# THERMAL AND FATIGUE ANALYSIS OF BOLT AND THREAD IN REACTOR PRESSURE VESSEL

Jin Ting[1], Bao Gang Qiang[2], Liu Pan[1], Zhang Qing Hong[1], Piao Lei[1], Wu Ying Xi[1]
[1] China nuclear power engineering company LTD, Shen Zhen, China
[2] PERA global LTD, Bei Jing, China
E-mail of corresponding author: jinting@gmail.com

## INTRODUCTION

In the pressurized water reactors, the head and cylinder segment of reactor pressurized vessel (RPV for short) are connected by bolts and threads. M310 has 58 bolts and threads in the upper head of RPV. Tensile the bolts make the upper closure header and shell of RPV connected. The lower part of bolt connect with the RPV shell flange by threads, the upper part of bolt connect with the upper closure header flange by nut. According to RCC-M code [1], we should carry out thermal and fatigue analysis of the bolts and threads. In the early stress analysis, 2D axisymmetric methods are widely used [2]. Due to none axisymmetric structure, it has to make equivalent parameters, such as young modulus of upper closure header of RPV. And the result should be modified because of the equivalence of bolts and threads. This method can give appropriate value of stress in upper closure header and shell of RPV, but in bolt and thread are not good for the thermal and fatigue analysis.

The development of the thermal and stress field during the last two decades is simulated numerically in the scope of a nonlinear analysis using the FE method. 3-Dimentional model is more and more popular. According to non-axisymmetric of this area, a 3-Dimentional model with bolt and thread was introduced. Applying pre-stress on bolt, bolt and thread contacting, a much more realistic model was established. More than 40 thermal and pressure transients are used calculate the thermal and stress with ANSYS code [3]. Use rain flow method and Miner rule to solve the fatigue problem.

## DESCRIPTION OF GEOMETRY

In order to decrease the complexity of analysis, some of components are ignored. The analyze area include RPV upper closure header, RPV shell, and bolts. The bolts connect shell and closure header with threads and nuts. The basic dimensions of RPV upper closure header, shell and bolts are given in table 1 and the overall drawing is shown in Fig. 1. Fig. 2 shows the bolt dimensional information.

Table 1: Basic dimensions of RPV closure header shell and bolt

| Basic dimensions | Values(mm) |
|---|---|
| Radius of RPV upper closure header | 2035 |
| Thickness of RPV upper closure header | 160 |
| Radius of RPV shell | 1982.5 |
| Thickness of RPV shell | 230 |
| Diameter of bolt(top) | 110.8 |
| Diameter of bolt(intermediate) | 149.5 |

