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A Numerical Analysis of the Stress-strain Behavior of Anchorage Elements and Steel Liner of a Prestressed Concrete Containment Wall

Petr Bílý*, Alena Kohoutková

Czech Technical University in Prague, Faculty of Civil Engineering, Department of Concrete and Masonry Structures, Thákurova 7, 16629 Prague, Czech Republic

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ABSTRACT

The paper presents a numerical analysis of the stress-strain behavior of the steel liner of a prestressed concrete containment wall and the anchorage elements between the liner and the wall. Models of a block segment of the wall were created and loaded by prestress, operation temperature, creep and shrinkage, loss of coolant accident (LOCA) temperature and LOCA pressure. The purpose of the block models was to observe the stress-strain behavior of the steel liner plate in the course of service life of the structure and to obtain boundary conditions for the detailed models of anchorage elements connecting the liner to the concrete wall. There were two different types of anchorage studied – headed studs and L-profiles. The detailed models of anchorage elements were loaded by displacements calculated in the block models and exploited for the determination of extreme stresses in the steel liner and widths of cracks in the concrete wall. The importance of initial geometry imperfections of the steel liner plate was appraised as well. According to the results, there is no risk of buckling of the liner or failure of the liner and anchorage elements during operation conditions and LOCA. There is also no substantial difference between the stress-strain behavior of the liners connected by headed studs or by L-profiles. However, the initial imperfections of the liner plate were found to be very important for the distribution of stresses in the liner and crack pattern in concrete.

1. Introduction

A steel liner is a key element of single-wall prestressed concrete containments of nuclear power plants. In case of a serious accident, it ensures the leaktightness of the containment, prevents the escape of radioactive material to the environment and minimizes the consequences of the accident. The correct design of the liner, the ability to predict its behavior and the possibility to rely on its function are therefore necessary for safe exploitation of nuclear energy. The dimensions of the liner and the connection between the liner and the concrete wall of the containment have to be verified carefully. The concept of safe design of the liner and anchorage system is based on three main Condition (2):

- The liner has to be fixed to the concrete wall to secure compatibility of strains of both parts of the structure. This is maintained by sufficiently small distances between the anchorage elements.
- The strain due to buckling between the anchorage elements under operation conditions has to be limited.
- In case of excessive strains (during accidents), the anchorage has to fail without causing damages to the liner.

1.1. State-of-the-art review

Several authors have dealt with the issue of the stress-strain behavior and the verification of safe design of steel liners exposed to mechanical or thermal loads in the past.

Young and Tate [3] conducted an experimental study of buckling and failure modes of a steel liner of prestressed concrete containment exposed to extreme loads. They compared the behavior of liners connected by L-profiles or by headed studs. They found that the thickness of the liner is quite important for its overall strain, but the values may vary significantly based on the properties of concrete (strength, elastic modulus, creep and shrinkage parameters). They also investigated the influence of cyclic loading and changes of internal temperature on the deformation behavior liner. For different setups having the ratio of distance between the anchorage elements (L) and the thickness of the liner (t) in the range of $L/t = 18–38$, buckling was never observed until the yield limit of steel was reached. Usually, buckling occurred at the strain of $1.1–1.2 * 10^{-3}$.

Ostapenko and Ulkumen [4] carried out a theoretical study aimed at deformation patterns of buckled steel liners. Geometrical parameters of the liners were set up so that the buckling occurred before reaching the

* Corresponding author.
E-mail address: petr.bily@fsv.cvut.cz (P. Bílý).

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ultimate strength of steel. Cylindrical and sinusoidal shapes were determined to be the most likely ones.

Doyle and Chu [5] compared the stress-strain behavior of various arrangements of anchorage elements of a steel liner by analytic calculations and experiments. The thickness of the liner plate, the yield strength of the steel and the distance between the anchorage elements were varied. The critical situation when one of the panels of the liner is initially deviated in the direction perpendicular to the plane of the liner, while the other panels are ideally flat was considered. The authors came to a conclusion that low yield stress should be specified for the liner to limit the stresses and strains in the connection of the liner to the anchorage elements. They also proposed that the ratio between the thickness of the liner and the thickness of the anchorage element should be < 2.7 (2.0 if possible) to avoid formation of cracks in the connection between the liner and the anchorage elements.

Armentrout [6] was one of the first researchers who employed the finite element analysis to study the stress-strain behavior of anchorage details. The failures occurring in the details were mainly attributed to the crushing of the concrete in the anchorage zone. The steel element itself remained undisturbed even for the highest strains. A set of experiments confirmed this finding.

