

Mechanical Design Verification of CHASNUPP Bottom Nozzle

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ABSTRACT

The bottom nozzle is a critical component of the fuel assembly of 340 MWe PWR Nuclear Power Plant at Chashma site (CHASNUPP). It bears axial loads during fabrication, handling, transportation, and reactor operation. The perforated plate, containing flow-holes of complex orientation, is the main critical load bearing and supporting component of the bottom nozzle. Therefore, mechanical strength and stresses of the bottom nozzle need to be analyzed and tested under limiting load conditions, i.e., transportation load 6g. The present study is an attempt to develop the finite element (FE) methodology in order to assess the structural integrity and determine the maximum stress concentration area of the bottom nozzle at applied limiting load of 6g, at standard temperature and pressure (STP). The FE model of the bottom nozzle was produced by solid element (C3D8R) and solved by the static linear analysis using computer code ABAQUS/CAE 6.10-1. Final results acquired from the FE analysis are compared with the mechanical compression test results for mechanical design verification. The values of maximum stress calculated through FE analysis are much comparable with the stress values obtained from each strain gauge at similar locations, which confirmed the accuracy of the FE methodology. The value of the max. von-mises stress (Seqv.), obtained by the FE analysis, and max. value of the stress obtained through test, under applied load of 6g, are less than the design stress limit (yield strength) of bottom nozzle material, SS-321, thereby verifying its structural integrity as well as satisfying its mechanical design criteria under limiting load of 6g.

Keywords: CHASNUPP, Bottom nozzle, Perforated plate, Finite element, Compression analysis, Stress measurement.

1. Introduction

In Pressurized Water Reactor (PWR) the Fuel assembly bears a variety of loads, such as compressive, tensile, torsional impact and bending etc., Moreover, the other external load as shipping, handling and reactor operation. The buckling structural strength of the fuel assembly is provided by the fuel assembly skeleton [1]. Bottom nozzle is a square box like structure which serves as the bottom structural element of the CHASNUPP fuel assembly. It consists of a perforated plate, four enclosure plates, and four bearing plates as shown in Fig 1.

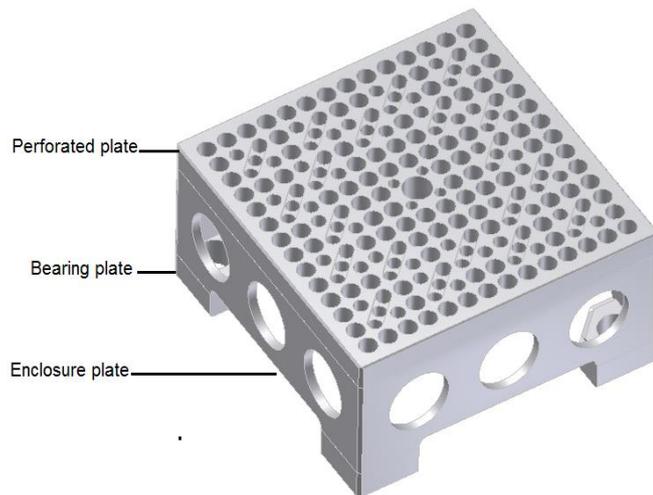


Fig. 1: Bottom nozzle of CHASNUPP fuel assembly.

The perforated plate has square cross-section, which is provided with number of holes to permit flow of coolant upward through the bottom nozzle, as well as provides connection to the bottom ends of the guide thimbles at respective hole positions through bolts.

Four enclosure plates are welded to the perforated plate to form a plenum. One bearing plate is welded at each corner of the plenum to form the bottom nozzle subassembly. Bearing plates act as supporting pads of the bottom nozzle. Each bearing plate has a hole that can mate with lower core plate pin for indexing and positioning of the fuel assembly.

During reactor normal operation entire weight of fuel assembly and associated core components passes to lower core plate through bottom nozzle. Moreover, the perforated plate has to bear axial loads during transportation and handling of fuel assembly. Among all axial loads, the load during transportation is considered as the limiting one [2]. Thus mechanical tests and finite element (FE) analysis for the CHASNUPP fuel assembly and components are needed for determination of structural integrity against such loads.

