

Structural and Thermal Analysis of the Pressure Vessel of VVER-1200 Nuclear Reactor Using ANSYS Software

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ABSTRACT

The efficient and safe operation of nuclear reactors significantly depends on the performance and integrity of their components, especially pressure vessels, because, pressure vessel is irreplaceable and the total lifetime of the NPP depends on the lifespan of the pressure vessel. Anticipating the thermo-mechanical behavior of pressure vessels in a nuclear power plant is essential to designing them effectively and averting failures during operation. The objective of this study is to analyze the structural and thermal analysis of the pressure vessel of the VVER-1200 reactor. The thermos-mechanical parameters such as deformation, stress, strain, temperature distribution, and heat flux of the pressure vessel have been evaluated with-ANSYS software. Using ANSYS, thermal distribution simulations under steady-state structural conditions reveal critical temperature gradients and peak temperatures and stress and deformation. Structural analysis assesses stress and strain from thermal expansion and operational loads, identifying high-stress regions and potential deformation. According to regulatory standards, the ANSYS software simulation results are deemed to be within permissible bounds. Reactor operators will find the simulation findings useful in comparing data collected during any changes to the structural and thermal integrity of the reactor pressure vessel during normal and abnormal operation of the reactor. Moreover, the combined thermal and structural analysis offers a comprehensive understanding of the pressure vessel's behavior in the VVER-1200 reactor, aiding in enhancing operational safety. This kind of research can be used to both typical and unusual circumstances at Bangladesh's Rooppur VVER-1200 nuclear power facilities, which are expected to be operational by 2025/2026.

Keywords: Low carbon energy, VVER-1200, Pressure Vessel, ANSYS



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1. Introduction

A pressure vessel is an enclosed container built to contain gases or liquids under pressure that significantly differs from the surrounding atmosphere. Due to the pressure difference, these vessels can be hazardous, and serious accidents have occurred throughout their design and operational history [1]. The reactor pressure vessel (RPV) is a vital part of a nuclear power plant, essential for maintaining the safety and security of the facility throughout its operational life. Therefore, preserving the vessel's structural integrity to the highest standard is critical to avoid accidents or incidents. For the VVER-1200 reactor, it is crucial that the vessel can endure abnormal operational scenarios or nuclear transients. During such transients, the RPV may face intense thermal stress due to extreme temperature variations, particularly during rapid cooling caused by the injection of emergency core cooling into the inner vessel [2]. The reactor pressure vessel, classified as a Class1 component, is of critical importance. To ensure that the material used in the vessel remains in optimal condition, an analysis based on thermal loads is necessary. The aim of this study is to assess the transient thermal behavior on the walls of the reactor pressure vessel. The thermal analysis performed will help evaluate how the operating temperature impacts the structural design of the vessel. This analysis focuses on temperature loads that vary over time [3]. The VVER-1200 reactor plant represents an

advanced version of the light water reactor, featuring numerous enhancements and improvements in the primary and secondary circuit parameters compared to earlier models. These improvements result in higher pressure, temperature, cooling capacity, and thermal output. However, with these advancements come new design challenges and heightened safety concerns, necessitating the use of reliable computational tools for robust transient analysis [4]. Pressure vessels refer to containers, pipelines, and tanks used to transport, store, or receive fluids. These vessels are defined by the pressure difference between their interior and exterior, typically with higher internal pressure, except in rare cases. While tanks are designed to operate only at atmospheric pressure, pressure vessels are built to withstand higher pressures and often include internal components, whereas tanks usually do not, except for basic additions like heating coils or mixers [5]. A pressure vessel is designed to endure both thermal and structural stresses. To achieve the optimal thickness, temperature distribution, and dynamic performance, a detailed design and analysis are required. Ribs, or stiffeners, are incorporated around the shell of the pressure vessel to prevent buckling failure. These stiffeners offer enhanced strength, helping to prevent buckling and bending failures in the vessel [6]. This paper presents a detailed thermo-mechanical analysis conducted to assess the structural integrity of the VVER-1200 reactor pressure

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vessel (RPV) under various operating transients. The analysis involves evaluating the time-dependent temperature gradient across the vessel wall thickness during different transients. The time-varying thermal gradient introduces additional complexities in determining the stress field across the vessel wall. A comprehensive finite element analysis was performed to evaluate the temperature and stress distribution, with the results validated through analytical solutions. The structural integrity assessment has been conducted according to ASME standards and is discussed in detail. [7].

