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A SOFTWARE FOR EVALUATING CREEP-FATIGUE FAILURE OF CLASS 1 NUCLEAR COMPONENTS BASED ON ASME Ⅲ-5 HBB-T

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ABSTRACT

1. INTRODUCTION

In nuclear power plants, there are some critical components working at high temperatures. For example, the design temperature of the fast reactor vessel is as high as 550℃. It is well known that the time-dependent creep behaviour happens when the temperature exceeds 0.3 times of the melting temperature. Meanwhile, the start-up and shut-down of the reactor would lead to the cyclic mechanical or thermal loads, inducing the fatigue damage of components. Both creep and fatigue behaviour could cause damage to materials, and more serious damage may take place due to the creep-fatigue interaction (Mann, et al. 2009). Therefore, the creep-fatigue damage evaluation is an essential issue for the structural design of nuclear power components.

So far, the ASME III has been widely accepted for the construction of nuclear power components. The creep-fatigue evaluation process is included in the ASME III-5-HBB-T, and is divided into two methods. One is based on the elastic analysis and the other is based on the inelastic analysis. Compared to the inelastic analysis method, the elastic analysis method has been widely used in engineering applications due to the relatively larger but acceptable conservativeness. It should be stated that there are many parameters in the elastic analysis method for considering influences of related factors, and accordingly these can increase the workload of designers (Michael, et al. 2017). Based on this, developing a software according to the ASME III-5-HBB-T can make the structural design and creep-fatigue damage evaluation more effective and economical.

The main structure of this paper is as follows. Section 2 summarizes the creep-fatigue evaluation process of the ASME III-5-HBB-T. An introduction of the software's structure is given in Section 3. Section 4 discusses the case study on creep-fatigue damage evaluation based on the software developed. Concluding remarks are provided in Section 5.

2. ELASTIC ANALYIS OF CREEP-FATIGUE IN ASME III-5-HBB-T

ASME III-HBB-T includes high temperature deformation limit and creep-fatigue evaluation, and provides material parameters of 304 stainless steel, 316 stainless steel, 800H alloy steel, 2.25Cr-1Mo steel and 9Cr-1Mo-V steel. The main focus of this work is the creep-fatigue damage evaluation of nuclear power plants, in which the elastic and inelastic stress analysis methods are included. In following, the elastic stress analysis routine is of the main concern of this work, and is provided below.

Figure 1 displays the flow chart of the elastic analysis method for creep-fatigue damage evaluation in ASME III-5-HBB-T. The core of the damage evaluation is to determine the fatigue damage and creep damage terms. For fatigue damage, the elastic and plastic strain range are deduced by the maximum stress range and Neuber equation. Moreover, the multiaxial effect on fatigue damage of the component is considered based on the K_v. In addition, for taking the effect of creep behaviour on fatigue into account, the creep strain increment term is included in the total strain range. Regarding the creep damage, an envelope stress-time curve need be established to determine the stress during creep process. When constructing the envelope stress-time curve, the stress relaxation obtained by the isochronous stress- strain curves should be corrected according to the multiaxial stress state.

