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Estimation of maximum axial force of anchor bolts in consideration of random bolt failures

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A R T I C L E I N F O

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A B S T R A C T

This paper proposes a method for structural reliability analysis of anchor bolts used in the support skirt of a reactor vessel. The method is based on the conservative assumption that a few anchor bolts within the skirt's inner-wall may fail in a random nature. Under the assumption, the maximum axial forces in the intact bolts are estimated. To reflect the uncertainty, random numbers are generated to simulate the possible failed bolts among a total of 60 bolts, which are circumferentially arranged along the inner side of the wall. Then the outcome of failed bolts together with their locations for every 60 bolts is defined as an experiment of a sample. The locations of failed bolt can significantly affect the stress analysis and its random outcomes require an efficient calculation scheme. In this paper we propose a rapid calculation algorithm, thus the direction of bending moment that causes the worst scenario in the stress analysis of bolts for each experiment can be rapidly found. Taking into consideration of design loads, the finite element method is further employed to calculate the maximum axial bolt force of each experiment. After statistical analysis of maximum axial forces from all experiments, the average maximum axial-force interval that the remaining bolts can withstand under a given random condition is estimated with a 95% confidence level. This interval can be used in conjunction with various results of structural integrity assessment to ensure the structural safety and reliability of a nuclear power plant component.

1. Introduction

The inner and outer sides of a common nuclear boiling water reactor (BWR) pressure vessel support skirt are both anchored by 60 bolts, with the locations and structural configuration shown in Fig. 1. The major function of these anchor bolts is to prevent lateral sliding of the vessel from severe external loadings. The bolts are important components to ensure a tight connection between the reactor pedestal and the skirt [1]. In view of the transmission of load between the pedestal and skirt, and the need to secure the reactor in the civil engineering structure of the reactor room, the structural integrity of the anchor bolts significantly affects the operation of the reactor during service [2].

The anchor bolts used in the vast majority of BWR nuclear power plants are made of ASTM A540-grade low-alloy carbon steel [3]. This type of high-strength bolt is commonly used to secure structural components. According to aging management guidance reports, if the yield strength of bolt in this type is greater than or equal to 150 ksi, it is recommended that the bolts have to be inspected for cracks [4], because these high-strength bolts are potentially subjected to stress corrosion cracking. The causes of stress corrosion cracking are widely discussed in literature, and the three main causes are considered to be the material, corrosion environment, and stress [5]. With regard to the corrosion environment, although the base of a reactor pressure vessel is not in direct contact with steam, moisture may accidentally enter into the gaps between the bolt threads during the construction period, and bolts subjected to long-term tensile stress may encounter the foregoing stress corrosion factors. In addition, when preloaded bolts are tightened, deficiencies in construction quality may similarly lead to the formation of small cracks. Based on these possible initial cracking mechanisms, as well as the alternating changes in bolts' internal forces during operation, fatigue factors may cause the growth of cracks, and ultimately lead to failure. Each anchor bolt in a system has an independent and identical chance of creating initial crack.

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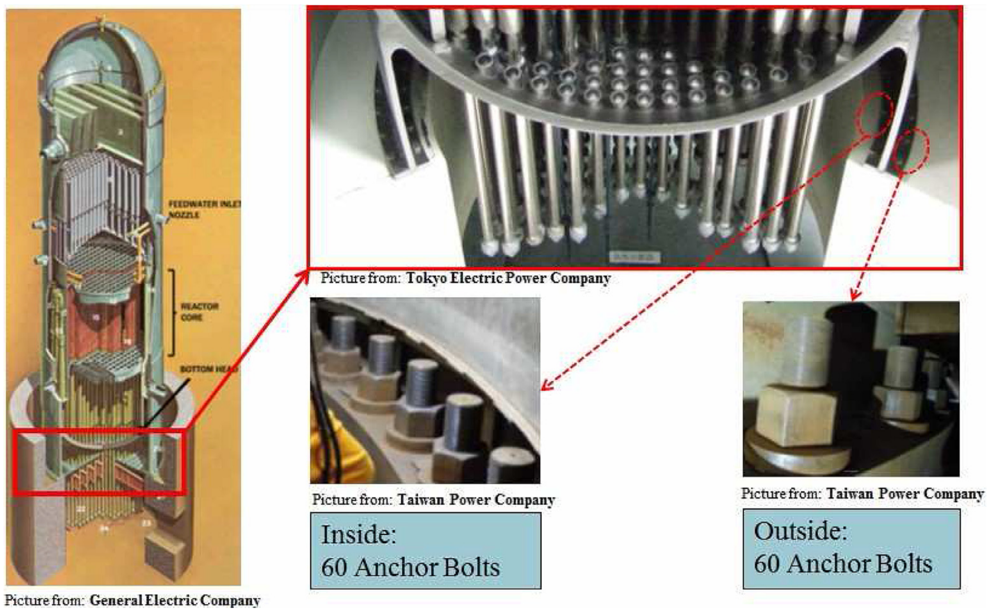