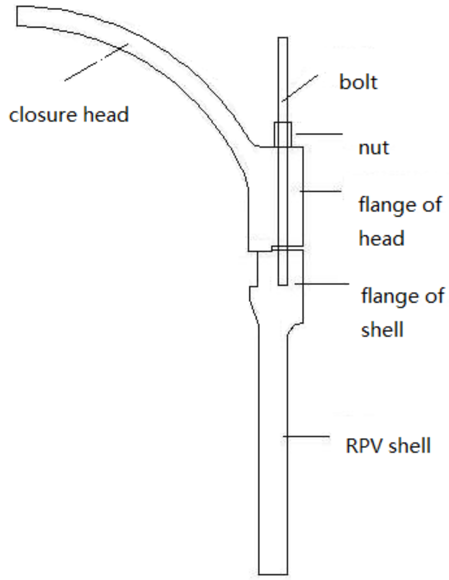



Fig. 1: Overall geometry of RPV closure header, shell and bolt

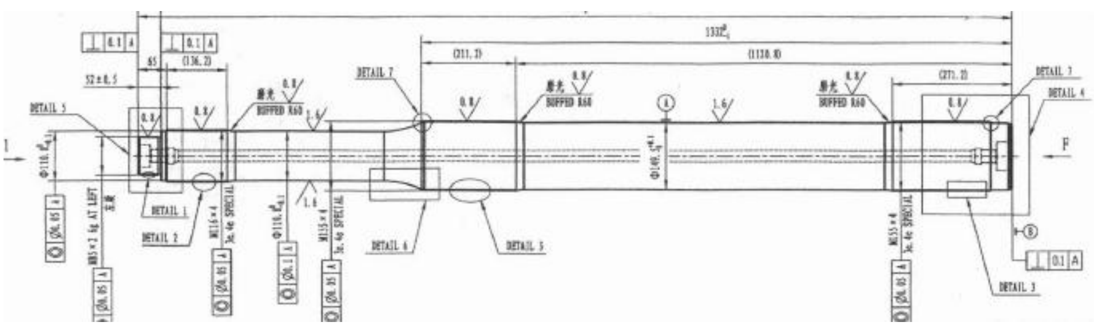


Fig. 2: Detailed dimension of bolt

## MATERIAL PROPERTIES

Due to the simplification of model, this paper only considers mainly components. The materials constituting closure, shell, bolt, nut, and cladding, are listed in Table 2.

Table 2: material of components

| Component | material |
|---|---|
| Closure header, shell (including flange) | 16MND5 |
| Bolt, nut and washer | 40NCDV7-03 |
| cladding | E309L+E308L |

Temperature-dependent material properties are used for the simulation of the thermal transients. They are collected from RCC-M. The following physical thermal and mechanical properties are determined as function of temperature: Mass density ρ[kg/m³], Thermal expansion coefficient α [°C$^{-1}$], Thermal conductivity λ [J/m s°C], Specific heat c [J/kg°C], Young's modulus E [MPa], Poisson's ratio, Yield strength σy [MPa] and Stress-Strain curves. A summary property of 16MND5， 40NCDV07-03 and 308L&309L are given in table 3, 4 and 5. It can be interpolated due to table 3 when the temperature is not exactly the following value.

Table 3: 18MND5 temperature-dependent material property

| Temperature(℃) / Property | 20 | 50 | 100 | 150 | 200 | 250 | 300 | 350 |
|---|---|---|---|---|---|---|---|---|
| E($10^3$MPa) | 204 | 203 | 200 | 197 | 193 | 189 | 185 | 180 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| $\nu$ | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 |
| $\alpha(10^{-6}.℃^{-1})$ | 11.22 | 11.45 | 11.79 | 12.14 | 12.47 | 12.78 | 13.08 | 13.4 |
| $\lambda$(W/m. ℃ ) | 37.7 | 38.6 | 39.9 | 40.5 | 40.5 | 40.2 | 39.5 | 38.7 |
| $\rho.C(10^{6}.J/m^{3}.℃)$ | 3.4875 | 3.5907 | 3.7748 | 3.9282 | 4.0868 | 4.2675 | 4.4233 | 4.6017 |

Table 4: 40NCDV07-03 temperature-dependent material property

| Temperature(°C) / Property | 20 | 50 | 100 | 150 | 200 | 250 | 300 | 350 |
|---|---|---|---|---|---|---|---|---|
| E(103MPa) | 204 | 203 | 200 | 197 | 193 | 189 | 185 | 180 |
| α(10-6. ℃-1) | 11.22 | 11.45 | 11.79 | 12.14 | 12.47 | 12.78 | 13.08 | 13.4 |
| λ(W/m. ℃) | 32.8 | 32.7 | 32.5 | 32.3 | 32.2 | 32 | 31.9 | 31.7 |
| ρ.C(106.J/m3. ℃) | 3.7150 | 3.7629 | 3.7923 | 3.9283 | 4.0759 | 4.1775 | 4.2992 | 4.4336 |

Table 5: 308L&309L temperature-dependent material property

| Temperature(°C) / Property | 20 | 50 | 100 | 150 | 200 | 250 | 300 | 350 |
|---|---|---|---|---|---|---|---|---|
| E(103MPa) | 197 | 195 | 191.5 | 187.5 | 184 | 180 | 176.5 | 172 |
| α(10-6. ℃-1) | 16.4 | 16.54 | 16.8 | 17.04 | 17.2 | 17.5 | 17.7 | 17.9 |
| λ(W/m. ℃) | 14.7 | 15.2 | 15.8 | 16.7 | 17.2 | 18 | 18.6 | 19.3 |
| ρ.C(106.J/m3. ℃) | 3.6029 | 3.7438 | 3.9012 | 4.1032 | 4.1646 | 4.2654 | 4.2956 | 4.3468 |

