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Effect of vibration loading on the fatigue life of part-through notched pipe

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ABSTRACT

A systematic experimental and analytical study has been carried out to investigate the effect of vibration loading on the fatigue life of the piping components. Three Point bend (TPB) specimens machined from the actual pipe have been used for the evaluation of Paris constants by carrying out the experiments under vibration + cyclic and cyclic loading as per the ASTM Standard E647. These constants have been used for the prediction of the fatigue life of the pipe having part-through notch of $a/t = 0.25$ and aspect ratio (2c/a) of 10. Predicted results have shown the reduction in fatigue life of the notched pipe subjected to vibration + cyclic loading by 50% compared to that of cyclic loading. Predicted results have been validated by carrying out the full-scale pipe (with part-through notch) tests. Notched pipes were subjected to loading conditions such that the initial stress-intensity factor remains same as that of TPB specimen. Experimental results of the full-scale pipe tests under vibration + cyclic loading has shown the reduction in fatigue life by 70% compared to that of cyclic loading. Fractographic examination of the fracture surface of the tested specimens subjected to vibration + cyclic loading have shown higher presence of brittle phases such as martensite (in the form of isolated planar facets) and secondary micro cracks. This could be the reason for the reduction of fatigue life in pipe subjected to vibration + cyclic loading.

1. Introduction

Piping components are subjected to vibration loading caused by rotary equipments viz. pumps, compressors etc in the piping system. These vibration loadings are of the low amplitudes but extend over the lifetime of plant operation and causes severe mechanical damage leading to reduction of the life of the piping components. Vibration induced fatigue may lead to excessive pipe vibration which can cause real problems like loosening of threaded connections, leakage through flanges, knocking off the pipes from their supports. S.N. Huang [1] brought out the procedure to assess the fatigue damage of the piping systems and explained the feasibility of the estimation of piping responses resulting from pump-induced vibration with the limited test data. ASME O&M design code [2] calls for qualification of piping system in terms of velocity and deflection of the piping system subjected to the vibration during plant operation. These piping components are also subjected to higher amplitude cyclic loading due to plant startup and shut down. The effect of simultaneous occurrence of cyclic loading along with the vibration loading on piping system has not been discussed in ASME.

Fatigue crack initiation has been studied in the past using notched small specimens by evaluating local stress or strain at the notch tip considering the stress or strain concentration, equivalent energy density method and low cycle fatigue curve [3]. Evaluation of fatigue crack initiation life using fracture mechanics approach has also been reported.

Austenite to martensite transformation has been observed in 300 series stainless steels, which results in a reduced fatigue life [4]. The extent of the martensite transformation depends on several factors such as the chemical composition of the steel and the temperature at which the deformation taking place [5,6]. Martensite can be induced in an austenitic stainless steel when the material is plastically deformed at certain temperature, which determine the stability of the austenite with respect to the formation of alpha martensite [7]. The formation of martensite during deformation at the room temperature in austenitic steel such as 304L and 304LN steel has been reported [8–11]. Strain induced martensite has a great influence on the mechanical properties of austenitic stainless steels. The presence of the martensite can produce significant changes in the tensile properties, strain hardening behavior and fracture toughness. There is no literature

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available showing that the formation of martensite will lead to increase in crack growth rate.

In view of this, effect of simultaneous occurrence of vibration and cyclic loading on fatigue life of the piping components is required to be investigated for the safe operation of the plant. In the present paper, a systematic experimental and analytical study have been carried out to investigate the effect of vibration loading along with cyclic loading on fatigue life of piping components. The effect of the crack tip radius on the fatigue crack initiation life has also been addressed.

2. Experimental details

The piping material under study is austenitic stainless steel SA312Type SS304LN in solution-annealed condition. The chemical composition and the tensile properties are given in Tables 1 and 2.

Cyclic stress–strain and low cycle fatigue properties have been obtained following ASTM E606 for different strain ranges at room temperature and air environment [12,13]. The cyclic stress–strain and the low cycle fatigue curves are given in equations (1) and (2) respectively. The various constants in the equation have been obtained by fitting the test data points and given in Table 3.

$$\Delta\varepsilon/2 = 100(\Delta\sigma/2E) + (\Delta\sigma/2k)^{1/n} \quad (1)$$

$$\Delta\varepsilon/2 = \sigma_f/E(2N_i)^b + \varepsilon_f(2N_i)^c \quad (2)$$

where $\Delta\varepsilon$ is strain range, $\Delta\sigma$ is stress range and N_i is the number of cycles required for failure (complete separation) of the specimen.

