STRUCTURAL INTEGRITY ASSESSMENT OF DISPOSAL PACKAGE FOR RADIOACTIVE WASTE
FAILURE ASSESSMENTS FOR OVERPACK USING FINITE ELEMENT ANALYSIS

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Key words: Geological disposal, Disposal package, Structural integrity, Failure mode, Failure assessment

Abstract

In Japan, it is planning for high-level radioactive wastes to undergo geological disposal after being vitrified and encapsulated into an overpack. The carbon steel overpack is required for at least 1,000 years' isolation of the vitrified waste to prevent its coming into contact with groundwater. The overpack is a cylindrical package and made of carbon steel as the primary candidate material. The basic specification of the overpack was proposed as a wall thickness of 190 mm, and with a corrosion allowance layer (40 mm), radiation shielding layer (150 mm), and mechanical withstanding layer (included in radiation shielding layer). In this study, to ensure the overpack's integrity over the period required for, failure assessments of the overpack using finite element analysis were performed for all failure modes assumed during operation and after emplacement. The results of the failure assessment showed the relationship between collapse load and overpack thickness, and the relationship between welding residual stress and critical crack size of welded parts. It was clarified that the strength of the weld joint can be sufficiently ensured by partial welding.

1. Introduction

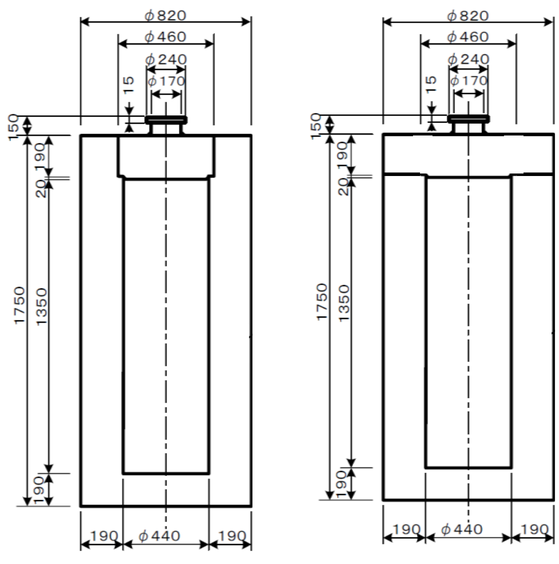
In Japan, it is planning for high-level radioactive wastes to undergo geological disposal after being vitrified and encapsulated into an overpack. The overpack is required for 1,000 years' isolation of the vitrified waste to prevent its coming into contact with groundwater [1]. One candidate material for the overpack is carbon steel. The thickness of the overpack was proposed to 190 mm as the sum of the radiation shielding 150 mm (including the pressure resistance 110 mm) and the corrosion allowance 40 mm. The pressure resistance was calculated using the formula specified in Notification No. 501 [2] (This Notification is a basis for the Code for Nuclear Power Generation Facilities: Rules of Design and Construction for Nuclear Power Plant edited by the Japan Society of Mechanical Engineers).

In an integrity assessment for a general structure, failure forms (positions of failure) are assumed and all failure modes (ductile failure, brittle failure, etc.) for each failure form are assumed. When all the failure modes are evaluated to not occur, the integrity of a structure is confirmed.

In this study, for the overpack designed using reference [1], failure assessments used finite element analysis and were aimed at confirming the integrity of the overpack. First, all failure modes for the overpack were investigated. Next, failure evaluations were performed on each failure mode and the relationships among wall thickness, welding depth, and load applied to the overpack were obtained.

2. Failure mode of overpack

The lid types proposed for the overpack are a drop-in lid type and a flat lid type as shown in Fig. 1. The jointing method of the lid and the body is welding [3]. Loads applied on the overpack are lifting load during the operation period, external pressure after emplacement, and welding residual stress. For these



(a) Drop-in lid type (b) Flat lid type

Fig. 1 Two types of lid structure model for overpack loads, failure parts of the overpack are conceivable as follow: (i) failure of the base metal part, (ii) failure from the tip of the welded part, and (iii) failure from a weld flaw. The failure modes for these failure parts are conceivable as follow:

(i) Plastic collapse
(ii) Plastic collapse, elastic-plastic failure, brittle failure
(iii) Brittle failure

Fatigue failure is also considered as a failure mode in a general structure. However, from the analysis result assuming the largest domestic earthquake, the cyclic load applied on the overpack is about 1.7 MPa at maximum [4]. There is no need to consider fatigue failure.

