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# Verification Calculation and Future Utilization Plan of the FDM Code 'Multilayer'

JaeYong Kim [a*], SungUk Lee [a], YongSik Yang [a], JuYeop Park [b], SeungKyun Kang [c]
[a]*LWR Fuel Technology Research Division, Korea Atomic Energy Research Institute, Daejeon, 34057, ROK*
[b]*Korea Institute of Nuclear Safety, Daejeon, 34142, ROK*
[c]*Seoul National University, Seoul, 08826, ROK*
[*]*Corresponding author: kjykjy@kaeri.re.kr*

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## 1. Introduction

Since the Fukushima nuclear accident in 2011, global research on the development of Accident-Tolerant Fuel (ATF) has been actively conducted and Lead Test Rods (LTRs) & Lead Test Assemblies (LTAs) with ATF technologies have already been loaded into several reactor cores. South Korea also plans to commence four LTAs irradiation campaign having ATF technologies in May 2025 [1]. This ATFl would enhance reactor safety significantly by suppressing hydrogen generation in case of LOCA through the Cr or CrAL coatings on outer surface of conventional zirconium alloy cladding. However, unlike conventional single-layer nuclear fuel, ATF has a multilayer structure with different mechanical properties. And this structural complexity leads to stress discontinuity in the thickness direction of the cladding due to internal and external loads.

The innovative Small Modular Reactor (i-SMR) has been under development with a boron-free concept to enhance the inherent safety of the core and improve construction efficiency. Additionally, to enhance economic feasibility and efficiently coordinate with renewable energy sources, it aims to support a wide range of daily load-following operations, including frequency control [2]. Such flexible operations and boron-free operation strategies are expected to involve complex control rod insertion maneuvers and variations in the power distribution within the core. Consequently, Pellet-Cladding Interaction (PCI) is likely to occur more frequently. However, currently, there is no established technology for comprehensive assessment on PCI during fuel performance evaluation.

To evaluate the performance of multilayer ATF and assess PCI in i-SMR fuel rods, improvements are required in the rigid pellet and membrane shell theory currently used in steady-state fuel performance evaluation codes, FRAPCON [3]. This paper describes the verification of the stand-alone FDM code, 'Multilayer,' developed to improve the rigid pellet and membrane shell theory, as well as future utilization plans.

## 2. Model improvement and V&V study

'Multilayer' derives from partial differential governing equations by applying force equilibrium, compatibility, and constitutive equations to an axisymmetric shape. After discretizing these equations by finite difference methods for a single element, "Multilayer" is finally developed using formulas that determine stress, strain, and displacement based on boundary and initial conditions for no contact, contact with axial slip, and contact without axial slip [4].

As illustrated in Fig. 1, this approach extends the existing analysis model [5], which only consists of a pellet divided into several segments and a single-segment cladding (1a), to an enhanced model (1b) incorporating both a segmented pellet and cladding. Additionally, it has been reformulated to apply appropriate boundary and initial conditions suitable for multilayer cladding structures [6].

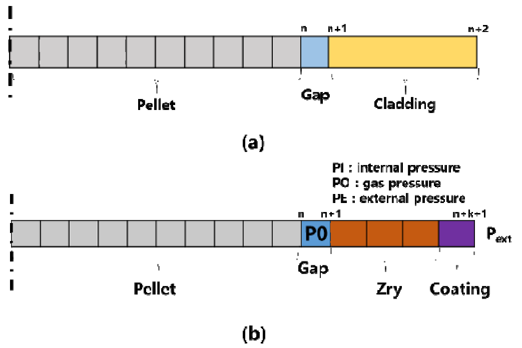



Fig. 1. Mechanical analysis model [6]: (a) existing model, (b) enhanced model for ATF.

### *2.1. Verification calculation of the 'Multilayer' mechanical analysis model*

For the verification of 'Multilayer', an analysis is conducted on a circular tube with a thickness of 5 mm subjected to an internal pressure of 3 MPa. For the elastic case,, the numerical analysis results obtained using 'Multilayer' are compared with theoretical solutions derived from the plane stress state equations (Equation 1~4) and computational analysis results obtained using the commercial finite element analysis software ABAQUS [7].

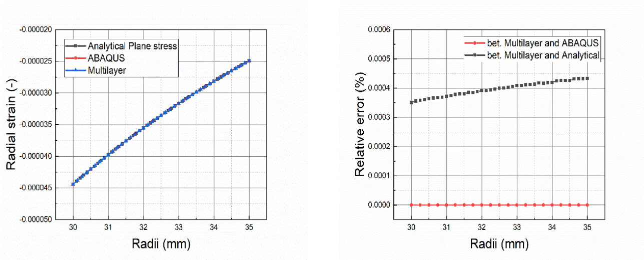
Fig. 2 compares the radial strain (2a) and displacement relative errors (2b) obtained from theoretical calculations, computational analysis, and numerical analysis. The relative displacement error is almost 0%, confirming that the numerical analysis results using the 'Multilayer' mechanical analysis model closely match both the theoretical solutions and computational analysis results.

