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Explosion Analysis of Nuclear Fuel Cladding using PINN-based Predicted Material Properties

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1. Introduction

Spent nuclear fuel (SNF) management extends beyond on-site storage and inevitably involves transportation to interim storage and final disposal facility. During transportation, the package system and its internal components should be assessed for integrity under credible accident scenarios.

In the package system, SNF cladding functions as the secondary barrier against release of radioactive materials. Zirconium alloys used for the cladding are susceptible to ductility loss due to hydrogen uptake and hydride precipitation [1]. This necessitates a framework to estimate mechanical properties in relation to hydrogen concentration.

Although transportation integrity assessments have traditionally focused on drop conditions, blast loading has received comparatively limited attention, despite regulatory frameworks recognizing accidental explosions along adjacent transportation routes [2]. Accordingly, a quantitative evaluation is required to ensure cladding integrity under explosion-induced loading.

In the present study, hydrogen dependent mechanical properties of a zirconium alloy were estimated using physics informed neural network (PINN), and cladding integrity was assessed under explosion induced loading. The hydride fraction was calculated from cross sectional images of a zirconium alloy. A three-dimensional (3D) representative volume element (RVE) model was then constructed, and a PINN algorithm was developed to estimate mechanical properties. Finite element (FE) analyses were performed to assess the structural integrity of the cladding under explosion induced loading.

2. RVE-based PINN framework

2.1 Image analysis

A cross sectional image of a hydrided cladding tube [3] was obtained from post irradiation examination, and the hydride and zirconium alloy regions were separated through an image processing workflow as shown in Fig. 1. Hydrides were identified as irregular dark features through color histogram-based thresholding, color space segmentation, and subsequent morphological processing, whereas the zirconium matrix was designated as the background phase. The measured hydride area fraction was then employed in the construction of the numerical model.

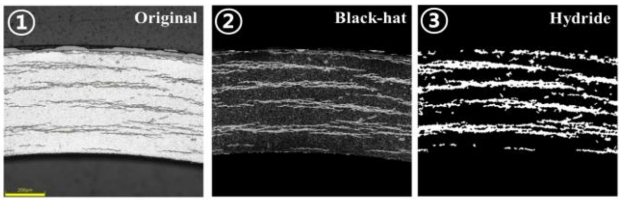
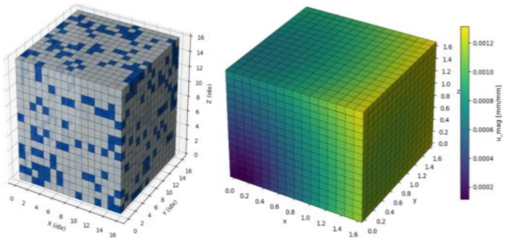


Fig. 1. Image processing workflow

2.2 RVE construction

A 3D RVE node set was generated from the measured area fraction. The image was first converted into a labeled pixel map, assigning 1 to hydrides and 0 to the zirconium matrix, and then extruded to construct a 3D grid. The node set was built using a regular lattice representation combined with statistical random sampling to reproduce the prescribed phase fraction. Each node stores its coordinates and phase label, which is shown in Fig. 2(a).



(a) 3D node set (b) Train result

Fig. 2. 3D RVE construction and PINN training

2.3 PINN algorithm and train results

The PINN was formulated to map spatial coordinates to the displacement field. A multilayer perceptron with tanh activations was employed to represent the nonlinear response. The loss function included the boundary conditions, residuals of the equilibrium equations, and the constitutive relations. Periodic boundary conditions were additionally imposed in the loss to represent the RVE as a unit cell, with loading applied along the +x direction. Training was performed using the adaptive moment estimation optimizer to promote stable and rapid convergence. The PINN algorithm is summarized in Fig. 3, and the result is shown in Fig. 2(b).