For this purpose, a FE model of bottom nozzle has been produced to evaluate the mechanical strength and stress concentration areas. Its static linear analysis has been performed using ABAQUS, CAE 6.10-1 software. The strength test of the bottom nozzle has also been conducted by SNERDI, China [3] to determine local stresses in the X and Y directions (axes in the plane of plate) at specified locations. The bottom nozzle test specimen was manufactured from stainless steel (SS-321). The details of material properties used for the test specimen and FE model are given in Table 1.

Table 1: Material properties of bottom nozzle at room temperature [4]

Material	Yield strength (MPa)	Tensile strength (MPa)	Modulus of elasticity (GPa)	Poisson's ratio (γ)
Bottom nozzle (SS 321)	≥ 205	≥ 515	200	0.3

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We have already made attempts towards research and design work of CHASNUPP fuel assembly. Our experience includes structural integrity assessment of the CHASNUPP fuel assembly and associated components, i.e. stiffness and stress measurement of the spacer grid support system using ANSYS Code [5], study of the buckling or deformation behavior as well as the stress has been determined across the fuel assembly at compression load using ANSYS Code [6], and study of the deformation behavior and the stress measurement of the skeleton of fuel assembly using ANSYS Code [1]. Moreover, Chen [7] had reviewed 300 MWe Qinshan fuel assembly and associated core components design and proposed some modification. Now, in the present study, we have performed FE analysis for CHASNUPP bottom nozzle using analytical code ABAQUS, CAE 6.10-1. The details of present analytical and experimental work along with the results are described in the subsequent sections.

2. FE model

The bottom nozzle of fuel assembly has symmetry in the cross section. The boundary conditions symmetry is true in geometry, loads, constraints and material properties. Therefore, the advantage of symmetry has been taken into account and only quarter part of the bottom nozzle has been simulated and analyzed. The solid model is illustrated in Fig. 2.

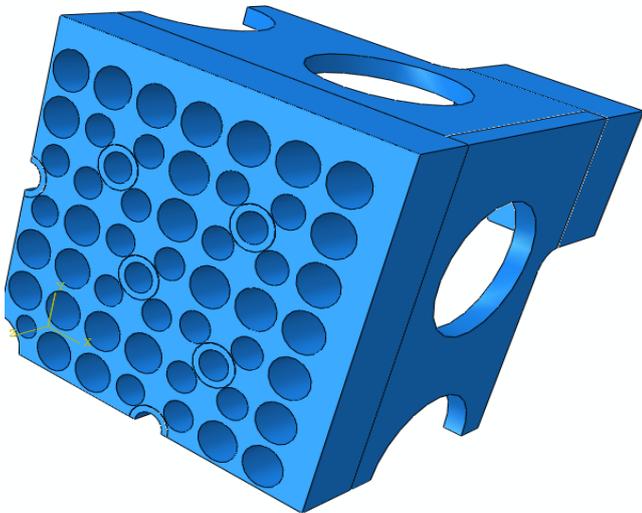


Fig. 2: Solid model (volume plot 3-D).

The FE model of the bottom nozzle has been developed using ABAQUS to simulate the applied boundary conditions, which prevail during transportation. The solid element C3D8R type is used to generate meshing of the geometry.

C3D8R is a 3D element having 8-nodes and reduced integration points (computationally inexpensive) with six degree of freedom at each node, well-suited for geometrically

linear or non-linear, large strain, displacement and rotation problems.

The symmetry of the geometry has been applied at all nodes associated with inside edges of quarter portion of the bottom nozzle. To constraint the FE model nodes associated with bottom surface of the bearing plates are fixed. The load has been applied on the upper surface area associated with the guide thimbles. The weight of fuel assembly is 450 kg or ~4410 N. The load has been applied in step multiples of 1g. Maximum applied load equivalent to 6g (26460 N) is distributed uniformly on 20 holes for the guide thimbles. The FE model with all boundary conditions is shown in Fig. 3.

