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Rolling Test Simulation of Sea Transport of Spent Nuclear Fuel Under Normal Transport Conditions

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In this study, the impact load resulting from collision with the fuel rods of surrogate spent nuclear fuel (SNF) assemblies was measured during a rolling test based on an analysis of the data from surrogate SNF-loaded sea transportation tests. Unfortunately, during the sea transportation tests, excessive rolling motion occurred on the ship during the test, causing the assemblies to slip and collide with the canister. Hence, we designed and conducted a separate test to simulate rolling in sea transportation to determine whether such impact loads can occur under normal conditions of SNF transport, with the test conditions for the fuel assembly to slide within the basket experimentally determined. Rolling tests were conducted while varying the rolling angle and frequency to determine the angles and frequencies at which the assemblies experienced slippage. The test results show that slippage of SNF assemblies can occur at angles of approximately 14° or greater because of rolling motion, which can generate impact loads. However, this result exceeds the conditions under which a vessel can depart for coastal navigation, thus deviating from the normal conditions required for SNF transport. Consequently, it is not necessary to consider such loads when evaluating the integrity of SNFs under normal transportation conditions.

Keywords: Normal conditions of transport, Rolling test, Sea transportation test, Spent nuclear fuel, Transportability

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1. Introduction

In the Republic of Korea, the wet storage capacity for spent nuclear fuel (SNF) is expected to reach saturation soon, thus making on-site or interim dry storage facilities the most feasible option to address this issue. As SNFs must be transported from wet storage pools in nuclear power plants to temporary on-site and interim dry storage facilities, it is critical to ensure their integrity during transport [1].

In 2009, it was necessary to ensure the structural integrity of high-burnup or degraded spent fuels during normal transportation to achieve long-term storage [2]. In 2013, Sandia National Laboratories performed uniaxial shake table tests, over-road truck tests, and multi-axis shake table tests to simulate normal truck and rail transport [2-5]. Several reports on relevant analyses and demonstration efforts on the structural integrity of spent fuels during normal transportation have also been published [6, 7].

In 2017, an ENSA/DOE multimodal transportation test (MMTT) was conducted using the ENSA ENUN 32P transportation package [8]. The strain and acceleration data were determined for three different surrogate fuel assemblies for three transport modes: rail, truck, and ship [7]. Additionally, between 2018–2019, 30 cm drop tests—part of the normal transport conditions— were conducted and relevant analyses were performed [9-12]. However, the tested cask (ENSA ENUN 32P) did not include a canister and the MMTT focused on rail transport [1].

Considering Korea's existing infrastructure and geographical conditions, SNF is expected to be transported by sea or roads. In our previous study, we conducted shock and vibration load evaluations and assessed the structural integrity of spent fuel during normal transportation in South Korea [1, 13]. The Korea Atomic Energy Research Institute conducted road transportation tests using surrogate spent fuel assemblies from KEPCO NF in September 2020 and sea transportation tests in November 2021. The data from each test were analyzed in this study. During the rolling test in the sea transportation test, excessive rolling motion occurred on the ship, causing the surrogate SNF assemblies to slip and collide with the canister [1, 13]. Hence, we designed and conducted a separate test to simulate rolling in sea transportation to analyze the conditions under which such impact loads occur and determine whether this event is possible under normal conditions of SNF transport, with the test conditions for the fuel assembly to slide within the basket experimentally determined. The impact load from object collisions on the fuel rods of a surrogate SNF assembly was measured based on the analysis of the data from the above-mentioned sea transportation test.

2. Rolling Test in Sea Transportation

Various experiments were conducted as part of the sea transportation tests, including cruising and rotation, acceleration, braking, and depth of water estimations. Fig. 1 shows the general arrangement of the test vessel (Jaewon Stella). The number 2 starboard ballast water tank of the test vessel was completely emptied before conducting the rolling test to amplify the rolling motion. Although a significant rolling motion already occurred before the ballast water tank was emptied because the wave was directed toward the side of the ship during preparation, the magnitude of the rolling motion significantly increased as the ballast water tank was emptied. The resulting rolling motion significantly shook the wheelhouse, resulting in small objects in the cabin falling out.

