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REGULAR ARTICLE

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Structural integrity assessment and stress measurement of chasnupp-1 fuel assembly skeleton: under tensile loading condition

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Abstract. Fuel assembly (FA) structure without fuel rods is called FA skeleton which is a long and flexible structure. This study has been made in an attempt to find the structural integrity of the Chashma Nuclear power plant-1 FA skeleton at room temperature. The finite element (FE) analysis has been performed using ANSYS, in order to determine the elongation of the FA skeleton as well as the location of max. stress and stresses developed in axial direction under tensile load of 9800 N or 2 g being the FA handling or lifting load [Y. Zhang et al., Fuel Assembly Design Report, SNERDI, China, 1994]. The FE model of grids, guide thimbles with dash-pots and flow holes has been developed using Shell 181. It has been observed that FA skeleton elongation values obtained through FE analysis and experiment are comparable and show linear behaviors. Moreover, the values of stresses obtained at different locations of the guide thimbles are also comparable with the stress values of the experiment determined at the same locations through strain gauges. Therefore, validation of the FE methodology is confirmed. The values of stresses are less than the design limit of the materials used for the grid and the guide thimble. Therefore, the structural integrity criterion of CHASNUPP-1 FA skeleton is fulfilled safely.

1 Introduction

CHASNUPP-1 fuel assembly consists of top and bottom nozzles, guide thimbles, fuel rods and spacer grids, as shown in Figure 1.

The structural strength of the fuel assembly (FA) is supplied by the skeleton of the FA [1]. FA skeleton containing 20 guide thimbles, eight spacer grids, top and bottom nozzles as shown in Figure 2.

Within this skeleton, 204 fuel rods are seized and supported by spacer grids support system (springs and dimples) [2]. The material of nozzles (top and bottom), and guide thimbles is SS-321 [3], whereas spacer grids are made up of Inconnel-718 [4].

The FA of pressurized water reactor (PWR) bears a variety of loads, such as tensile, compressive, bending, torsional, impact, etc., when it is undergoing through handling, shipping and reactor operation. The tensile loading in the guide thimble is produced due to the larger axial thermal expansion and irradiation induced axial growth of fuel rods, which is higher than that of the guide thimble.

The guide thimbles are connected with grids by means of spot welds. The top end of the guide thimbles are TIG welded with the top nozzle, while the lower end of guide thimbles are fastened to the perforated plate of the bottom nozzle by bolting.

Design of a PWR FA skeleton is a challenging task, which requires consideration of the multi-disciplinary physical aspects. A lot of research has been devoted to experiments and Finite element (FE) analyses of nuclear FA and its components. Such as Racine et al. [5] studied an experimental investigation of strain, damage and failure of hydride zirconium alloys with various hydride orientations. Jaramillo et al. [6] have developed a method for evaluating the room temperature ductility behaviour of irradiated Zircaloy-4 nuclear fuel cladding and applied to evaluate tensile hoop strength of material irradiated to different levels. Waseem et al. [7] developed a FE methodology in order to determine the CHASNUPP-1 FA deformation behavior. And Chen and Jing [8] have reviewed 300 MWe FA design and suggested some improvements.

Our present study is a part of series of studies which are being made in an attempt to contribute towards current research on the design and development work of the PWR FA and its components. We have now performed the non-linear analysis to determine the elongation and to assess structural strength of the FA

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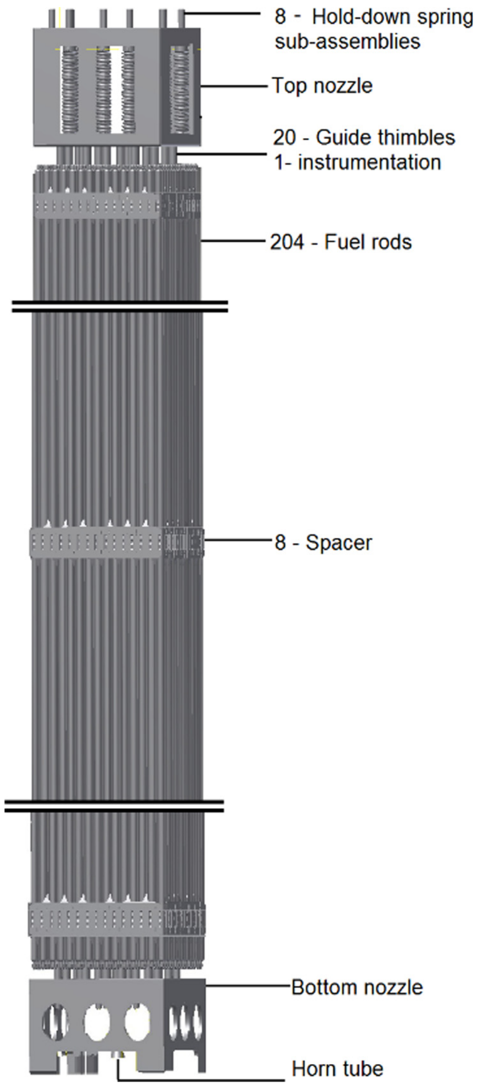