The ANSYS model necessitates specifying the material properties for each component, along with defining the geometry, mesh configuration, and the applied thermal and static structural loads. The structural analysis evaluates mechanical parameters, including elastic and plastic strains or stresses, under static loading conditions [8].

A steady-state thermal analysis is first conducted, and the thermal results are then utilized as input for the structural model. To maintain brevity, this study focuses solely on the structural analysis results, although ANSYS predictions for temperature distribution are available where ANSYS predictions for temperature distribution can be found in [9]. The main research gap is the lack of information about the structural dimension of the entire reactor. And the research field is not very enriching enough. That's why the objectives of the study in to analyze the sustainability of fuel rods in the high pressure and temperature ambient and enrich information about the VVER reactors can help solve problems that will be faced in the future.

2. Governing Equation

2.1 Stress Strain Analysis

The distribution of thermal stress within a thick-walled vessel can be represented as follows.[10,11]:

Stress in Radial axis,

$$\sigma_r = \frac{\alpha}{(1-\theta)r^2} \frac{1}{r^2} \left[\frac{r^2 - a^2}{b^2 - a^2} \int_a^b T r dr - \int_a^b T r dr \right] \quad (1)$$

And the Longitudinal stress,

$$\sigma_L = \frac{P d}{4t} \quad (2)$$

The mentioned integrals have been calculated using the trapezoidal rule.

2.2 Thermal Analysis

The equation governing time-dependent heat flow in the radial direction is represented as:[12]:

$$\frac{1}{r} \frac{\delta T}{\delta r} + \frac{\delta^2 T}{\delta r^2} = \frac{1}{\alpha} \frac{\delta T}{\delta t} \quad (3)$$

Equation-3 can be numerically addressed through the forward difference method, leading to a series of algebraic equations that determine the temperature distribution at the nodal points. The temperature at an interior node can be expressed as follows:[13]:

$$T_m^{p+1} = F_0 \left[\frac{r_{m-1} + r_m}{2r_m} T_{m-1}^p + \frac{r_{m+1} + r_m}{2r_m} T_{m+1}^p \right] + (1 - 2F_0) T_m^p \quad (4)$$

where p is an integer representing the elapsed time 'Δt,' as expressed by:

$$t = p\Delta t$$

For boundary nodes, specifically at the outer surface, the temperature distribution is described as:[13]

$$T_n^{p+1} = 2F_0 \left[\frac{r_{n-1} + r_n}{2r_n} T_{n-1}^p + B_i T_0 \right] + \left[1 - 2F_0 \left(\frac{r_{n-1} + r_n}{2r_n} + B_i \right) \right] T_n^p \quad (5)$$

And can be calculated as:

$$\Delta t = \frac{\Delta r^2 F_0}{\alpha}$$

The following conditions must be met to ensure the stability of the solution:

$$0.5 > F_0 < \frac{1}{\left[\frac{r_{n-1} + r_n}{r_n} + 2B_i \right]} \quad (6)$$

Equations 3 and 4 describe the temperature distribution through the thickness of the vessel wall.

3. Material Preparation

In Russian VVER-type reactors [14], a higher content of chromium steel is utilized for the pressure vessel[15]. Specifically, these are VVER-1200 reactors, which are water-moderated and water-cooled [16]. It is essential to ensure protection against irradiation, corrosion, and fracture. Irradiation embrittlement, resulting from prolonged exposure to high-energy neutrons, leads to mechanical property alterations such as increased hardness, yield strength, and tensile strength, while toughness decreases [17]. For the pressurizer, 15Cr2NiMoVA steel is employed. The steel grade 15Cr2NiMoVA was utilized, having the following chemical composition: 0.14% carbon, 2.6% chromium, 0.31% nickel, 0.79% molybdenum, 0.63% vanadium, 0.67% manganese, 0.08% phosphorus, 0.28% silicon, 0.33% copper, with the remaining balance being iron.[18]