## FINITE ELEMENT MODEL

(1)Model setting

In order to decrease the analyze size, this paper takes a 1/58 model. Eliminate holes on closure head, use equivalent material property, and make equivalence material property of pad at flange position. Divide model into several parts, so it can be easy to make hexahedral elements. Axisymmetric boundary conditions are applied at both sides of model, and define contact regions and set appropriate contact setting.

Ignore corrosion, neutron flux and welding's influence.

(2)Bolt pre-load

It can be use direct structure-thermal coupling method if only consider thermal and pressure. But when include bolt pre-load, pre-load element has to be assured no temperature degree. This will bring trouble for transient's calculation. If use in-direct coupling, it is easy to use pre-load element Prets179. When generate elements associated with prets179, node coincide with section of bolt. So this node should be delete when perform the thermal analysis.

(3)Bolt contact

Due to more than 40 transient's calculation, it is not easy to establish a model with detailed screw dimensioning. In this paper, contact methods are induced to simulate the bolt-thread contact. When define the contact region, increased contact radius method and update stiffness in each step are introduced. Penalty function and Lagrange methods hard to converge in this case, so choose MPC method. Use coefficient to consider stress concentration between bolt and thread.

For the detailed screw analysis, even if generate fine meshed FE model, thread lift angle and root radius still will cause big trouble. So, in this paper, no detailed screw information is included. Consider stress concentration factor between thread and blot instead. As mentioned above, number 4is selected.

(4)Pad

Stiffness matrix is used to simulate pad affection. By a 3-Dimensional model and apply axis force, stiffness matrix is obtained.

(5)Element type and boundary

Thermal and structure are using same FE model except elements type and boundary condition. Real constants of contact element used for thermal calculation should be settled up well. For structure analysis, degrees of axisymmetric sides should be transferred to their normal direction, and apply displacement boundary. For thermal calculation, apply adiabatic boundary at axisymmetric sides.

Transients and pre-stress simulation

Prets179 element was used in order to simulate pre-stress of bolt. In order to decrease the calculation scale, each temperature and pressure transient, only important points and their interpolation are used for calculation. Due to stress result of bolt sensitive with elements size, element size sensitivity analysis was performed. More than 40 transients for each thermal and pressure are calculated under appropriate element size.

The overview of model can be seen in Fig.3. Element size sensitivity has been studied. During the calculation of the model, 5 kinds element size had performed. Fig. 4 shows the element size versus maximum stress at bolt. It founds 22 mm is enough for stress calculation.

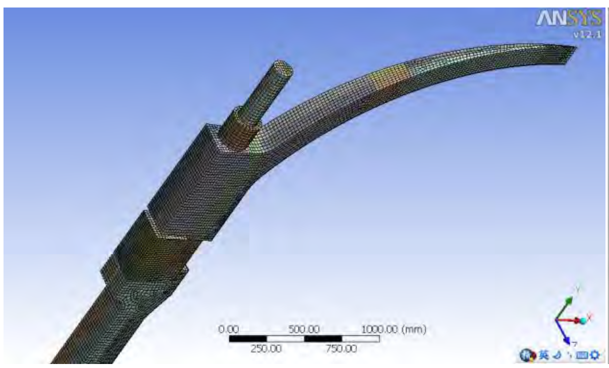



Fig. 3: overview model

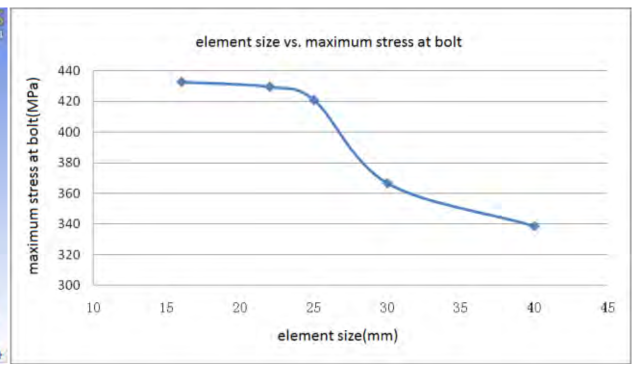



Fig. 4: element size vs. maximum stress

Use ANSYS 12.1 to discrete the structure, and select element types for each part. Table 6 shows the element types of each component.