Fig. 1. 3D solid model of CHASNUPP-1 FA.

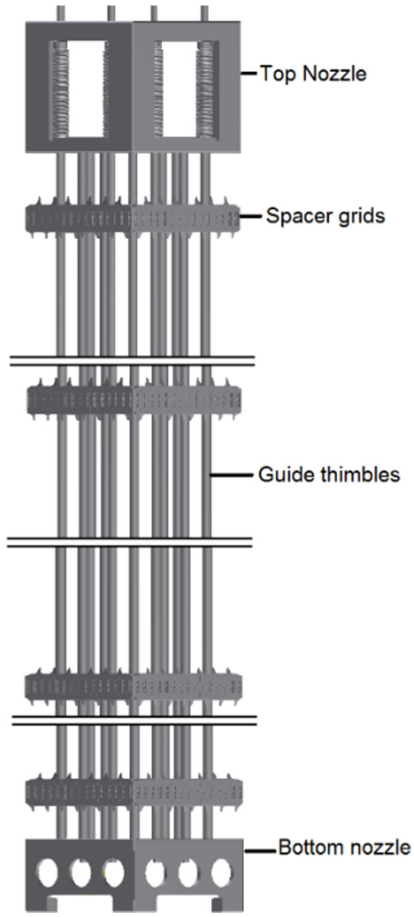

Fig. 2. 3D model of CHASNUPP-1 FA skeleton.

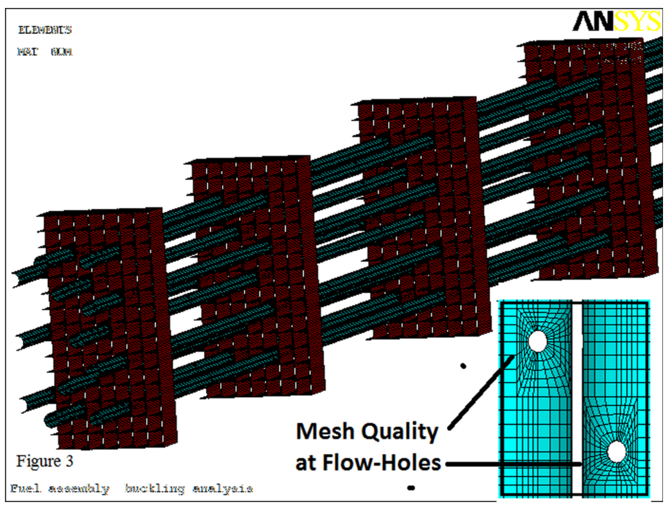

Fig. 3. Element plot of FE model.

skeleton under applied tensile load of 9800 N. The results obtained through the FE analysis have been compared with the experimental results, which show good agreement and confirms the validation of FE methodology.

2 FE model and computational details

All the components of the FA skeleton are similar in geometry, material properties and loading conditions. Therefore, in this analysis advantage of symmetry has been taken into account by considering half symmetry of FA skeleton to reduce the size and computational time of the FE model.

The detailed FE model of CHASNUPP-1 FA skeleton, consisting of guide thimbles, spacer grids and spot welds (diameter 2.4 mm) between the guide thimbles and the grid's tabs, has been developed using ANSYS 13.0. Non-linear analysis has been performed to determine elongation behavior and the area of stress concentration of the FA skeleton under the applied load of 9800 N at room temperature conditions.

