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A Study on the Optimization of NSSS components

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1. Introduction

According to the development of nuclear technology in Korea, new designs for nuclear-related structures and components are necessary. The optimization technique is considered as one of the tools to make a better design[1]. In this research, several points to be considered when the optimization technique is applied to nuclear-related structures are discussed. And a method to manipulate these problems is proposed.

2. Structural Optimization to Meet ASME Code Section III

The code of ASME Sec. III prescribes the general rules of "design by analysis" upon the design of a NSSS[2]. To meet the code requirements of ASME Section III in optimizing the design of a NSSS, there are two differences in optimizing nuclear-related structures. One is a manipulation of the multiple loads with different stress limits. And the other is a different procedure to calculate the stresses used as constraints.

2.1 Multiple Loading Condition Based on Stress Categories in the ASME Code

Based on the code of ASME, stresses are categorized into three types with different stress limits. The stress limits change for different service levels. The three categories of a stress are a primary, secondary, and peak. Primary stresses are load controlled; secondary stresses are displacement controlled; and peak stresses are local in nature. Stress limits are established for Design, Level A(normal condition), Level B(upset condition), Level C(emergency condition), and Level D(faulted condition) loadings. Since the stress limits change for the types of stresses and the service levels, the multiple loading conditions should be utilized during an optimization. The optimization formulation under the multiple loading conditions is presented in Eq. (1).

$$\begin{aligned} &\text{Find} && \mathbf{b} \\ &\text{to minimize} && \varphi(\mathbf{b}) \\ &\text{subject to} && \mathbf{K}(\mathbf{b})\mathbf{z}_u = \mathrm{f}_u, \quad u = 1,\Lambda\ ,NLC \\ & && \mathrm{g}_{ju}(\mathbf{b},\mathbf{z}_u) \le 0, \quad j = 1,\Lambda\ ,m,\ u = 1,\Lambda\ ,NLC \end{aligned} \tag{1}$$

In Eq. (1), the total number of constraints treated in the optimal structural design is $NLC \times m$. So an effort should be made to logically delete redundant constraints. In the case of stress constraints the worst violation among the elements of a group, over all the loading conditions, may be treated instead of enforcing a constraint on each element under each loading condition. Thus the *i*th stress constraints may be expressed as Eq. (2).

$$\mathrm{g}_i = \max_{j,u}\{\mathrm{g}_{ju}(\mathbf{b},\mathbf{z}_u)\} \le 0, \quad j = 1,\Lambda\ ,NMi,\ u = 1,\Lambda\ ,NLC \tag{2}$$

Where *NMi* is the number of elements in the *i*th group. By this manipulation, the total number of stress constraints reduces and a sensitivity analysis for the redundant constraints is not necessary. It helps in a reduction of the calculation time and the optimization efficiency.

2.2 Linearized Stress as Stress Constraint

The stress linearization of the ASME Sec. III is a procedure to divide the total stress at concerned section into three different stress components such as a membrane stress, bending stress, and peak stress. The membrane stress has the meaning of a mean value, the bending stress has a linear distribution of the stress, and the peak stress has a nonlinear distribution of the stress.

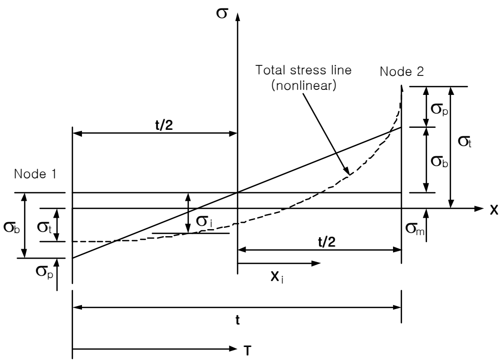

Figure 1. The linearized stress components

In Fig. 1, let us assume that the stress components at an arbitrary nodal point on the concerned SCL are represented as follows:

$$\boldsymbol{\sigma} = \begin{bmatrix} \sigma_x & \tau_{xy} & \tau_{xz} \\ \tau_{yx} & \sigma_y & \tau_{yz} \\ \tau_{zx} & \tau_{zy} & \sigma_z \end{bmatrix} \tag{1}$$

The membrane stress matrix and the bending stress matrix at a given SCL can be formulated as follows:

$$\boldsymbol{\sigma}_\mathbf{m} = \frac{1}{t}\int_{-t/2}^{t/2} \boldsymbol{\sigma}\, dx \tag{2}$$

$$\boldsymbol{\sigma}_\mathbf{b} = \pm\frac{6}{t^2}\int_{-t/2}^{t/2} \boldsymbol{\sigma}\cdot x\, dx \tag{3}$$

The stress intensity is calculated from the combined stress of $\boldsymbol{\sigma}_\mathbf{m}$ and $\boldsymbol{\sigma}_\mathbf{b}$. The calculation procedure is based on Tresca's maximum shear stress theory and is to find the maximum difference between the principal stresses. In order to calculate the stress intensity, the eigenvalue problem in Eq. (4) is solved. The calculated stress intensity is a linearized stress. The linearized stresses are used as stress constraints during an optimization for nuclear-related structures.