3. Failure assessments

3.1 Analysis method and Analysis model

In order to perform failure assessment for the overpack, it is necessary to calculate stress intensity factor K by elastic finite element analysis, and to calculate plastic collapse load and J-integral by elastic-plastic finite element analysis. In this study, the failure analyses used the general purpose program ABAQUS standard. The physical properties of the material used for the analysis are shown in Table 1. The analysis model for the overpack is shown in Fig. 2.

3.2 Analysis results

3.2.1 Failure of base metal part

In failure of the base metal part, the failure mode is plastic collapse of the body or lid. For the calculation of the collapse load, the Twice-Elastic-Slope Method [5] was applied. In the Twice-Elastic-Slope Method, collapse load is calculated using the relationship between load and displacement. The applied load used external pressure and the displacement used a representative point (the center of lid or the center of internal body). As a deformation characteristic of the material, elastically-perfect plastic material of yield strength S_y was assumed.

Fig. 3 shows the relationship between wall thickness of overpack and collapse load. The collapse load decreased with decrease of the wall thickness, and the collapse load depended on the yield strength. In the case of wall thickness of 50 mm and S_y = 100 MPa, the collapse load was the smallest 19.7 MPa. Since the external pressure applied on the overpack is 10.7 MPa at 1,000 m depth in hard rock [6], the collapse strength was about 1.8 times the safety margin, for 50 mm thickness of the overpack.

3.2.2 Failure from the tip of welded part

In the case of failure from the tip of the welded part,

Table 1 Analysis conditions

Temperature (°C)	Young's modulus (GPa)	Poisson's ratio (-)
90	199	0.3

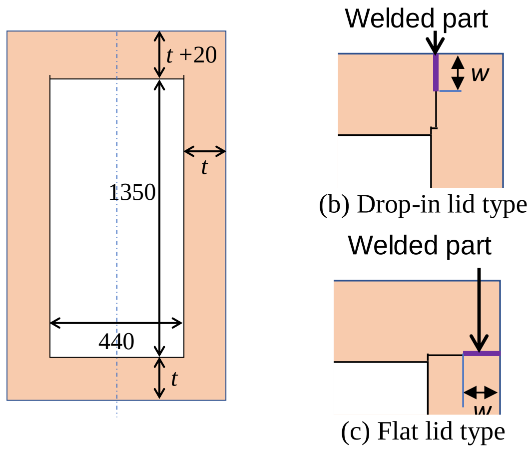


Fig. 2 Failure analysis model of overpack

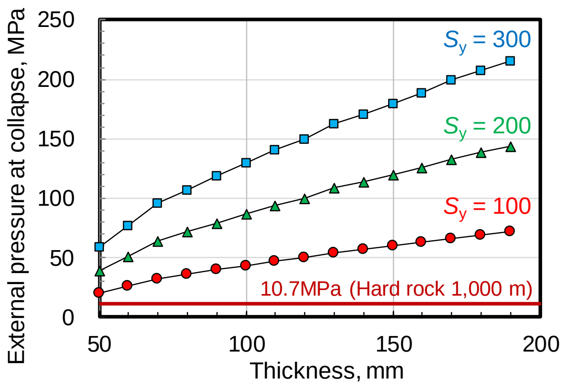


Fig. 3 Relationship between external pressure at collapse and thickness of overpack

the failure modes are plastic collapse and elastic-plastic failure at lifting up during operation, and plastic collapse due to external pressure after emplacement of the overpack.

(1) Plastic collapse of welded part for lifting load

For the calculation of the collapse load, the Twice-Elastic-Slope Method [5] was applied. The relationship between yield strength required for the welded part and weld depth is shown in Fig. 4. When the welding depth was 70 mm or more, the yield strength required for the overpack was about 1 MPa. When the welding part was smaller than 60 mm, the yield strength increased. However, the yield strength did not become larger than 5 MPa in either lid case. Since 40 mm thickness of the corrosion allowance is considered to be welded and the yield strength of typical carbon steel is greater than 200 MPa, it was