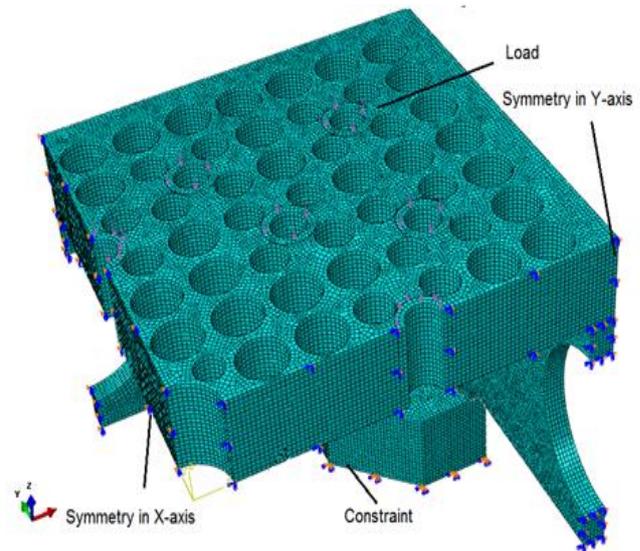


Fig. 3: Applied boundary conditions (element plot 3D).

3. Numerical results

1. A high mesh refinement level based on sensitivity analysis has been applied to final FE model at which results are converged.
2. The max. elemental Seqv, 128 MPa, is located at upper surface of the perforated plate, near the edge of the instrumentation tube flow hole, which is the stress concentration area, as shown in Fig. 4. The Seqv. value 128 MPa is less than the yield strength of the bottom nozzle material, 205 MPa [4], fulfilling the structural integrity criterion. The min. elemental Seqv, 0.03 MPa, is located at the corner of the bottom nozzle.
3. Maximum tensile stress at Y-direction, 84.39 MPa, is located at the bottom surface of the perforated plate and near the edge of the instrumentation tube flow hole as shown in Fig. 5.
4. The max. compressive stress in Y-direction, -88.4 MPa, is located near the joint of bearing plate and enclosure plate as illustrated in Fig. 6.

