Stress Analysis for the Canister under Earthquake Induced Fracture Shear Displacement considering Long-term Creep Effect of Copper Shell

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Abstract

The canister design for spent nuclear fuel final disposal (SNFD) should consider three containment failure modes: rock confining pressure, rock deformation, and corrosion. For deposal concept in hard rock such as KBS-3 in Sweden, Finland, and current Taiwan test sites, the rock fractures surrounding deposition hole may turn into the permanent shear displacement during earthquake; therefore, the stress analysis should be performed to evaluate seismic capacity for shear displacement. On the other hand, for long-term disposal environment, copper canister needs to consider the creep of copper shell, so the capability to perform analyses combing these two phenomena should be established in final disposal research team. To perform the analyses, the three dimensional canister and buffer assembly model was built, and model test was carried out by comparing the results with SKB data to achieve the model confidence. Several shear displacement scenarios including different loading position and direction were carried out to understand the safety margin of canister design through von Mises results compared with allowable stress of copper material for canister shell and cast iron material of canister insert, and also the long-term creep effect was considered in the analysis procedure. Based on the analysis models, the parameterized sensitivity studies are also performed, and the stress and safety factor data are produced. They demonstrate the way to keep canister safe during earthquake by enlarging deposition hole or thickness of cast iron, the information can be used for design modification when large accumulative shear displacements occur in the future disposal sites.

1. Introduction

Repetitive seismic loads from earthquakes and thermal loads generated by the decay of emplaced waste are two significant factors for near-field instability in spent nuclear fuel final disposal [1]. Although regulatory standard for the high-level radioactive waste siting in Taiwan have requirement of exclusive zone regarding fault movement by active fault, the accumulated influences of earthquake through wave propagation still need to evaluate due to multiple events occurring in long-term span for safety analysis. When the KBS-3 deposition concept is employed, shear failure due to earthquake induced fracture displacement intersecting deposition holes will cut buffer and canister is one of the failure modes; therefore, the structural capacity of canister needs to be calculated. In the SKB KBS-3 design, since the canister has 95 cm diameter cast iron insert, 5 cm thickness copper shell, and 35 cm buffer ring block, with regard to the long-term isostatic pressure from buffer and ground water, the creep effect of copper shell has been discussed and particular formula of oxygen free copper (Cu-OFP) material is adopted [2][3][4]. Because the long-term creep of full scale copper shell could not be tested, the better way to realize stress distribution of canister is performing numerical analysis. Therefore, several numerical analyses to reflect disposal scenarios have been carried out by SKB [6]. However, for the use of KBS-3 design as reference in Taiwan, because of different earthquake environment between Scandinavian region and Circum-Pacific seismic region, the SKB reference is only the basis for adapting the foreign design, and the domestic seismic analysis capability for canister-buffer assembly needs to be established when modification of design needed. Regarding the safety criteria of KBS-3 canister, SKB set 5 cm displacement of fracture as the shear capacity considering potential initial manufacture defect in SR-Site, although the structural analysis of canister can withstand 10 cm shear displacement without the scenario of fracture mechanics previously. Hence, cumulative displacement reaching 5 cm limit should be check under the multiple events occurring possibly in Taiwan, so the development of seismic analysis including shear and creep effect is necessary in SNFD program. Since Taiwan SNFD program will go into the siting stage, the evaluation of different sites regarding the failure rate of earthquake induced shear on canister will be important, also accompanied validation tests using scaled down specimens will be planned to enhance the reliability.