A device in the wheelhouse of Jaewon Stella displays the rolling angle; however, we found it difficult to accurately measure the rolling angle of the vessel because the device could not record numerical values.

An IMU sensor was used to measure the angular velocity. Although the rolling angle can be calculated by integrating the measured angular velocity, it is difficult to determine the accuracy of the calculated value owing to noise effects.

The load calculation criteria for sea transport specified

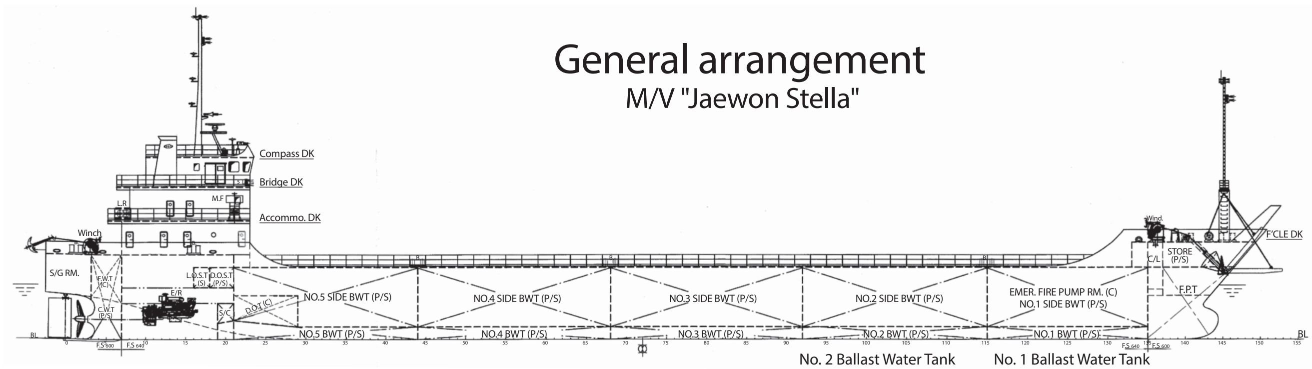


Fig. 1. Location of ballast water tanks in Jaewon Stella.

Nature of transportation	Case	LOA (m)	B[1] (m)	L/B[1]	Block Coeff	Full cycle period (secs)	Single amplitude		Heave
							Roll	Pitch	
Unrestricted (these values to be used unless any of the following apply)	1	> 140 and > 30		n/a	< 0.9	10	20°	10°	0.2 g
	2	> 76 and > 23		n/a	any	10	20°	12.5°	0.2 g
	3	≤ 76 or ≤ 23		≥ 2.5	< 0.9	10	30°	15°	0.2 g
	4				≥ 0.9		25°		
	5	≤ 76 or ≤ 23		< 2.5	< 0.9	10	30°	30°	0.2 g
	6				≥ 0.9		25°	25°	
Weather restricted operation in non-benign areas for a duration <24 hours (see Section 7.9.2.d. For L/B < 1.4 use unrestricted case.	7	any		≥ 2.5	any	10	10°	5°	0.1 g
	8	any		< 2.5, ≥ 1.4	any	10	10°	10°	0.1 g
Weather restricted operation in benign areas [2] (see Section 7.9.2.e). For L/B < 1.4 use unrestricted case.	9	any		≥ 2.5	any	10	5°	2.5°	0.1 g
	10	any		< 2.5, ≥ 1.4	any	10	5°	5°	0.1 g
Inland and sheltered water transportations (see Section 7.9.2.f). For L/B < 1.4 use unrestricted case.	11	any		≥ 1.4	any	Static	Equivalent to 0.1 g in both directions		0.0
Independent leg jack-ups, ocean tow on own hull. For L/B ≥ 1.4 use unrestricted Cases 1 to 6	12	n/a	> 23	< 1.4	n/a	10	20°	20°	0.0
Independent leg jack-ups, 24-hour or location move. For L/B ≥ 1.4 use Cases 7 or 8 as applicable	13	n/a	> 23	< 1.4	n/a	10	10°	10°	0.0
Mat-type jack-ups, ocean tow on own hull. For L/B ≥ 2.5 the pitch angle may be reduced to 8°	14	n/a	> 23	< 1.4	n/a	13	16°	16°	0.0
Mat-type jack-ups, 24-hour or location move.	15	n/a	> 23	n/a	n/a	13	8°	8°	0.0

Fig. 2. DNVGL's default motion criteria [14].

by the DNV-GL Classification Society are shown in Fig. 2, with the benign areas defined by the criteria shown in Fig. 3 [14]. The Korean coastal sea is not included in the benign area; therefore, the rolling motion was set to 10° and the pitching motion was set to 5° in the load calculation criteria.

