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Damage assessment of steel pipe elbow under cyclic loading

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ABSTRACT: The damage assessment of the pipe elbow components was considered to study on their failure criteria through the experiments and their corresponding numerical models. Therefore, total seventeen sets of experiments were conducted on the three inches steel pipe elbow specimens. The numerical simulation of the specimen under monotonic and cyclic loading was well matched with the test data. The damage indexes available in the literature were used for failure estimation of the component. It is suggested that the failure point of the steel pipe elbow could be fairly assessed through the Park and Ang, and Banon damage index for a constant amplitude loading. It is suggested that the damage calculated based on one failed specimen under any constant cyclic loading, can be set as the failure criteria. Hence, the number of cycles to failure under different amplitude can be estimated based on the simulation response which proved to be reliable. In this scenario a quite accurate low cycle fatigue curve can be derived, using just one experiment through analysis of the structure using numerical model.

1 INTRODUCTION

Steel pipe elbows have been used in many different (manufacturing, hydraulics, refineries, offshore engineering, power plant construction and other steam systems) pipe settings to convey gas, water, oil, …. These sections have been often considered to be one of the most critical parts of a piping system. The piping systems are mostly exposed to a cyclic loading due to earthquakes, wind, wave, and industrial machinery.

The elbow components have been reported to be the most critical points of the nuclear pipelines based on the experimental (Touboul et al., 1999) and analytical (Salimi Firoozabad et al., 2015) investigations. The extensive experimental researches on structural behavior of the steel elbows under monotonic (Hilsenkopf et al., 1988, Tan et al. 2002) and cyclic loading history by Slagis, (1998), and Varelis et al. (2013) have been performed. In addition, the low cycle fatigue analysis and the fatigue life of steel elbow have been investigated by Takahashi et al., (2014), and Varelis and Karamanos, (2015).

Several damage accumulation indexes as a function of certain response parameters have been proposed for the structural components. It was suggested that the damage of a structure can be represented as a function of ductility and/or plastic deformation (Gosain et al., 1977, Krawinkler, 1987) or the energy dissipation capacity (Darwin and Nmai, 1986) or the combination of both (Banon et al., 1981, Hwang and Scribner, 1984, Park and Ang, 1985). In addition, Bracci et al. (1989) estimated the damage based on the ratio of damage consumption to damage capacity, and Consenza et al. (1993) defined their index as a ratio of maximum induced ductility to the ultimate ductility.

The proposed damage indexes in the literature have been either used for reinforced concrete structures or specific steel structures. Therefor the applicability and reliability of those suggested indexes on estimation of failure criteria of steel pipe elbow was carried out. Seventeen sets of experiments were conducted on the three inches steel pipe elbow specimens subjected to various loading history with the internal pressure. The numerical analysis of the pipe elbows was performed and compared to the test data. The failure criteria of those elbows were represented as the damage capacity by using damage indexes.

2 TEST SETUP AND RESULTS

The tensile stress test of the material used in the specimen, was performed in order to indicate the elasto-plastic behavior of the material. The elastic modulus of the material was calculated equal to 204,929 MPa. The photo of the specimen and the results of the tensile stress test of all three specimens are shown in Figure 1-2.