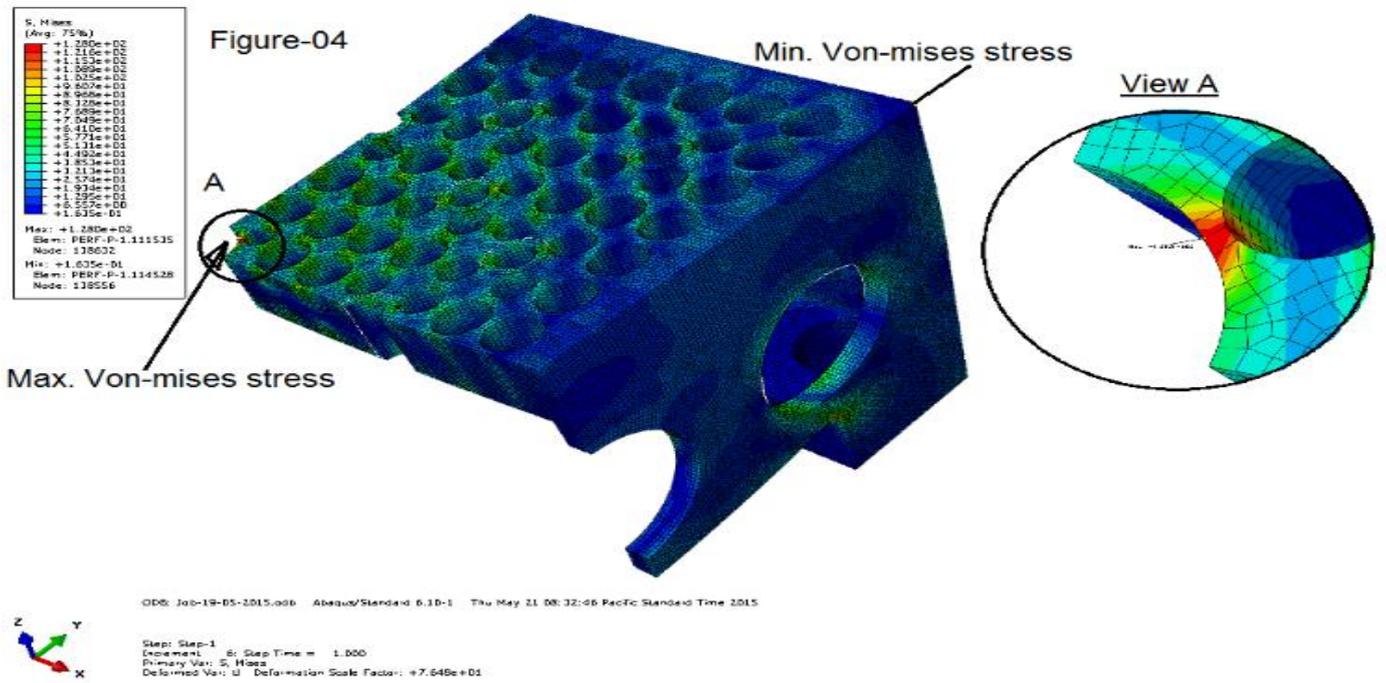


Fig. 4: Plot of elemental von-mises stress.

