Transactions of the Korean Nuclear Society Autumn Meeting
Jeju, Korea, October 21-22, 2010

Development of Clad Collapse Analysis Code - XGCOL

J.M.Choi, Y.H.Heo, H.T.Han*
Korea Nuclear Fuel, 493 Deokjin-Dong, Yusung-Gu, Daejon, Korea, 305-353
**Corresponding author: hthan@knfc.co.kr*

1. Introduction

Fuel rod design is responsible for guaranteeing fuel rod integrity under conditions I and II operation for the entire fuel cycles, which would be performed using fuel rod performance analysis code for those design criteria specified in US NRC SRP 4.2 [1]. Clad flattening shall be evaluated as one of the fuel rod design criteria. Clad flattening criterion is defined as the fuel rod design shall preclude clad flattening during the projected exposure. This criterion was established to prevent the long-term creep collapse of the fuel rod into axial gaps which can form within the fuel column. Therefore, KNF has developed the XGCOL code for evaluating clad collapse.

2. Modeling and Solving of the Clad Flattening

The most important point when fuel rod design considers whether clad flattening failure will be occurred or not during the exposure time is to get and check the clad flattening time. In order to get the clad flattening time, the equilibrium equations including clad creep and ovality are derived based on the thin wall tube formula and the gap length are calculated with fuel densification/swelling model.

Using the equilibrium equations and the relation between strain and stresses for thin wall tube cell outlined in [2], the governing equations were derived considering (1) thin wall tube approximation, (2) generalized plane strain condition, (3) Hook's law in stress/strain, (4) elastic and creep strain, and (5) ovality. The final form of the main equations is given below.

$$(1+\beta)\frac{\partial^2 v}{\partial\theta^2}-\frac{\partial W}{\partial\theta}+\beta\frac{\partial^3 W}{\partial\theta^3}=-\frac{\partial w_o}{\partial\theta}+\beta\frac{\partial^3 w_o}{\partial\theta^3}+\frac{1}{\gamma}\left(\frac{\partial N_{yc}}{\partial\theta}-\frac{1}{a}\frac{\partial M_{yc}}{\partial\theta}\right)$$
$$-\frac{\beta}{a}\left(\frac{\partial^3(W-w_o)}{\partial\theta^3}+\frac{\partial^2 v}{\partial\theta^2}\right)\left(\frac{\partial v}{\partial\theta}+\frac{\partial^2 W}{\partial\theta^2}\right)-\frac{1}{a^2\gamma}\frac{\partial M_{yc}}{\partial\theta}\left(\frac{\partial v}{\partial\theta}+\frac{\partial^2 W}{\partial\theta^2}\right) \quad (1)$$

$$(1-\frac{\overline{w}}{a})\frac{\partial v}{\partial\theta}-\beta\frac{\partial^3 v}{\partial\theta^3}-W-\frac{\overline{w}}{a}\frac{\partial^2 W}{\partial\theta^2}-\beta\frac{\partial^4 W}{\partial\theta^4}=+\overline{w}-w_o-\beta\frac{\partial^4 w_o}{\partial\theta^4}-\nu a\frac{\partial u}{\partial x}-\frac{qa}{\gamma}$$
$$+\frac{1}{\gamma}\left(N_{yc}-N_{yrt}+\frac{1}{a}\frac{\partial^2 M_{yc}}{\partial\theta^2}\right)-\frac{1}{a}\left(\frac{\partial v}{\partial\theta}-(W-w_o)+\nu a\frac{\partial u}{\partial x}-\frac{N_{yc}-N_{yrt}}{\gamma}\right)\left(\frac{\partial v}{\partial\theta}+\frac{\partial^2 W}{\partial\theta^2}\right) \quad (2)$$

$$\frac{\partial u}{\partial x}=\frac{(1-\nu^2)F_x}{EA}+\frac{\nu\overline{w}}{a}-\frac{\nu}{aA}\iint\left(\frac{\partial v}{\partial\theta}-W\right)dA+\frac{1}{A}\iint\left(\varepsilon_{xc}+\nu\varepsilon_{yc}\right)dA$$
$$-\frac{\nu(1+\nu)}{EA}\iint\sigma_r dA+T(\nu\alpha_y+\alpha_x) \quad (3)$$

where u, w, and v are axial, radial and transverse displacement, respectively.

The equilibrium equations are solved numerically for the radial and transverse displacements by using numerical differentiations and integrals. For the nonlinear analysis, iterative scheme as in figure 1 is used.

The following adjusting factor is used to consider the finite gap length effect during creep calculation.

$$f=\left[\frac{(1-\nu^2)}{3(1+(2l/\pi a)^4)}+\frac{h^2}{12a^2}\left(3+\frac{7-\nu}{1+(2l/\pi a)^4}\right)\right]\Big/(\frac{h}{2a})^2$$

Where *l*, *h* and *a* are finite gap length, wall thickness and radius, respectively.

It is assumed that the clad flattening will occur when the clad ID effective stress exceed the clad yield strength.