Table 1 Physical characteristics of the materials [19,21]

15Cr2NiMoVA Steel	
Properties	Value
Plastic Strain, %	0.200
Stress, MPa	280
Yield Strength MPa	400
UTS, MPa	580
Density, g/cm ³	7.85
A, %	14
Z, %	50
Isotopic Thermal Conductivity (Structural Steel), Wm ⁻¹ C ⁻¹	60.5
Specific Heat, (Structural Steel) JKg ⁻¹ C ⁻¹	434

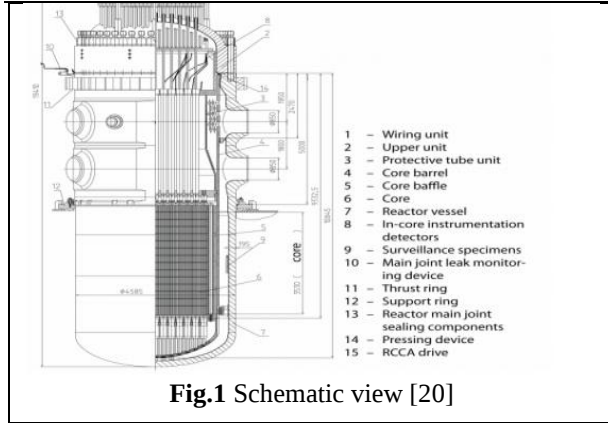


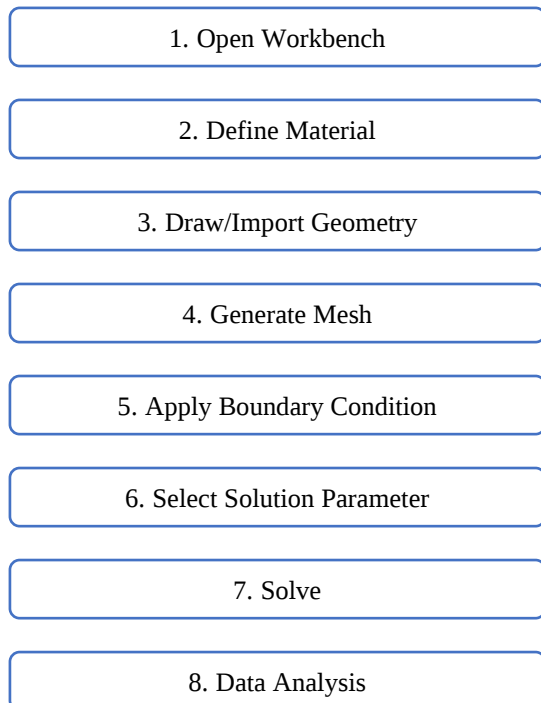
Fig.1 Schematic view [20]

Table 2 Technical Data Considered for Analysis [20]

Reactor Pressure Vessel	
Diameter	4585 mm
Thickness	195 mm
Hot-leg, Cold-leg dia	850 mm
Height from Upper head joint	10845 mm
Inlet No	4
Outlet No	4
Upper head joint to Outlet center	1850 mm
Outlet center to Inlet Center	1850 mm
Upper head joint to Support	5000 mm
Internal Temperature	350°C

4. Finite Element Modeling

General flowchart of the analysis procedure in the ANSYS Workbench:



4.1 Material Data

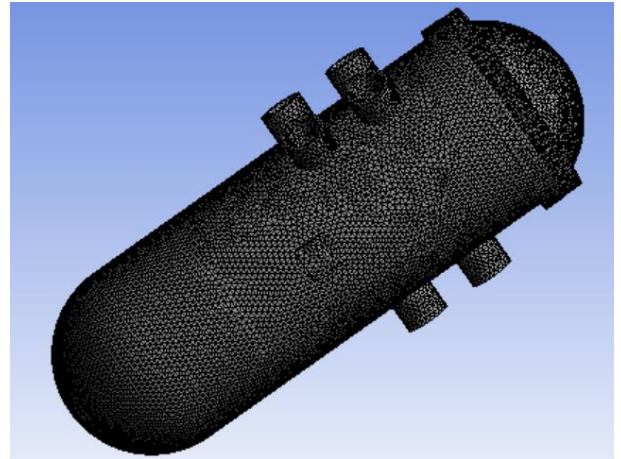
The pressure vessel is made of 15Cr2NiMoVA steel, as defined in the 'Engineering Data' section, according to the values in Table 2.