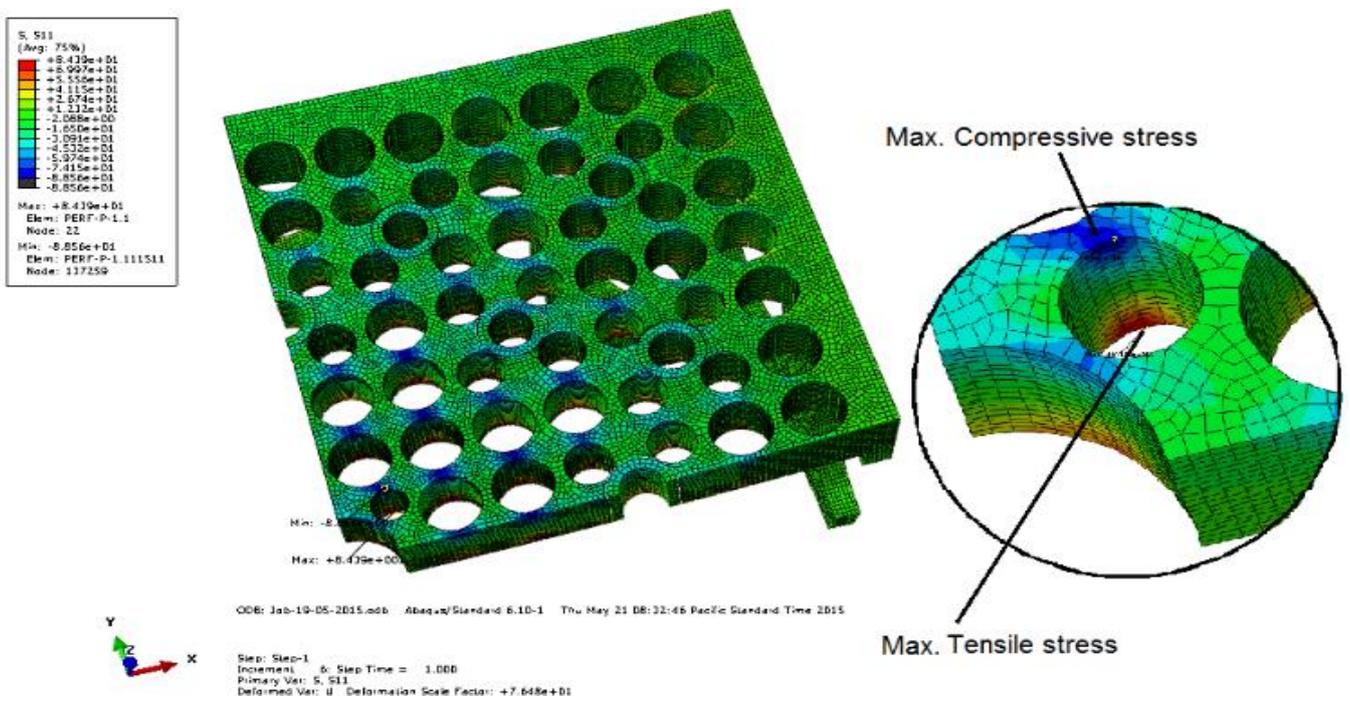


Fig. 5: Plot of elemental stress along x-direction.

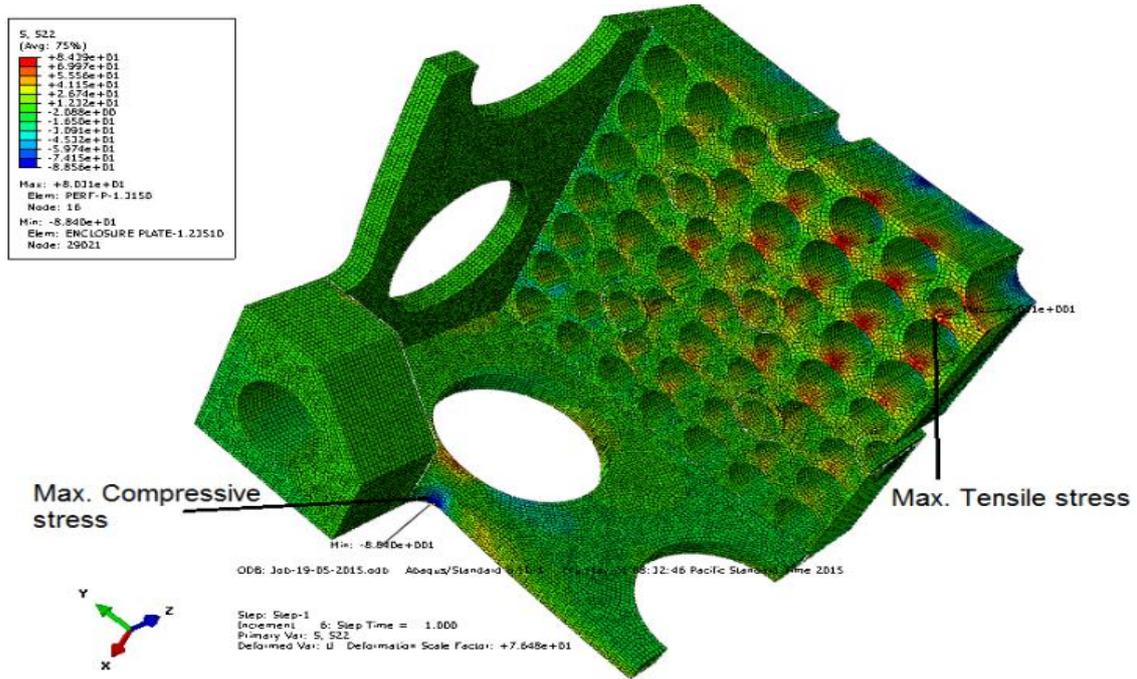


Fig. 6: Plot of elemental stress in y-direction.

4. Experimental work

The Mechanical (compression) test has been performed to measure the strength of bottom nozzle under the applied load of 6g (26460 N). This load is considered as the maximum limiting load on the CHASNUPP bottom nozzle. There is a symmetrical loading condition on the bottom nozzle in all respects. The structural design of the bottom nozzle is also symmetrical. Therefore, 1/8th of the bottom nozzle is selected for the test measurements, to save the data analysis time and to facilitate the installation of strain gauges, as there is a space limitation for the gauge pasting and taking out the lead-wires safely.

5. Design and fabrication of test specimen

In order to perform test, the bottom nozzle test specimen has been designed considering as the structural part of a 15×15 CHASNUPP fuel assembly. For applying the load at the guide thimbles locations as per actual fuel assembly, 20 guide thimble tubes are connected with loading plate by using argon arc welding.