Shell181 element type is used to create mapped meshing (Quadrilateral Elements). It is a 4-node element with six degrees of freedom, well-suited for linear, large rotation or

Table 1. Entity details of the FE model.

Entity	Quantity
Key Points (KP)	41362
Lines (L)	71855
Areas (A)	29580
Nodes (N)	379599
SHELL181 Elements	353034

Table 2. Material properties of grid & guide thimble.

Materials	Yield strength (MPa)	Modulus of elasticity (GPa)	Poisson's ratio (γ)
Grid Inconel-718	≥1034	205	0.3
Guide thimble (SS 321)	≥207	200	0.3

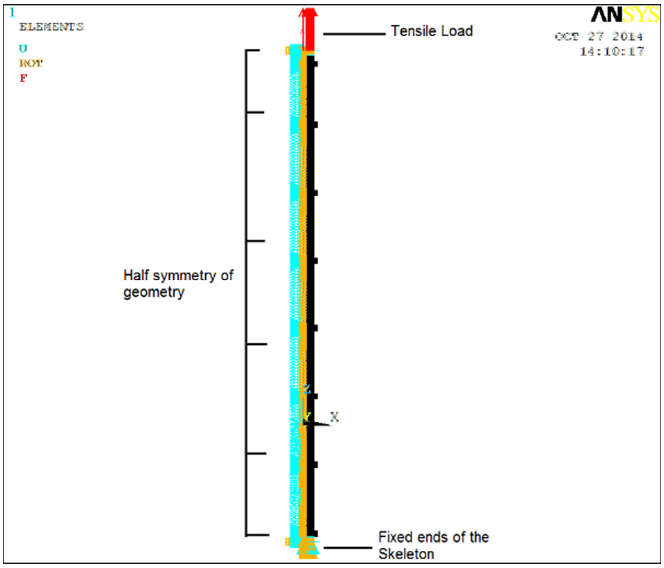

Fig. 4. Applied boundary conditions (3D plot).

displacements, and/or large strain non-linear application [9]. The quality and density of mesh of the FE model are shown in Figure 3.

The details of entities in the FE model are mentioned in Table 1.

The thickness of guide thimble and grid, 0.5 mm and 0.3 mm, respectively, are defined by giving real constants values. The material properties of guide thimble and spacer grid used in the present FE analysis are given in Table 2.

Simulations of the boundary conditions of CHASNUPP-1 FA skeleton under applying tensile load are as follows:

– to constraint the FE model, all nodes at lower end of the guide thimble are fixed in all directions, i.e. all DOF (Ux, Uy, Uz, ROTx, ROTy and ROTz) are set at zero;
– to simulate the symmetry boundary conditions, translation of all the nodes at inside edge of one-half portion of the FA skeleton are fixed, i.e. nodes along *X*-axis are fixed in *Y*-direction;
– the applied tensile load of 9800 N has been divided into 20 guide thimbles and the load of each guide thimble is distributed on the nodes associated with the upper end of the guide thimble in *Z*-direction;
– all nodes associated with the upper end of the guide thimbles have been free in load direction, i.e. *Z*-direction, other degrees of freedom are set to be zero.

