

## Application of code case 2605 to evaluate hydrogenation reactors constructed with 2.25Cr-1Mo-V for creep-fatigue life

Teng-Fei Zhou<sup>1</sup>, Xiao-Cheng Zhang<sup>2</sup>, Kai-Shu Guan<sup>3\*</sup>, Lin-Ling Guo<sup>4</sup>,  
Ming-Xue Fu<sup>5</sup>, Rui-Bin Huang<sup>6</sup>

<sup>1</sup>Graduate Student, Key Laboratory of Pressure System and Safety, Ministry of Education, East China University of Science and Technology, China

<sup>2</sup>Graduate Student, Key Laboratory of Pressure System and Safety, Ministry of Education, East China University of Science and Technology, China

<sup>3</sup>Professor, Key Laboratory of Pressure System and Safety, Ministry of Education, East China University of Science and Technology, China

<sup>4</sup>Graduate Student, Key Laboratory of Pressure System and Safety, Ministry of Education, East China University of Science and Technology, China

<sup>5</sup>Graduate Student, Key Laboratory of Pressure System and Safety, Ministry of Education, East China University of Science and Technology, China

<sup>6</sup>Graduate Student, Key Laboratory of Pressure System and Safety, Ministry of Education, East China University of Science and Technology, China

### Abstract

Hydrogenation reactors is extensively used in the petroleum and refining industry in order to fulfill the demand of petroleum products. 2.25Cr-1Mo-V steel is a commonly material to manufacture hydrogenation reactors due to its excellent mechanical properties in high temperature and hydrogen attack resistance. Considered the environment of hydrogenation reactors, the effect of coupled creep and cyclic load should be taken into account when evaluating the life in design. CC2605 provide two options to evaluate the creep-fatigue life of reactors constructed with 2.25Cr1MoV. This paper compared the difference of results obtained from ratcheting analysis and calculation of  $L_{cwf}$  on a typical structure by ANSYS according to option 1 and option 2, respectively. The result shows that creep-fatigue life is almost same calculated according to both the two options, and thus demonstrating the option 1 is able to evaluate the creep-fatigue life. Some recommendation is also proposed to extend the creep-fatigue life.

**Keywords:** 2.25Cr-1Mo-V; creep-fatigue life; hydrogenation reactors; Code case 2605.

### Introduction

With the increasing demand for petroleum and relative products, hydroprocessing units including hydrocracking and hydrofining are becoming more attractive alternatives in the petroleum and refining industry due to strict environmental fuel specifications, tighter emission controls and lower quality crude oil [1-2]. Hydrogenation reactors is a key facilities in hydroprocessing units, which can be classification with hot-wall and cold wall reactor according its wall temperature on operating condition.

2.25Cr-1Mo-V steel is a kind of material which is widely used in the manufacturing of hot-wall hydrogenation reactor since its high strength, excellent high temperature performance and temper embrittlement resistance. As the complexity of operating conditions, hydrogenation reactors constructed with 2.25Cr-1Mo-V subjected to evaluated temperature and fluctuating loads, which the influence on creep-fatigue life must be considered in design.

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\* Corresponding author. Tel./fax: +86 21 64253055  
E-mail address: guankaishu@ecust.edu.cn

For a pressure vessel that subjected to fluctuating loading condition (include temperature and pressure), the design of vessels involved fatigue should be satisfied the demand of ASME Boil and Pressure Vessel Section VIII Division 2 [3] (ASME standard). Additionally, to simplify the assessment procedure of fatigue design, the existing ASME standard provides two methods to screen the thermal and mechanical loading histograms. However, the current ASME standard does not permission neither method A to screen when the ultimate strength greater than 585MPa (85ksi) nor method B when the operating temperature greater than 371 °C (700 °F). Meanwhile, there is no fatigue curves in ASME standard to be applied for operating temperatures greater than 371 °C (700 °F) and less than or equal to 482 °C (900 °F) until ASME B&PV Code Case 2605 (CC2605) [4] was approved in 2008. CC 2605 was based on Omega method [5] that developed in 1980s by American Petrochemical Institute (API), in which two options is provided, option 1 is a simplified method and option 2 is relatively complex that apply actual time-dependent thermal and mechanical loading histograms, to assess the creep-fatigue life of hydrogenation reactors constructed with 2.25Cr-1Mo-V.