These guide thimbles along with the loading plate are tightened with perforated plate, using bolts after inserting through their respective holes and locations as per actual conditions. The bottom nozzle test specimen has been manufactured using the same material (SS 321) and dimensions as per actual fuel assembly. All of these parts are assembled to simulate actual bottom nozzle of CHASNUPP fuel assembly as shown in Fig. 7.

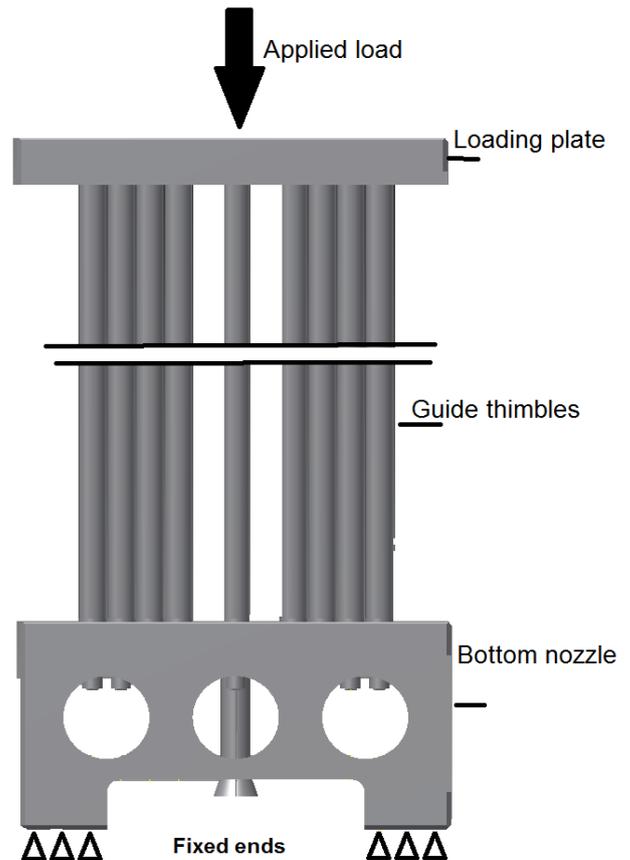


Fig. 7: Bottom nozzle test specimen.

Test Description

1. Mechanical (compression) test of the bottom nozzle has been performed at SNERDI, China [3]. The strain gauges of very small size of dimension 1mm × 1mm have been used for measurement of the strain during the test. These gauges are pasted on the 1/8th top surface of the perforated plate. The compression load is applied through a computerized Universal Testing Machine (UTM). Its calibration and verification has been performed as per ASTM Standard [8] and strain values on the bottom nozzle have been calculated from the strain data obtained from the Data Acquisition System.
2. Total 22 biaxial strain gauges have been used for the test of bottom nozzle to obtain strain data from 22 locations. All these gauges have been installed on the compression (upper) side of perforated plate. The critical 22 locations, where it is desired to measure the stress values, are shown in Fig. 8.

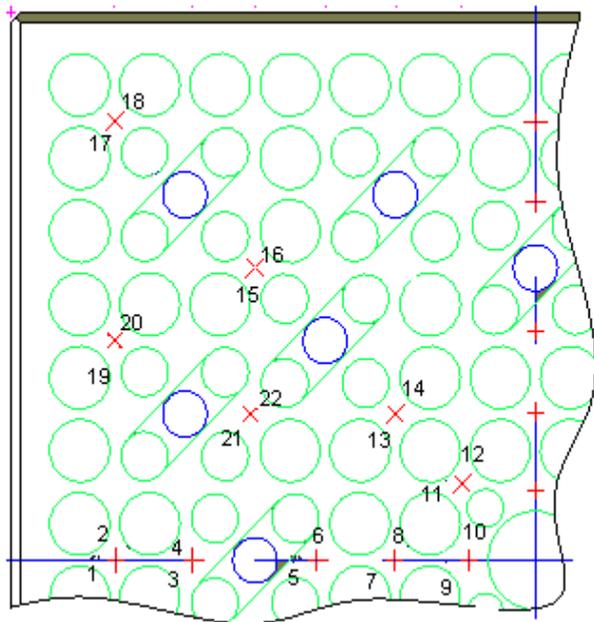


Fig. 8: Arrangement and orientation of the gauges on test specimen.