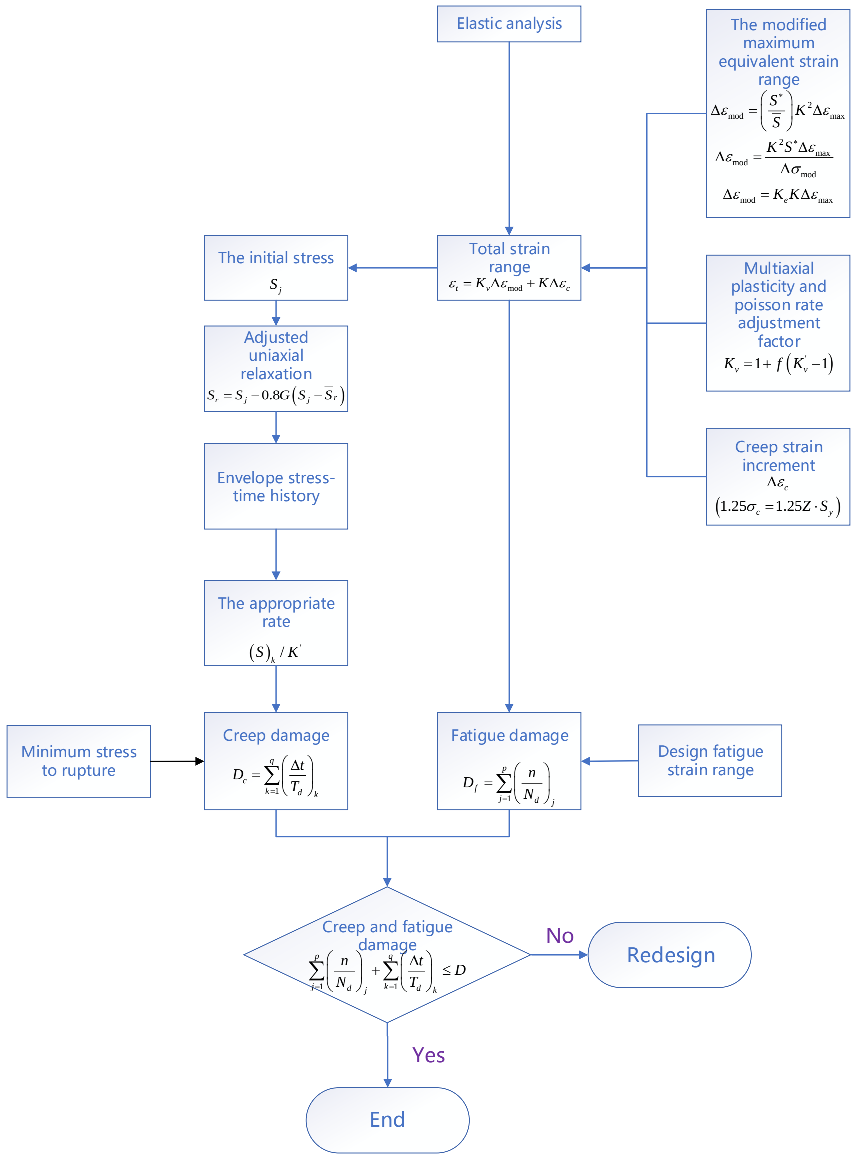

Figure 1 Flow chart of creep fatigue evaluation based on elastic analysis

The creep-fatigue damage limit is given in HBB- T- 1411 (see Eq. (1))

$$\sum_{j=1}^{p}\left(\frac{n}{N_d}\right)_j + \sum_{k=1}^{q}\left(\frac{\Delta t}{T_d}\right)_j \leq D \tag{1}$$

where D is the total creep-fatigue damage, $(N_d)_j$ is the number of design allowable cycles for cycle type determined from the design fatigue curves, $(T_d)_k$ is the allowable time duration determined from stress to rupture curves. Eq. (1) shows that the creep and fatigue damage of different load types are linearly accumulated, wherein the low cycle fatigue damage is based on the ratio between the practical and the allowable cycles, and the creep damage is based on the ratio of the practical creep exposure time and the allowable creep rupture lives. The creep-fatigue damage limit diagram of ASME is shown in Figure 2. It can be seen that the creep-fatigue limit is a double line diagram and the intersection points for different materials are not the same. HBB-T-1431 includes the general requirements of creep-fatigue based on elastic analysis, it is noticeable that the thermal induced membrane stresses should be classified as primary stresses.

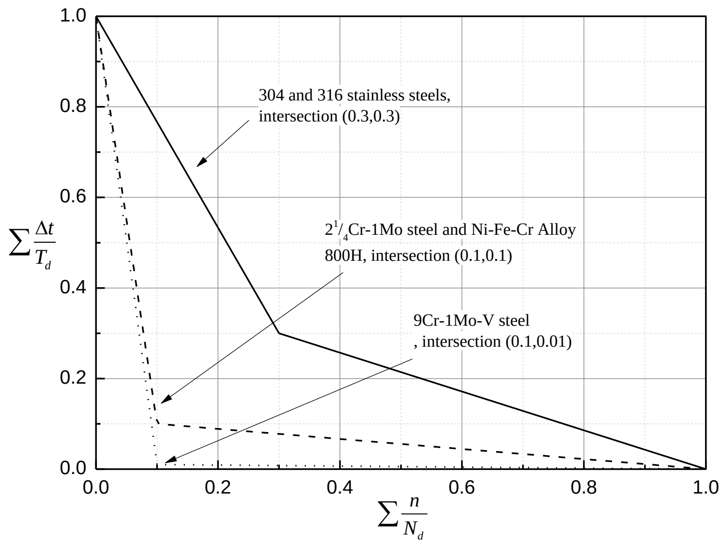

Figure 2. The creep-fatigue damage limit of ASME III-5- HBB- T. (ASME III-5- HBB, 2015)