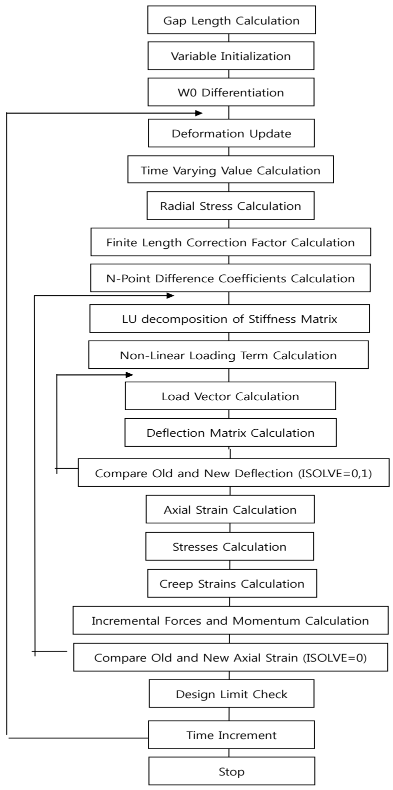


Fig. 1. Calculation Flow of the XGCOL Code

3. Comparison of Code Calculations

Some comparisons were made in order to confirm the applicability of the developed XGCOL code. The COLLAP and CEPAN [3] codes are used in this comparison.

Figure 2 shows the clad ovality evolution with time for infinite gap length. The comparison shows that fully nonlinear analysis including axial strain gives more conservative results.

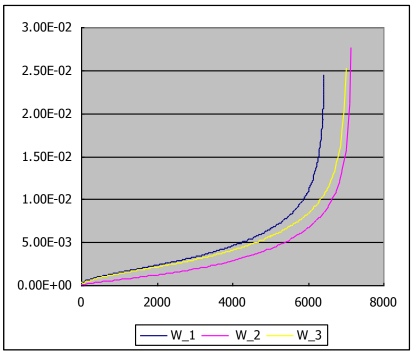
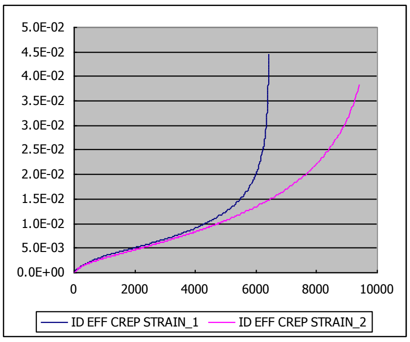
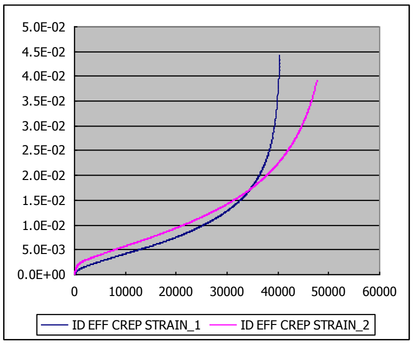


Fig. 2. Calculation results by XGCOL (1) COLLAP (2) and fully nonlinear analysis (3) without axial strain updating

Figure 3 shows the comparison of clad ID creep strain evolution using different creep models. It reveals that as time proceeds, the behavior of creep strain variation at later period is different because two creep models have a different stress dependency.



(a) infinite gap



(b) finite gap

Fig. 3. Comparison of calculated results by XGCOL

Figure 4 shows the comparison of collapse time by the XGCOL and COLLAP codes at the same rod conditions and it can be seen the collapse time is comparable in two codes results. As expected, the code calculations have shown that the lower rod internal pressure, the larger ovality and the higher cladding temperature, the shorter clad collapse time.

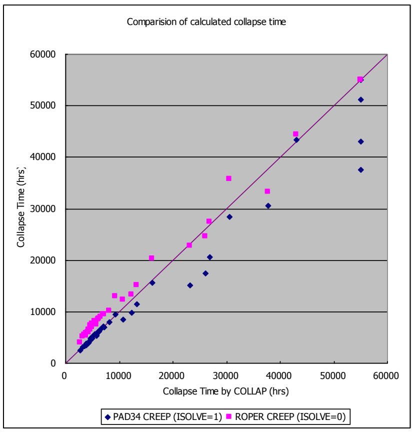


Fig. 4. Comparison of calculated results by XGCOL and COLLAP

The analysis method for the clad collapse time using governing equation used in the development of the XGCOL code is somewhat similar to the CEPAN code. The comparison of CEPAN and COLLAP code performed internally shows that for the infinite gap condition, there shows minor difference between CEPAN and COLLAP cases, whereas for the finite gap condition, the CEPAN case shows more conservative results compare to the COLLAP case, which is a good similar tendency to the XGCOL code.

In conclusion, it can be seen from the infinite gap analysis there is no difference in evaluation method. And for the finite gap, the code calculations show that the calculation using the ROPER creep model give comparable results with finite gap correction and fully nonlinear analysis method.

4. Conclusions

For evaluating clad flattening design criterion, XGCOL code has been developed and it shows comparable results to currently available codes.

Acknowledgement

This work was supported by the Nuclear Research & Development of the Korea Institute of Energy Technology Evaluation and Planning (KETEP) grant funded by the Korea government Ministry of Knowledge Economy.

REFERENCES

[1] NUREG-0800, US NRC SRP 4.2, Fuel System Design, Rev. 3, Mar. 2007.
[2] Timoshenko, S.P. and Gere, J.M., "Theory of Elastic Stability", McGraw-Hill, New York, 1961
[3] "CEPAN-Method of Analyzing Creep Collapse of Oval Cladding", Combustion Engineering, CENPD-187, 1976