2. Structural Model

In this study, finite element code ABAQUS was the analysis tool to model SKB-designed buffer and canister [3], and nonlinear analysis is performed to consider the large displacement on the model. The phenomenon is the same as direct shear test. Through the dislocation amid deposition hole, the stress imposed by the deposition hole will be redistributed through buffer, copper shell and cast iron insert section. To model the stress effect, the canister and buffer assembly model was built, and the shear movement of model was applied by setting boundary condition. The element for cast iron insert and copper shell canister is C3D8I which has the capability for nonlinear analysis, and the element for buffer is C3D8P which allows the input of groundwater parameters. The contact behavior between canister and buffer is employed by using tangential behavior to allow the slip to occur on canister surface, and the coefficient is set as 0.1 referred to SKB data [3]. To study the effect of shear displacement angle and location on canister-buffer assembly, analysis cases include shear displacements that are located at middle section and at quarter section, and the shear angles are 90^{o} and 22.5^{o} for each location. The symmetrical models shown in Fig. 1 and Fig. 2 were utilized to save computer time, and fine meshes are conducted at the section where the 5 cm shear displacement is applied.

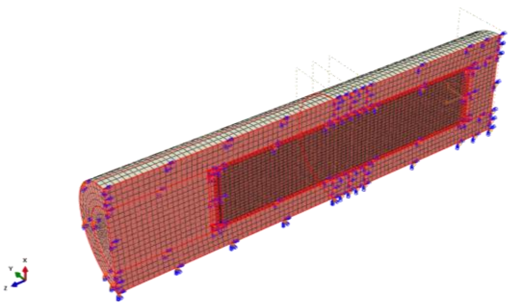

Fig. 1 Canister-buffer assembly model for 90^{o} shear direction at middle section case

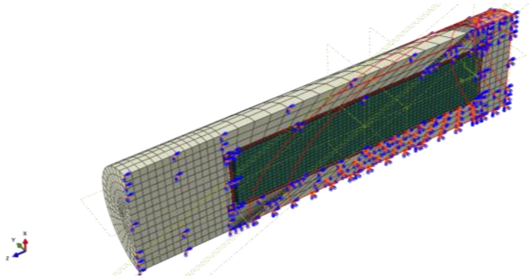

Fig. 2 Canister-buffer assembly model for 22.5^{o} shear direction at middle section case

3. Material Model

In this study, material test data are referred to SKB test result, and materials are modeled as elastic-plastic behavior. For stress strain curve of Copper, Young's modulus is 120,000 MPa, the yielding stress is 72 MPa, Poisson's ratio is 0.308, and the data of stress-strain test is shown in Table 1 [4]. For Cast iron, Young's modulus is 166,000 MPa, the yielding stress is 293 MPa, Poisson's ratio is 0.32, and the data of stress-strain test is shown in Table 2[4]. For buffer material which uses MX-80 bentonite, the design density is 2,050 kg/m^3, Young's modulus is 294 MPa, the yielding stress is 2.94 MPa, Poisson's ratio is 0.49, and the data of stress-strain test is shown in Table 3. Because the properties of buffer is strain-rate dependent, the strain rate for the data in Table 3 is 1 m/sec. Also, because pore water will influence the behavior of buffer material, the related material data is shown in Table 4.

To understand the safety margin, the safety factor is defined by the ratio of allowable stress to maximum analyzed stress, and von Mises stress will be analyzed. The cat iron stress corresponding to half of the strain of the ultimate elongation in uniaxial tensile test was set as the allowable stress, which is 395 MPa according to SKB test and definition [4].

For long-term pressure application, creep of copper shell will be modeled. Compared to SKB model method, they carried out the CREEP subroutine in ABAQUS for modeling the creep curve. In this study, Power law in ABAQUS creep model as below is used.

$$d\varepsilon_c/dt = A\sigma^n t^m \qquad (1)$$

where

$d\varepsilon_c/dt$ is the uniaxial creep strain rate;

σ is the uniaxial stress;

t is the creep time.

The curve fitting result is shown in Fig. 3; the parameter A is 7.6×10^{-26}, n is 10.16, and m is -0.649. Compared to the test data, the initial range can match test data of both 170 MPa and 175 MPa compressive tests, but the larger strain part only can meet 175 MPa test.