Three Point Bend specimens have been machined as per ASTM E647 [14] from the pipe of outer diameter 168 mm and thickness 14.3 mm with notch in L-C direction (L refer to load in longitudinal direction and C refer to notch in circumferential direction). Location of the specimens and crack plane orientation with respect to pipe is shown in Fig. 1.The dimensions such as width (W), thickness (B), initial crack length (a_o) of TPB specimen are 20 mm, 10 mm and 5 mm respectively. These specimens were having different crack tip radius as 0.2, 0.3 and 0.5 mm.

Three Point Bend specimens were fatigue tested under constant amplitude sinusoidal vibration + cyclic and cyclic loading. The tests were conducted with load ratio(R) of 0.1. The loading frequency was 20 Hz for vibration loading and 2.5–5 Hz for cyclic loading. The constant amplitude load applied during the test was calculated based on the fact that the initial stress-intensity factor for the TPB specimens is same as that of the notched pipe. The details of the load applied during vibration loading and cyclic loading are given in Table 4.

The full-scale pipes of 168 mm outer diameter and 14.3 mm wall thickness have been used for tests. The pipe specimens were having surface notch, machined at the outer surface in the circumferential direction. The detail of the notch and pipe test setup has been shown in Fig. 2. The length ($2c$) and depth (a) of the crack was 36 mm and 3.5 mm respectively. Full-scale pipe tests have been carried out at room temperature and air environment under constant amplitude sinusoidal vibration + cyclic and cyclic loading. The tests were conducted with stress ratios (R) of 0.1. The loading frequency was 10 Hz for the vibration loading and 0.05–1 Hz for the cyclic loading. The maximum applied loading was such that the linear elastic condition is maintained. The vibration and cyclic loadings corresponding to 10% and 40% of collapse load respectively has been applied.

Table 2
Room temperature tensile properties of pipe material.

Yield strength (MPa)	Ultimate strength (MPa)	Young's modulus (GPa)	% Elongation
298	620	195	69

Table 3
Constants for Cyclic stress–strain and Low cyclic fatigue curve.

k (MPa)	n	σ_f (MPa)	ε_f (%)	b	c	E (GPa)
217.36	0.3248	1116.515	33.3	0.1428	−0.5266	195

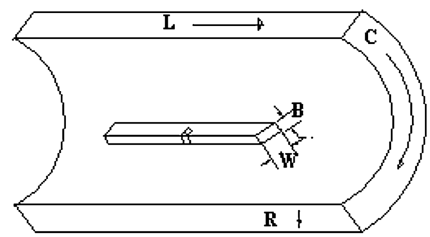

Fig. 1. Location of the TPB specimen machined from pipe.

3. Experimental results

The fatigue crack initiation life has been evaluated considering the effect of notch tip radius for vibration + cyclic loading and cyclic loading. The details of the fatigue crack initiation results have been shown in Table 4 for TPB and pipe test. No crack initiation has been observed in TPB specimens during the vibration loading. This was confirmed by observing the notch tip of TPB specimen under optical microscope. In case of TPB specimen number of cycles to crack initiation as given in Table 4 corresponds to the 0.5 mm of crack growth. In case of pipe, crack initiation was assumed to occur for the measured crack growth of 0.1 mm. This is the minimum crack length, which could be measured using instrument based on the Alternating Current Potential Difference (ACPD) technique.

The fatigue initiation life increases with increase in crack tip radius. During the experiments on the TPB specimen subjected to vibration + cyclic loading and cyclic loading only, it has been found that the fatigue life has been increased by 45%–75% for the crack tip radius variation from 0.2 to 0.5 mm. There is a reduction in the fatigue crack initiation life by 20–35% for specimens subjected to vibration + cyclic loading in comparison to specimens subjected to cyclic loading only.

During the Fatigue Crack Growth Rate (FCGR) tests, crack length and number of cycles have been recorded. The crack length and numbers of cycles recorded have been shown in Figs. 3 and 4. The curves shown in Figs. 3 and 4 for crack growth life includes the numbers of cycles to crack initiation. The difference in fatigue life is due to the variation in crack initiation life. The variation of stress-

Table 1
Chemical composition (in wt %) of pipe material.

C	Mn	Si	P	S	Mo	Cr	Ni	Ti	N	Nb	Cu
0.017	1.76	0.29	0.022	0.0029	0.19	18.9	9.65	0.006	0.08	0.02	0.2