(1) $$\varepsilon_r = \frac{1-\nu}{E}\left(\frac{r_i^2 P_i - r_o^2 P_o}{r_o^2 - r_i^2}\right) - \frac{1+\nu}{E\times r^2}\left(\frac{r_i^2 r_o^2 (P_i - P_o)}{r_o^2 - r_i^2}\right)$$

(2) $$\varepsilon_\theta = \frac{1-\nu}{E}\left(\frac{r_i^2 P_i - r_o^2 P_o}{r_o^2 - r_i^2}\right) + \frac{1+\nu}{E\times r^2}\left(\frac{r_i^2 r_o^2 (P_i - P_o)}{r_o^2 - r_i^2}\right)$$

(3) $$\varepsilon_z = \frac{-\nu}{1-\nu}(\varepsilon_r + \varepsilon_\theta) = \frac{2\nu}{E}\left(\frac{r_i^2 P_i - r_o^2 P_o}{r_o^2 - r_i^2}\right)$$

(4) $$u = \varepsilon_r \times r$$

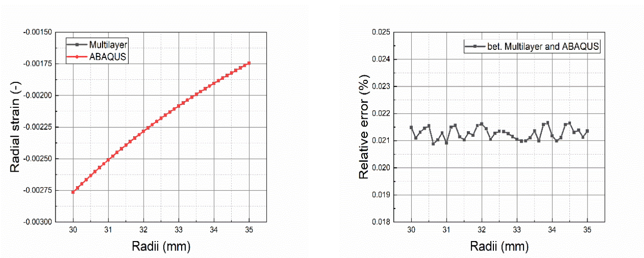



(a) Radial strain comparison (Elastic) (b) Relative displ. error (Elastic)

Fig. 2. Comparison of theoretical Solution, computational analysis, and 'Multilayer' results (Elastic).

For the case of elastoplastic analysis, direct comparison with theoretical solutions is not possible; therefore, the results are compared with computational analysis. A bi-linear elastoplastic material model is used, applying the same geometry and loading conditions as in the elastic analysis.

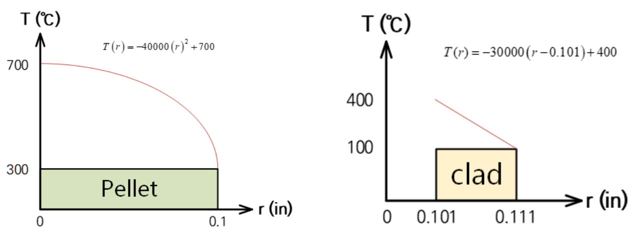
Fig. 3 compares the radial strain (3a) and relative displacement error (3b) obtained from numerical analysis and computational analysis. The relative displacement error is within 0.022%, confirming that the numerical analysis results using the 'Multilayer' mechanical analysis model closely matched the computational analysis results.




(a) Radial strain comparison (Elastoplastic) (b) Relative displ. error (Elastoplastic)

Fig. 3. Comparison of theoretical Solution, computational analysis, and 'Multilayer' results (Elastoplastic).

*2.2. Verification calculation of the 'Multilayer' thermal stress analysis model*




a) Temperature gradient of the pellet (b) Temperature gradient of the cladding

Fig. 4. Temperature conditions for the verification calculation of the 'Multilayer' thermal analysis model.

A verification calculation is performed for the case where the temperature gradient in the pellet and cladding is given as shown in Fig. 4. The numerical analysis results obtained using 'Multilayer' are compared with theoretical solutions derived from the equation (Equation 5~6) for calculating displacement and radial stress as a function of temperature.

(5) $$u = \frac{1+\nu}{1-\nu}\frac{\alpha}{r}\int_0^r T(r)rdr + \frac{1-3\nu}{1-\nu}\frac{\alpha r}{a^2}\int_0^a T(r)rdr$$

(6) $$\sigma_{rr} = \frac{\alpha E}{1-\nu}\left(-\frac{1}{r^2}\int_0^r T(r)rdr + \frac{1}{a^2}\int_0^a T(r)rdr\right)$$

Table I presents the displacement and radial stress obtained through numerical analysis for the pellet and cladding, along with the relative error compared to the theoretical solution. The relative displacement error is within 0.11%, confirming that the numerical analysis results using the 'Multilayer' thermal analysis model closely match the theoretical solutions.