3 THE SOFTWARE SCOPE AND STRUCTURE

The creep-fatigue evaluation program is implemented in mathematical software MATLAB. Two kinds of materials are considered in the software, i.e. 316H and 2.25Cr-1Mo. The temperature ranges involved in the software are 427-566℃ for 316H steel and 371-566℃ for 2.25Cr-1Mo steel, respectively.

The creep-fatigue evaluation software consists of several structures: *Material database*, *Input*, *Evaluation process* and *Output*.

Material database includes the required mechanical properties at high temperature for evaluations, such as elastic modulus, yield strength, fatigue design curves, isochronal stress-strain curves, etc. Note that these curves have been dispersed into points in databases. The results of the stress linearization are read directly by the software as input. For different service levels A, B, and C, time and cycle number can be entered into the creep-fatigue damage evaluation.

For *Evaluation process*, the general requirements of the elastic analysis should be checked firstly and detailed assessment procedure is mentioned in Fig. 2. It should be clarified that the linear interpolation is used if the data to be computed falls between the points of the database. Further, if it exceeds the maximum value in the database, software will use the slope of the last two points to make the linear extrapolation. This strategy is mainly limited to creep rupture life during the creep-fatigue evaluation of the components.

The *Output* of the software is written into a log file with the calculation results. Most information focuses on whether or not the design passes a particular test and what tests are conducted. In addition, if the general requirements are not satisfied, software will skip the evaluation process and output which requirements are not met.

The frameworks of *Material database, Input*, and *Output* are constructed in three independent documents, which are convenient for users to edit and add more material data.

4 CASE STUDY

4.1 Finite element model

In this paper, the feasibility of the software is analyzed based on a creep-fatigue evaluation case of the nozzle on a vessel. The cylindrical vessel is made of 316H, and the inner and outer diameters are 800mm and 908mm. The length of the nozzle is 170mm, and the inner and outer diameters are 60mm and 130mm respectively. The internal fillet radius between the nozzle and the vessel is 12mm and the external fillet radius is 45mm. The operating temperature of the component is 550℃, and there are 14616 load cycles with the inner pressure ranging from 1.6MPa to 9MPa for each cycle, as shown in Figure 3. As displayed in Figure 4, the 1/4 model is established due to symmetry of the structure. The model is meshed by the element type C3D8R, and the meshes close to the joint between the nozzle and the vessel are refined. After mesh generation, 144419 elements and 160932 nodes are generated.

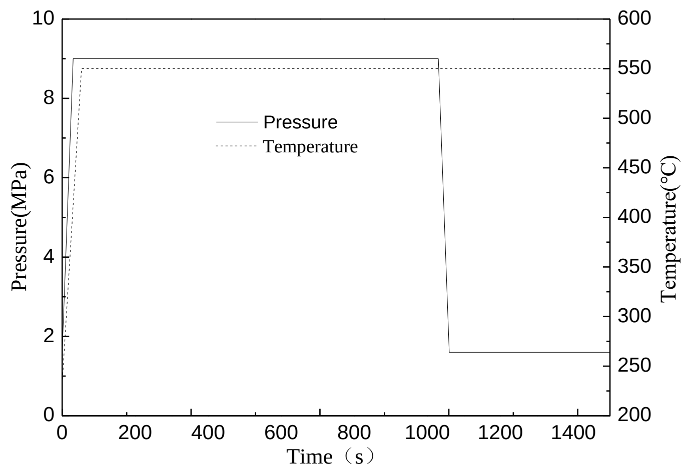

Figure 3 The pressure and temperature evolution behaviours along with time in one cycle.