When a domestic vessel requests for departure, it includes the result of the cargo fastening load calculation based on the rolling and pitching angles listed in the preceding criteria and then proceeds with lashing as necessary. Under normal transport conditions, domestic vessels are

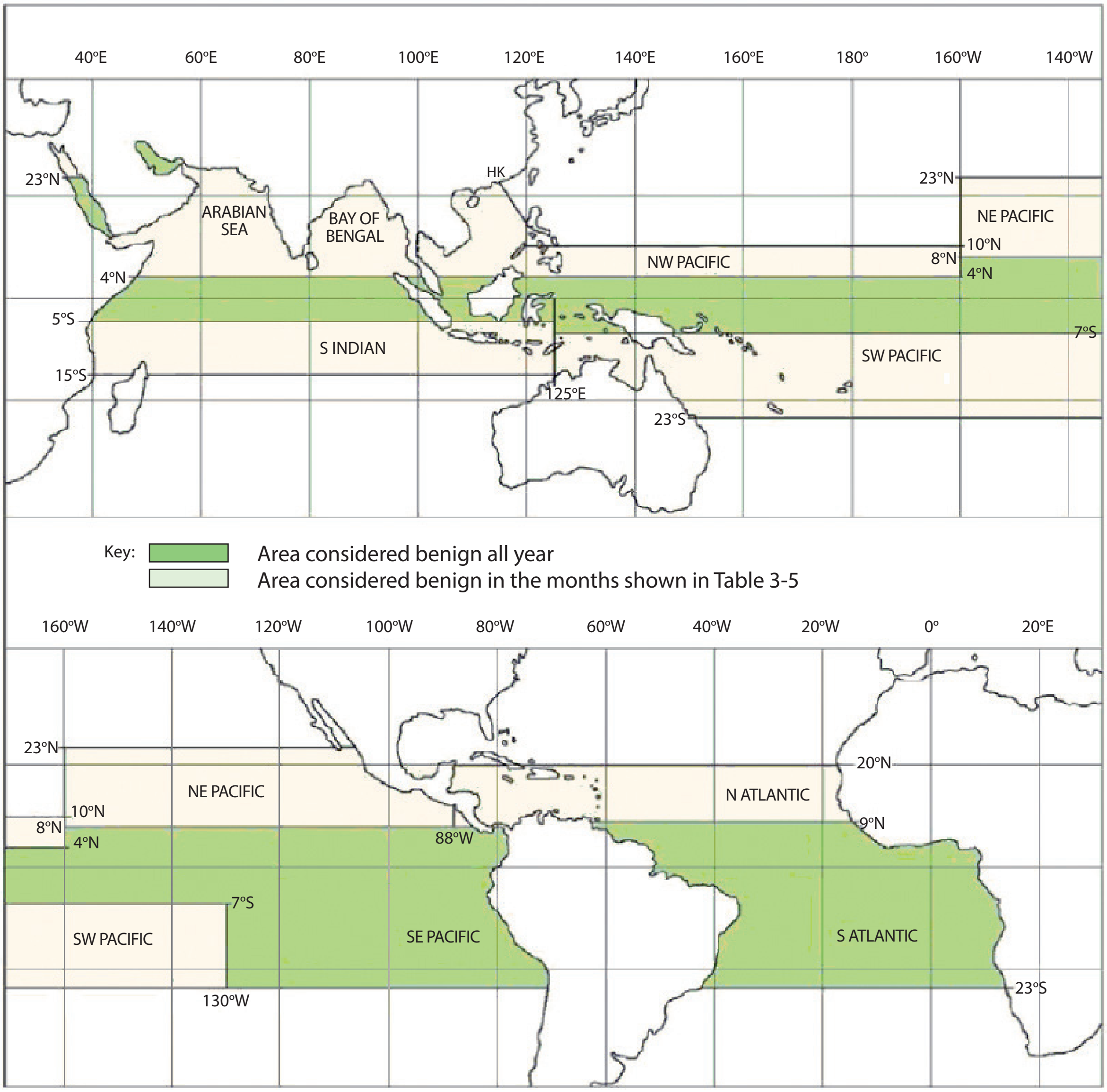


Fig. 3. Benign areas in DNVGL's default motion criteria [14].

operated at a rolling angle of 10° or lower and a pitching angle of 5° or lower.

