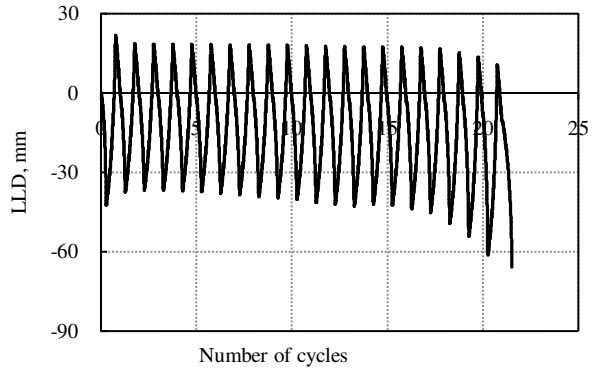

Fig. 9: Variation of LLD with number of cycles for the specimen QCSP-12-60-TWC-NGW-L2

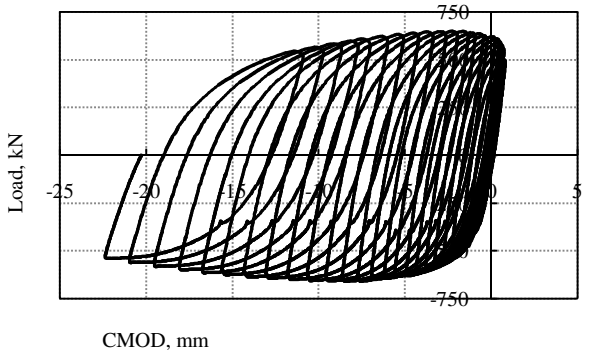

Fig. 10: Load versus CMOD curve for the specimen QCSP-12-60-TWC-NGW-C1

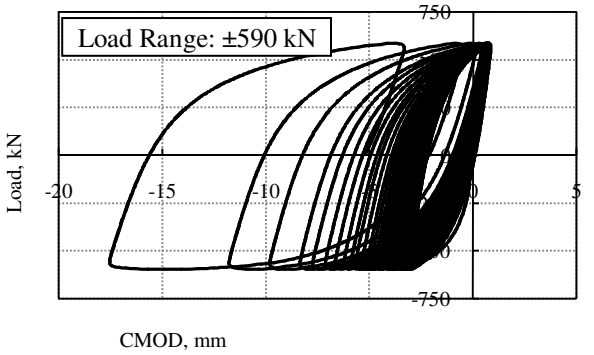

Fig. 11 Load versus CMOD curve for the specimen QCSP-12-60-TWC-NGW-L5

The fracture experiments were continued till failure of the specimens. The failure was implied when the crack grew in an unstable manner or the pipe collapsed making it incapable of carrying any further load. The number of cycles to final failure of the specimen tested under combined load- and displacement-control loading was 28. The total crack length corresponding to final failure was 325 mm. Among the remaining four pipes tested under load-control, specimen which was subjected to ±650 kN (85% of static load carrying capacity) withstood minimum number of cycles, i.e., 21 cycles. The number of cycles to failure was dependent on the applied load/displacement amplitude. The values of total crack length corresponding to final failure of the specimens tested under load-control loading of 90%, 80%, 70% and 85% of the static load carrying capacity of the specimen were 270 mm, 390 mm, 410 mm and 370 mm respectively. The corresponding crack angles at the end of fracture tests are given in Table 4.

Figure 12 is a plot of the cyclic load amplitude (as a percentage of maximum load carrying capacity of a specimen under monotonic fracture) and number of cycles to failure of four specimens tested under load-control. The test results indicate that the piping components may fail in limited number of loading cycles with the load amplitude sufficiently below the monotonic fracture/collapse load. The failure load reduces to 82% and 74% of the monotonic failure load for withstanding 50 and 100 high amplitude loading cycles respectively. Figure 13 shows crack growth versus number of cycles curves for all the specimens. All the specimens tested under load-control, failed by ductile tearing till sufficient length of crack was developed, followed by sudden rupture and collapse. Figure 14 shows deflected shape of a typical NG welded specimen. Figures 15 (a) and (b) show close-up views of crack location for one of the pipes at the end of fracture experiment.