$$(\boldsymbol{\sigma}_m - \lambda \mathbf{I})\mathbf{V} = \mathbf{0}, \quad (\boldsymbol{\sigma}_b - \lambda \mathbf{I})\mathbf{V} = \mathbf{0}$$
$$[(\boldsymbol{\sigma}_m + \boldsymbol{\sigma}_b) - \lambda \mathbf{I}]\mathbf{V} = \mathbf{0}, \quad [(\boldsymbol{\sigma}_m - \boldsymbol{\sigma}_b) - \lambda \mathbf{I}]\mathbf{V} = \mathbf{0} \quad (4)$$

3. Example

The central cover and the annular cover in an integral reactor are connected by the mechanism of segment gates and a torus seal that is shown in Fig. 2. The relative displacement in the vertical direction happens due to the tolerance from the production and installation. The relative displacement in the horizontal direction also happens due to the difference of the thermal expansion between the two covers. The design pressure is applied as an internal pressure.

3.1 Problem Definition

The loads applied to the torus seal are presented in Fig. 2 and the characteristics of the loads are listed in Table 1. The loading combinations are in Table 2 with the allowable stress limits. The loading combination 3 has an allowable stress limit of 3.0 S_m because a thermal loading is included. The cost function is the outer radius of the torus seal. The selected five design variables and the loading/boundary conditions are shown in Fig. 2. For the linearized stress constraints, seven stress classification lines (SCLs) are selected.

3.2 Results

The optimum design of the torus seal is shown in Fig. 3. The stress intensities and the allowable stress limit for the initial design and the optimum design are shown in Fig. 4 for the loading combination 2. The stress intensities for the optimum design satisfy the allowable stress limit.

Table 1. Stress category classified by the loading and boundary condition

No.	Phenomena	Loading/Boundary Condition	Magnitude	Stress Category
①	Internal Pressure	Pressure (L.C.)	17 MPa	Primary
②	Installation Tolerance of Segment Gate	Vertical Disp. (B.C.)	1 mm	Primary
③	Thermal Expansion	Horizontal Disp. (B.C.)	0.5 mm	Secondary

Table 2. Loading combination

No.	Loading Combination	Allowable Stress
1	①	1.5 S_m
2	①+②	1.5 S_m
3	①+②+③	3.0 S_m

4. Conclusion

A structural optimization technique was proposed for the design of NSSS components which is governed by the code of ASME Section III. The proposed optimization technique has two characteristics. First, different stress limits for the stress categories are applied as multiple loading conditions. Second, section-wise stress constraints are adopted instead of point-wise stress constraints. The proposed method is applied to a shape optimization of a torus seal. The five design variables and the seven SCLs are selected. The linearized stresses at the selected SCLs are applied as stress constraints during an optimization. The optimum design satisfies all the constraints for each loading condition. The proposed method was successfully applied to an optimization of the NSSS components under multiple loading conditions and linearized stress constraints.

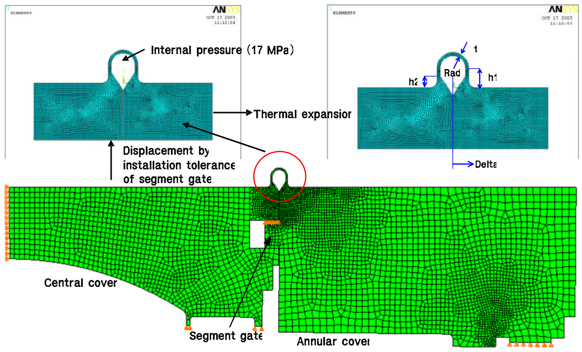

Figure 2. The shape of torus seal, the selected design variables, the loading/boundary condition

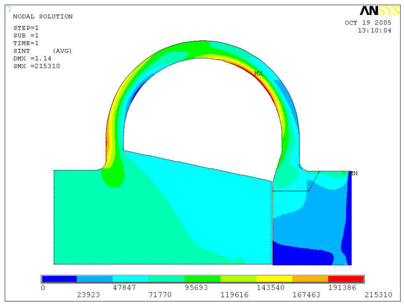

Figure 3. Stress results in optimum design

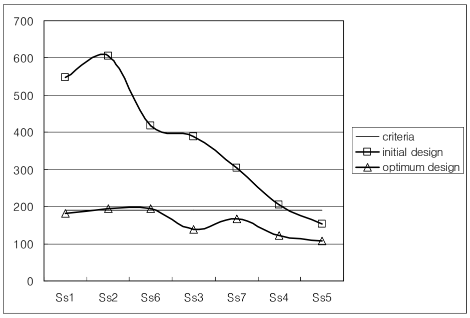

Figure 4. Stress intensities under the load combination 2

Acknowledgments

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[2] ASME Boiler and Pressure Vessel Code, Section III, Rules for Construction of Nuclear Power Plant Components.