Table 6: ANSYS element types of each component

| Component | ANSYS element type | description |
|---|---|---|
| Bolt pre-stress | Pres179 | pre-stress element |
| Structures, including bolt, nut, closure head, shell, cladding etc. | Solid185 | 3D structure element |
| Thermal transfer | Solid70 | Thermal element |
| Contact | CONT174,TARGET170 | Contact element |

## THERMAL AND PRESSURE CALCULATION

### Thermal distribution and stress simulation

Firstly, use thermal element to calculate thermal distribution result, and then modify the element type from thermal to structure, which was called indirect coupling method, and apply pressure transients to calculate stress results. During this process, the transient step versus bolt stress result was studied. Both thermal distribution and stress analysis are using same element size. Also this procession takes more than 40 transients.

Assume heat transfer sufficient between coolant and vessel inner wall, inner wall temperature equal to coolant. Use constant heat transfer coefficient (0.093 W/(m℃ )) between bolt and hole of closure head flange. Use constant heat transfer coefficient (0.04426 W/(m℃ )) between closure head flange and shell flange.

**Sample loading**

An sample loading, loading 2, are described as Fig. 5a and 5b. The pressure and temperature are function of time.

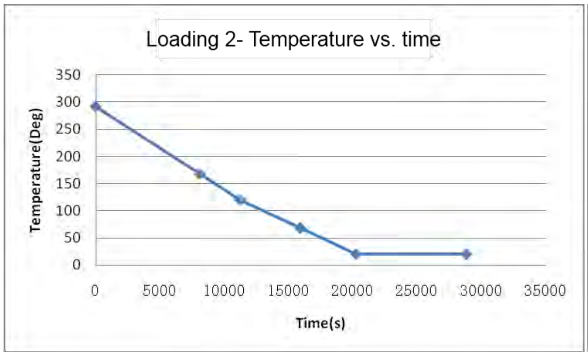



Fig.5a: loading 2- Temperature vs. time

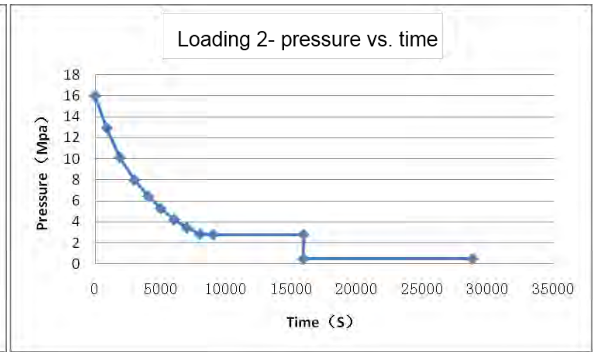



Fig.5b: loading 2- Pressure vs. time

**Thermal transient**

Under loading 2 thermal transient, thermal stress distribution is changing with time due to loading is a function of time. Fig.6 to 7 displays thermal stress at 0s and 28000s.