Stefanovic [2] analyzed a nozzle of typical diesel hydrotreater reactor at the period during normal start-up and planed shut down in accordance with CC2605 option 1, thus providing a guideline to prepare a User's Design Specification. Three nozzle models of a reactor on different location was analyzed by TERADA [6] through option 1 and option 2, respectively. Zhao [7] discussed that the influence on the creep-fatigue life caused by a small excursion from normal operating condition, it was found that a significant reduction of creep-fatigue life due to the fluctuation temperature and pressure. However, in spite of the convenience of option 1, the reliability of option 1 on CC2605 has not been verified by option 2 that involved actual loading condition by other researchers.

It is the purpose of this paper to evaluate the creep-fatigue life through the two options specified in ASME VIII-2 code case 2605 and compare the results obtained by finite element analysis (FEA) according to option 1 and option 2. Furthermore, to validate that the results calculated on the basis of option 1 is sufficient to evaluate the creep-fatigue life of hydrogenation reactors constructed with 2.25Cr-1Mo-V.

### CC2605 methodology

As mentioned above, CC2605 provide two options to evaluate the reactor built with 2.25Cr1MoV that subjected to fluctuating load at creep regime with the operating temperature between 371 °C and 482 °C.

The procedure of evaluation consists of three parts: ratcheting analysis, calculation of creep life absent fatigue ( $L_{caf}$ ) and calculation of creep life with fatigue ( $L_{cwf}$ ).

Ratcheting analysis is aimed to ensure that the vessel would not fail due to exceed plastic deformation in the whole operation life. Option 1 is an approximately method that based on a conservative and simplified load histogram, which need considerate minimum two complete cycles of extreme loading condition of loading with minimum one year of holding time in order to establishing the effect of creep relaxation. On the contrary, option 2 is based on the actual operating histogram including all cycles as a full inelastic analysis, which is a time-consuming work. The shakedown was demonstrated if the equivalent total accumulated inelastic strain not exceed the value shown in [Table 1](#), it should be noted that option 1 could not be selected if the analysis fail to demonstrate elastic shakedown.

Table 1 Total accumulated inelastic strain

Type of stress	Equivalent total accumulated inelastic strain	
	Weld and HAZ	Other parts
Membrane	0.5%	1.0%
Membrane plus bending	1.25%	2.5%
Local (at any point)	2.5%	5.0%

The second step is to calculate the creep life absent fatigue ( $L_{caf}$ ) no matter which option is selected.  $L_{caf}$  is defined as the time when the creep damage ( $D_c$ ) is reached 0.95 if the time is less than 1,000,000 hours, or the life regarded as 1,000,000 hours. Sufficient locations shall be selected to ensure that the most critical conditions have been considered. [4]

Finally, the creep life with fatigue ( $L_{cwf}$ ) could be calculated by  $L_{caf}$  per CC2605. The equations to calculate  $L_{cwf}$  is different from option 1 and option 2, when option 1 is selected,  $L_{cwf}$  shall be calculated as follows:

$$L_{cwf} = L_{caf} \left( \frac{\beta_{cf} \cdot \Delta\varepsilon_{peq} \cdot N}{\exp[\beta_{cf} \cdot \Delta\varepsilon_{peq} \cdot N] - 1} \right), \Delta\varepsilon_{peq} > 0 \quad (1)$$

$$L_{cwf} = L_{caf}, \Delta\varepsilon_{peq} = 0 \quad (2)$$

Where  $L_{cwf}$  is creep life with fatigue,  $L_{caf}$  is creep life absent fatigue,  $\beta_{cf}$  is creep fatigue damage factor equal to 2.0,  $N$  is the permissible number of cycles determined in step 3 of para. 5.5.2.4 in ASME standard and  $\Delta\varepsilon_{peq}$  is equivalent plastic strain amplitude based on the alternating equivalent stress amplitude determined from *Table 4 in CC2605*.

