STUDY ON FRACTURE ANALYSIS MODEL FOR THE STEAM GENERATOR TUBES

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ABSTRACT

In nuclear power plant, steam generator tubes are the weakest link between the primary loop with radioactivity and the secondary loop without radioactivity. In order to evaluate and ensure the integrity of tubes, it is important to build fracture analysis models. ABAQUS provides two fracture analysis methods, one is called Contour Integral Method, and the other is Extended Finite Element Method (XFEM). This paper combines these two methods to evaluate the stability of cracks in the flawed SG tubes by comparing K with the critical stress intensity factor. After building the straight pipe model with some kind of crack, XFEM is used to determine the crack extension direction, and then Contour Integral Method is used to compute the fracture parameters such as stress intensity factor. It has been shown that this modeling method is feasible.

INTRODUCTION

In the safety evaluation system of SG tubes, the crack behavior and the leakage caused by through wall (TW) crack are often the most two important factors needing to be focused on. And many evaluation methods are also carried out aiming at these two factors. But SG tubes having no corresponding models in stress intensity factor manual, so finite element analysis becomes a very suitable method under this circumstance.

The numerical simulation of fracture mechanics must resolve two problems: one is how to exactly determine when the crack initiates based on the fracture criterion, and the other is how to accurately and efficiently simulate the crack propagation process. Fracture analysis is one of the remarkable functions of ABAQUS, and this paper chooses ABAQUS to model the tubes with a crack.

TWO FRACTURE ANALYSIS METHODS OF ABAQUS

XFEM

ABAQUS contains a lot of fracture analysis methods, such as Contour Integral Method, Extended Finite Element Method, Line Spring Element Method, Virtual Crack Closure Technique, and etc. Since the Line Spring Element Method can be only used in 2-dimensional models, and the Virtual Crack Closure Technique is mainly used for composite material models, this paper chooses Contour Integral Method and XFEM to do the fracture analysis.

XFEM is one of the most promising crack simulation methods, and one of its most advanced features is mesh-independent. In XFEM, crack can propagate through an element, so complex shapes of cracks can be modeled in regular meshes. XFEM can obtain accurate solutions on relative coarse meshes, by using appropriate shape functions to capture the singular field around the crack tip region. Besides, when the crack propagates, there is no need to remodel the crack and rebuild the meshes to simulate the crack propagation process.

CONTOUR INTEGRAL METHOD

The basic principle of Contour Integral Method is the singularity of crack tip region. If the geometry of the crack region defines a sharp crack, the strain field becomes singular at the crack tip. Including the singularity in the model for a small-strain analysis improves the accuracy of the contour integral and the stress and strain calculations [1].

Contour Integral Method needs to specify the virtual crack propagation direction first, and it can accurately compute J integral, Ct integral, T stress, and stress intensity factor K. And Interactive integration method is used to compute the stress intensity factor K

MODELING SG TUBES WITH A CRACK USING THESE TWO METHODS

XFEM

For the TW crack, the crack propagation direction is obvious, i.e. propagating to both ends in the axial direction. However, for the part through wall crack (PTW), the crack propagation direction may be either in the axial direction, or in the depth direction. So, when the crack initiates and before it penetrates through the tubes wall, the crack propagation direction must be determined.

As have mentioned above, Contour Integral Method is mainly used for the initiation of the crack, and needs to specify the virtual crack propagation direction; and XFEM can simulate arbitrary shape cracks of different angles, and even has no need to specify the initial crack, not to mention the crack propagation direction. This paper intends to combine these two methods to use the advantages of both. The detailed steps are:

a) Modeling tubes with a crack by XFEM to determine the crack propagation direction, and then
b) Using the crack propagation direction determined in the first step to model tubes with a crack by Contour Integral Method, and the J integral and stress intensity factor K can be obtained.

As shown in Fig. 1, tube with a PTW axial crack is modeled by XFEM. The tube length is 30mm, so as to exclude end effect, and the tube wall thickness is 2mm. The crack length is 2mm, and its depth is 25%, i.e. 0.5mm. The top half part of this tube is set to be the crack region, and the intersection of the shell and the tube is set to be the crack location. The crack is set to be allowed to grow, and in order to see the crack propagation process as more complete as possible, the inner pressure of this tube will increase to 15MPa linearly. And one end of this tube is fixed.

