Advances in Engineering Software 102 (2016) 97–104

Contents lists available at ScienceDirect

Advances in Engineering Software

journal homepage: www.elsevier.com/locate/advengsoft

Research paper

Structural design optimization of roof slab of a pool type sodium cooled fast reactor

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ARTICLE INFO

Article history:
Received 16 June 2016
Revised 30 August 2016
Accepted 25 September 2016

Keywords:
Roof slab
Optimization
Structural integrity
Numerical analysis

ABSTRACT

The roof slab of the nuclear reactor supports all the components of the reactor. Roof slab is essentially a box structure with top and bottom plates interconnected by vertical shells and radial stiffeners welded to them. The gap between the top and bottom plates is filled with concrete that provides biological and thermal shielding in the top axial direction of the reactor. The 500 MWe Prototype Fast Breeder Reactor (PFBR) is designed based on the Operating Basis Earthquake (OBE) and Safe Shutdown Earthquake (SSE) which are categorized under level A and level D loadings respectively. The primary objective of this work is to optimize the design of the roof slab and to predict and ascertain the structural integrity of the optimized roof slab under static, harmonic and seismic loading conditions. Regression models for critical design parameters are developed and are used in the optimization algorithm.

1. Introduction

Fast Breeder Reactor (FBR) is a sodium cooled pool type reactor with two primary pumps and two secondary loops. A few significant structural dynamics problems such as pump induced as well as flow induced vibration and seismic excitation is very critical in a fast breeder reactor. Roof slab, which is the top cover for the main vessel forms the top shield along with rotating plugs. It provides biological and thermal shielding in the top axial direction of the reactor. It also acts as a support for various components such as main vessel (MV), Intermediate Heat Exchangers (IHX), Decay Heat Exchangers (DHX), Control Plug (CP), Primary Sodium Pump (PSP), in-vessel transfer machine, etc.

The reactor assembly of prototype fast breeder reactor is shown in Fig. 1 and roof slab is shown in Fig. 2. Chetal et al [1] described the salient features of PFBR including the design of the reactor core, reactor assembly, main heat transport systems, component handling, steam water system, electrical power systems, instrumentation and control, plant layout, safety, research and development. Commercial Fast Breeder Reactors (CFBRs) are planned to be built by 2023 after PFBR [2]. CFBR have many innovative features in reactor assembly design to achieve cost reduction. The design adequacy of PFBR components has been confirmed jointly by the scientists of IGCAR and other researchers from academia using several analyses. Chellapandi et al [3] predicted the vibration response of primary pump as well as dynamic forces developed at its supports using numerical analysis. Chellapandi et al [4] have investigated the effect of inter-connection of the nuclear reactor with the adjacent building during seismic event.

Chellapandi et al [5] have investigated the seismic analysis of reactor assembly considering the fluid-structure interaction effects. An axisymmetric finite element analysis is performed with Fourier option to account for the circumferential load variations. The reactor assembly components were modeled as axisymmetric shell structures with FEM. Prakash et al [6] discussed on the experiments carried out of PFBR subassemblies for its design qualifications. The tests include pressure drop measurements, cavitation testing, flow induced vibration studies and subassembly hydraulic lifting studies.

Prakash et al [7] performed the flow induced vibration studies on a scaled down model of PFBR control plug. From the experimental results, it is concluded that the control plug internals are subjected to flow induced vibration away from the resonance and the level of vibration and the bending stress induced are well

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http://dx.doi.org/10.1016/j.advengsoft.2016.09.006
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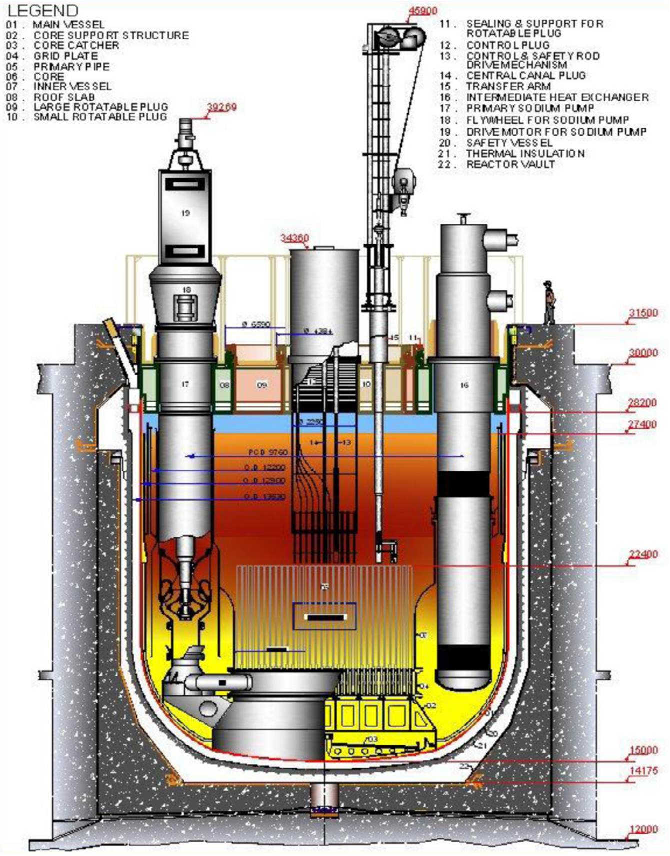

Fig. 1. Schematic of PFBR reactor assembly.