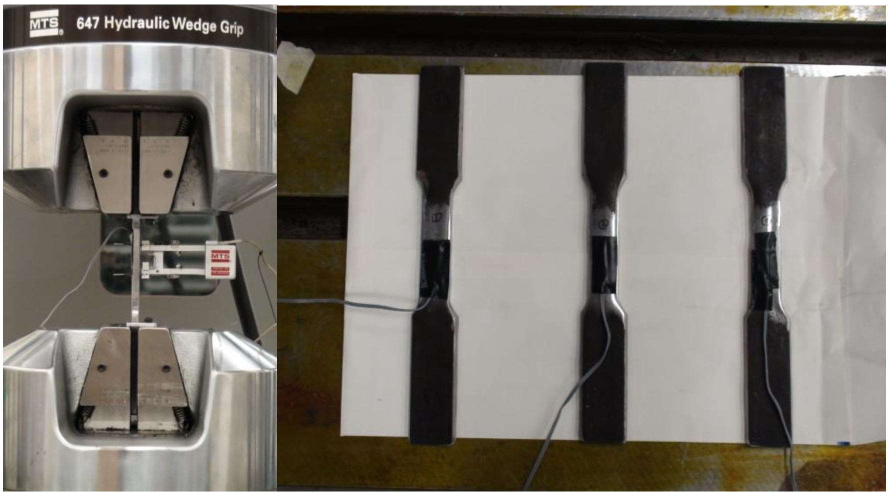


Figure 1. Tensile test specimens

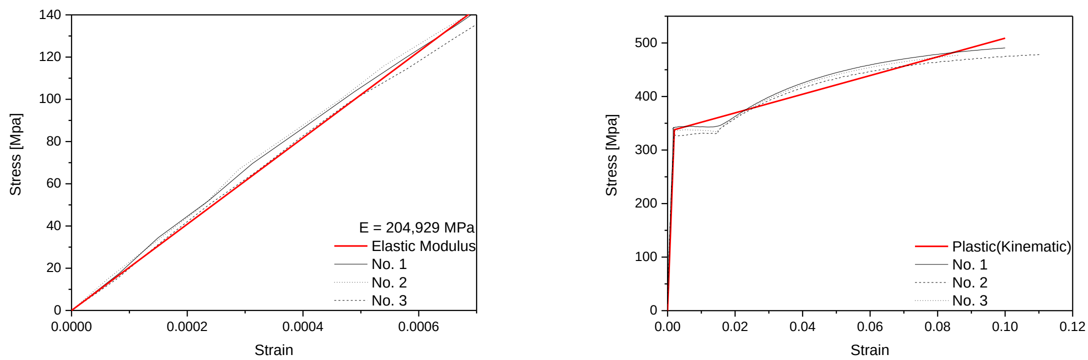


Figure 2. Tensile test results

A total 17 specimens (ASME B36.10, carbon steel, weld pipe, SA-106, SCH. 40 (STD), diameter = 88.9 mm, thickness = 5.49 mm) were made to conduct the experiments. The first two tests were performed on the elbow subjected to a monotonic loading under tension and compression. Then the next 15 tests were conducted for a constant cyclic loading, subjected to the five different loading amplitudes (tests loading history description are given in Table 1). It must be noted that all the test specimens were subjected to an internal pressure of 3 MPa and maintained during the experiments. The specimen cross sectional details, material description, and their photos are shown in Figure 3.

Table 1. Test loading description

Test No	Mode	Velocity (mm/s)	Loading Amplitude (mm)	Internal Pressure (mm)	Number of Cycle	Leakage
P1-7	Monotonic Closing	6	195	3		No
P1-8	Monotonic Opening	6	240	3		No
P1-2	Constant Cyclic	32	±40	3	18	Yes
P1-3	Constant Cyclic	32	±50	3	12	Yes

P1-4	Constant Cyclic	32	±60	3	7	Yes
P1-5	Constant Cyclic	32	±70	3	5	Yes
P1-6	Constant Cyclic	32	±80	3	4	Yes