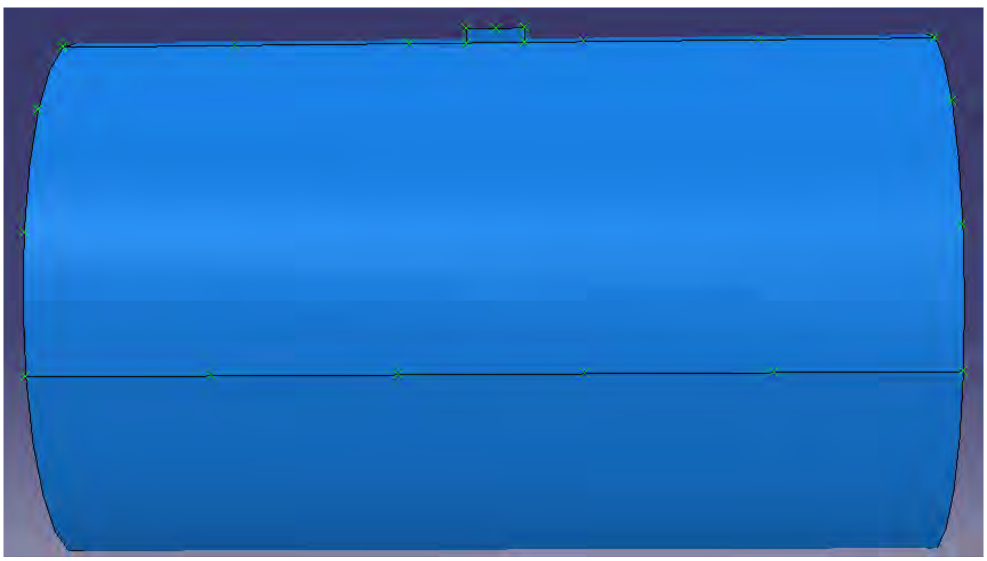
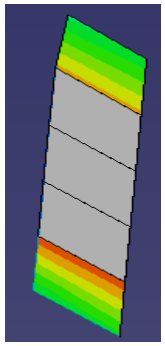
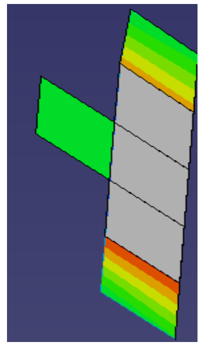
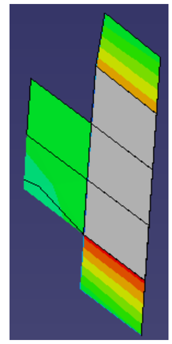
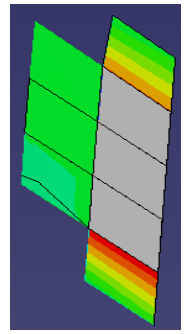
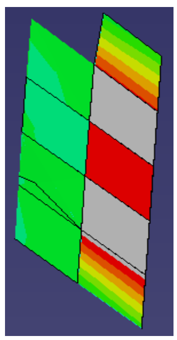
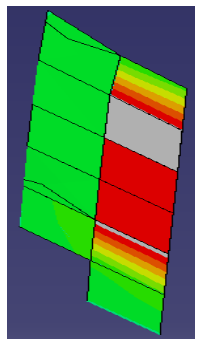
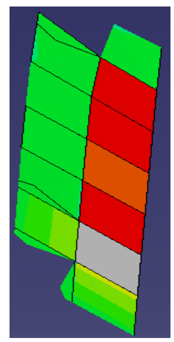
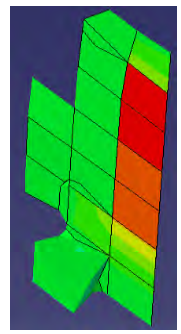


Fig. 1: Using XFEM to model the tube with a PTW axial crack

In XFEM, there are two damage initiation criteria available at present, one is maximum principle stress criterion (MAXPS), and the other is maximum principle strain criterion (MAXPE). And this model chooses the former one as the criterion. The type of damage evolution criteria is specified as power-based and linear softening, and the mixed mode behavior is specified as Power Law. Although XFEM is mesh-independent method, the meshes are built as fine as possible, because this method can only simulate the propagation of integer elements so far. C3D8R is chosen to build the meshes, and the whole number is 37076. The crack growth process is shown in Table 1.As can be seen from Table 1, under the tube inner pressure, when the pressure is relative low, the crack will grow in the depth direction; as the pressure increases to a certain value, the crack propagation direction will change to the axial direction. And lots of tests and theoretical research [2, 3] indicate that, no matter the pressure pipe is under tension or tension and bending, the propagation direction of shallow long cracks is mainly in the depth direction, and change in the axial direction is minimal.

Table 1: Simulation for the crack propagation direction

Time/s	0.795	0.815	0.835	0.855
Crack face form				
Time/s	0.895	0.935	0.955	1
Crack face form				

CONTOUR INTEGRAL METHOD

After determining the crack propagation direction, Contour Integral Method can be used to quantitative calculate the fracture parameters. For 2-dimensional models, Contour Integral Method will change the elements around the crack tip region from quadratic elements to triangular elements to simulate the singularity of the crack tip field. Fig. 2 shows the details, and the heavy solid line presents the crack line. This plate is 400mm long and 35mm wide, and the crack length is 10mm. One side is fixed, and the other side is in tension, σ=4MPa. Stress intensity factor K given by this model is 36.58MPa • $m^{1/2}$.