4.2 Geometry

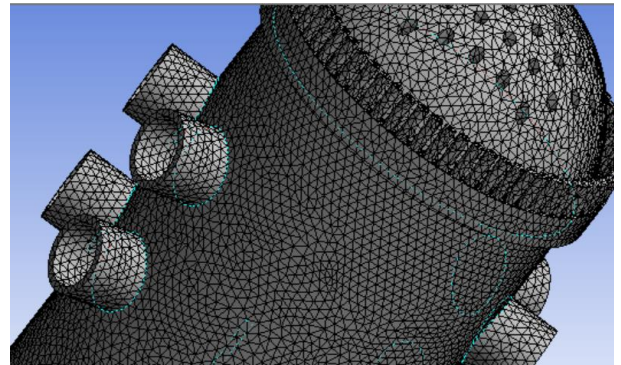
The geometry of the pressure vessel is constructed as per measure mentioned in table 2 and Fig.1. As we see that, contains two hemispherical upper and lower heads, two supports, 4 inlets and 4 outlets. Fig.2 shows the 3D view of Mesh Generation and Fig.1 shows schematic view.

5. Meshing

Fine mesh is used in this study. Because fine mesh calculates more nodes and elements for solving which reduce the single problem solving area and increase the resolution of solution. Table 3 shows the statistical data of the mesh generation.



(a) Full View



b. Parical View

Fig.2 3D view of Mesh Generation

5.1 Mesh Sensitivity Analysis

In the following table 3 several values are compared according to mesh size and according to table 4 desired mesh size will be selected.

Table 3 Experimental result of different mesh size

Mesh Size, mm	130	135	140
Skewness	0.23437	0.23962	0.24635
Maximum Stress, MPa	631.11	635.36	640.9
Deformation, mm	11.788	11.778	11.776

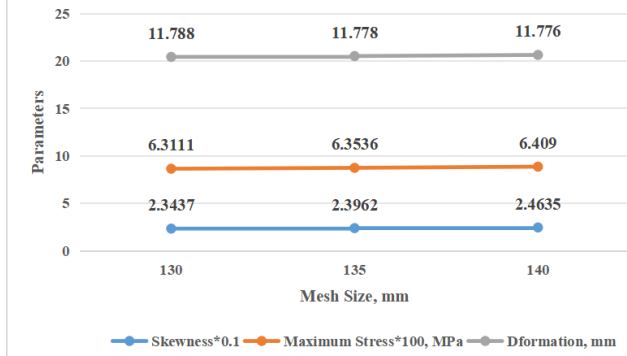


Fig 3 Mesh Independence Test

Fig 3 shows the mesh independence to result.

Table 4 Skewness and Mesh Quality List [22]

Value of Skewness	Cell Quality
1	Degenerate
0.9 - < 1	Bad
0.75 - 0.9	Poor
0.5 - 0.75	Fair
0.25 - 0.5	Good
>0 - 0.25	Excellent
0	Equilateral

So, further calculation is done by mesh size 130 mm. And the statistical value is in table 5.

Table 5 Statistical Data of the generated mesh

Size	Nodes	Elements	Method
0.13 m	303509	177292	Tetrahedral

6. Boundary Conditions

6.1 Structural Analysis

Operational pressure inside the pressure vessel is 16.2 MPa [20]. So 16.2 MPa pressure is applied to the entire inner wall of the pressure vessel. And fixed support is applied in the two supportive plates. And as thermal boundary condition internal heat generation and convection is used.