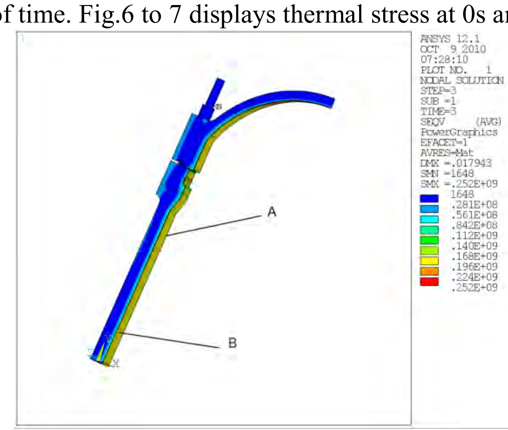



Fig.6a: thermal stress distribution at 0s on shell

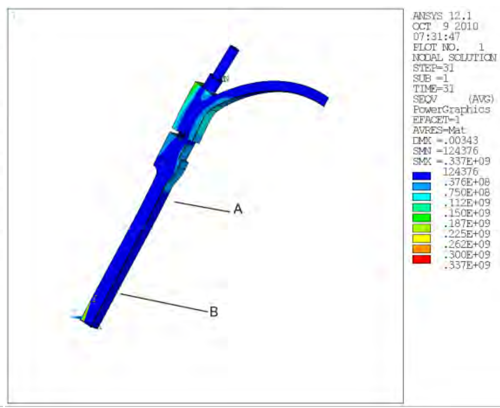



Fig.6b: thermal stress distribution at 28000s on shell

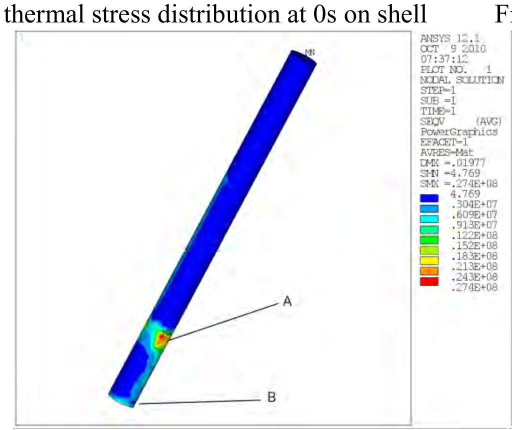



Fig.7a: thermal stress distribution at 0s on bolt

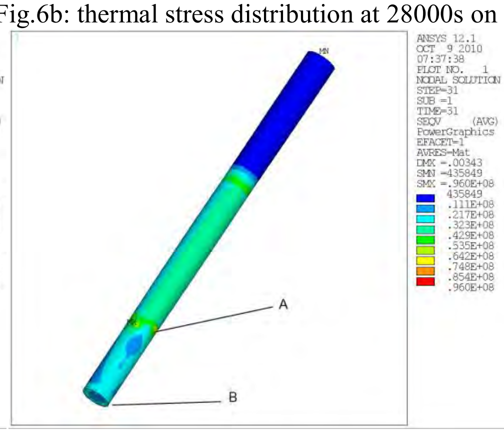



Fig.7b: thermal stress distribution at 28000s on bolt

Variation of stress at point A and B on shell and bolt are showed at Fig.8a and 8b. It shows variation on shell is greater than on bolt.