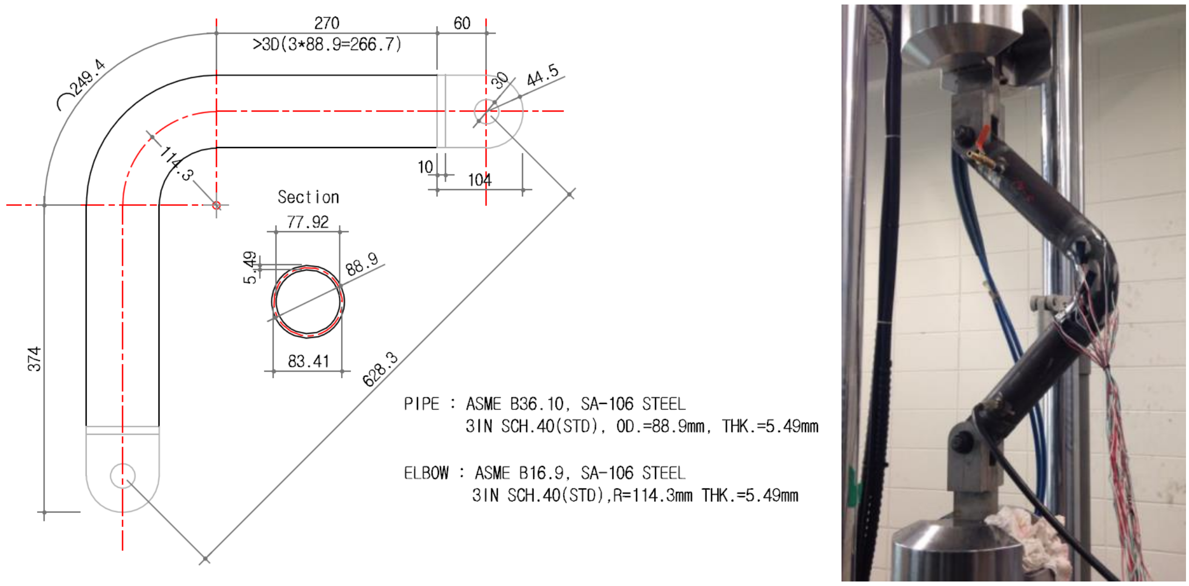


Figure 3. The elbow specimen cross sectional details

It is well established that, for all the experiments, the pipe cracked and leaked in the same point (crown) of the elbow (as shown in Figure 4) mostly in the opening modes of cyclic loading. The same results (cracked area) also reported in the literature (Takahashi et al., 2009, Vishnuvardhan et al., 2013, Varelis et al., 2013) based on the experiment on different size of pipe elbows. The numerical analysis also later proved that the maximum stress concentration would happen in the same area as we expected and observed during the experiments.

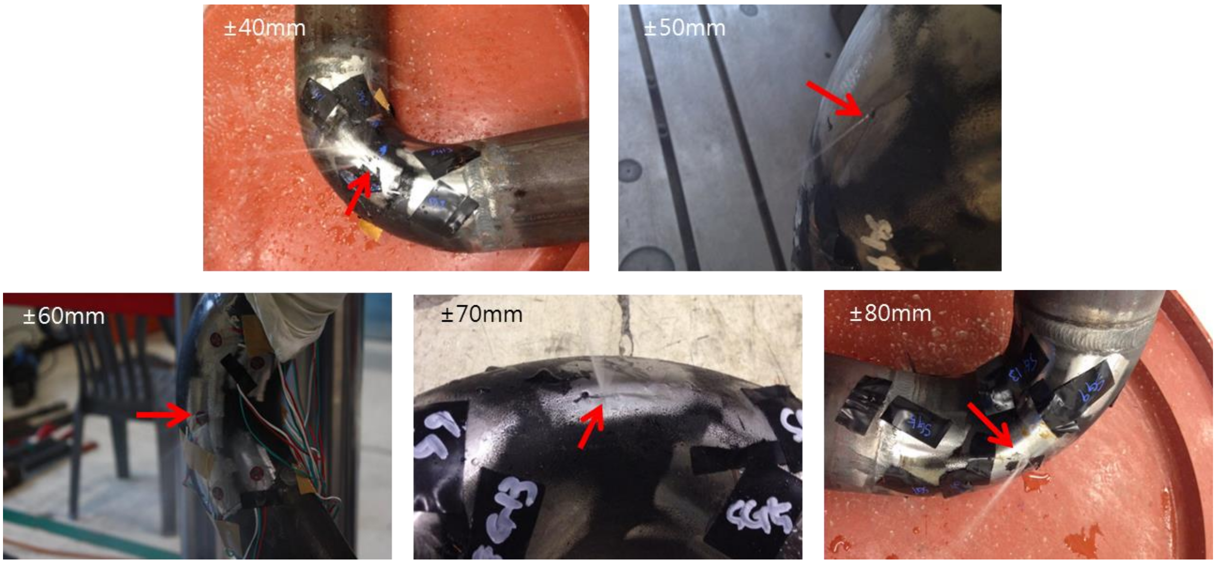


Figure 4. Crack location in specimens for all applied displacement

3 NUMERICAL SIMULATION

The pipe elbow was modelled as shell elements (shown in Fig. 5) with a beam steak model for the load point at the both end of the elbow. The beam steak length was 60 mm as the original test specimen load point, and it was coupled with the elbow structure. The material properties as obtained in the tensile test and kinematic hardening rule (shown in Fig. 2) and Poisson ratio of 0.3. A quadrilateral standard shell element (S4R) was used on the analysis. The geometric nonlinearity effect was also considered as the analysis case was cyclic loading to capture the stiffness and strength degradation. The static analysis performed in ABAQUS6.12 for the cyclic and monotonic loading tests, subjected to 3 MPa internal pressures. The monotonic loading of the elbow was performed under both tension and compression hereafter called opening and closing mode respectively.