6.2 Thermal Analysis

In the thermal analysis, the core is modeled as a heat generating body and the magnitude of 100 W/cm³. Convection is applied in all the phases. And the magnitude is 0.5 W/cm²·s for water and 0.005 W/cm²·s for air. And structural and thermal analysis is separately done.

7. Results and Discussion

We can calculate the longitudinal stress from equation 2 as

$$\sigma_{47.68} = \frac{16.2 \times 4584}{4 \times 47.68} = 389.5 \text{ MPa}$$

For bench-marking our result, compare analytical and experimental data in the following table 6 and comparison between analytical and simulation data is shown in figure 4. The table 6 and Fig. 4 compare longitudinal stress values from simulation and analytical methods for material thicknesses ranging from 47.68 mm to 49.98 mm. The stress values closely align, with deviations ranging from 0.207% (minimum at 49.98 mm) to 1.53% (maximum at 48.38 mm). The graph shows two trends: simulation (blue) and analytical (orange), both decreasing slightly with increasing thickness.

The small deviations and overlapping trends confirm strong agreement between the methods, validating the simulation model.

Table 6 Result Comparison between analytical and experimental

Thickness, mm	Longitudinal stress (MPa) Simulation	Longitudinal stress (MPa) Analytic	Deviation from analytical value, %
47.68	391.5	389.5	0.51
48.38	389.7	383.82	1.53
48.48	384.5	383.03	0.38
49.5	376.4	375.13	0.34
49.98	372.3	371.53	0.207

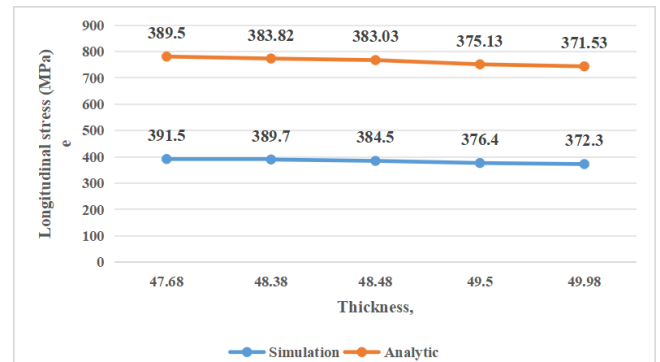
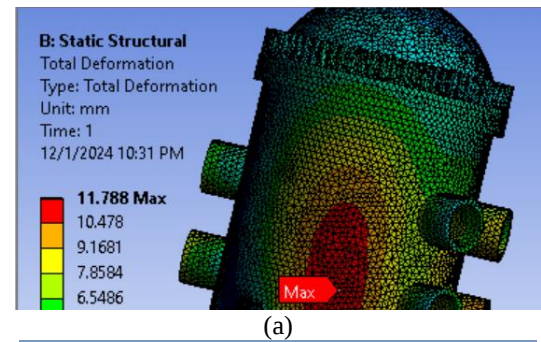
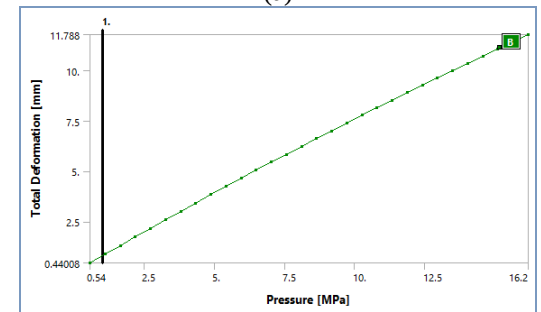


Fig. 4 Data Benchmarking Curve

Fig 5 shows the total deformation and the maximum deformation is 11.046 mm which is found around the outlet and inlet pipe. Percentage of elongation we can calculate by, $\frac{11.788 \text{ mm}}{195 \text{ mm}} \times 100\% = 6.04\%$. And according to the table, the tolerance level of elongation is 20%. So the value of total deformation is in the allowable level.



(a)



(b)

Fig.5 Total deformation (a) and Deformation vs Pressure Graph (b)

Figure 6 illustrates the stress analysis of a component using static structural analysis in ANSYS. Sub-figure (c) represents the distribution of normal stress along the X-axis,

with a maximum value of 475.2 MPa and a minimum of -1470.9 MPa, indicating areas of tensile and compressive stress, respectively.

