PVP-Vol. 313-2, International Pressure Vessels and Piping
Codes and Standards: Volume 2 — Current Perspectives
ASME 1995

FATIGUE EVALUATION OF ASME CLASS 1 COMPONENTS CONSIDERING THE ENVIRONMENTAL EFFECTS

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ABSTRACT

A discussion considering fatigue design basis (FDB) and fatigue operating basis (FOB) approaches is presented. These two concepts are applied to evaluate the lifetime of typical ASME III class 1 components through simplified and detailed stress analysis. The cumulative usage factor (CUF) calculated using S-N fatigue curves available in the ASME III are compared to those obtained by S-N curves modified by the reactor environment. Some recommendations are presented to assess the fatigue in nuclear power plants structures.

NOMENCLATURE

E - Young's modulus
n - number of operating cycles
N - number of allowable cycles
S - stress
Sa - alternating stress

α - thermal expansion coefficient
$\Delta T_1, \Delta T_2$ - linear and nonlinear parts of the temperature distribution
ν - Poisson's ratio

CUF - cumulative usage factor
FDB - fatigue design basis
FOB - fatigue operating basis

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 in design phase and Fatigue Operating Basis (FOB) used when in service.

The FDB considers the methodology shown in ASME III (1992a), and its used to qualify components 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 components 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 formulae 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.

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 stresses resulting from mechanical loads calculated for simple geometries (cylinders, spheres, plates, beams) using formulae from standard handbooks such as Roark and Young (1976). The calculation assumes the thickness of the model equal to the smallest thickness of the actual structure and stress concentration factors at the discontinuity points.

When thermal loads are present, a simplified formulation to obtain the stresses is used in the form, (Harvey, 1980)

$$S = E\alpha\,\Delta T_1/2(1-.\nu) \;+\; E\alpha\,\Delta T_2/(1-.\nu) \qquad (1)$$

where S is the total stress, E is the Young's modulus, α is the thermal expansion coefficient and ν is the Poisson's ratio of the material. ΔT_1 and ΔT_2, defined respectively as the linear and non-linear part of the temperature distribution at the wall of component, are calculated using a one dimensional heat transfer model.

In the other hand, to perform detailed analyses the finite element method is used. In this case, the geometry and the mechanical and thermal loads may be defined in detail The temperature and stress distributions are obtained from tridimensional or axisymmetric models using available commercial programs.

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.

However, according to O'Donnell (1988) and O'Donnell and Porowski (1991), the generation of valid S-N fatigue tests taking into account the factors cited above (temperature, strain rates, etc.) is quite difficult. In order to overcome this problem, O'Donnell (1988) proposed an approach, based on crack growth data (tests are easier than strain-controlled tests) and elastic-plastic fracture mechanics, to obtain S-N curves which include reactor water environmental effects.

In NUREG/CR-5999 (1993) there are S-N fatigue curves obtained using an approach similar to that considered by O'Donnell (1988). 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.

EXAMPLES

In order to make some comparison between the concepts presented in this paper, two components from different nuclear power plants, under different cyclic and environmental conditions, were evaluated. The first is a steam generator auxiliary feedwater nozzle (fabricated with German materials 20 MnMo 55 and 15 Mo 3) and the other is a pressurizer surge nozzle (fabricated with SA-508 class 2).

Table 1 and 2 show the CUF's calculated for the auxiliary feedwater nozzle. In these tables, n is the number of operating cycles, Sa is the alternate stress, N is the allowable number of cycles and ni/Ni is the usage factor that corresponds to the stress cycle i. The thermal stresses due to through-wall temperature gradient were calculated using simplified and detailed methodologies, described before. These calculations are based on S-N fatigue curve presented in the ASME III. 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.

For the auxiliary feedwater nozzle, a similar analysis is performed using the S-N fatigue curve from NUREG/CR-5999 (1993), which takes 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.

In the investigation of the pressurizer surge nozzle only detailed finite element analysis is considered and similar results are found. Tables 5 and 6 show that there is an increase in CUF factor from 0.07 to greater than 1.0 when S-N curves associated to the environmental effects are adopted.

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

ni	Sai(MPa)	Ni	ni/Ni
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) auxiliary feedwater nozzle

ni	Sai(MPa)	Ni	ni/Ni
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) auxiliary feedwater nozzle

ni	Sai(MPa)	Ni	ni/Ni
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) auxiliary feedwater nozzle

ni	Sai(MPa)	Ni	ni/Ni
400	322	3000	0.13
800	322	3000	0.27
10000	125	60000	0.17
60	322	3000	0.02
			0.59

TABLE 5 - CUF based on S-N curves from ASME III (detailed methodology) pressurizer surge nozzle

ni	Sai(MPa)	Ni	ni/Ni
600	233	15000	0.04
1E6	85	∞	≈ 0
30	192	25000	0.00
555	145	100000	0.01
1500	132	100000	0.02
			0.07

TABLE 6 - CUF based on S-N curves from NUREG/CR-5999 (detailed methodology) pressurizer surge nozzle

ni	Sai(MPa)	Ni	ni/Ni
600	233	3000	0.20
1E6	85	<1E6	>1
30	192	8000	0.00
555	145	35000	0.02
1500	132	35000	0.04
			>1

CONCLUSION

In the first example, the auxiliary feedwater nozzle was qualified in the design phase using a simplified analysis methodology and S-N curves 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).

The pressurizer surge nozzle was initially qualified through a detailed analysis, with CUF=0.03. The evaluation of the CUF for life extension using modified S-N curves led to a value greater than 1.0. In this case a verification according to ASME XI, where a small crack is postulated and its propagation is evaluated, is necessary.

From these two 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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