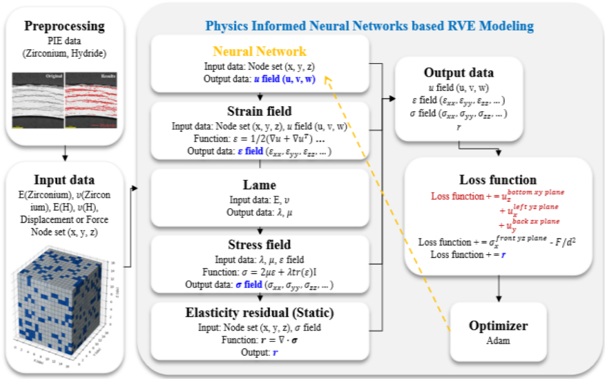


Fig. 3. PINN-based material properties estimation algorithm

3. Explosion analyses

3.1 Hypothetical explosion scenario

The analysis considered an transport cask and an SNF assembly. A land transportation accidental scenario was assumed in which an LPG truck explosion on a 3 m wide road causes damage to the package. The truck fuel tank capacity was 25.4 gal.

3.2 Analysis model and conditions

The finite element models of SNF assembly shown in Fig. 4 was developed to evaluate blast induced damage, and the geometry and material properties were taken from a previous study [4].

PE4 was used as the explosive, and the charge mass was conservatively estimated as 47.07 kg using an equivalent mass model. The explosive was modeled with a cube charge geometry. A coupled Eulerian-Lagrangian method was used, and detonation products were described using the JWL equation of state. The explosion response was simulated using a commercial explicit dynamic solver [5]. To reflect the transport process, the trunnions were fixed, and the detonation was varied as illustrated in Fig. 4.

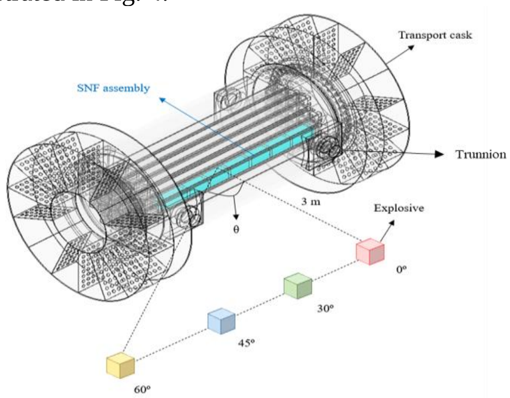


Fig. 4. Schematic of the hypothetical explosion scenario and model configuration [4]

3.3 Analysis results

The maximum principal strains of the cladding were calculated for each detonation angle and presented in Fig. 5. As the detonation angle increases, the standoff distance increases, and the strain decreases. The strains are below the 1 % strain-based failure criterion, indicating that the structural integrity of the cladding is maintained under explosion scenario.

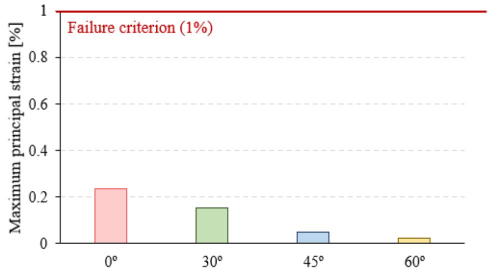


Fig. 5. Variation of maximum principal strains with different detonation angles

4. Conclusions

In this study, a 3D RVE-based PINN framework was established to predict hydrogen dependent mechanical properties of zirconium alloy and the values were applied to assess the integrity of fuel cladding under explosion scenario. The conclusions are as follows:

(1) Hydride area fraction was quantified from cross-sectional images and used to construct a relevant node set for PINN training.

(2) Maximum principal strains of the cladding decreased with increasing detonation angles, consistent with the increased standoff distances.

(3) For all detonation angles, the maximum principal strains were below the conservative strain-based failure criterion, supporting cladding structural integrity under the hypothetical explosion scenario.

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