Although it seemed that Jaewon Stella had a rolling motion of approximately 5–15° during the rolling experiment of the sea transportation tests, the data obtained under test conditions outside the normal transport conditions were excluded from the analysis because the primary objective of this research is to evaluate the shock and vibration load characteristics of SNF under normal transport conditions [1]. As a ship is not allowed to depart under weather conditions in which rolling motion can occur at more than 10°, data in the section where rolling motion occurs at more than 10° during the sea transportation test should be excluded from data analysis, such as fatigue evaluation data.

During the rolling test, the largest measured acceleration and strain were under the impact between the fuel

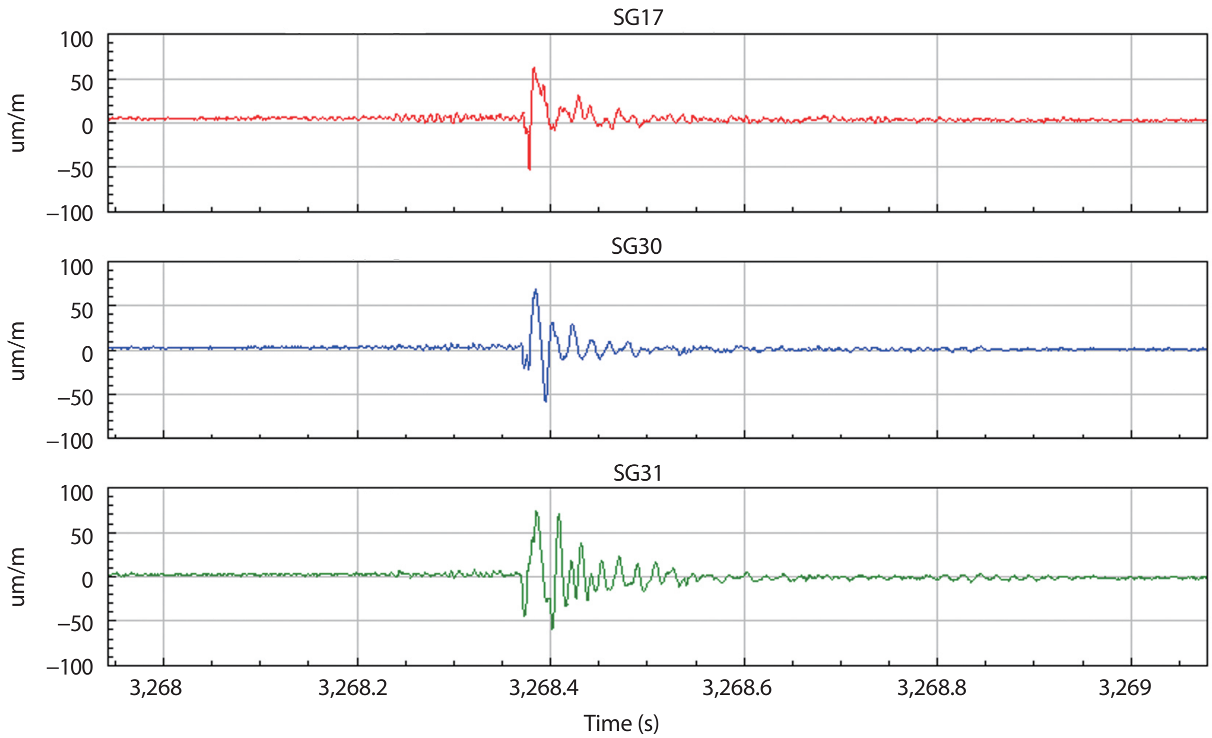


Fig. 4. Measured strain during rolling test as part of the sea transportation tests.