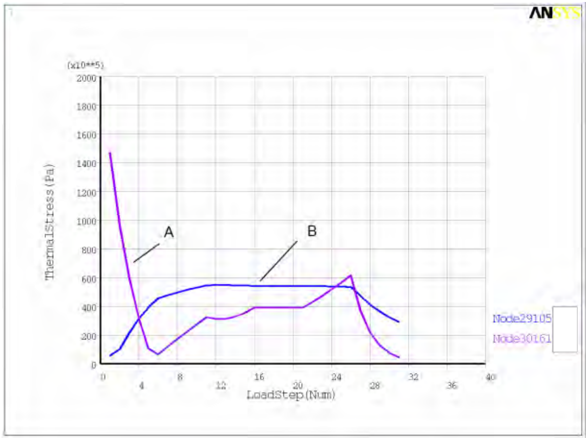



Fig.8a: thermal stress at point A and B on shell

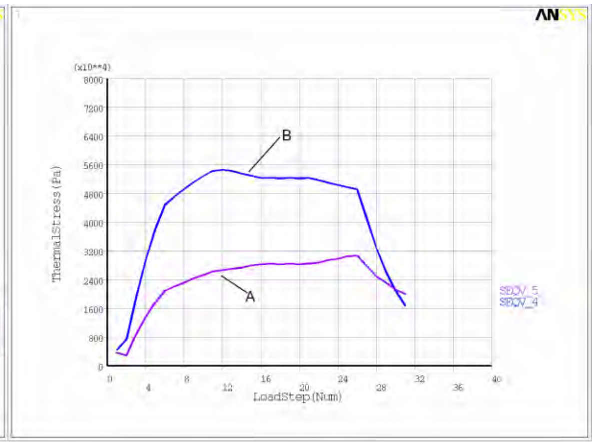



Fig.8b: thermal stress at point A and B on bolt

**Pressure transient**

Same as thermal transient, under loading 2 pressures transient, stress distribution is changing with time due to loading is a function of time. Fig.9 to 10 displays stress at 0s and 28000s.