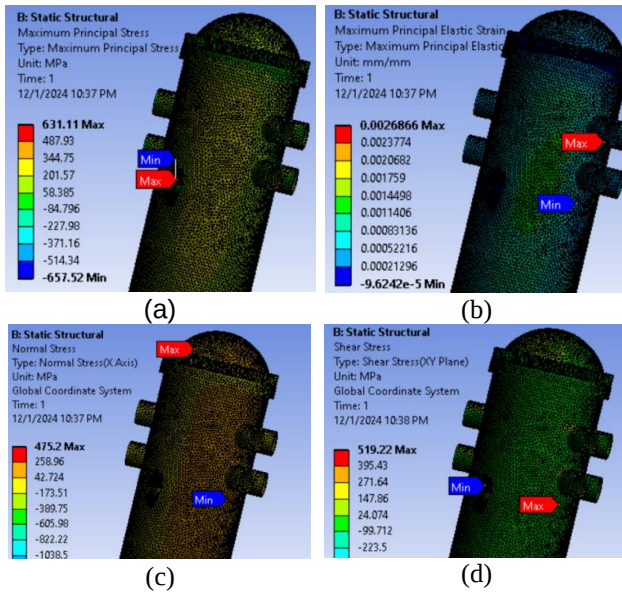


Fig.6 Maximum Principle Stress(a), Maximum Principle Elastic strain(b), Normal Stress(c), Shear Stress(d)

Subfigure (d) shows the shear stress distribution on the XY plane, where the maximum value reaches 519.22 MPa and the minimum is 594.85 MPa, highlighting regions of maximum distortion. Figure 7 presents the global maximum temperature distribution over time, showing a linear increase in temperature from 350.36°C to 498.91°C within 5 seconds, suggesting consistent heat buildup during the simulation. According to table 1 the Ultimate maximum Tensile Strength is found to be 580 MPa. And all of the value of diffidence types of stress is less than the maximum tolerance level.

Figure 9 illustrates the stress and strain values obtained from simulation, presented in two bar charts. The top chart compares three stress components: Principal Stress (631.11 MPa), Normal Stress (475.2 MPa), and Shear Stress (519.22 MPa), with Principal Stress being the highest. The bottom chart shows the corresponding elastic strain values: Principal Elastic Strain (0.00067 mm), Normal Elastic Strain (0.00269 mm), and Shear Elastic Strain (0.00244 mm). Among these, the Normal Elastic Strain is the largest, followed by Shear Elastic Strain, while Principal Elastic Strain is significantly smaller. This figure effectively visualizes the relationship between stress and strain components in the simulation.