3. The bottom nozzle compression test is performed at room temperature in air. The load is applied on the test specimen in small steps of load 1g (4410 N). The data acquisition system is attached with the strain gauges, installed at the specified locations on the specimen, to attain the test data in the form of strains. The strain data has been further processed manually to get stress values using principal stresses formula [9].
- 7. Experimental Results and Discussion**
1. The results of three strain gauges, Nos.1, 10 and 19, are not included in the study, as they are located in the low stress concentration areas and have small stress values, i.e. $\leq \pm 3.11$ MPa. However, absolute error of the results (both FE and test) is also low for these strain gauges.

2. The value of the local stress obtained by the FE analysis at each strain gauge location is compared with the experimental result [3] obtained at the same location, as mentioned in table 2.

Table 2: FE and test results Comparison at load of 6g (26460 N).

Gauge No.	Stress (MPa)		% Error
	FE Analysis	Test	
2	-14.2	-12.1	14.7
3	-9.83	-9.92	-0.9
4	-22.2	-19.63	11.7
5	-21.8	-24.91	-14.2
6	-19.02	-22	-15.6
7	-25.84	-29.51	-14.1
8	-24.04	-22	8.5
9	-7.5	-8.6	-14.6
11	-18.38	-18.5	-0.6
12	-14.83	-14.4	2.9
13	-30.49	-30.2	0.9
14	-19.94	-16.8	15.7
15	-37.18	-33.2	10.7
16	-20.6	-17.43	15.5
17	-23.88	-21.8	8.7
18	-24.03	-23.32	3.0
20	-11.32	-10.6	6.4
21	-16.8	-18.81	-11.9
22	-26.65	-23	13.7

**Error= (Test-FE analysis)/Test×100*

3. It is clear from table 2, that the values of stresses obtained through FE analysis are comparable with the test values at most of the strain gauges locations. The errors between the two studies lie within the range of $\pm 15.7\%$, which indicates the validity of the FE model.
4. Some dispersion in the experimental results mainly caused due to the allowance of the specimen over all height and thickness / flatness of the perforated plate. All strain gauges are pasted on the perforated plate which has too many flow holes due to the very limited available solid area it was very difficult to placed strain gauges there hence it may also cause some error.
5. The value of max. principal stress, -37.18 MPa, is obtained at strain gauge No. 15, at the same location of the FE result, i.e. -33.2 MPa (see Table 2). The max. principal stresses obtained through both studies are comparable and lie within the error of 10.7%.
6. The max. Seqv obtained by the FE analysis, 128 MPa, is obtained at the top surface of the perforated plate, near the edge of instrumentation tube flow hole. The test result is not available for the same location because pasting of the gauge at this location is not possible. Therefore, at this location the stress value determined by FE analysis cannot be compared with the test result. However, the max. Seqv, 128.9 MPa obtained by FE analysis is significantly less than the design

stress limit of the material, i.e., 205 MPa in case of SS 321 material, at room temperature.

8. Conclusions

The present study involved assessment of the structural integrity and determination of the stress concentration area of the bottom nozzle subassembly at load of 6g. The following conclusions have been drawn.

1. The max. stress values of both studies are in good agreement and significantly smaller than the limit of design stress of the bottom nozzle, thus bottom nozzle strength has safely fulfilled its mechanical design criterion at limiting load of 6g (26460 N).
2. The developed FE methodology can be utilized for evaluation of the designs changes in the bottom nozzle of CHASNUPP fuel assembly before conducting the confirmatory tests. Therefore, this analysis is useful for refining the safety and reliability of supplementary design modifications such as different material, minor changes in the geometry, etc.

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