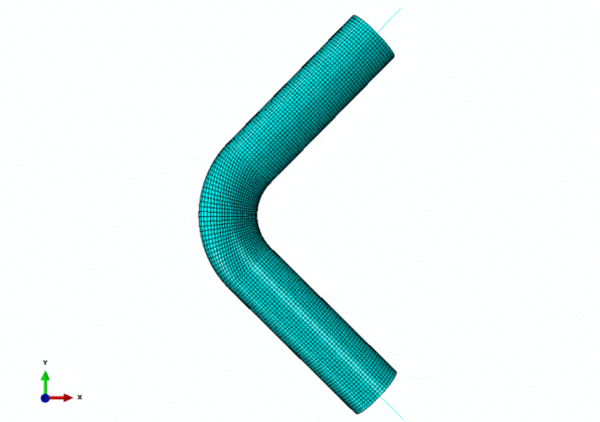


Figure 5. The modelled and meshed steel pipe elbow

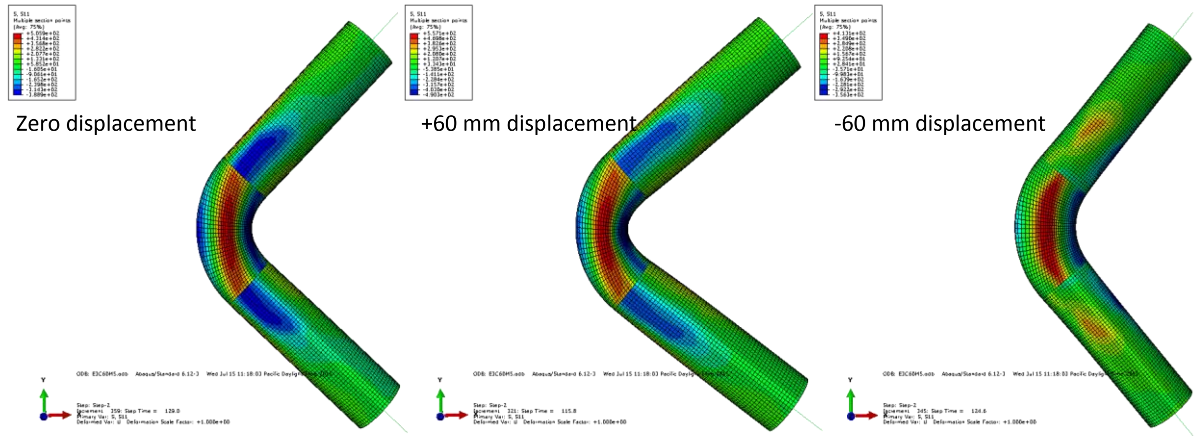
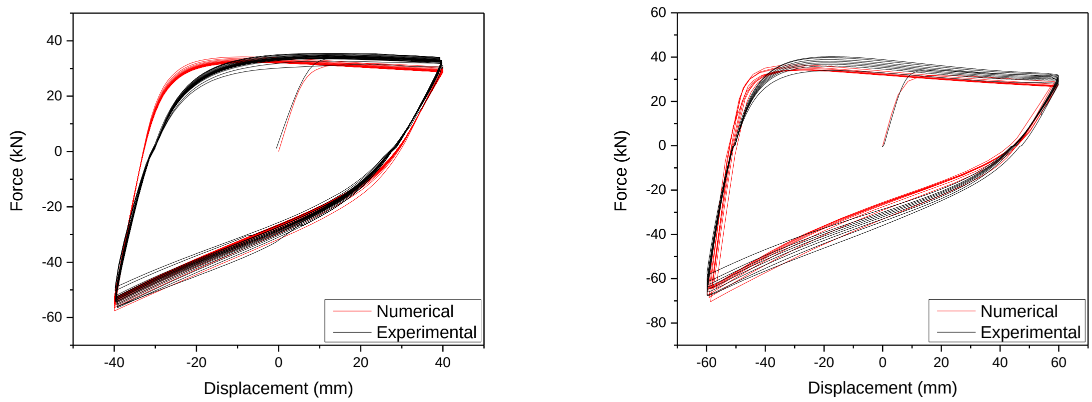