As stated above, the two screening method in ASME standard could not be applied to reactor built with 2.25Cr1MoV and operate in the temperature range from 371 °C to 454 °C. To solve this limitation, a fatigue curves based on the value of  $L_{caf}$  is offered in CC2605 to replace the curves in method B in ASME standard. In the procedure of screen, the value of  $S_{as}$  shall be base d on 10000 cycles and the alternating equivalent stress amplitude based on the primary plus secondary plus peak stress determined from shakedown analysis [6].

When option 2 is selected,  $L_{cwf}$  shall be calculated as follows:

$$L_{cwf} = L_{caf} \left( \frac{\beta_{cf} \cdot \sum_{i=1}^k \Delta\varepsilon_{peq,k}}{\exp\left[\beta_{cf} \cdot \sum_{i=1}^k \Delta\varepsilon_{peq,k}\right] - 1} \right), \Delta\varepsilon_{peq} > 0 \quad (3)$$

$$L_{cwf} = L_{caf}, \Delta\varepsilon_{peq} = 0 \quad (4)$$

Where  $L_{cwf}$ ,  $L_{caf}$ ,  $\beta_{cf}$  are same as equation (1), while  $\Delta\varepsilon_{peq,k}$  is equivalent plastic strain amplitude for the  $k$ th loading condition or cycle which is directly determined in fatigue analysis results,  $\Delta\varepsilon_{peq}$  is equivalent plastic strain amplitude based on the alternating equivalent stress amplitude determined in fatigue analysis.

From [equation \(1\)](#) to [equation \(4\)](#), it could be noticed that whether the creep life with fatigue damage equal to the creep life absent fatigue depends on the equivalent plastic strains during the entire operating period. That is to say that creep life would not be affected by cyclic operating if the plastic strains cycle do not exist.

The plasticity is introduced through the elastic perfectly plastic stress-strain curves of 2.25Cr1MoV based on the yield strengths consistent with the operating temperature. [8] The creep damage is calculated per the creep constitutive model specified in CC2605, which was developed based on Omega project. What's more, the creep model is not available in common commercially finite element analysis software like ANSYS and ABAQUS, though it was programmed in FORTRAN to investigate the creep behavior. [1]

## Finite element analysis on a nozzle

### Geometry and model

This paper investigate a nozzle in hemispherical head of hydrogenation reactor as an example to compare the creep-fatigue results obtained by option 1 and option 2, the geometry is shown in [Figure 1](#). The design life of this reactor is 20 years (175,200hours) with total 7300 cycles (1 cycle per day), which the loading histogram of 2 cycles is shown in [Figure 2](#). The operating temperature and maximum pressure is 450°C and 20Mpa, respectively. The nozzle and hemispherical head are both built with forged 2.25Cr1MoV, which the material properties is shown in [Table 2](#). [9]

Table 2 Mechanical properties of 2.25Cr1MoV on 450°C

Young's modulus MPa	Yield strength MPa	Tensile Strength MPa	Allowable stress MPa
180000	339	485	145

The FEA is carried out by axi-symmetric elements, which is used to improve the computational efficiency. 8 node 2D axi-symmetric structural solid element PLANE 183 has been used to analyze the creep-fatigue life, while the temperature is constant thus it was not considered. [Figure 3](#) shows the finite element model for the nozzle and head, which have 3108 node and 942 element in total.