A comprehensive research program focused on containments was under way in Sandia National Laboratories in USA between 1983 and 2001 [7]. Several large-scale experiments were performed, some of them dealing also with the performance of the steel liner. Liner failures were found to be a common limiting factor for both the leaktightness and the overall capacity of the containment. Several papers analyzing the response of steel liners in Sandia experiments were published [8,9,10].

In 1987, a 1:6 scale model of concrete containment with a steel liner was constructed. The containment failed due to the vertical crack in the liner located near the first row of headed studs next to the insert around the equipment hatch. Spletzer et al. [8] proposed a hypothesis describing the mechanism of formation of cracks in the yielded areas of the liner. The hypothesis was partially confirmed by a set of experiments.

Anderson [9] created a 3D FEM model of the equipment hatch area in the 1:4 scale Sandia experiment. The simulation results revealed that the steel liner separates from the concrete surface in the region of the out-going bend line around the equipment hatch. This leads to additional strains of the liner reaching up to 10%. As the ultimate strain considering the biaxial stress state and the influence of welding was evaluated to around 12%, the described effect was found to be very important for the failure of the liner.

Anderson [10] carried out a parametric study of the influence of through-wall concrete cracks on the strain level of the liner. It was shown that the effect from friction between the concrete and the liner may be significant, causing high concentrations of plastic strains. One of the conclusions was that the concentrations of strain due to friction increase with decreasing liner thickness. This effect should be accounted for when interpreting the scaled test results. The scale models, which have thinner liners, could get significantly higher liner strains than the actual full-scale containment, and, consequently, such results might be considered as overly conservative. Anderson also found that the distance of anchorage elements has a relatively small impact on the liner strains. The variation of the calculated values was insignificant in the range of 0.15–1 m.

1.2. Objectives of the research

The containment liner constitutes the ultimate leak-barrier, which prevents leakage at high internal pressure loads. Section 1.1 mentioned several papers and other research works dealing with the behavior of the liner exposed to severe loads. Some of these studies were created a long time ago. Some of them were oriented just on the experiments. There are almost no works exploiting modern computer modeling approaches to study the stress-strain behavior of the steel liner and anchorage elements, probably the only exception being the study of Anderson [9]. Therefore the authors decided to pursue this extremely important issue and to develop a set of FEM models that could be used for the analysis of the deformation behavior of the steel liner.

This paper is based on results of the previous work [11] which was focused on preparation of a model for global analysis of the containment. A horizontal ring FEM model of the containment was created, the analysis of the sensitivity of the model to various changes in geometry, loads or FEM model parameters was performed. As a result, optimal setup of the model was obtained.

This numerical study aims at preparation of partial models studying the behavior of the steel liner of a prestressed concrete containment. Two types of the models have been prepared:

- Models of block segments of the containment wall (referred to as "block FEM models" in this paper). In these models, a segment of the steel liner exposed to operation and LOCA loads have been studied. The differences of the stress-strain behavior of liners connected by headed studs or L-profiles have been compared.
- Detailed models of anchorage elements (referred to as "detailed FEM models" in this paper) aimed at determination of the stress-strain behavior of the steel liner anchorage area and estimation of width of cracks in the concrete wall. As in case of the block models, two different anchorage systems have been considered. The effect of initial imperfections of liner plate has been assessed.

All the analyses have been performed for one particular type of structure (single-wall prestressed concrete containment with torospherical dome, orthogonal layout of tendons and internal steel liner) with geometrical, material and loading conditions defined in Sections 2 and 4. In principle, similar behavior can be expected for all containments of the given type, although the values of stresses and strains would differ based on geometry, material and loading of the given structure. The results are not generally applicable to other types of prestressed concrete containments such as double-wall structures, containments with helicoidal tendons or structures with hemispherical dome etc. For these structures, a special analysis should be conducted exploiting the methods and approaches described in this paper.

2. Description of the structure

Project documents of real nuclear power plants are unavailable for the public. Therefore, the layout and dimensions of the experimental containment built in Bhabha Atomic Research Centre (BARC) in Tarapur, India [13] were used as a basis for the analysis. BARC containment is a 1:4 scale close representation of the existing prestressed concrete containments no. 3 and 4 of Tarapur Atomic Power Station in India. The main parameters of BARC are clearly described in Fig. 1. The stresses and strains calculated in the concrete wall were not affected by scaling. In general, they are directly proportional to the containment wall radius and inversely proportional to the containment wall thickness. Both these dimensions were properly scaled. The cross-sections of tendons and reinforcement were also scaled to preserve the same magnitude of internal stresses.

For the block FEM models, a segment of the containment wall from the middle of the height of the wall was selected (the elevation of the upper surface of the block was + 3.150 m).

BARC containment was built without lining. In practice, several types of connection of the liner to the concrete wall are used. The authors selected two common arrangements of the liner and its anchorage (headed studs and L-profiles) and attached them to the inner surface of