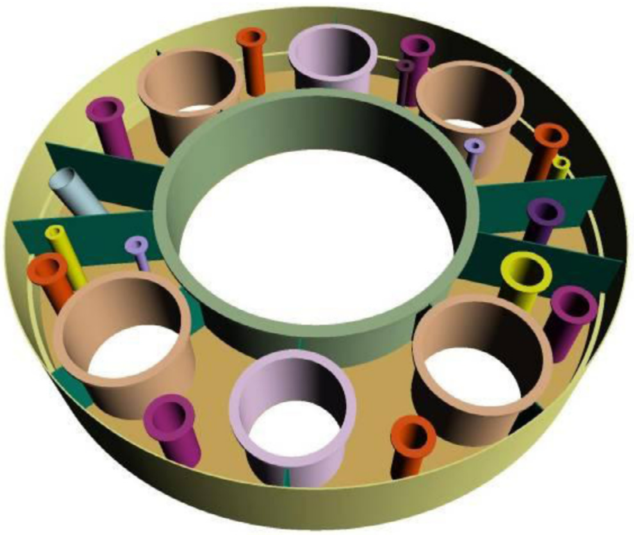

Fig. 2. Typical view of roof slab (top plate removed for clarity).

below the permissible limit. Chellapandi et al [8] have investigated the issues related to structural integrity of primary containment and reactor containment building of PFBR under core disruptive accident condition. Prabhu Raja et al [9] have carried out an investigation of the roof slab based on 1/12th scaled down model made of perspex material.

Constructional experiences show that FBR is costly by a factor of 2 or 3 than pressurized water reactors. Therefore considerable cost reductions are required for their commercialization. Cost of FBR involves construction cost, operation and maintenance cost and fuel cost, of which construction cost alone accounts for 75% of the total cost. The objective of the present study is to minimize the cost of the roof slab by varying the thicknesses of the various plates of roof slab and the height of the roof slab. In this present study, an attempt was made to optimize the existing roof slab design and the optimized roof slab was checked for the design adequacy using harmonic and seismic analysis.

2. Finite element modeling

A parametric model of the roof slab developed using the finite element analysis package ANSYS is shown in Fig. 3. The finite element meshing of the model is done with SHELL63 elements. The SHELL63 element has both bending and membrane capabilities and in-plane and normal loads are permitted [10]. The element has six degrees of freedom at each node: translations in the nodal x, y, and z directions and rotations about the nodal x, y, and z axes. In order to ensure that a mesh independent solution is obtained, seven finite element models were examined with different number of elements. It is found that the difference in results obtained using fourth and fifth models in terms of stress intensity is 0.03% which is very less and hence the fourth model is adopted for further numerical simulation.

Fig. 4 shows the finite element model of the roof slab. The loads of the components supported over the roof slab can be incorporated in the model using two methods: (i) uniformly distributed pressure load and (ii) load per node. In the first method, the weights of the components are converted as uniformly distributed pressure loads by dividing the component weight with the respective surface area over which the component is seated. In the second method, the component weights are converted into load per node, i.e., by dividing the component weight with the total number of nodes attached to the respective surface area over which the component is seated.

In the current analysis, the weights of various components supported by the roof slab are incorporated as weight per unit area on the supporting flanges. An additional flask load of 250 t is considered at PSP/IHX location (one location at a time). The concrete is filled within cooling box sectors and the concrete load acts on the bottom plate through the contact edges of the cooling box sectors (Fig. 5). The weight of the shielding concrete is applied as load per unit node on the nodes of the bottom plate interconnected to contact edges of cooling box sectors.

The incorporation of loads acting on the roof slab has been verified with the reaction forces obtained using the finite element model.

3. Optimization of the roof slab

The objective of the optimization is to reduce the weight of the roof slab within the limit of state variables. Optimization is carried out by two methods: (i) using ANSYS optimization module and (ii) Meta model based optimization. The former method employs a parametric model of the roof slab for optimization within the limitation of state variables. In the later method, a metamodel of the roof slab was developed using Response surface methodology (RSM). Metamodels are a cheaper alternative to costly analysis tools such as finite element method and can significantly reduce the computational time involved.

RSM involves the use of design of experiments for proper sampling of the design space and metamodeling techniques for the development of metamodel. The experimental design adopted for the study was Central Composite Design (CCD) and Orthogonal Array (OA). The metamodeling technique used in this study is polyno-