Fig. 1. Locations and structural configuration of anchor bolts on inner and outer side of boiling water reactor pressure vessel support skirt.

There are many researches and discussions, in which the probabilistic fracture mechanics is used to assess the structural integrity of internal reactor components, such as the reactor core shroud, reactor pressure vessel, and piping [6–8]. Most of these studies employ a sample derived from experimental results and power plant operating experience, in conjunction with an assessment of possible transient load, or linear elastic fractural criteria [9], to determine the structural integrity. However, with regard to anchor bolts of the pressure vessel support skirt, in view the fact that the anchor bolts are discrete while the foregoing targets of assessment are continuous, with the foregoing methods used to assess individual bolts and the results extended to the entire bolt group may be a little different. In particular, the calculation methods (models) of crack distributions by adopting test samples from material toughness experiments [10] may not be effective enough. This is because such a method would have to investigate possible crack distributions in all support skirt bolts, and then have to perform extensive calculations and consideration of parameters such as the decrease in preload and whether the bolts are subject to external force to the point of failure. Another consideration is the distribution of bolts that have entirely or partially lost their function. Only afterwards finite element analysis can be used to determine the system's structural safety.

In view of the foregoing considerations, this paper proposes a method for quickly and simply assessing structural integrity of the aforementioned structure. This method directly employs conservative failure probability assumptions, such as that a few bolts have failed completely, in conjunction with the use of random numbers to obtain the locations of completely failed bolts within the inner ring. The remaining bolts and 60 bolts in the outer ring are considered an experiment of sample for ensuring the structural integrity, and the fixed overturning moment angle leading to the maximum axial force on the bolts is determined for each randomly picked experiment. The finite element analysis software ABAQUS is used to calculate the maximum axial force for the experiment, and the statistical T-distribution method is used to estimate with a 95% level of confidence of the overall load that can be withstood by the skirt bolt group, as well as the average maximum axial force interval of the bolt subjected to the strongest force. This possible average maximum axial force interval can be used in conjunction with various safety inspection standards such as ASME B&PV Codes Section III, NF [11] to provide a reference for determination whether a reactor generating unit can be operated continuously. The approach in this paper can avoid the necessity of assuming at the beginning that failed bolts are mutually adjacent, which will ensure that excessively conservative maximum axial forces are calculated, and may lead to unnecessary shutdowns. Finally, the binomial theory is used to estimate the probability of bolt failure. At any assumed bolt failure rate, even if the calculated probability of occurrence is relatively low, this assessment method can be used to describe the possible forces on the bolts in the wake of failure.

2. Failure probability of bolts

With regard to anchor bolt failure events at a nuclear power plant, there are, in general, two types of failure probability calculation methods that can be extended to estimate the future probability of recurrence.

First, actual cases of failure are used as a particular experiment, and the bolt failure rate obtained. Next, a binomial distribution is used to estimate the probability of recurrence during each subsequent year. For instance, assume that 5 of the 60 anchor bolts on the inner side of the skirt wall have been found to have failed 20 years after a certain power plant began operation, and no bolts on the outer side have failed. Furthermore, the probability of different numbers of failed bolts after one year is shown in Table 1, where the binomial distribution formula used in calculations is:

$$C_n^{55}\left(\frac{5}{60}\times\frac{1}{20}\right)^n \times \left(1-\frac{5}{60}\times\frac{1}{20}\right)^{(55-n)}; \tag{1}$$

where n is the number of anchor bolts suffering failure after one year.

It can be seen from Table 1 that the greater the number of bolts concurrently suffering failure, the lower the probability. However, it