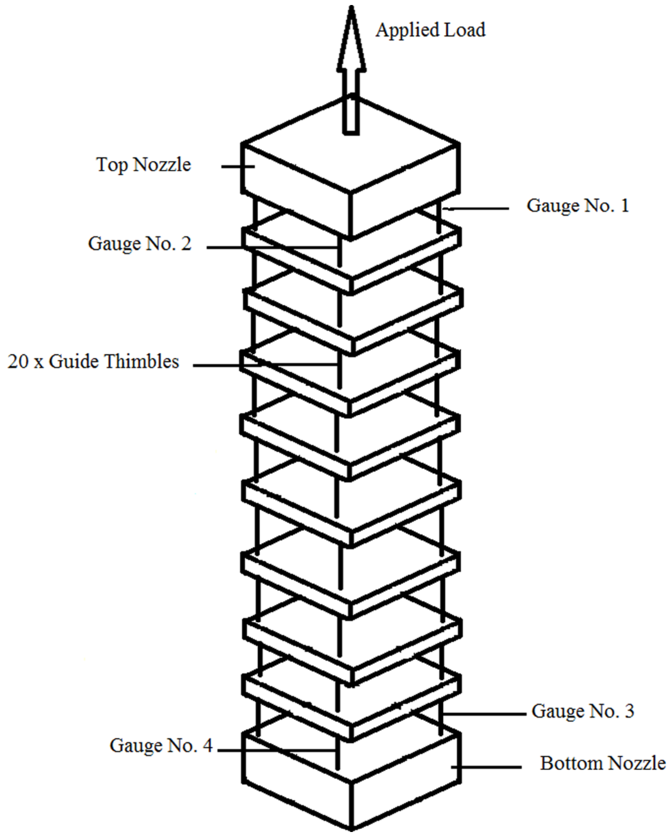

Fig. 5. Strain gauge locations.

FE model, including all above mentioned boundary conditions, is illustrated Figure 4.

3 Experimental model

The fuel assembly (FA) bears a variety of loads as discussed earlier. Therefore, FA should have adequate stiffness, strength and dimensional stability to reduce the damage and large deformation & elongation failure. In the present study, we have considered the tensile test of the FA skeleton which has been performed on the prototype full-scale test specimen of the FA skeleton, in order to determine the stress measurements and elongation behavior of the FA skeleton.

The test facility contains a frame structure, of high stiffness and strength. The frame structure is made through welding of the channels beams and steel plates. A convenient

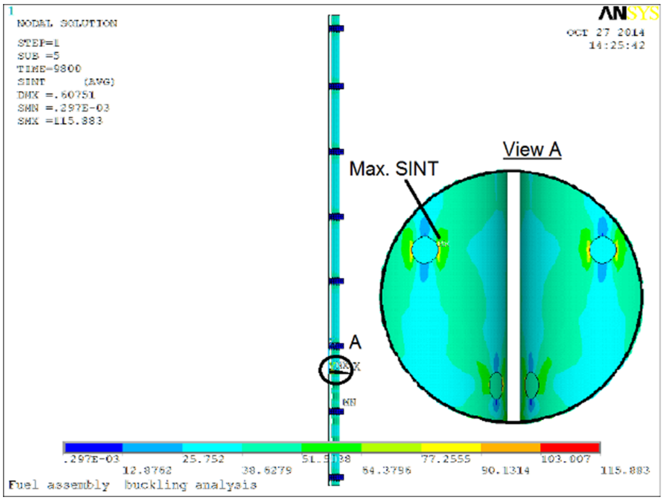

Fig. 6. Plot of nodal SINT.

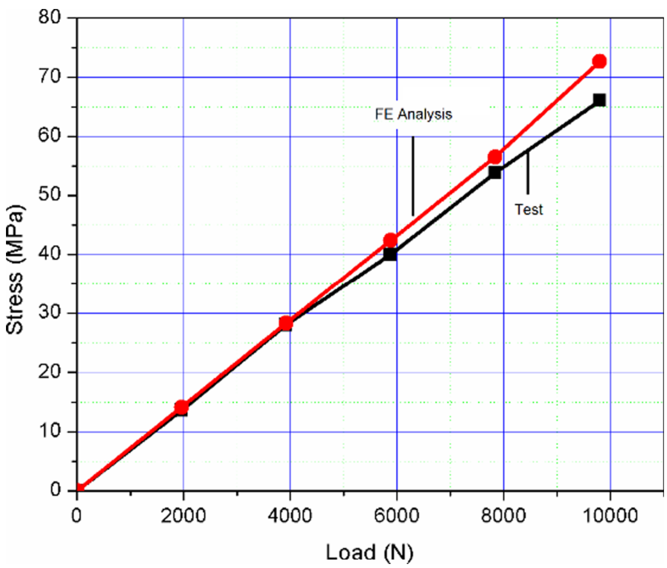

Fig. 7. Test & FE results at gauge-1 location.

load applying system is also developed in order to measure the signals under loading conditions and to operate the test. The force transducer of BLR-1 type is used for the tensile load to measure the force. Foil-type strain gauges of 2×3 mm are used for the strain measurement. The resistance of the strain gauges is $120 \pm 0.2\,\Omega$, and its sensitivity coefficient is $2.17 \pm 1\%$. The material, silastic, which solidifies at room temperature, is used for moisture proof seal [10]

First of all, the FA skeleton is placed within the calibrated leveled support plates of load applying system and the parallelism of the support plates is adjusted within the specified tolerances of the FA skeleton. Then maximum tensile load of 9800 N with load increment of 1960 N is applied on the frame plate of top nozzle, which has been divided onto 20 guide thimbles in axial tensile direction.