Figure 6. Stress contours in horizontal direction in the case of 60 mm displacement at the last cycle

The simulation results show the elastic and plastic behaviour of the structure, well matched with the experimental data. The comparative force–displacement curves for the specimens (under 40, 60 and 80 mm cyclic test shown in Fig. 7), indicates the reliability of the numerical simulations.



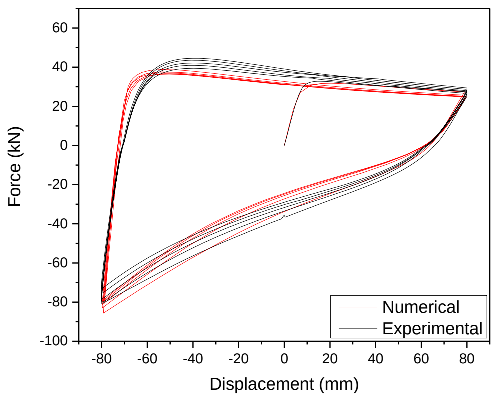


Figure 7. Force-displacement graphs in the case of 40, 60 and 80 mm respectively

The numerical simulation of the elbow component given in Figure 6 perfectly shows the modes of cyclic deterioration (strength and stiffness deterioration) that occurs in the cyclic loadings (which was detected during the experiments) due to geometric nonlinearity. It also can be seen (Fig. 6) that the maximum stress concentration is in the leaked area (elbow crown) previously observed during the experiments.

4 DAMAGE ANALYSIS

Damage of a structure can be assessed by using different parameters. The most commonly used parameter is ductility, which relates the damage of the structure only to the maximum deformation and is still regarded as a critical design parameter by code provisions. Such approaches for determination of the plastic limit deformation, including the tangent-intersection method and the twice-elastic-deformation (TES) method which is adopted by the American Society of Mechanical Engineers (ASME) for the plastic limit load material criterion. Later, the energy dissipation capacity (cumulative-type indices) has been included and in some indexed, linearly and/or non-linearly combined with the maximum deformation. Furthermore, Stiffness and strength degradation have been incorporated in further damage indices to account for the effects of cyclic loading.

It must be noted that these indexes were mainly proposed for the reinforced concrete structures and some of those have just been investigated for the different steel structures. Hence the indexes shall be considered for the application to be used in particular cases such as steel pipes under repeated cyclic loading. As the initial aspect, it was obvious (based on the structural behaviour of the specimen) that the failure of the steel pipe elbow cannot be expressed by neither deformation nor hysteretic based formulations alone. Therefore the combined type (deformation and energy dissipated) indexes such as, Banon and Park and Ang were examined. These two indexes and their formulations were briefly presented in Equation 1-2.

- Banon et al. (1981):

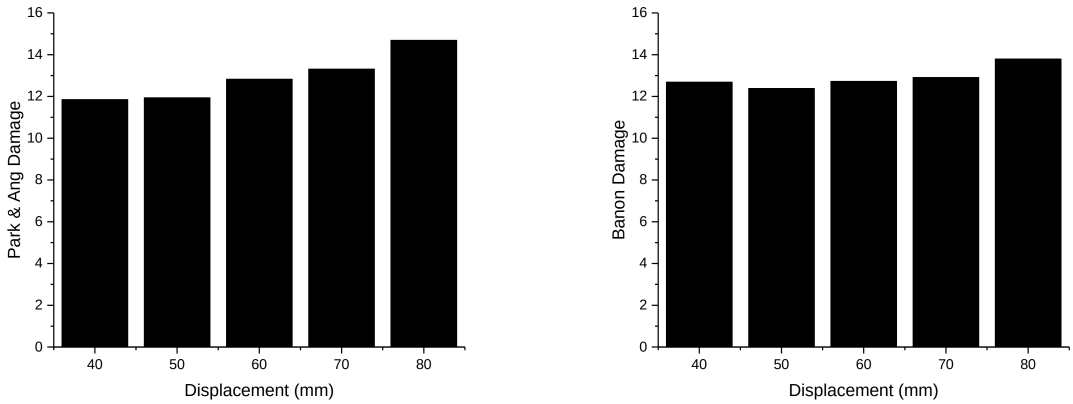
$$D = \sqrt{\left(\max\left(\frac{D_i}{D_y} - 1\right)\right)^2 + \left(\sum_{i=1}^{N} c \cdot \left(2\frac{E_i}{F_y \cdot D_y}\right)^d\right)^2} \tag{1}$$