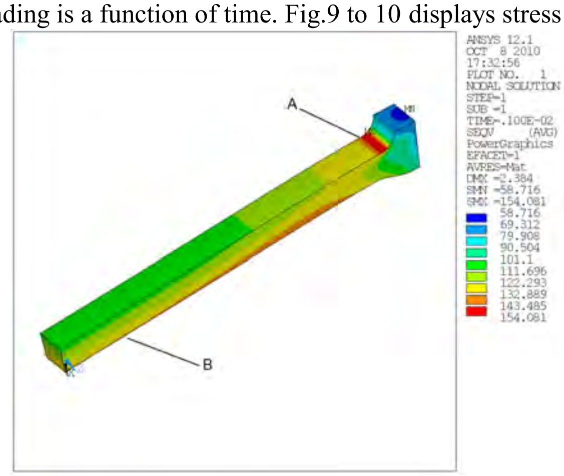



Fig.9a: stress distribution at 0s on shell

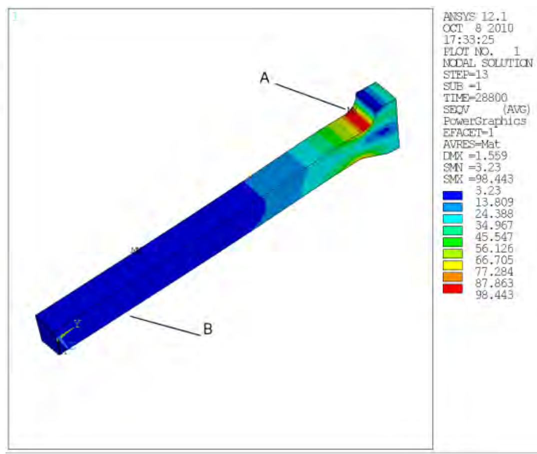



Fig.9b: stress distribution at 28000s on shell

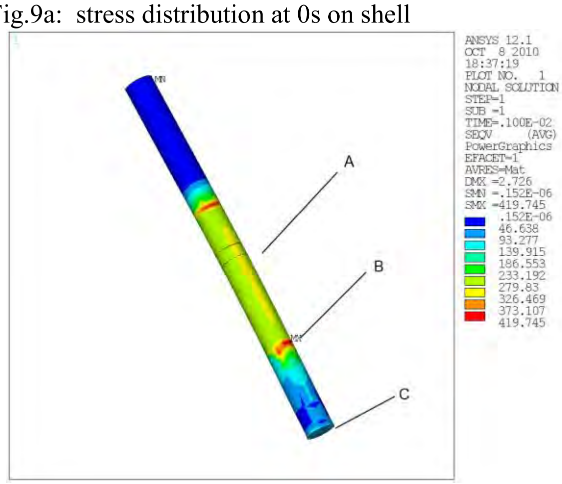



Fig.10a: stress distribution at 0s on bolt

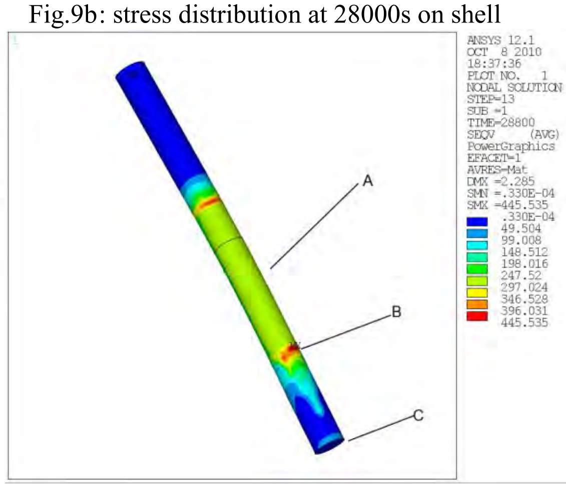
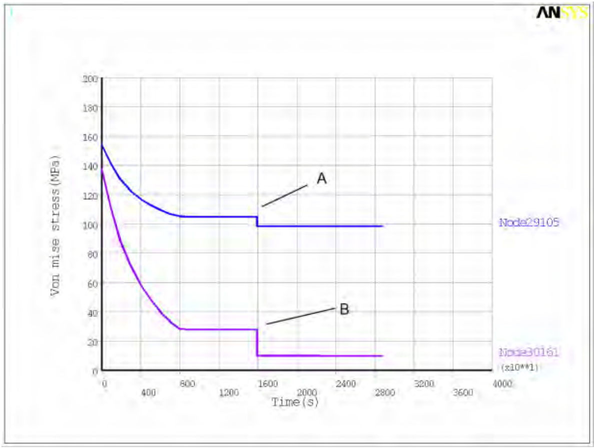



Fig.10b: stress distribution at 28000s on bolt

Variation of stress at point A and B on shell and A, B, C on bolt are showed at Fig.11a and 11b. It shows variation on shell is greater than on bolt.



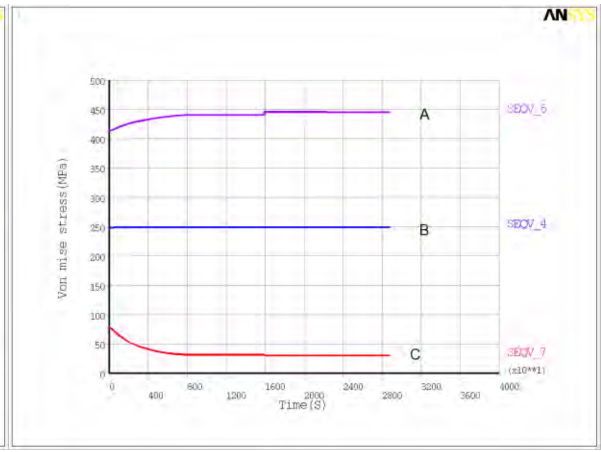




Fig.11a: thermal stress at point A and B on shell Fig.11b: thermal stress at point A and B on bolt

Combination

From thermal stresses under thermal transients and stresses under pressure transients, the final result can be retrieved by combining each components stresses. More than 40 results can be obtained.

## FATIGUE CALCULATION

At each step, extract 6 stress components, temperature and 6 membranes plus bending stress result, total 13 components, for fatigue analysis. Before calculate the fatigue usage factor, the stress concentration factor had to be included. Due to RCC-M, number 4 was used for concentration simulation. Considering elastic-plastic strain correction factor and applying S-N curve, fatigue analysis was studied with 13 stress components which were mentioned above.

Using rain flow method and miner linear cumulative damage theory, usage factors at shell and bolt are easy to calculate. The maximum usage factor of bolt is 0.935 at contact position, and this data is under 60y design life.

## CONCLUSION

This paper tries to find an effective method to calculate bolt and screw usage factor, while pre-load of bolt and contact between bolt and screw are involved. With a 3D dimensional model, the simulation is much more real than before. During modeling and calculating, contact, pre-load and thermal-structure interaction methods are used. Calculating more than 40 transients of thermal and pressure, combining these thermal and pressure results, finally use rain flow and miner rules to calculate usage factor. The result shows this method works and with better accuracy than before.

## REFERENCES


[1] Design and construction rules for mechanical components of PWR nuclear islands RCC-M 2000
[2] LING AO STRESS ANALYSIS REPORT, Reactor vessel upper head, flange and bolts.
[3] ANSYS theory manual, 12.1