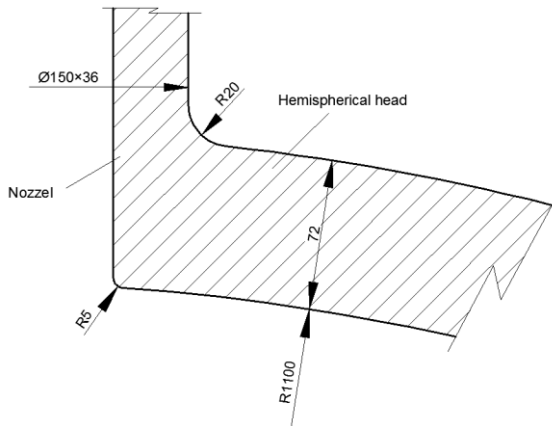


Figure 1. Geometry of the nozzle

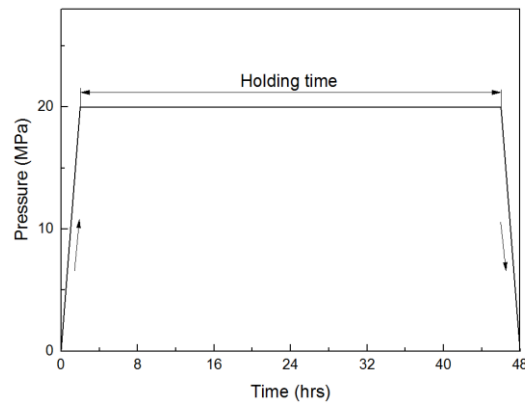


Figure 2. The loading histogram of 2 cycles

### Intensity check under static load

The purpose of this part is to ensure that the strength of the structure is satisfied the requirement of design method, in addition, the location experience the most extreme condition of pressure could be selected. The contour of elastic stress analysis could be seen in [Figure 4](#), it is found that the node number of suffering maximum stress is 2397, which is selected to be analysis in following section. Additionally, the results of stress assessment is listed in [Table 3](#).

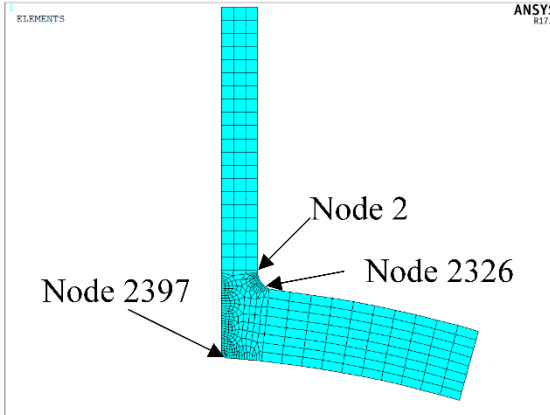


Figure 3. Finite element model for the nozzle and head

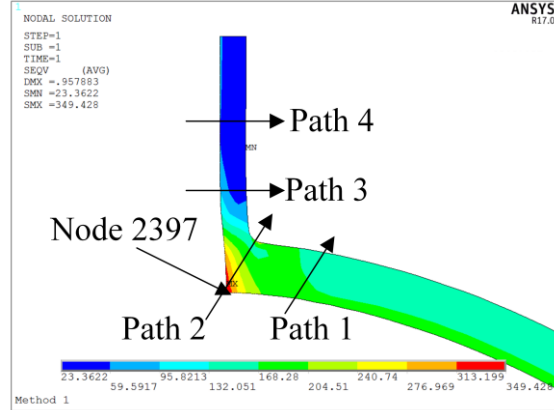


Figure 4. Contour of Mises stress on elastic stress analysis

Table 3 Results of stress assessment

Path	Stress classification, MPa	Assessment of stress intensity, MPa
1	PL=201.1	$\leq 1.5S_m=219$
	PL+Pb+Q=188.5	$\leq 3.0S_m=435$
2	PL+Pb+Q =356.2	$\leq 3.0S_m=435$
3	PL=121.2	$\leq 1.5S_m=219$
	PL+Pb+Q=163.8	$\leq 3.0S_m=435$
4	Pm=51.26	$\leq 1.5S_m=219$
	Pm+Pb+Q=81.59	$\leq 3.0S_m=435$

### Ratcheting analysis

As state in previous section, the creep ratcheting analysis has been carried out to establish the elastic shakedown. The effect of creep behaviour is programmed in FORTRAN and activated as a subroutine by the command (TB, CRREP, , , , 100) in ANSYS. Figure 5 is the modified loading histogram which include 3 cycles with 1 year holding time (9,000hrs) under the maximum temperature (475°C) and pressure (20Mpa) as per option 1. In addition, another analysis include all cycles was conducted per option 2. The results of ratcheting analysis is shown in Figure 6 and Figure 7, respectively. It is demonstrated that the stress could reach to the previous value after unload, which indicates that shakedown is established with both option after several cyclic load.

