Study on Pellet-Cladding Mechanical Interaction Behavior Using EDC-DIC Experiment and FE Analysis

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1. Introduction

As the share of variable renewable energy such as solar and wind power increases in the process of energy transition to respond to climate change, the introduction of flexible operation of nuclear power plants is required for grid stability. Flexible operation involves frequent power fluctuations unlike conventional base-load operation, and Pellet-Cladding Mechanical Interaction (PCMI) occurs as stress is transferred to the cladding due to the thermal expansion of the pellets during power ramps, which is a major cause of degrading fuel integrity. Expansion Due to Compression (EDC) tests have been performed in previous studies as a test method to simulate PCMI behavior [1,2,3]. Point-wise measurement methods have limitations in capturing the overall deformation behavior of the cladding during PCMI behavior, and this study measured the real-time strain field of the cladding by applying the Digital Image Correlation (DIC) technique to the EDC test. In addition, numerical simulation using the commercial Finite Element Analysis (FEA) code Abaqus was performed and compared with the experimental results.

2. Experimental methods

2.1 EDC Test

The fundamental principle of the EDC test is to induce radial expansion of the pellets by applying an axial compressive load, thereby generating hoop deformation in the cladding.

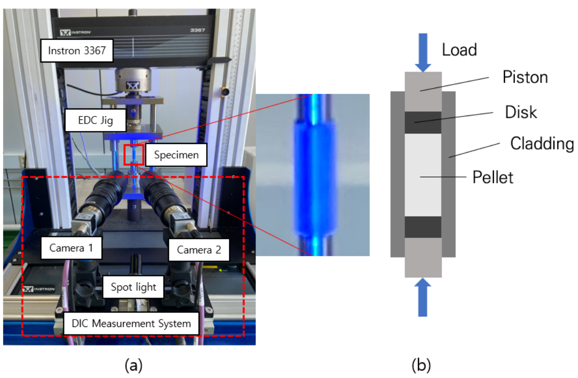


Fig. 1. Experimental setup for EDC test: (a) Overall experimental setup, (b) Schematic of the EDC test

Table I: Specimen configuration

Component	Material	Dimensions
Cladding	Zr-4	Outer diameter: 9.5mm Thickness: 0.57mm Length: 27mm
Pellet	Teflon	Diameter: 8.36mm Length: 14mm

Fig. 1 illustrates the overall configuration and a schematic diagram of the EDC test apparatus. The specifications of the specimens used in the test are summarized in Table I. All tests were conducted at room temperature with a strain rate of $10^{-4}/s$.

2.2 DIC measurement system

In this study, the DIC technique was employed to measure the deformation of the cladding. DIC is a non-contact strain measurement technology that captures images of the speckle pattern on the specimen surface, as shown in Fig. 2 [3]. By analyzing the evolution of these patterns over time, the technique enables the real-time measurement of the strain distribution at each point on the surface during the deformation process.

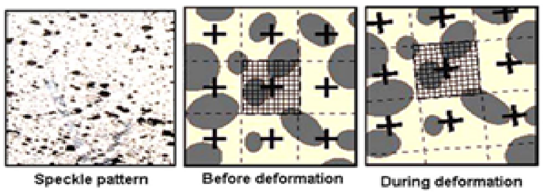
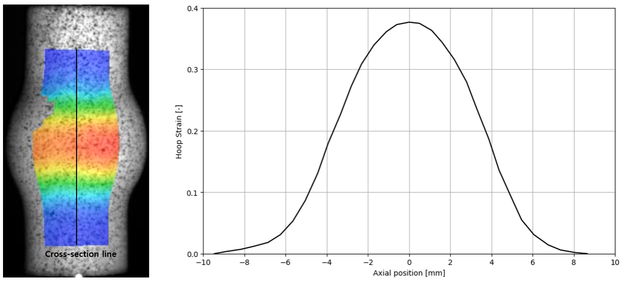


Fig. 2. Digital Image Correlation method

2.3 Experimental Results

Fig. 3 illustrates the hoop strain distribution on the cladding surface measured via DIC at a crosshead displacement of 8 mm. The measurement results indicate that the deformation is most pronounced at the center of the cladding, where the loading is concentrated, and exhibits a symmetrical profile that gradually diminishes toward both the top and bottom ends. This behavior implies that the radial expansion of the pellets, induced by axial compression, was effectively transferred to the mid-section of the cladding. The hoop strain profile along the axial direction provides a quantitative assessment of the deformation at specific locations, with the maximum hoop strain recorded at approximately 0.376.



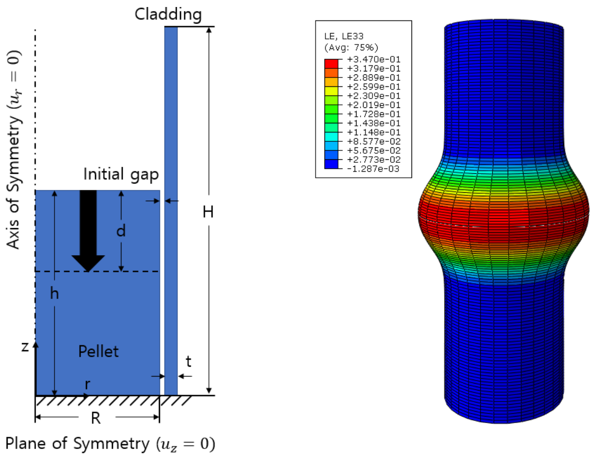
(a) (b)

Fig. 3. DIC measurement results: (a) Hoop strain field, (b) Hoop strain along the axial direction

3. Numerical simulation

3.1 Finite element modeling

FEA was performed using the commercial software Abaqus. Considering the geometric symmetry of the specimen and the loading conditions, an axisymmetric model was developed. An initial radial gap of 0.005 mm was applied between the pellet and the cladding. A surface-to-surface contact formulation with hard normal contact was applied between the pellet and the cladding. The geometry and boundary conditions of the FE model are illustrated in Fig. 4, while the detailed dimensions and geometric parameters for each component are summarized in Table II.



(a) (b)

Fig. 4. Finite element model for EDC test: (a) Geometry and boundary conditions, (b) 3D view of the model

Table II: Geometric parameters and dimensions of the FEA model

Symbol	Description	Value (mm)
R	Outer radius of pellet	4.175
t	Thickness of cladding	0.57
h	Height of pellet	7
H	Height of cladding	13.5
d	Displacement	4

3.2 Material Properties

The cladding was modeled as an isotropic Zr-4 with elasto-plastic behavior based on the MATPRO data at room temperature [4]. For the pellets, an isotropic hyperelastic model (Marlow model) was employed to capture the non-linear deformation of the Teflon material under compressive loading.

3.3 Comparison with Experimental Results

A comparison of the maximum hoop strain in the EDC test revealed an experimental value of 0.376 and a numerical result of 0.347. The absolute difference was 0.029, corresponding to a relative error of approximately 7.7%. Overall, the simulation results tended to slightly underestimate the experimental data. These discrepancies are attributed to several factors, including uncertainties in material properties, the idealization of contact and friction conditions, and the simplification of boundary conditions.

4. Conclusions

In this study, EDC tests were conducted to simulate PCMI behavior, and the hoop strain of the cladding was measured using the DIC technique. The experimental and numerical results exhibited similar trends in the strain distribution. The relative error within 10% is considered acceptable, given the experimental variability and model simplifications. Consequently, the proposed numerical model is deemed to possess sufficient reliability for predicting the maximum hoop strain. Future work will focus on improving the prediction accuracy by refining contact conditions and material models, as well as evaluating PCMI behavior under various parametric conditions.

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