Table 1 Copper stress strain curve data

Plastic Strain (%)	0	0.1	0.2	0.3	0.4	0.5
Stress (MPa)	72	178	235	269	288	300

Source: Hernelind (2010, p23) [6]

Table 2 Cast iron stress strain curve data

Plastic Strain (%)	0	1	2	4	5	6
Stress (MPa)	293	324	349	389	404	418
Plastic Strain (%)	7	8	9	10	11	12
Stress (MPa)	428	438	447	456	465	472

Source: Raiko et al. (2010, p25) [4]

Table 3 Buffer stress strain curve data

Plastic Strain (%)	0	0.4	1	1.8	2.6	3.6
Stress (MPa)	2.94	3.93	4.52	4.83	5.03	5.10
Plastic Strain (%)	46	100				
Stress (MPa)	5.04	5.04				

Source: Börgesson et al. (2010, p57) [5]

Table 3 Pore water related buffer material data

Permeability (mm/s)	Specific weight (N/mm^3)	Bulk Modulus for skeleton (MPa)	Bulk Modulus for water (MPa)
1×10^{-13}	1×10^{5}	2,100,000	2,100

Source: Hernelind (2010, p23) [1]

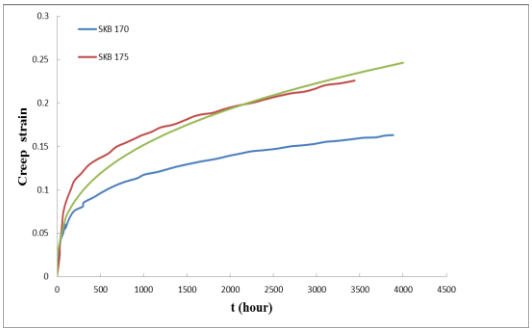

Fig. 3 Creep strain curve of copper matched by ABAQUS power-law creep model (green line)
Data source: SKB (2009, p54)

4. Results

Three analysis results consisting different shear angle and location are shown in Table 4; the maximum von Mises stress occurs on cast iron insert, but maximum plastic strain occurs on copper shell. The deformation result for Case (2) and Case (3) are shown in Fig. 4 and Fig. 5 respectively, and both canisters show they have no dislocation under 5 cm displacement on the buffer surfaces. It means 5 cm majorly influence on the stress and deformation of buffer, so buffer role can be played very well at this moment.

From stress view on Fig. 7 and Fig. 8, the maximum case is 90^{o} shear direction at quarter section, and the behavior is similar to cantilever beam subject to a transverse load. For the inclined loading, Table 4 shows it will have lesser stress, and even cast iron will maintain elastic state. Because the longitudinal loading will impose on the insert column which has higher rigidity than transverse sections and the lesser transverse load component will produce lesser stress.

Since rejection criteria of deposition holes considering one earthquake event scenario have been developed in SKB, the deposition hole can be adjusted to reduce the failure rate when facing detrimental fractures. However, to deal with accumulative displacement for multiple earthquake conditions, modifications of KBS-3 design maybe the useful approach. The influence of design parameters including geometry, buffer density, and confining pressure are studied, and the results are shown in Table 5 to Table 9. They mean the safety of canister against earthquake induced shear displacement can be achieved by using larger buffer thickness, insert diameter but keeping same fuel cassette dimension, larger copper shell thickness, and lesser density of buffer, so it's possible to design a SNFD repository with very rare earthquake failure rate even if multiple earthquake events definitely let 5 cm limit be reached. However, the decision of which countermeasure is used and how low failure rate is acceptable depend on cost-effective evaluation and the failure impact on radioactive safety.

Table 4 Analysis case and result(including shear and creep effect)

Shear angle	Shear location	Plastic strain (%)	von Mises (MPa)
Cast iron insert			
(1) 90^{o}	Middle section	0.0992	287.5
(2) 90^{o}	Quarter section	0.5426	320.3
(3) 22.5^{o}	Middle section	0	244.9
Copper shell			
(1) 90^{o}	Middle section	2.611	160.9
(2) 90^{o}	Quarter section	0.5622	84.09
(3) 22.5^{o}	Middle section	4.981	245.9

Table 5 Safety factor for different buffer thickness

Buffer thickness (cm)	20	25	35	40	45	50
von Mises stress (MPa)	330	327	319	296	240	216
Safety factor	1.19	1.21	1.24	1.34	1.64	1.87