- Park and Ang (1985):

$$D = \max\left(\frac{D_i}{D_y}\right) + b \cdot \sum_{i=1}^{N} \left(\frac{E_i}{F_y \cdot D_y}\right)_i \tag{2}$$

In the presented equations, D_y, F_y are the yield displacement and force, D_i, E_i are the displacement and the dissipated energy in the ith cycle, and N is the number of cycles. The constant *c* and *d* are taken as 1.1 and 0.38 respectively (Castiglioni and Pucinotti, 2009), in the literatures and the constant b can be adopted as 0.025 for steel structures (Cosenza et al., 1993). Since the element behaviour in the tension and compression was different, the damage parameters were evaluated separately; hence, the average value was taken for maximum displacement, and those values were summed for the energy dissipated capacity part.

The damage of the elbow was calculated using those presented indexes under all considered loading amplitude. The results for all the cases must be equal/close to each other as all the specimens failed (leaked) under applied loading history. The closer the result to each other, the more reliable is the damage index. First the damage was obtained based on the equations, using available constant value in the literature. Therefore the constant b, c and d, were taken as previously mentioned and the results were compared and shown in Figure 7. The yield point obtained from the monotonic force-displacement curve and defined as the reference elastic limit as the intersection between the tangent at the origin (E) of the force-displacement curve and the tangent that has a slope of E/10.



It is shown that the damages calculated for each case of loading, were quite close to each other, for our specific case of steel pipe elbow. Therefore, it is well established that, these damage indexes can be used to express the "failure" state of a steel pipe elbow under constant amplitude loading. The main use of suggested procedure is in low cycle fatigue analysis which needs many experiments to drive a reliable Fatigue curve. It is suggested that the damage calculated based on one failed specimen under any constant amplitude cyclic loading, can be set as the failure criteria. Hence, the number of cycles to failure under different amplitude can be estimated based on the simulation response on the same structure which previously proved to be reliable. In this scenario a quite accurate low cycle fatigue curve can be derived, using just one experiment through analysis of the structure using ABAQUS FEM software.

It was shown that the Banon index gives more accurate (close results in different amplitudes) than the Park & Ang index. Hence, the nonlinear combination of the displacement and dissipated energy is more suitable than the linear one to assess the damage of the structure. It was also seen that the average of all the calculated damages for each case of amplitude, in both the indexes were almost equal (12.924 in Banon, 12.899 in Park & Ang index). Therefore it could be considered as the failure criteria in a more general terms, however further investigation such as various elbow size and more displacement amplitude, are required to validate this assumption.

It must be said that there are also other damage indexes more recently proposed in the literature such as the one suggested by Castiglioni (1999) based on the reduction of the energy absorption capacity although, the application condition didn't verify in our case of study. Kamaris et al. (2011) accounted for strength and stiffness degradation in low cycle fatigue failure based on the moment and axial force capacity and response. This index also is not accurate in our specific structure that exhibits not failure after the ultimate force in tension hence, the effect of maximum displacement should has been considered.

5 CONCLUSION

The structural behaviour of the pipe elbow components was studied on their failure criteria through the experiments and their corresponding numerical models. The numerical analysis of the pipe elbows was performed and compared to the test data. The numerical simulation of the component under monotonic and cyclic loading was well matched with the test data.

The failure criteria of those elbows were represented as the damage capacity by using damage indexes available in the literature. It is shown that the damages calculated through the Park and Ang, and Banon damage index, for each case of loading, are quite the same hence, the failure point of the steel pipe elbow could be fairly assessed for constant amplitude loading.