Table I: Relative error of displacement and radial stress in the pellet and cladding under temperature conditions

| | | multilayer results | | | relative error (%) | | |
|---|---|---|---|---|---|---|---|
| comp | radii (in) | Temp (℃) | u (in) | $\sigma_{rr}$ (psi) | Temp | u | $\sigma_{rr}$ |
| pellet | 0.05 | 600 | 0.00510529 | -20570.90779 | 0 | -0.11 | -2.53e-3 |
| | 0.1 | 300 | 0.007988543 | 0 | 0 | -0.14 | 0 |
| clad | 0.101 | 400 | 0.003986 | 0 | 0 | 0.04 | 0 |
| | 0.111 | 100 | 0.004578 | 0 | 0 | 0.04 | 0 |

## 3. Future utilization plans

*3.1. Comparison of coated cladding stress analysis results using the equivalent and multilayer model*

Using the layer-specific local properties of Cr-coated optimized ZIRLO cladding at room temperature, obtained from a publicly released by conference paper [8], a stress analysis of ATF is conducted under an internal pressure of 3 MPa. The coated cladding is modeled using an equivalent and a multilayer model, and the results are compared.

The equivalent model applies the same room-temperature material properties of optimized ZIRLO to both the base cladding and the coating layer in 'Multilayer'. In contrast, the multilayer model assigns room-temperature optimized ZIRLO properties to the base cladding and Cr coating properties to the coating layer.

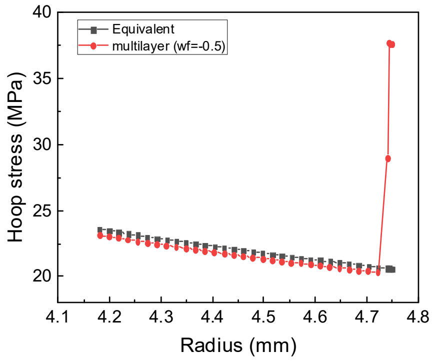



Fig. 5. 'Multilayer' calculation results with the equivalent and multilayer model (hoop Stress comparison).

Fig. 5 illustrates the radial distribution of hoop stress in the cladding. In the equivalent model, the circumferential stress gradually decreases from the inner to the outer surface of the cladding. However, in the multilayer model, the hoop stress in the base layer is up to 1.94% lower than in the equivalent model, while a significant difference is observed in the coating layer. This indicates that stress discontinuities occur at the interface between the base and coating layers under loading conditions, a phenomenon that can only be estimated when using a multilayer model with distinct material properties for each layer.

Currently, research on layer-specific local property measurements has been actively conducted as part of a Korea-Poland international collaboration. From this year, newly published high-temperature layer-specific local properties and ion-irradiated coating cladding properties will be integrated into 'Multilayer' within FRAPCON [9], enabling steady-state fuel performance evaluations for ATF.

### *3.2. Development of 3D FEM code and comparative analysis*

Research is underway to conduct various tests (mandrel, EDC, EDCT, MBT) in hot cells to evaluate the stresses acting on the cladding under PCI. The study aims to perform tests not only on as-received cladding but also on irradiated cladding. Additionally, a 3D FEM code has been developed to predict the stresses in the cladding using measured strain data.

The developed code will include the following features:

- Implicit scheme
- 3D deformable solid elements for stress analysis of pellet and cladding
- 3D contact modeling for PCI
- Plasticity and creep analysis

The 3D detailed structural analysis code will be compared with 'Multilayer', which is developed using FDM method, to evaluate the differences in analysis results. This code is expected to be used for assessing the structural integrity of nuclear fuel at specific operating time points.

## 4. Conclusions

To evaluate ATF with a multilayer structure and assess PCI in i-SMR fuel rods, verification calculations were performed for 'Multilayer', an improved model of rigid pellet and membrane shell theory used in FPAPCON. The mechanical and thermal stress analysis models of 'Multilayer' were validated through comparisons with theoretical solutions and computational analysis results. The relative displacement error was found to be within 0.11%, confirming excellent agreement with both theoretical and computational results.

'Multilayer' integrated into FRAPCON will incorporate high-temperature layer-specific local properties and ion-irradiated coating cladding properties, which will be released publicly this year, to conduct steady-state fuel performance evaluations for ATF. Additionally, a 3D FEM code will be developed to assess the stresses acting on the cladding in PCI conditions, as well as in mandrel, EDC, EDCT, and MBT tests conducted in hot cells. The developed code will be compared with 'Multilayer' to analyze differences in results.

**Acknowledgement**

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