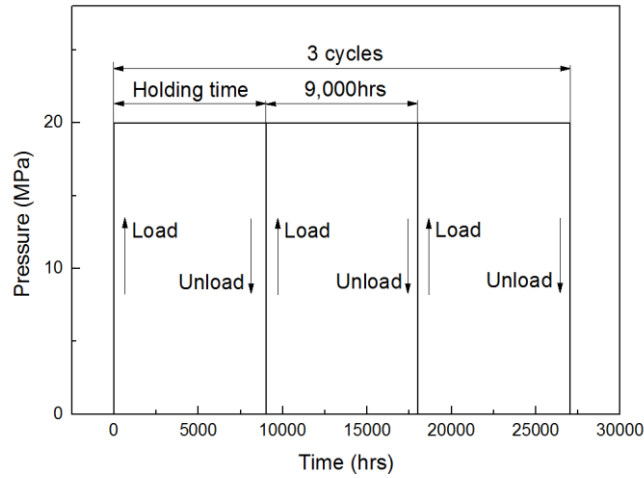


Figure 5. Loading histogram of ratcheting analysis per option 1

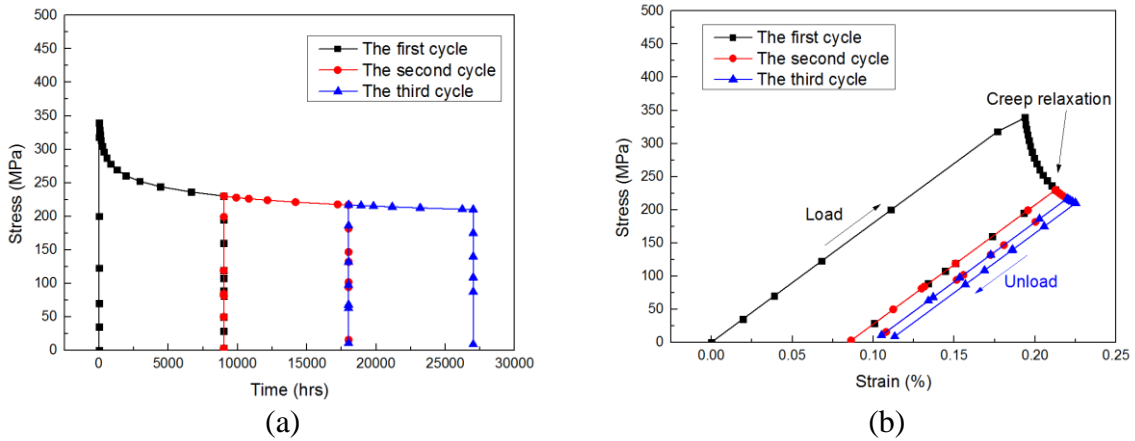
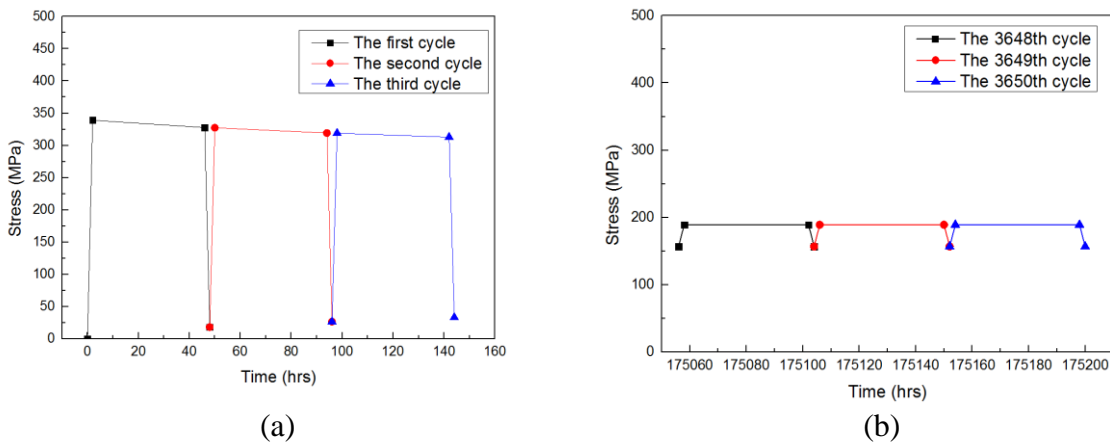