It is suggested that the damage calculated based on one failed specimen under any constant amplitude cyclic loading, can be used as the failure point. Hence, the number of cycles to failure under any other different amplitude can be estimated based on the numerical simulation response. In this scenario a quite accurate low cycle fatigue curve can be derived, using just one experiment through analysis of the structure using numerical model.

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REFERENCES:

American Society of Mechanical Engineers (ASME), 2007. Boiler and Pressure Vessel Code.

Banon, H., Irvine, H. M., & Biggs, J. M. (1981). Seismic damage in reinforced concrete frames. Journal of the Structural Division, 107(9), 1713-1729.

Bracci, J. M., Reinhorn, A. M., Mander, J. B., & Kunnath, S. K. (1989). Deterministic model for seismic damage evaluation of reinforced concrete structures. Technical report (No. NCEER-89-0033).

Castiglioni, C. A., & Pucinotti, R. (2009). Failure criteria and cumulative damage models for steel components under cyclic loading. Journal of Constructional Steel Research, 65(4), 751-765.

Cosenza, E., Manfredi, G., & Ramasco, R. (1993). The use of damage functionals in earthquake engineering: a comparison between different methods. Earthquake engineering & structural dynamics, 22(10), 855-868.

Darwin, D., & Nmai, C. K. (1986). Energy dissipation in RC beams under cyclic load. Journal of Structural Engineering, 112(8), 1829-1846.

Firoozabad, E. S., Jeon, B. G., Choi, H. S., & Kim, N. S. (2015). Seismic fragility analysis of seismically isolated nuclear power plants piping system. Nuclear Engineering and Design, 284, 264-279.

Gosain, N. K., Jirsa, J. O., & Brown, R. H. (1977). Shear requirements for load reversals on RC members. Journal of the Structural Division, 103(7), 1461-1476.

Hilsenkopf, P., Boneh, B., & Sollogoub, P. (1988). Experimental study of behavior and functional capability of ferritic steel elbows and austenitic stainless steel thin-walled elbows. International journal of pressure vessels and piping, 33(2), 111-128.

Hwang, T. H., & Scribner, C. F. (1984). R/C member cyclic response during various loadings. Journal of Structural Engineering, 110(3), 477-489.

Kamaris, G. S., Hatzigeorgiou, G. D., & Beskos, D. E. (2013). A new damage index for plane steel frames exhibiting strength and stiffness degradation under seismic motion. Engineering Structures, 46, 727-736.

Krawinkler, H. (1987). Performance assessment of steel components. Earthquake spectra, 3(1), 27-41.

Park, Y. J., & Ang, A. H. S. (1985). Mechanistic seismic damage model for reinforced concrete. Journal of Structural Engineering, 111(4), 722-739.

Slagis, G. C. (1998). Experimental data on seismic response of piping components. Journal of pressure vessel technology, 120(4), 449-455.

Takahashi, K., Ando, K., Matsuo, K., & Urabe, Y. (2014). Estimation of low-cycle fatigue life of elbow pipes considering the multi-axial stress effect. Journal of Pressure Vessel Technology, 136(4), 041405.

Tan, Y., Matzen, V. C., & Yu, L. (2002). Correlation of test and FEA results for the nonlinear behavior of straight pipes and elbows. Journal of pressure vessel technology, 124(4), 465-475.

Touboul, F., Sollogoub, P., & Blay, N. (1999). Seismic behaviour of piping systems with and without defects: experimental and numerical evaluations. Nuclear engineering and design, 192(2), 243-260.

Varelis, G. E., Karamanos, S. A., & Gresnigt, A. M. (2013). Pipe Elbows Under Strong Cyclic Loading. Journal of Pressure Vessel Technology, 135(1), 011207.

Varelis, G. E., & Karamanos, S. A. (2015). Low-Cycle Fatigue of Pressurized Steel Elbows Under In-Plane Bending. Journal of Pressure Vessel Technology, 137(1), 011401.

Vishnuvardhan, S., Raghava, G., Gandhi, P., Saravanan, M., Goyal, S., Arora, P., ... & Bhasin, V. (2013). Ratcheting failure of pressurised straight pipes and elbows under reversed bending. International Journal of Pressure Vessels and Piping, 105, 79-89.