INTEGRITY EVALUATION OF SPENT NUCLEAR FUEL CLADDING IN USE OF MACHINE-LEARNED EMBRITTLED PROPERTIES

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Abstract
Integrity of spent nuclear fuel (SNF) cladding should be remained during transportation as well as long-term storage and disposal. At first, this paper addresses machine learning to predict degraded mechanical properties of an advanced zirconium alloy. Subsequently, taking into account the estimated data, finite element analyses of a typical fuel rod were carried out under hypothetical drop accident conditions and resulting integrity was discussed.

1. Introduction

The SNF exposed to reactor environment demands careful management. In principle, the cladding, one of SNF safety barriers, undergoes change of mechanical properties due to high temperature, excessive hydride, and radioactive nuclides. Although lots of experimental and numerical investigations have been performed for representative cladding materials such as Zircaloy-2 and Zircaloy-4, due to lack of researches on advanced alloys, relevant data for integrity evaluation are not sufficient. In this paper, mechanical properties of ZIRLO™ cladding under an embrittlement environment were predicted and verified by using a machine learning method. Then, these estimated properties were adopted for finite element (FE) analyses of a typical fuel rod under hypothetical drop accident conditions and the integrity of its cladding was evaluated.

2. Results

The machine learning process employed in the present study can be summarized as follows:

a. In order to establish a Data Base (DB) for training, axial tensile test data of unirradiated Zircaloy-4 and ZIRLO™ were gathered. Virtual data of irradiated Zircaloy-4 was generated through the PNNL-17700 model for learning the relationship to neutron embrittlement. Furthermore, a few data of irradiated ZIRLO™ axial tensile test data were added in training stage. Input variables consist of strain (ε), hardening exponent (n), neutron flux (Φ), hydrogen concentration ([H]), and temperature (T).
b. For efficiency of learning, the data sets were preprocessed through interpolation as the increase of strains at a constant interval. By adding variables that can distinguish degradation conditions as well as material types.
c. The machine learning model was developed based on open sources. It consists of 26 nodes hidden, 52 nodes hidden, drop-out, and 1 node output layers in that order. Activation functions of ‘relu’ and ‘linear’ were applied to the hidden layers and output layer, respectively, and the drop-out ratio was 0.3. For validation of predicted data, some of the irradiated ZIRLO™ test data were not used in the training stage.

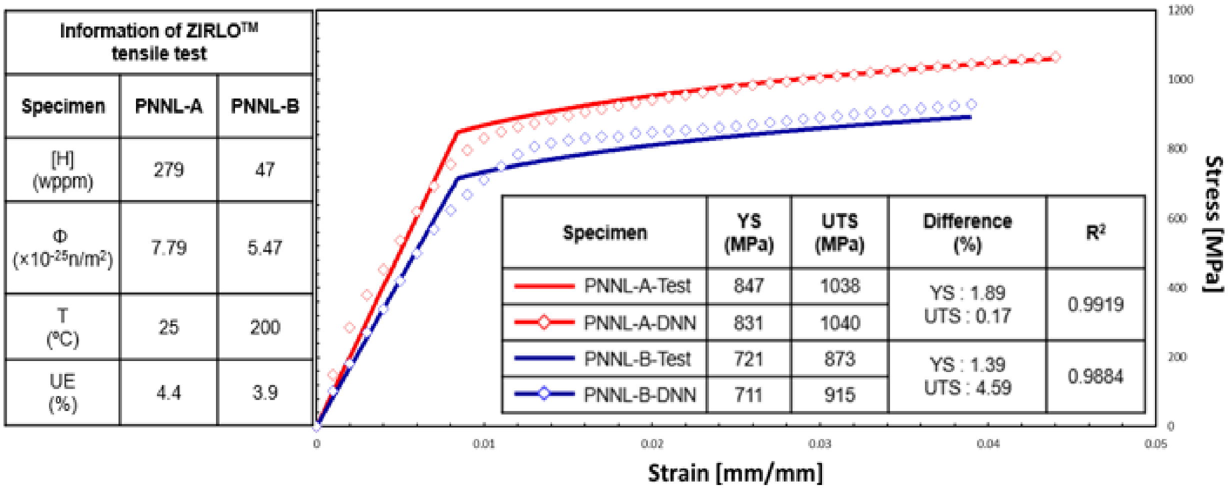
Stress values were predicted up to Ultimate Tensile Strength (UTS) by the proposed machine learning model. Information of the axial tensile test conditions and verification of stress-strain curves are shown in Fig. 1. R-squared (R^2) values are 0.9919 for PNNL-A and 0.9884 for PNNL-B. Yield Strength (YS) was determined by 0.2% offset method, and UTS was set to stress value at Uniform Elongation (UE).