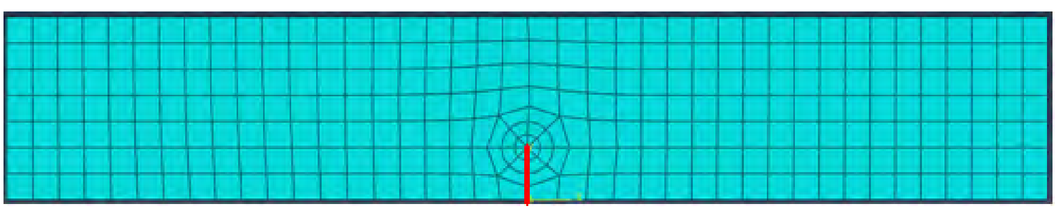


Fig. 2: Model of a plate with a unilateral crack

Stress intensity factor manual gives out the analytic solution for this model [4]

$$K_{\mathrm{I}} = F\sigma\sqrt{\pi a} \tag{1}$$

When h/b≥1and a/b≤0.6, the correction factor F is given by

$$F = 1.12 - 0.23\frac{a}{b} + 10.6\left(\frac{a}{b}\right)^2 - 21.7\left(\frac{a}{b}\right)^3 + 30.4\left(\frac{a}{b}\right)^4 \tag{2}$$

After put the relevant parameters in Eq. (1) and Eq. (2), the stress intensity factor K can be computed, and the result is 36.3MPa • $m^{1/2}$, which is almost the same as the finite element analysis result. So, the Contour Integral Method can be quite accurate.

For 3-dimensional models, Contour Integral Method will change the elements around the crack tip from hexahedral element to wedge element. The details are shown in Fig. 3; only the crack tip region is displayed. The whole model is a tube with a PTW axial crack, and the dimensions are the same as the XFEM model. However, the inner pressure here is 4.0MPa. The tube material is 2.25Cr1Mo, and its mechanical property at room temperature is given by Table 2.

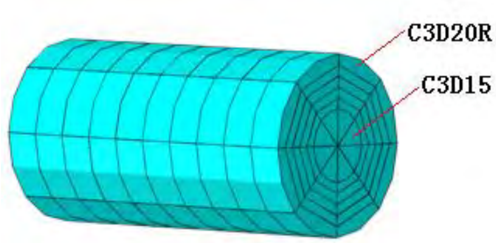


Fig. 3: Elements around the crack tip

Table 2: Mechanical property of 2.25Cr1Mo at room temperature

Material	Young's modulus /10^3MPa	Poisson's ratio	Yield strength /MPa	ultimate strength/MPa	Critical stress intensity factor/MPa • $m^{1/2}$
2.25Cr1Mo	211.1	0.3	207	414	82

When specifying the crack propagation direction, the result given by XFEM is used. Table 3 presents the stress intensity factor K, J integral computed directly, and J integral computed by K. It is shown that, the former J integral is almost the same as the latter computed by K.

Table 3: Results given by Contour Integral Method

Node Set	Fracture parameter	Contour					Average value
		1	2	3	4	5	（Contour2~5, or3~5）
9	J/10-3	1.525	1.225	1.224	1.224	1.224	1.224
	J_K/10-3	1.97	1.226	1.225	1.224	1.224	1.225
	K_I	21.38	16.86	16.86	16.85	16.85	16.85
10	J/10-3	0.955	1.222	1.221	1.221	1.221	1.221
	J_K/10-3	0.709	1.223	1.223	1.222	1.222	1.222
	K_I	12.82	16.84	16.84	16.84	16.83	16.84
11	J/10-3	1.523	1.224	1.222	1.222	1.222	1.223
	J_K/10-3	1.969	1.224	1.223	1.223	1.223	1.223
	K_I	21.37	16.85	16.84	16.84	16.84	16.84

CONCLUSION

In order to ensure the integrity of SG tubes, it is important to build fracture analysis models. And finite element analysis (FEA) is a very suitable choice. This paper chooses two methods, i.e. XFEM and Contour Integral Method in ABAQUS to model tubes with a crack, and combine these two methods by using advantages of both. It has been preliminarily shown that the method to compute the fracture parameters based on these two methods is established.

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REFERENCES

[1] DASSAULT, "ABAQUS/Standard User's Manual Version 6.9", 2009.

[2] Chen S Y, Cui Z Y, "Surface crack growth behavior under tensile cyclic loading", *International Journal of Fatigue*, Vol.10, 1988, pp. 43~47.

[3] Gilchrist M D, Chipalo M I, Smith R A, "Shape development of surface defects in tension fatigue finite thickness plate", *International Journal of Pressure Vessel and Piping*, Vol. 49, 1992, pp. 121~137.

[4] Qiu Z Y, "Stress Intensity Factor Manual", *Beijing: Science Press*, 1993.

[5] Saurin Majumdar, Sasan Bakhtiari, KenKasza, "Validation of Failure and Leak Rate Correlations for Stress Corrosion Cracks in Steam Generator Tubes", NUREG/CR-6774.