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A simple approach to fatigue analysis in nuclear class 1 components

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ABSTRACT: The paper presents two different concepts to be applied for fatigue evaluation in typical ASME class 1 components: the Fatigue Design Basis concept (FDB), to be considered for components during construction phase, and the Fatigue Operating Basis (FOB), related to components in operation phase. Simplified and detailed stress analyses are adopted to calculate the cumulative usage factor (CUF), being the lifetime of the components based on S-N fatigue curves available in the ASME III and on S-N curves modified by the reactor environment. Some recommendations are presented to assess the fatigue in nuclear power plants structures.

1 INTRODUCTION

Safety and economic reasons are motivations to apply modern technology to nuclear power plants lifetime extension. New plants have incorporated this requirement in their construction phase because they are designed according to recent developments in the area of fracture mechanics, finite element methods, material failure processing, etc. However, for commercial operating plants, constructed with existing technology in the past, the requirement of life extension beyond the original life is possible only if the design is re-evaluated to take into account the state-of-art in the above mentioned areas.

According to Gosselin et al. (1994), the modern technology applied to components considering cyclic load is based on the combination of two concepts: Fatigue Design Basis (FDB) used to components in design phase and Fatigue Operating Basis (FOB) related to components in service.

The FDB considers the methodology shown in ASME III (1992a), and is used to qualify equipment before they are placed in service. This concept is based on the evaluation of the cumulative usage factor (CUF) for the design cyclic conditions (design transients). When ASME III is adopted, the conservatism related to life estimation is due to: a) definition of design transients; b) material properties specification; c) stress and heat transfer analysis; d) S-N fatigue design curves.

During the operational phase, the conservatism associated with the design defined in FDB approach should be eliminated due differences in service loads or additional cycles. Besides, the environment in the reactor coolant system may have an influence in fatigue life and this effect was not taken into account during experimental development of S-N curves used in the ASME III (obtained for polished unnotched specimens in air at room temperature and with safety factor 2 on stress or 20 on cycles).

Therefore, for operating plants, it is recommended to evaluate the components under actual service conditions, in a FOB approach. The requalification of the component design, using the existing ASME III design stress reports and new analyses under the additional cyclic loadings, to demonstrate that CUF is lesser than 1 throughout the intended operational period, is an acceptable procedure (Gosselin et al., 1994). If the calculated CUF is greater than 1, the guidelines of ASME XI (1992b) should be followed to component qualification and the definition of the periodicity of inspections.

Until now, however, there is not a established requirement to consider the influence of the reactors environment effects in the estimation of components lifetime. This issue is being studied by ASME and some future changes in the code design basis may be possible. The goal of this paper is to give a little contribution on this subject and to provide additional information to verify the importance of reactors environment effects.

The present work conducts an evaluation to find the CUF's of typical ASME III Class 1 component used in commercial nuclear power plants. The CUF's are calculated with ASME III S-N design fatigue curves and S-N fatigue curves modified by environmental effects. Simplified and detailed methods were used in the thermal and stress analyses. In the simplified analyses, the thermal and stress evaluations are performed using simple formulas from handbooks. In detailed analyses, the thermal and stress distributions were computed through the finite element method. The possibility of application the FDB or FOB approaches is investigated.

2 SIMPLIFIED AND DETAILED ANALYSIS

Heat transfer and stress analysis used for evaluating fatigue in components have several degrees of refinement and conservatism. Simplified or detailed methodologies should be applied to obtain stresses due to mechanical and thermal loads.

Simplified analyses consider the local stresses in cylindrical nozzles or piping with attachments under external loadings calculated using approaches presented in WRC Bulletins No. 297 (1984) or according different ASME Code Cases such as CC N-391 (1983), CC N-318-3 (1985).

For simple geometries (cylinders, spheres, plates, and beams), the stresses from mechanical loads are calculated using formulas from standard handbooks such as Roark and Young (1976). When thermal loads are present, a simplified formulation to obtain the stresses, where the temperature distribution at the wall of the component is calculated using a one dimensional heat transfer model, is showed in Harvey (1980).

The technical basis for the equations provided in all those mentioned references are based on the combination of simple formulas from strength of materials, tests programs, and industry practice. Despite the usefulness of these formulations, their application are sometimes restricted by geometrical limitations or substantial conservatism incorporated in the analysis.

In the other hand, a more realistic evaluation is possible if the analysis is based on the finite element method. To perform the analysis a highly refined mesh is provided at the critical region (nozzle-shell transition, pipe-attachment intersection), being the geometry and mechanical/thermal loads defined in detail. The temperature and stress distributions are obtained from tridimensional or axisymmetric models using available commercial programs. When the detailed analysis is considered, the stresses are separated into membrane, bending, and peak components, being the evaluation possible in accordance with the ASME III Section NB-3200.