All guide thimbles are similar in material, geometry and loading conditions, therefore, the strain gauges are mainly pasted on the guide thimbles located on the two corners of one side of the FA skeleton test specimen. There are mainly

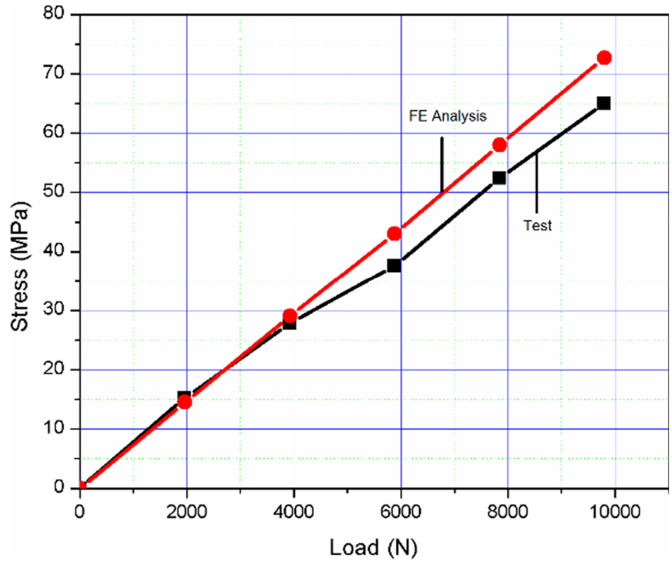

Fig. 8. Test & FE results at gauge-2 location.

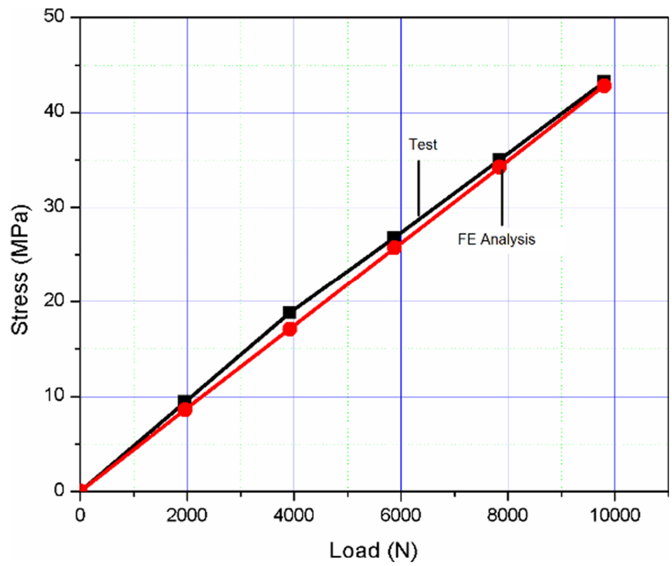

Fig. 9. Test & FE results at gauge-3 location.

two measuring critical points or levels on the FA skeleton that have been considered, which are determine through FE analysis. The strain gauges are pasted on the upper and lower positions of the guide thimbles as well as near to top and bottom nozzles of the FA skeleton, which are used to measure the local stress concentration at the root of the guide thimble. The detailed methodology and arrangement of the strain gauges is illustrated in Figure 5.

4 Discussion of FE and test results

- Mesh density is the most important parameter which affects both convergence and accuracy respectively. Therefore, a sensitivity analysis has been performed to set a mesh refinement level at which converged results are obtained.

