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Failure criterion for steel pipe elbows under cyclic loading

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ABSTRACT

Steel elbow components are considered to be critical parts in industrial piping system due to their probability of collapse or failure. Therefore, the structural behavior of elbows is considered with respect to failure criteria through experiments and corresponding numerical models. Thirty-eight sets of experiments were conducted on three inch pipe elbow specimens. The numerical simulation results of the specimens are in good agreement with the test results. Damage indices available in the literature are used for failure estimation of the elbows. We suggest that the damage calculated using the Park and Ang damage index, and the Banon damage index, based on only one failed specimen under any constant amplitude cyclic loading, can be defined as the failure point and used to predict the failure of the component under other loading amplitudes. Therefore, the low cycle fatigue curve of an elbow can be derived using these simulation results. We also found that the calculated damage of an elbow component under constant, non-constant, and fully or partial amplitude reversals is quite similar.

1. Introduction

Steel pipe elbows are used in many different applications (manufacturing, hydraulics, refineries, offshore engineering, power plant construction, and other steam systems) to convey fluids such as gas, water, and oil. Elbows are considered to be critical parts in piping systems. Piping systems are often exposed to cyclic loading due to earthquakes, wind, waves, and vibrations from industrial machinery. It is well known that piping components frequently fail due to a fatigue-ratchet mechanism, rather than a plastic collapse, under reversing dynamic loads [1]. Therefore, the fatigue behavior of a pipe elbow under cyclic loading was investigated in this study in order to understand its failure criteria.

Elbow components have been reported to be the most critical points of nuclear pipelines based on experimental [2] and analytical [3] investigations and also vulnerable component of piping systems in erosive environments [4]. The failure analysis of various type of steel pipe elbow due to the thermal fatigue [5], stress corrosion cracking [6], erosion [7] and buckling of an axially cracked elbow [8] has been studied in the literature. Extensive experimental studies on the structural behavior of steel elbows under monotonic loading [9–11] and cyclic loading [12–15] have been performed. Low cycle fatigue analysis and fatigue life analysis of steel elbows have been performed [16,17]. Vishnuvardhan et al. [18] and Hassan et al. [19] examined the ratcheting response and failure of elbow components.

Several damage accumulation indices as a function of certain response parameters have been proposed for structural components. It has been suggested that the damage of a structure can be represented as a function of ductility and/or plastic deformation [20,21], the energy dissipation capacity [22], or a combination of both [23–25]. Bracci et al. [26] estimated the damage based on the ratio of damage consumption to damage capacity. Consenza et al. [27] defined their index as a ratio of maximum induced

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ductility to the ultimate ductility. Castiglioni [28] proposed that the reduction of the energy absorption capacity is a suitable parameter in the case of a steel component. More recently, Sucuoglu and Erberik [29] developed a hysteresis model for a deteriorating system consisting of displacement and fatigue components, and Kamaris et al. [30] defined the damage of a steel structure based on the acting axial force and bending moment on the structure.

The structural failure point of a steel pipe elbow has yet to be defined. Thus, we investigated the possibility of estimating the failure point of an elbow using the damage indices available in the literature. These damage indices have either been used for reinforced concrete structures or steel structures (not a steel pipe elbow). Therefore, the applicability and correctness of these proposed indices for steel pipe elbows was carried out. Thirty-eight sets of experiments were conducted on 3 in. steel pipe elbow specimens subjected to various loading histories with internal pressure. Numerical analyses of the pipe elbows were performed and compared to the test data. The failure criterion of the elbows was represented as their damage capacity by using applicable damage indices. The procedure was also applied to 8 in. elbow components based on the experimental results reported in Varelis et al. [14].

2. Test setup and results

A tensile stress test of the material used in the specimens was performed in order to determine the elasto-plastic behavior of the material. The measured sizes of the three specimens used in test are given Table 1. The elastic modulus of the material was found to be 204,929 MPa. A photograph of the specimens and the results of the tensile stress tests for three specimens are shown in Fig. 1.

A total of 38 specimens were made for the experiments (ASME [31] B36.10, carbon steel, weld pipe, SA-106, SCH. 40 (STD), diameter = 88.9 mm, thickness = 5.49 mm). The specimen cross sectional details, material descriptions, and photos are shown in Fig. 2. The first two tests were performed on an elbow subjected to monotonic loading under tension and compression. The next 20 tests were conducted under sine wave constant cyclic loading, subjected to nine different loading amplitudes (from ±20 mm to ±100 mm, as given in Table 2 Nos. 4 to 12). The next two tests were separately subjected to a constant closing in one case (compression), and opening the other case (tension), to observe elbow behavior under compression and/or tension.

The other loading histories were chosen based on non-constant stepwise increasing cyclic loading according to the European Convention for Constructional Steelwork (ECCS) recommendations [32] (Table 2 No. 15, Fig. 3). Then, a random history starting with a small displacement (30 mm) under six cycles, increasing to 80 mm for three cycles, and then back to 30 mm were applied until failure to see the effect of geometric nonlinearity and a sudden increase of applied loading. The last case was considered for partial deformation reversals (30 mm closing following by 60 mm opening), as it is known that most cyclic loads in nature do not have fully symmetric amplitude loading. Descriptions of the loading histories are given in Table 2.

All test specimens were subjected to an internal pressure of 3 MPa, and this pressure was maintained during the experiments. The experiments were repeated three times for each case of loading amplitude to reduce experimental errors and obtain more reliable results. Therefore, the number of cycles to failure (given in Table 2) is the average of results from three conducted experiments.

In all the experiments, the pipe cracked and leaked at the same point, located on the outside middle (crown) of the elbow in the opening modes of cyclic loading, as shown in Fig. 4. The same results (i.e., the cracked area) are also reported in the literature [14,15,18] based on experiments with different sizes of pipe elbows. Our numerical analysis shows that the maximum strain concentration occurs in the same area, as we expected and observed during the experiments.

3. Numerical simulation

The pipe elbow was modeled using finite element shell elements (shown in Fig. 5) with a beam stick model for the load point at both ends of the elbow. The beam stick length was 60 mm as the original test specimen load point, and it was coupled with the elbow structure. The material properties were obtained from the tensile test (shown in Fig. 1), the kinematic hardening rule was chosen and Poisson's ratio is 0.3. A quadrilateral standard shell finite element (S4R) was used in the analysis. The geometric nonlinearity effect for the cyclic loading was also considered in order to capture the stiffness and strength degradation. The static analysis was performed using ABAQUS 6.12 for the cyclic and monotonic loading tests, and the elbow was subjected to a 3 MPa internal pressure. Monotonic loading of the elbow was performed under both tension and compression, hereafter called

Table 1
Tensile test specimens size description.

Test specimen	No. 1	No. 2	No. 3
Width (mm)	18.95	19.09	18.95
	18.97	19.02	18.94
	18.99	19.02	18.93
	19.01	19.03	18.92
	19.02	19.05	18.92
Thickness (mm)	5.48	5.51	5.66
	5.48	5.5	5.68
	5.48	5.49	5.66