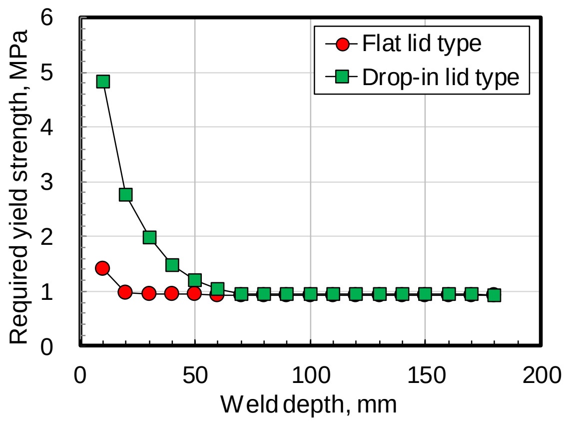


Fig. 4 Relationship between required yield strength and weld depth

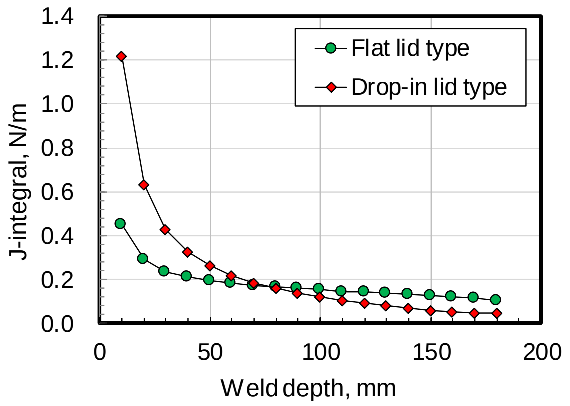


Fig. 5 Relationship between J-integral at tip of weld and weld depth

revealed that the collapse strength for lifting up is sufficient.

(2) Elastic-plastic failure for lifting load

If the welding depth is small, there is a possibility of elastic-plastic failure from the tip of unwelded. The driving force of elastic-plastic failure is J-integral. Therefore, the J-integral of the tip of the unwelded part for own weight was calculated by elastic-plastic analysis. For the stress-strain curve required for the elastic-plastic analysis, the result was approximated by the Ramberg-Osgood equation from the result of the tensile test using the typical carbon steel SM400.

Fig. 5 shows the relationship between J-integral and welding depth. When the welding depth became smaller, the J-integral became larger. If the J-integral is smaller than the fracture toughness which is the strength of the carbon steel, failure does not occur. The fracture toughness obtained from the SM400 was 589 kN/m, J-integral was sufficiently smaller than fracture toughness. Therefore, it is evaluated that elastic-plastic failure from the tip of unwelded area does not occur.

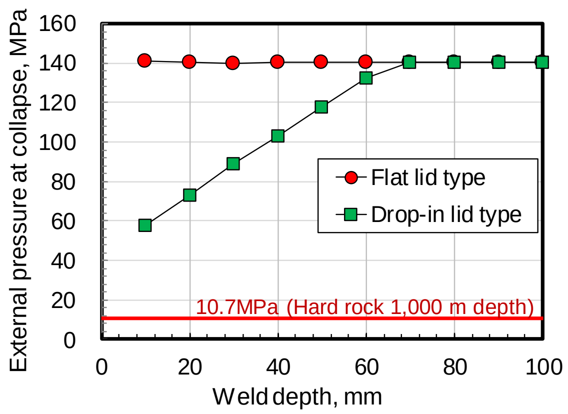


Fig. 6 Relationship between external pressure at collapse and weld depth (yield strength 300 MPa)

(3) Plastic collapse for external pressure

The relationship between external pressure at plastic collapse in the welded part and welded depth is shown in Fig. 6. In the case of the flat lid type, external pressure at plastic collapse was constant with welding depth. The length of the unwelded part did not influence the collapse load because unwelded parts of the flat lid and the body were in close contact with the external pressure. In the case of the drop-in lid type, when the welding part was 70 mm or more, the collapse load equaled that of the flat lid type.

3.2.3 Failure from weld flaw

In the case of failure from a weld flaw, the failure mode assumed brittle failure, assuming irradiated carbon steel from vitrified waste. The weld flaw was modeled as a semi-circular opening crack along the welded part, and stress intensity factor at the tip of the crack was calculated. The wall thickness was set at 110 mm of pressure resistance. The external pressure and weld residual stress for the overpack applied were 10.7 and 100 MPa, respectively.