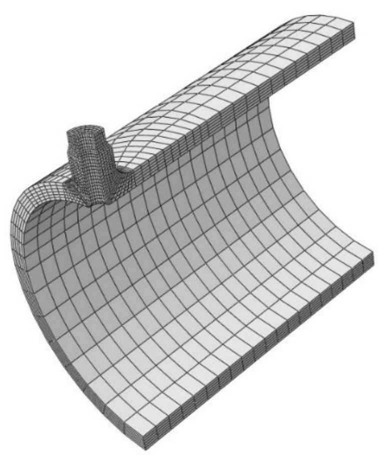

Figure 4. The mesh model of component for creep-fatigue evaluation

4.2 The output of the software

Figure 5 displays the von-Mises stress distribution based on the elastic analysis framework. It shows that the maximum von-Mises stress is located at the inner surface of the joint between the nozzle and the vessel, and a path through the node with the maximum stress value is established for creep-fatigue damage evaluation.

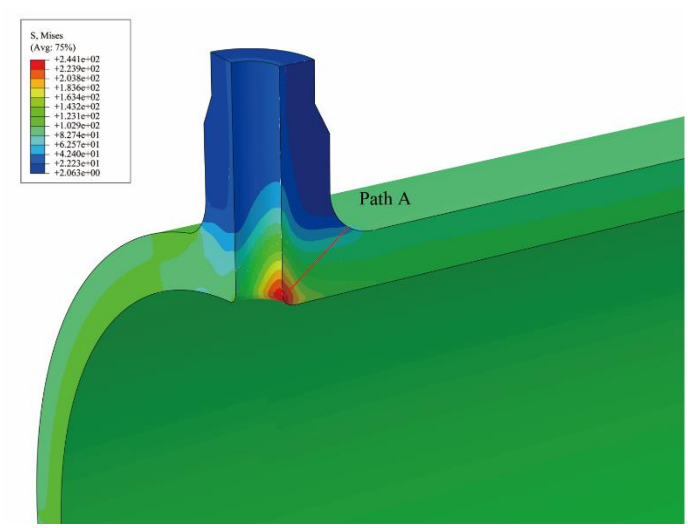

Figure 5. The von-Mises stress distribution by the elastic analysis.

The inputs for this case study are listed in Table 1, where P_L is the local membrane stress, P_b is the primary bending stress, Q is the secondary stress, F is the peak stress, ε_{max} is the maximum strain range, σ_1 is the maximum principle stress, σ_2 is the middle principle stress, σ_3 is the minimum principle stress, T_H is the operating temperature, t_i is the total creep exposure time and N is the cycle number. For the sake of simplicity, only one service level is considered in this case. The results of the stress linearization and the principal stress components are gained from the finite element analysis.

Table 1 The input of the creep-fatigue evaluation software

F	P_L	P_b	Q	ε_{max}	σ_1	σ_2	σ_3	T_H	t_i	N
33.14	70.11	0	53.19	0.001217	249.1	14.1	-3.01	550	4060	14616

The output of the software is written into a log file, as shown in Figure 6. As mentioned above, the general requirements of elastic analysis are checked firstly. The important results during the creep-fatigue damage evaluation process and the judgment results are output, which makes it easy to check for users. Taking the above case for example, the creep damage and the fatigue damage are 0.2997 and 0.1428, respectively. This indicates that the creep-fatigue limit is satisfied. Furthermore, the items of output can be customized by the user.

```
Creep-Fatigue Evaluating Software
Start
General Requirements: Pass
X=0.6044; Y=0.4586; Z=0.6067
Total Strain Range: 0.1357%
Corresponding Stress Level: Sj=130.2526
Creep Damage: Dc=0.299710
Fatigue Damage: Df=0.142833
Total Damage: Pass
Finish
```

Figure 6. The output of the software for creep-fatigue damage evaluation of components.

5 CONCLUSIONS

Creep-fatigue damage evaluation based on elastic analysis routine in ASME III- 5-HBB-T has been widely employed in engineering applications due to the relatively larger but acceptable conservativeness. It should be stated that, however, the workload of the users for this analysis routine is relatively higher. To reduce the workload of user, a software for creep-fatigue damage evaluation of components at elevated temperature is developed based on the mathematic software MATLAB. The software can completely evaluate the creep-fatigue damage of components according to the elastic analysis framework of ASME III-5- HBB- T. The important parameters and judgements during the evaluation process is output, making it easy for users to check. The software developed can remarkably reduce the computational efforts of the engineering designers.

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