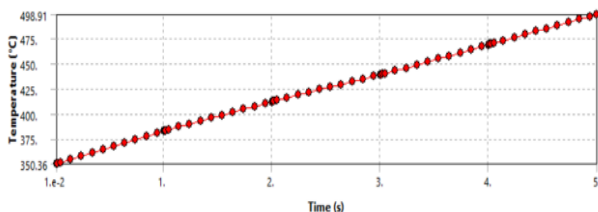


Fig.7 Global Maximum temperature Distribution

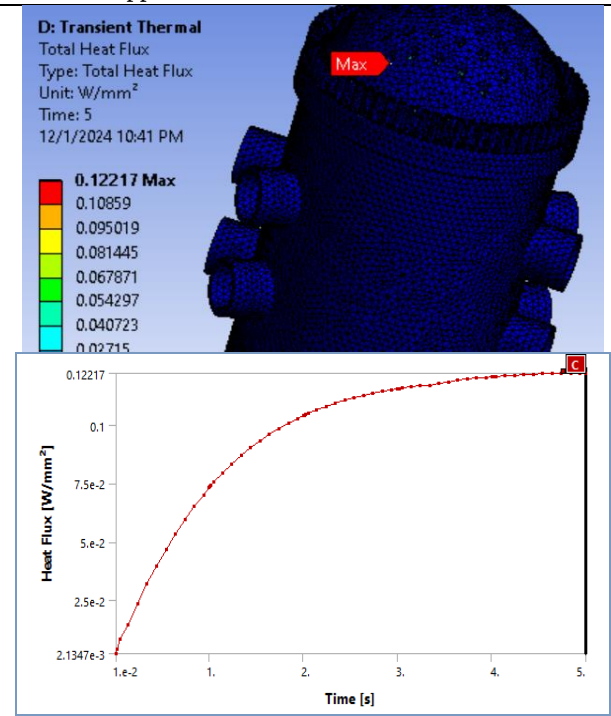


Fig.8 Total Heat Flux

Fig.8 represents Total Heat Flux. And Maximum heat flux is 0.12217 W/mm².

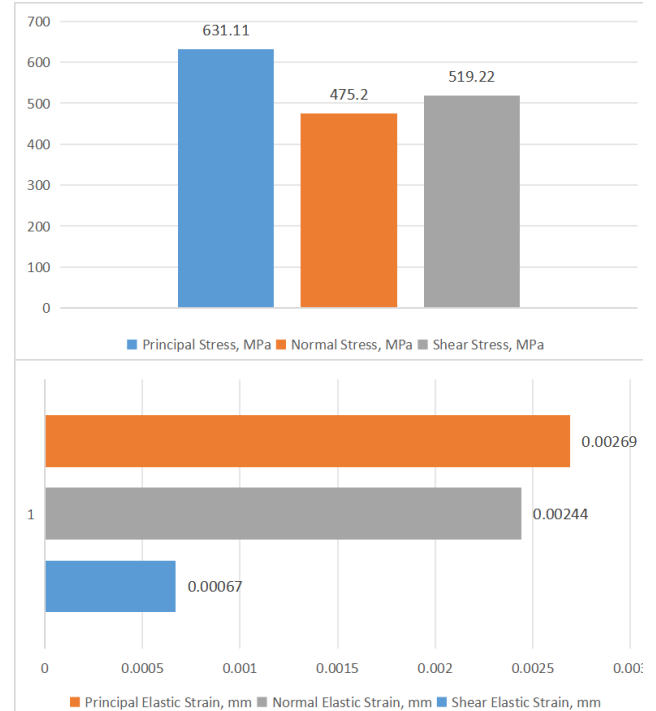


Fig 9 Obtained Stress and strain values from Simulation

8. Conclusion:

- ANSYS workbench is used for the solution, which is a reliable and advanced simulation software for analyzing 3D mechanical structures.

- The reactor pressure vessel is irreplaceable. So, integrity and safety is very important to a NPP operation. Therefore, this study can enrich the research field of the VVER-1200 reactor and can help to find more details about the structural analysis of the core of the VVER-1200 NPP, which is new and important from our country's perspective.
- The structural and thermal analysis of the pressure vessel in the VVER-1200 nuclear reactor, conducted using ANSYS software, provides valuable insights into the performance and safety of the reactor's core.
- The study highlights the ability of the pressure vessel to withstand the operational stresses and thermal loads.
- Limitation of using the Finite Element Method (FEM) in ANSYS Workbench is its reliance on mesh quality, computational resources, and user expertise, with challenges in handling complex geometries, nonlinear problems, and multi-physics simulations, often requiring validation to ensure accurate and reliable results.
- The simulations reveal the critical regions of stress concentration and thermal hot-spots, aiding in optimizing the pressure vessel design for enhanced safety margins.
- Reactor operators will find it easier to compare data from simulations when the structural and thermal integrity of the reactor pressure vessel changes during normal and abnormal conditions.
- The Rooppur VVER-1200 nuclear power stations in Bangladesh, which are expected to be operational by 2025/2026, can benefit from this kind of study in both typical and unusual circumstances.

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NOMENCLATURE

- σ_L : Longitudinal stress, MPa
 σ_r : Stress in Radial axis, MPa
 d : Diameter, mm
 T : Thickness, mm
 R : Radius, mm
 B_i : Biot number
 Δr : Spatial increment, mm
 Δt : Time increment, s
 F_0 : Fourier number
 T : Temperature, °C
 P : Pressure, MPa