The cladding integrity evaluation was performed through FE analyses with Abaqus Dynamic/Explicit and the detailed process is summarized as follows:

a. A PWR spent nuclear fuel rod was selected, of which length is 4 m and thickness is 0.57 mm, approximately. For the efficiency of analyses, a simplified FE model was constructed as depicted in Fig. 2. It consists of pellet, spacer grids, spring, and dimple.

b. Different mechanical properties were set for Zircaloy-4 and ZIRLO™ materials at room temperature, 700 wppm hydrogen concentration, and either unirradiated condition or 7×10^{25} n/m^2 fast neutron flux condition.

c. Sensitivity FE analyses were performed under hypothetical drop accident conditions and the integrity of cladding was evaluated by comparing resulting engineering parameters such as von-Mises stress and strain values with the corresponding YS and UE data, respectively.



Specimen	PNNL-A	PNNL-B
[H] (wppm)	279	47
Φ (×10^{-25}n/m^2)	7.79	5.47
T (°C)	25	200
UE (%)	4.4	3.9

Specimen	YS (MPa)	UTS (MPa)	Difference (%)	R^2
PNNL-A-Test	847	1038	YS : 1.89 UTS : 0.17	0.9919
PNNL-A-DNN	831	1040		
PNNL-B-Test	721	873	YS : 1.39 UTS : 4.59	0.9884
PNNL-B-DNN	711	915		

Fig.1 – Verification of mechanical properties for cladding materials.

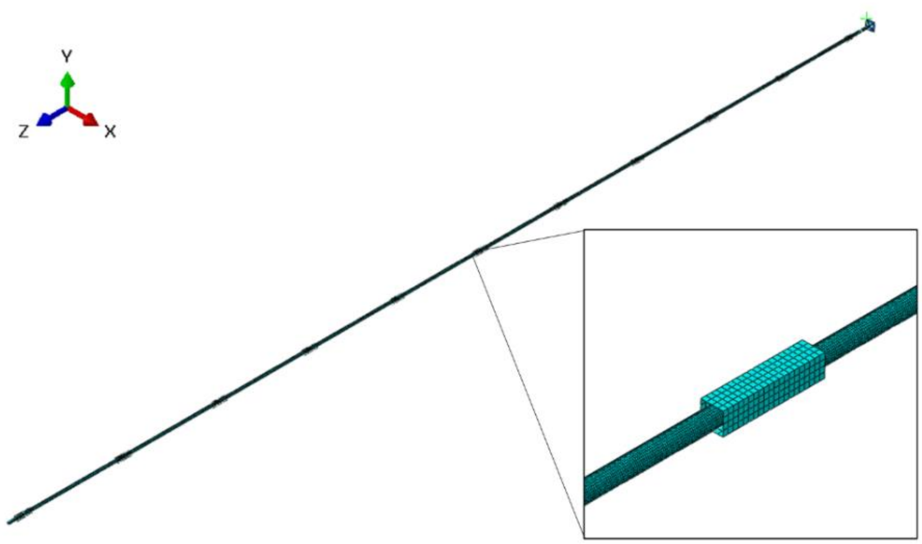


Fig. 2 – FE model of a simplified spent nuclear fuel rod.

3. Conclusions

A machine learning method was proposed and verified by the difference between the test and predicted data within 5 %. Then, the degraded mechanical properties of ZIRLO™ were predicted and used for FE analyses of a typical fuel rod under hypothetical drop accident conditions. Details of its integrity and key findings will be discussed.

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