Figure 6. Results of ratcheting analysis per option 1 on node 2397



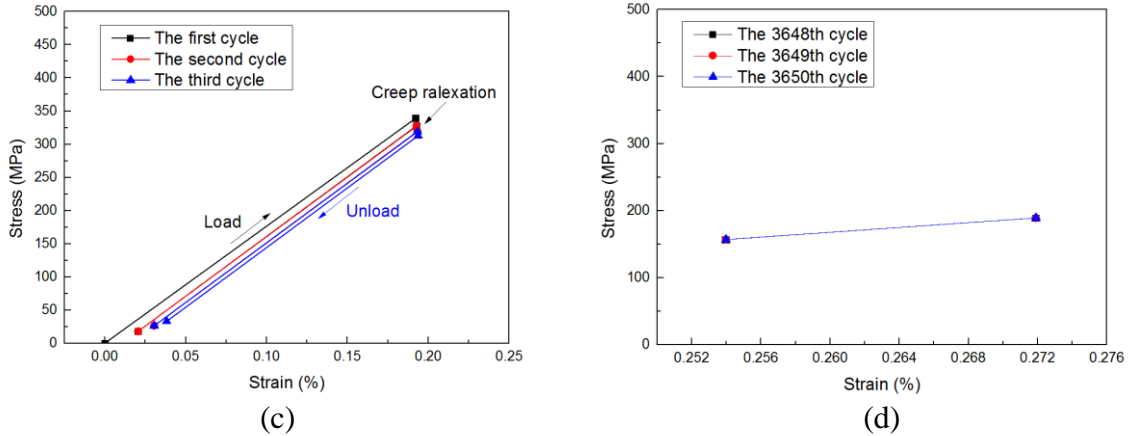


Figure 7. Results of ratcheting analysis per option 2 on node 2397

### Creep life absent fatigue

When the shakedown was demonstrated, it is ensured that the plastic deformation of any locations on the reactor would not increase immeasurably with the result of plastic collapse. Then the calculation of  $L_{caf}$  is required, with the purpose to select the design fatigue curve which offered by CC2605. The procedure of calculation of  $L_{caf}$  is not different on matter which option is selected per CC2605, which means that the parameter is completely same in the process of calculation. The creep damage  $D_c$  with the most extreme condition (20Mpa and 450°C) was computed in a period of 1,000,000 hours, the result shows that  $D_c$  did not reach to its critical value (0.95) when the time was equal to 1,000,000 hours, so the value of  $L_{caf}$  is 1,000,000 hours.

Figure 8 shows Mises stress distribution in 1,000,000 hours of the model, the location with maximum stress is still node 2397. Meanwhile, Figure 9 shows the creep damage of the structure on the same time, the node number with maximum damage is 2326 which is located in the outer fillet instead of 2397. Figure 10 displays the history of Mises stress and damage in the range of 1,000,000 hours of node 2397, node 2326 and node 2. The stress of three nodes have different tendency with increased time. The increased stress of node 2 and the decreased stress of node 2397 is caused by creep relaxation, and the three stages of the stress of node 2326 is considered to be effected by the combination of compatibility of deformation and creep relaxation as its high stress triaxiality. Figure 11 indicates that the damage of node 2397 is higher than other two nodes in a little period, but it turns out node 2326 is the most critical location to failure due to its damage is maximum.