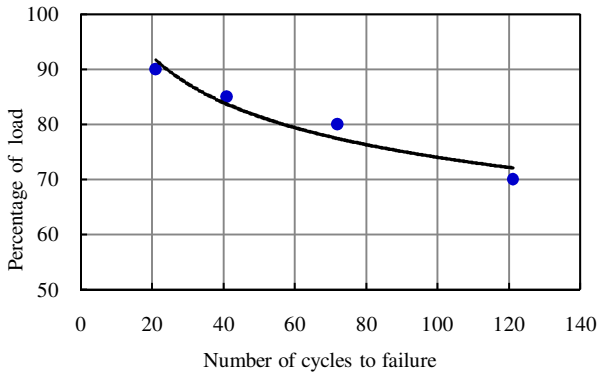

Fig. 12 Normalised load amplitude versus number of cycles to failure

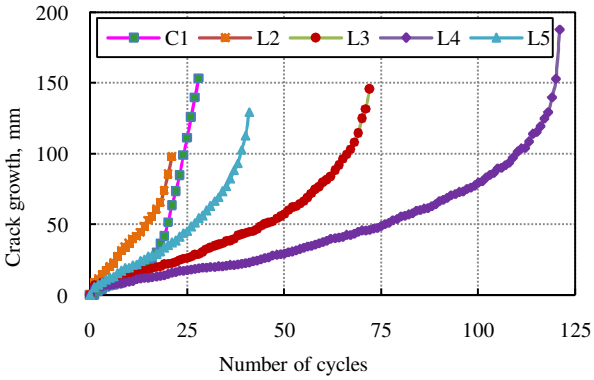

Fig. 13: Crack growth versus number of cycles curves

Fig. 14: Deflected shape of a pipe at the end of fracture experiment

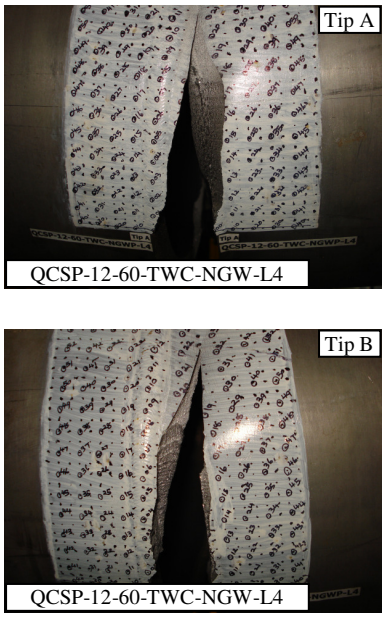

Fig. 15: Close-up views at notch location at the end of fracture experiment

CONCLUSIONS

Experimental investigations were carried out on five numbers of narrow gap welded stainless steel straight pipes having circumferential through-wall notch in the weld under quasi-cyclic loading. The crack growth and fracture behaviour of NG welded pipes under combined load- and displacement-controlled cyclic loading and load-controlled cyclic loading are discussed. The area of the load versus LLD hysteresis loop increased gradually with the number of loading cycles and it increased very rapidly at a few cycles before failure in the case of specimens tested under load-controlled loading. Based on the load-controlled experimental results, material specific plot between cyclic load amplitude (as a percentage of maximum load carrying capacity of a specimen under monotonic fracture) and number of cycles to failure was obtained. The test results indicate that the piping components subjected to quasi-cyclic loading may fail in very less number of loading cycles even when the load amplitude is sufficiently below the monotonic fracture/collapse load. The failure load reduces to 82% and 74% of the monotonic failure load for withstanding 50 and 100 high amplitude loading cycles respectively. All the specimens tested under load-control failed by ductile tearing till sufficient length of crack was developed, followed by sudden rupture and collapse.

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REFERENCES

[1] N. Miura, T. Fujioka, K. Kashima, S. Kanno, M. Hayashi, M. Ishiwata, and N. Gotoh, "Evaluation of dynamic fracture strength for Japanese carbon steel pipes", Report No. ET92001 of Central Research Institute of Electric Power Industry, Japan, 1993.

[2] D. L. Rudland, F. Burst, and G. M. Wilkowski, "The effect of cyclic and dynamic loading on the fracture resistance of nuclear piping steel", *NUREG/CR-6440*, 1996.

[3] D. Venukumar, D. S. Ramachandra Murthy, S. Seetharaman, S. K. Gupta, V. Bhasin, K. K. Vaze, and H. S. Kushwaha, "Cyclic tearing and crack growth in circumferentially cracked straight pipes", *Fatigue Fract. Engng. Mater. Struct*. 27, pp. 1061-1072, 2004.

[4] S. Vishnuvardhan, P. Gandhi, M. Saravanan, DM. Pukazhendhi, G. Raghava, Sumit Goyal, Suneel K. Gupta, and Vivek Bhasin, "Quasi-cyclic fracture studies on TP 304LN stainless steel straight pipes", *Proceedings of the International Conference on Theoretical, Applied, Computational and Experimental Mechanics*, Kharagpur, India, December 27-29, 2010.

[5] "Guidelines for cyclic seismic testing of components of steel structures", *ATC-24, Applied Technology Council*, California, 1992.

[6] ASTM A312/A312M - 09, "Standard specification for seamless, welded and heavily cold worked austenitic stainless steel pipes", *ASTM International*, 2009.

[7] S. Vishnuvardhan, M. Saravanan, DM. Pukazhendhi, P. Gandhi, and G. Raghava, "Cyclic fracture tests on 324 mm OD narrow gap welded stainless steel straight pipes", *Report No. 3 on Sponsored Research Project SSP 06541*, August 2010, CSIR - Structural Engineering Research Centre, Chennai.