The relationship between stress intensity factor and crack size for the flat lid type was shown in Fig. 7. For axial stress σ_z of 10.7 MPa, the stress intensity factor decreased with crack size. However, for axial stress σ_r of 10.7 MPa, the stress intensity factor increased with crack size. The stress intensity factors in both cases were negative regardless of crack size. That means failure from weld flaws by external pressure does not occur for crack size of 55 mm. On the other hand, when the residual stress σ_R of 100 MPa was applied, the stress intensity factor became larger than the stress intensity factor by external pressure. For example, the stress intensity factor for the crack size of 55 mm was over 50 MPa·m$^{0.5}$. The relationship between allowable residual stress and critical crack size for wall thickness of 110 mm is shown in Fig. 8. When fracture toughness, K_{IC}, of

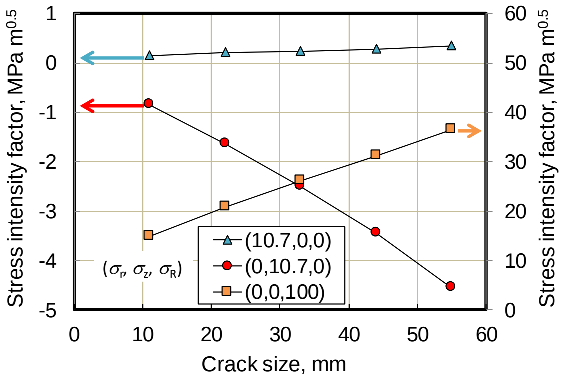


Fig. 7 Relationship between stress intensity factor and crack size in weld part for flat lid type

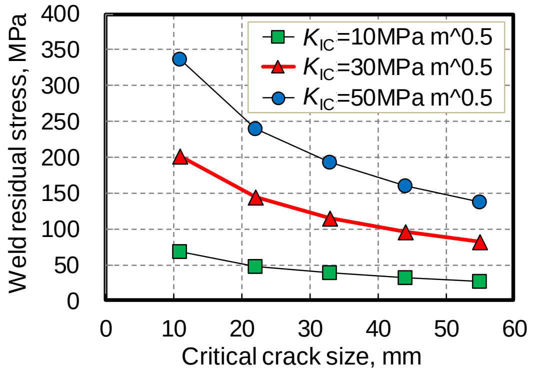


Fig. 8 Relationship between weld residual stress and critical crack size in weld part for flat lid type

carbon steel after 1,000 years is estimated, allowable residual stress or critical crack size can be calculated using this figure.

4. Thickness of overpack

The thickness of the overpack was set to 190 mm as the sum of the radiation shielding 150 mm (including the pressure resistance 110 mm) and the corrosion allowance 40 mm. From the results of the collapse analysis (Fig. 3), it was found that when carbon steel with a yield stress of 200 MPa was used, wall thickness of 110 mm of the overpack has about 8.7 times larger than the external pressure of 10.7 MPa at 1,000 m depth of hard rock.

Ohe *et al.*, reported that for the thickness of radiation shielding and corrosion allowance set by reference [1], when the design conditions and evaluation formulas were revised, the thickness of the overpack became 110 mm [7]. This report has no mention of decrease in strength by reduction in thickness of the overpack due to corrosion; however, the result of the collapse analysis shows that the strength of 50 mm wall thickness is about 3.6 times the external pressure. Therefore, it is revealed that there is a possibility of reducing the thickness of the overpack.

Also, from the results of failure assessment of welded parts, it is not necessarily required to perform a full penetration weld of 190 mm. The welded part has enough strength even by partial welding. Compared with full penetration welds, partial welds have the advantage of reduction of welded residual stress, reduction of welding time, and improvement of measurement accuracy (weld flaw size and location).

5. Summary

Failure assessment by the finite element method was carried out for all failure modes assumed for the overpack, and the relationship among the wall thickness, the welding depth, the weld flaw size, and the failure load was calculated. The obtained results were as follow.

- Even if the wall thickness is 50 mm, the strength against external pressure applied to the overpack after emplacement is sufficient.
- It is not necessarily required to do a full penetration weld of 190 mm. The welded part has enough strength even by partial welding.
- It was clarified that brittle failure from a weld flaw does not occur due to external pressure. On the other hand, the welding residual stress contributes to brittle failure from a weld flaw.
- When fracture toughness, K_{IC} of carbon steel after 1,000 years is estimated, allowable residual stress or critical crack size can be calculated using figure 8.

This research is a part of “Development of Advanced Technology for Engineering Components of HLW Disposal” under a grant from the Japanese Ministry of Economy, Trade and Industry (METI).

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