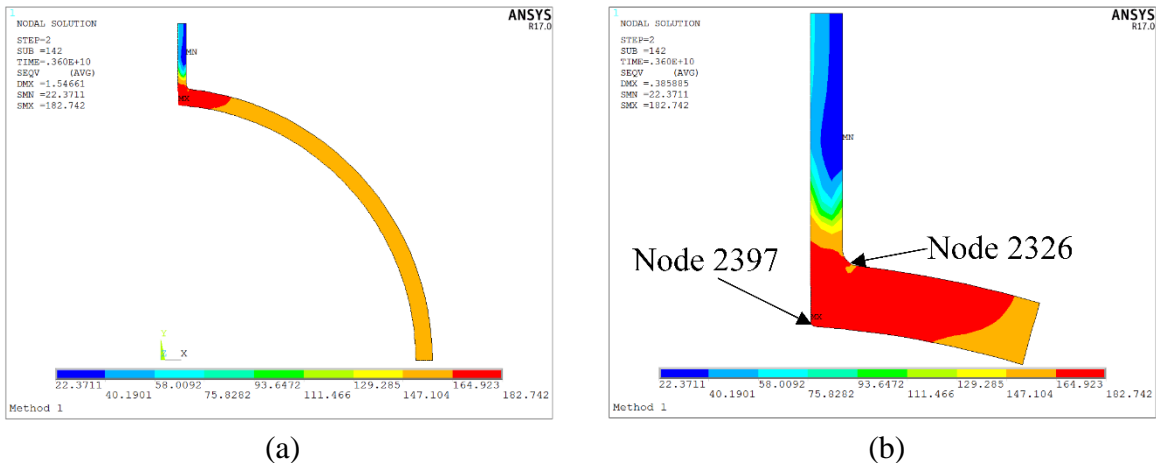


Figure 8. Contour of Mises stress of the nozzle on 1,000,000 hours

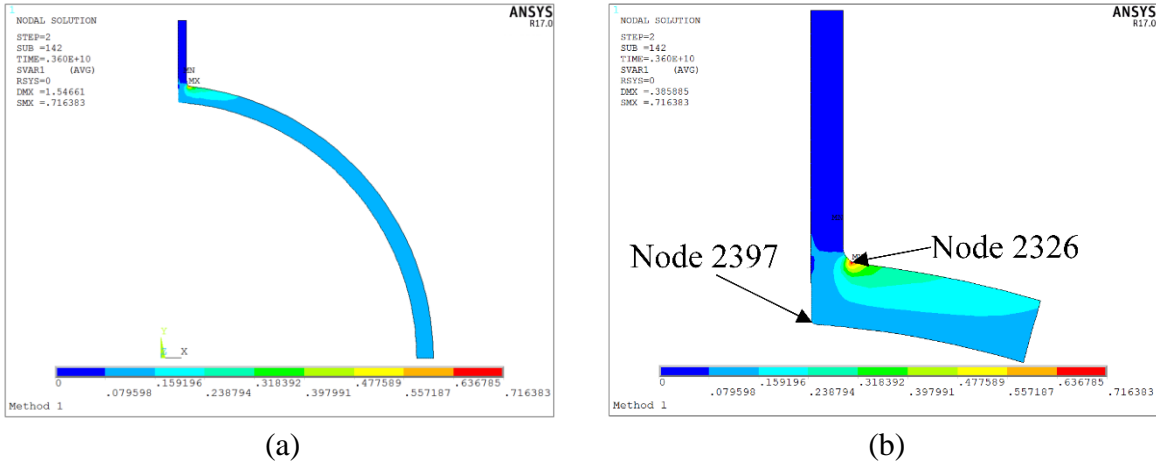


Figure 9. Contour of damage of the nozzle on 1,000,000 hours

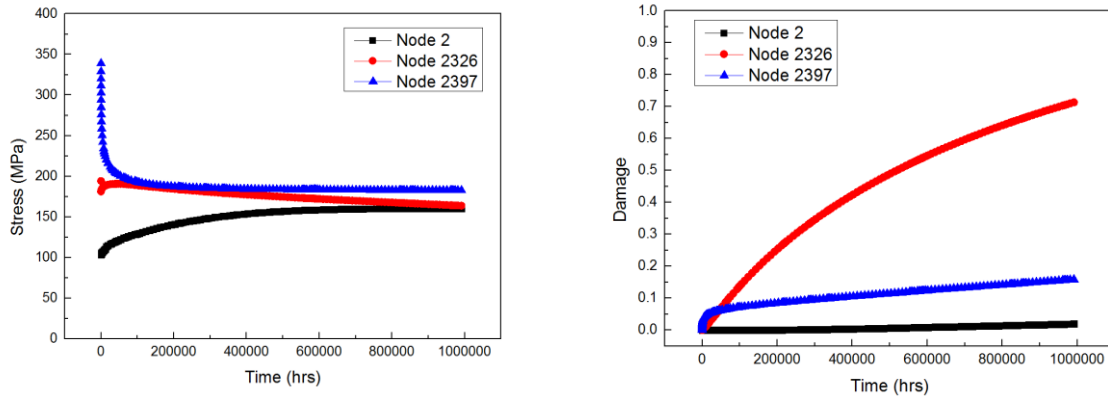


Figure 10. History of Mises stress of the model

Figure 11. History of damage of the model

**Creep life with fatigue**

Finally, the creep life with fatigue  $L_{cwf}$  could be calculated as described in equation (1) to equation (4) based on which option is selected.

