Fracture Mechanics Analysis for Multipurpose Canister of Spent Nuclear Fuels

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1. Introduction

Spent nuclear fuels (SNFs) generated by a nuclear power generation have been stored at a water pool in plants however, a capacity is being saturated. To solve the problem, research for a multipurpose canister (MPC) that occupies relatively small sites and is easy to transport have been conducted. For the long-term storage of dry storage casks more than 60 years, a defect evaluation was also conducted by the U.S. Department of Energy (DOE) [1]. A defect called chloride-induced stress corrosion cracking (CISCC) can be occur at the external surface of the canister by tensile residual stresses and susceptible material under corrosive environments. Incorporated by these defects and unhomogeneity of the weld process, a crack generated at the canister after the long-term storage is vulnerable for a drop accident during the transport. To evaluate the crack stability at the canister by the drop accident, a method using the fracture mechanics analysis (FMA) will be explained in this work.

2. Finite Element Dynamic Analysis

In this Section, a geometry of the MPC and material properties for conducting the finite element (FE) analysis is described. FE result by the dynamic analysis and the stress calculated for applying to the FMA is presented.

2.1 Geometry of MPC and material properties

The canister made of 316L austenitic stainless steel (ASS) seals the SNFs and protected from external loads by the dry storage cask and impact limiters as shown in Fig. 1.

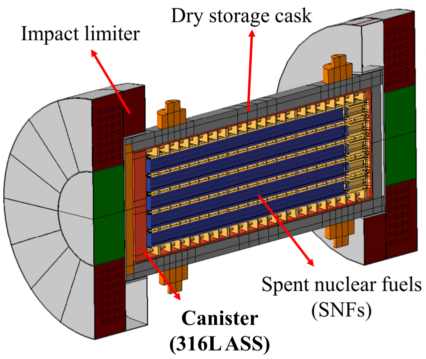

Fig. 1. Geometry and components of the MPC.

To consider the dynamic impact behavior by the drop accident of canisters, an elastic-plastic property of 316L ASS is required to be determined. Tensile tests considering the strain rate effect were performed and yield strength (σ_y) and tensile strength (σ_{UTS}) for each strain rate are shown in Table I [2]. Mechanical properties increases as the applied strain rate increases.

Table I: Mechanical properties of 316L ASS for different strain rates [2].

Material	Strain rate (/s)	σ_y [MPa]	σ_{UTS} [MPa]
316L ASS	4E-4	255	573
	4E-3	272	565
	4E-2	283	566
	1	326	590
	10	348	619

To consider the strain rate effect, Johnson-Cook (JC) constitutive model is used as presented in Eq. (1).

$$\sigma_{eq} = \left[A + B\varepsilon_p^n\right]\left[1 + C_{JC}\ln\dot{\varepsilon}^*\right] \qquad \text{Eq. (1)}$$

where σ_{eq} is the equivalent stress, $\varepsilon_p{}^n$ is equivalent plastic strain rate, A, B, n are material constants for the plastic hardening and C_{JC} is the material constant for the strain rate. For the material constant for the temperature effect is ignored since the tensile tests were conducted at the constant room temperature.

2.3 FE analysis and results

To perform the FE analysis for the accident case of the canister, the impact direction was assumed as horizontal and the acceleration and height were set as 1g and 9 m, respectively. ABAQUS v.2018 was used and the terminal velocity considering the drop height was applied to the assembly. For the analysis efficiency, an incompatible mode eight-node brick element (C3D8I) was incorporated and the stress after the impact was calculated at the external surface of the canister. The transient stress history is presented in Fig. 2 and the peak stress was calculated at the 1st drop impact. The peak stress is considered as the driving force of the unstable fracture so hoop stresses were calculated when

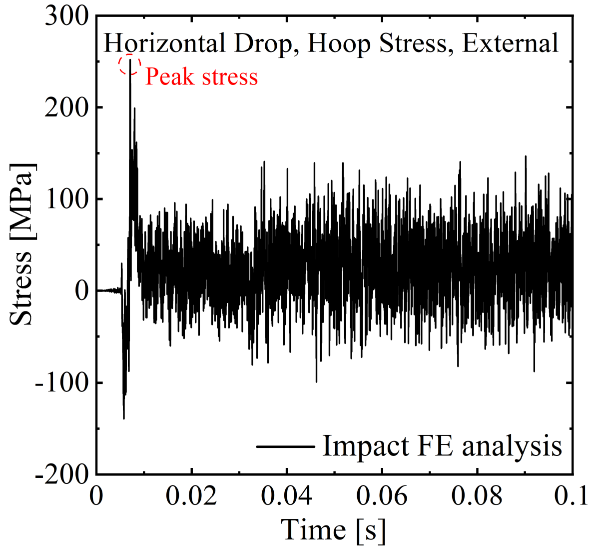

Fig. 2. Stress history at the external surface of the canister for the horizontal 9 m free drop.

the defect was assumed to be the axial semi-elliptical crack.

3. Fracture Mechanics Analysis

To conduct the FMA, a failure assessment diagram (FAD) is incorporated. FAD consists of the stress ratio to the plastic collapse (L_r; abscissa) and the stress intensity factor ratio to the fracture toughness (K_r; ordinate). When the assessment point for a defect locates below the failure assessment line (FAL), the crack is regarded as stable to the fracture. To calculate the stress ratio (L_r), a reference stress method is applied in API 579-1 [3] as presented in Eq. (2):

$$L_r = \frac{\sigma_{ref}}{\sigma_y} \qquad \text{Eq. (2)}$$

where σ_{ref} is the reference stress and σ_y is the yield strength.

To calculate the stress intensity factor ratio (K_r), the primary stress intensity factor (K_I^p) was determined using the weight function method for the cylinder case in ASME BPVC Section XI, Appendix A [4]. Determined K_I^p is then divided by the fracture toughness (K_{mat}) of the 316L ASS so K_r can be expressed as presented in Eq. (3):

$$K_r = \frac{K_I^{\,p}}{K_{mat}} \qquad \text{Eq. (3)}$$

To validate the stress intensity factor, the contour integral using the FE analysis was compared. As increasing the crack ratio to the thickness (a/t), assessments points were marked on the FAD.

4. Conclusion

In this work, the fracture mechanics analysis (FMA) method is proposed for the MPC with containing the initial crack under the horizontal drop case. The material properties were determined using the Johnson-Cook model and the dynamic FE analysis was performed to calculate the stress history for the FMA. The stress ratio was calculated using the reference stress and the stress intensity factor was verified using the contour integral from the FE analysis. Evaluation of the crack stability was conducted using FAD.

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[3] API, API 579-1/ASME FFS-1 Fitness-For-Service, American Petroleum Institute, Washington, D.C., 2007

[4] ASME B&PV Code, Section XI, Rules for Inservice Inspection of Nulcear Power Plant Components, 2019 Edition.