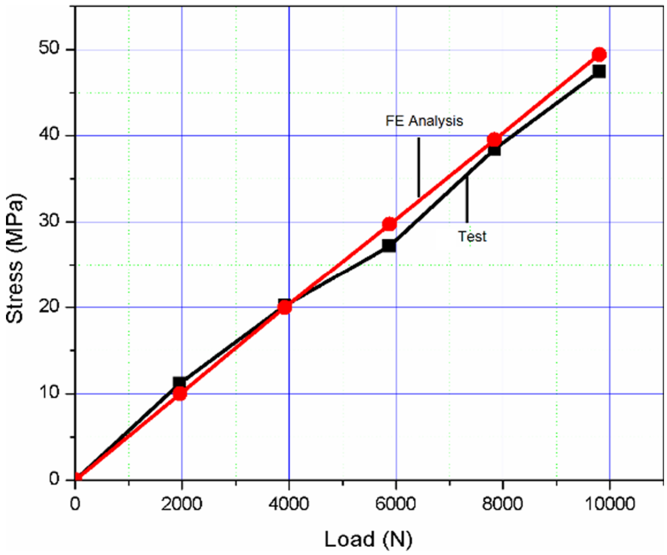

Fig. 10. Test & FE results at gauge-4 location.

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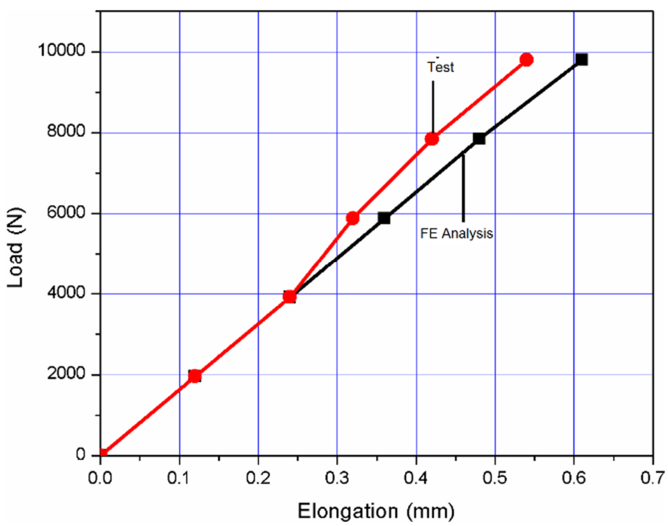

Fig. 11. Elongation behaviors of skeleton.

SINT is the difference between the algebraically largest and smallest principal stresses at a given point [11].The max. nodal SINT, 115.9 MPa, under applied tensile load of 9800 N is located at the edge of outer surface of the flow holes, as shown in Figure 6.

- The value of the SINT is less than the design stress limit, which is equal to the yield strength [11] of the guide thimble material, 207 MPa [3], fulfilling the structural integrity criteria of FA skeleton under applied max. load of 9800 N.
- The experimental results of the axial stresses obtained through different strain gauges (Nos. 1–4), under applied tensile load, 9800 N with a load increment of 1960 N, are compared and plotted with the analytical results obtained through FE analysis at the same loads and locations, as shown in Figures 7–10.

Table 3. Comparison of FE and test results at load of 9800 N.

Gauge No.	Stress (MPa)		% Error
	FE	Test	(FE & Test)
1	72.6	66	−10
2	72.7	65	−12
3	42.8	43.2	1
4	49.4	47.4	−4

*% error = [(experimental − FE analysis)/experimental] × 100

- As seen from Figures 7–10, the test results, i.e. stresses obtained at all strain gauge locations are much comparable with the FE analysis results.
- The percentage errors between the analytical and test results are calculated at max. applied load of 9800 N, as shown in Table 3.
- From Table 3, the calculated error between the FE analysis and test results on gauges lie within the error band of ±12%, which show good agreement between both studies and confirm the validity of the FE methodology.
- FA skeleton elongation behaviours, obtained from both studies (experimental and FE analysis), under applied tensile load of 9800 N are plotted in Figure 11.
- In Figure 11, it can be seen that the elongation in the FA skeleton in axial direction, obtained from the test and FE analysis, increases linearly with the increase in load.
- The max. elongation obtained from both studies (test and FE Analysis) at max. applied load of 9800 N, 0.53 mm and 0.61 mm (see Figs. 6 and 11), respectively. The error calculated between these two values comes to be 15%. Therefore, the elongations obtained by the FE and Test results are comparable which also confirm the validity of FE methodology.

5 Conclusions

The stresses & elongation of the FA skeleton, obtained from the test and FE analysis, show a good agreement thereby validating the FE methodology. The values of maximum stress at the skeleton, obtained from the test and FE analysis, are less than the design stress limit of the guide thimble material. Therefore, FA skeleton is satisfying the structural integrity criteria at a load of 9800 N.

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