For option 1, as the result obtained in intensity check under static load, the alternating equivalent stress amplitude is  $(P_L+P_b+Q+F) / 2=175\text{MPa}$ , thus  $\Delta\varepsilon_{peq}$  is 0 according to Table 4 in CC2605. According to the analysis of creep, the curve of 1,000,000 hours is selected to determine the permissible number of cycles,  $N$ , in Figure 3M in CC2605, which is  $4514 > 3650$  cycles. Meanwhile, the creep life with fatigue is 1,000,000 hours as equation (2), which is also greater than the design life 175,200 hours.

For option 2, the fatigue analysis is performed to ensure that the accumulated fatigue damage is satisfied the requirement of ASME standard. Table 4 shows the results of fatigue analysis, it is displayed that the accumulated fatigue damage  $D_f$  is less than the critical value 1.0, so the requirement is satisfied. According to equation (3), the value of  $L_{cwf}$  is 999,962 hours, which is very close to 1,000,000 hours.

Table 4 Results of fatigue analysis

$\Delta\varepsilon_{peq}$	$\Delta S_p/\text{MPa}$	$\Delta\varepsilon_{eff}$	$S_{alt}/\text{MPa}$	N	1/N	$D_f$
3.76E-05	170	9.8E-04	176.768	4226	0.00024	0.864

## Discussion

From Figure 6 and Figure 7, it could be seen that the Mises stress after loading in the last cycle does not have much difference no matter which is selected, while the residual stress calculated per option 2 is much greater than option 1. Additionally, the decreased effect of creep is observed in Figure 6(b) as the tendency from Figure 7(c) to Figure 7 (d), which means that the creep relaxation is fully considered.

According to CC2605, the creep-fatigue life is related to damage and equivalent plastic strain amplitude. The contour of Mises stress and damage in 1,000,000 hours is plotted in Figure 8 and Figure 9, from which it is suggested that the node number with maximum damage is 2326 but 2397 which could be found in Figure 4. Therefore, the critical location where should be paid attention is the inner and outer fillet in the process of design and maintain. In order to extend the creep-fatigue life, some measures could be made, for example, improve the situation with high stress triaxiality [10] and reduce the strain amplitude.

The results computed per option 1 and option 2 suggest that the creep life with fatigue  $L_{cwf}$  have not too much difference. In fact,  $L_{cwf}$  calculated per option 2 is little less than option 1, which is resulted from the fact that the equivalent plastic strain amplitude has been neglected. Thus, compared with the result of ratcheting analysis and  $L_{cwf}$ , it could be concluded that the option 1 is able to evaluation the creep-fatigue life when the requirement in CC2605 is satisfied.

## Conclusion

Inelastic analysis and fatigue evaluation were performed per the two options in code case 2605 on a typical structure including a nozzle and a hemispherical head constructed with 2.25Cr1MoV. With the results of the analysis, following conclusion were obtained:

- 1) Shakedown is established with both the simplified method that including 3 modified cycles per option 1 and full inelastic analysis per option 2 in CC2605.
- 2) Node 2326 and node 2326 is the critical locations of the presented model, attention should be paid to extend the creep-fatigue life. Some measures might be an effective such as improve the situation with high stress triaxiality and reduce the strain amplitude.
- 3) The creep-fatigue life  $L_{cwf}$  is 1,000,000 hours and 999,962 hours calculated on the basis of option 1 and option 2, respectively. The life almost the same, which demonstrated option 1 is sufficient to evaluate the creep-fatigue life of the reactor constructed with 2.25Cr1MoV.

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