Table 6 Safety factor for different insert diameter

Insert diameter (mm)	949	969	989	1009	1049
von Mises stress (MPa)	296	217	202	198	169
Safety factor	1.33	1.82	1.95	2.0	2.34

Table 7 Safety factor for different copper shell thickness

Shell diameter (mm)	1050	1070	1110	1130	1150
von Mises stress (MPa)	296	214	201	193	186

Safety factor	1.33	1.84	1.96	2.04	2.12

Table 8 Safety factor for different buffer density

Buffer density (Kg/cm^3)	1,970	2,020	2,050	2,070
von Mises stress (MPa)	195	212	232	268
Safety factor	2.05	1.85	1.7	1.47

Table 9 Safety factor for different confining pressure

Pressure (MPa)	25	35	45	55	65	85	95	115
von Mises stress (MPa)	91	143	195	247	291	299	330	370
Safety factor	4.3	2.7	2.02	1.6	1.35	1.32	1.19	1.06

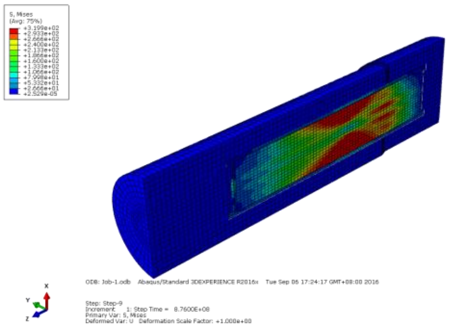

Fig. 4 Deformation and stress for assembly model imposed by 5cm shear displacement for 90^o shear direction at quarter section case

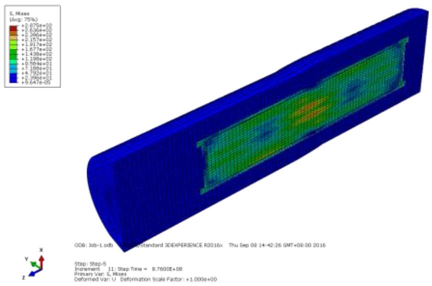

Fig. 6 Deformation and stress for assembly model imposed by 5cm shear displacement for 90^o shear direction at middle section case

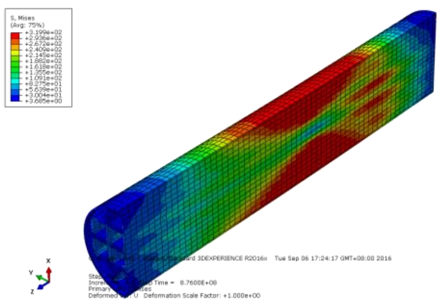

Fig. 7 Stress distribution of cast iron insert for 90^o shear direction at quarter section case

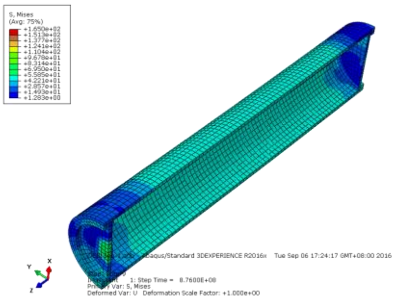

Fig. 8 Stress distribution of copper shell for 90^o shear direction at quarter section case

5. Conclusion and Discussion

The numerical analyses conclude modeling process and results as follows.

[1] ABAQUS numerical model for canister under earthquake induced fracture displacement and considering creep of copper shell under long-term confining pressure has been establish in Taiwan; therefore, they can be used in future prediction on seismic capacity of canister. However, some numerical models regarding inclined loading condition are still investigated due to difficulty of numerical convergence, so that the testing methods will need implementation in the future.

[2] The influence of design parameter on seismic capacity for canister and buffer are studied, and the safety factor data could be the basis for the decision of countermeasures.

[3] The study only focuses on structural capacity for a given earthquake hazard quantity. However, the earthquake induced hazards on deposition holes need more effort to realize how displacements impose, so that the different loading steps of displacement can be input in the models.

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