3 ENVIRONMENTAL EFFECTS ON S-N CURVES

As pointed out before, existing data in the literature have shown that the reactors environment affects the fatigue life of components. The S-N fatigue curves presented in the ASME III may change for different factors, namely water chemistry, temperature, cyclic strain rate, and the composition of the materials.

Higuchi and Iida (1991) shows S-N curves for carbon and low-alloy steels considering aggressive environment simulated by dissolved oxygen in the water. The fatigue tests were conducted in specimens under strain-controlled conditions, and the results showed that safety margin, related to ASME III S-N design fatigue curves, was, in some cases, completely eliminated.

NUREG/CR-5999 (1993) shows S-N fatigue curves considering the reactors environments. They take into account temperatures, dissolved-oxygen level in the water, the sulfur level in the steel and strain rate and should be used for fatigue evaluation in carbon, low-alloy, and austenitic stainless steels. As NUREG/CR-5999 S-N fatigue curves are similar in format to those presented in ASME III they may be used directly in the CUF evaluation. It is important to notice that NUREG/CR-5999 S-N fatigue curves have safety factors (2 on stress or 10 on cycles) smaller than those of ASME III S-N design fatigue curves.

4 EXAMPLES

In order to make some comparison between the concepts presented in this paper, a steam generator nozzle existing in a operating plant, and subjected to thermal transients, is studied. The component was qualified in the design phase by a simplified calculation, according formulas presented in Harvey (1980). Then a detailed calculation by finite element method is performed to justify life extension beyond the original life.

Tables 1 to 4 show the applied cycles n_i, allowable cycles N_i, the alternate stresses S_{ai}, and the cumulative usage factors CUF's (sum of the ratios of n_i/N_i) calculated using S-N fatigue curves from ASME III or NUREG/CR-5999.

Table 1 and 2 show, respectively, the results obtained by simplified and detailed methodologies. These calculations are based on ASME III S-N fatigue curves. From the tables it is observed a decrease in the CUF from 0.87 to 0.34 when a detailed finite element evaluation is considered. A similar analysis is performed using S-N fatigue curves from NUREG/CR-5999, which take into account the environmental effects . As it can be noticed, the aggressive conditions presented in a reactor environment affect the fatigue life of component. Table 3 and 4 show CUF's equal to 5.58 (simplified analysis) and 0.59 (detailed analysis), respectively. It may be observed an increase in the CUF values when they are compared with those previously calculated in Tables 1 and 2.

TABLE 1- CUF based on S-N curve from ASME III (simplified methodology)

n_i	S_{ai} MPa	N_i	n_i/N_i
400	414	2860	0.14
800	550	1380	0.58
10000	136	77000	0.13
60	393	3000	0.02
			0.87

TABLE 2 - CUF based on S-N curve from ASME III (detailed methodology)

n_i	S_{ai} MPa	N_i	n_i/N_i
400	322	5300	0.08
800	322	5300	0.15
10000	125	100000	0.10
60	322	5300	0.01
			0.34

TABLE 3 - CUF based on S-N curve from NUREG/CR-5999 (simplified methodology)

n_i	S_{ai} MPa	N_i	n_i/N_i
400	441	400	1.00
800	590	200	4.00
10000	151	20000	0.50
60	393	800	0.08
			5.58

TABLE 4 - CUF based on S-N curve from NUREG/CR-5999 (detailed methodology)

n_i	S_{ai} MPa	N_i	n_i/N_i
400	322	3000	0.13
800	322	3000	0.27
10000	125	60000	0.17
60	322	3000	0.02
			0.59

5 CONCLUSION

In the example, the steam generator nozzle was qualified in the design phase (FDB concept) using a simplified analysis methodology and S-N curve from ASME III (CUF=0.87). The introduction of modified S-N curves due to environmental effects to evaluate the conditions to lifetime extension of the components (FOB concept) increases CUF from 0.87 to 5.58. This shows that it is necessary to adopt a more refined and realistic analysis methods to qualify the equipment. With the temperatures and stresses calculated by finite element axisymmetric models the CUF changes from 0.34 (ASME III S-N curves) to 0.59 (modified S-N curves).

From this simple examples it is observed that:

a) A simplified analysis, that is, in general, conservative, in conjunction with modified S-N curves due to environmental effects may lead to an exaggerated conservatism and to a rejection of adequate designs;

b) The use of a simplified or detailed analysis plus ASME III S-N fatigue curves remains an acceptable procedure to qualify components in the design phase (FDB approach) and in the operation (FOB approach). However, the safety margins related to ASME III S-N design fatigue curves may not be maintained under reactors environment conditions. To overcome this problem the modified S-N fatigue curves, including reactors environment effects, may be used.

c) If equipment existing in an operating plant is required to increase its remaining life, it is recommended, for licensing purposes, to re-evaluate the original design using a detailed analysis (thermal and stress evaluation with finite element models), actual service loads, and methodologies presented in ASME Code Section III and XI considering the reactors environment effects.

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