Fig. 5. Hypothetical sea transport scenario.

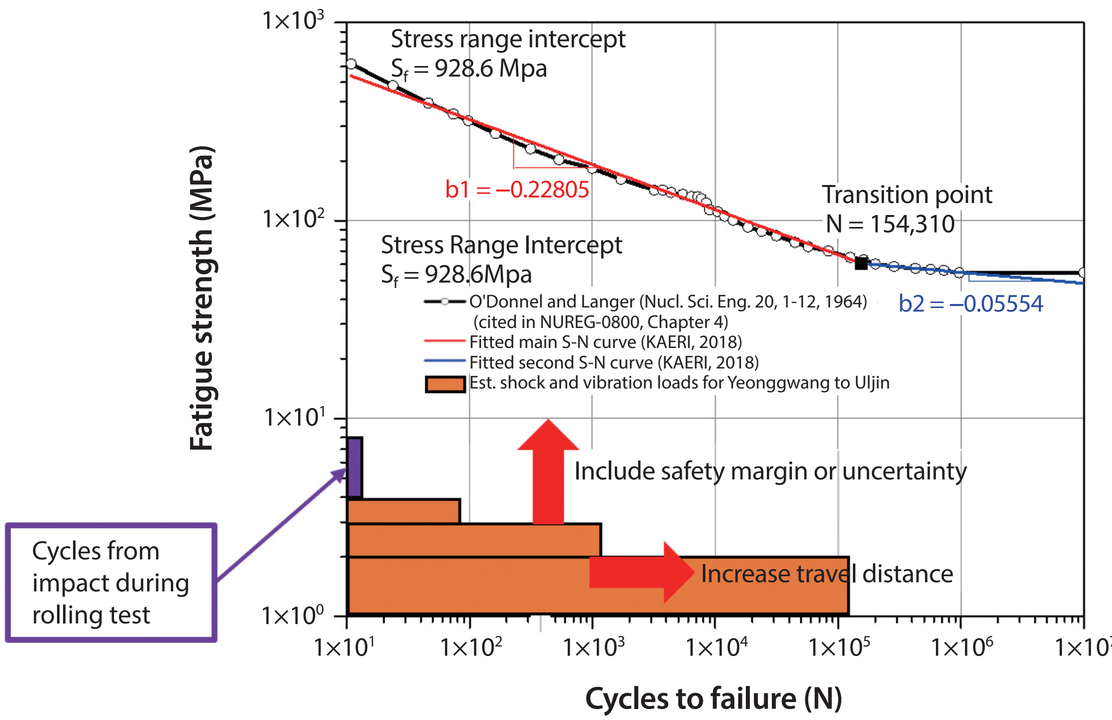


Fig. 6. S–N diagram of sea transportation.

assembly and bottom of the canister (Fig. 4). SG17, SG30, and SG31 strain gauges were attached to the fuel rod close to the bottom nozzle in the PLUS7 [1].

Although the measured strain data under impact conditions are not sufficiently large to cause damage to the SNF, it is necessary to determine the range of acceleration and strain that can occur under normal sea transportation conditions to determine whether the impact load is included in the normal transport conditions.

Fig. 5 depicts an imaginary sea transport scenario based on the measured strain data obtained from the test results. A fatigue evaluation of the SNF rod was performed based on this scenario, which is summarized as follows:

1) Mounting the cask on the supporting structure and loading it on the trailer
2) Road transport to the port
3) Loading onto the ship
4) Sea transportation for 4.3 days (Uljin → Yeonggwang → Uljin)
5) Unloading from the ship and loading back on the trailer
6) Road transport to the facility
7) Unloading from the trailer

Fig. 6 shows an S–N diagram of the imaginary sea transport scenario based on the data from the sea transportation tests. The number of accumulated stress cycles is plotted in orange in the S–N diagram. If the transport distance and the number of transports increase, the orange region in Fig. 6 expands to the right. Additionally, the orange region expands upward considering uncertainty or a safety margin [1].

If the assembly impact event that occurred in the aforementioned rolling test is included under normal transport conditions, then the purple region should be included in the result. Conversely, if the assembly impact event is not included under normal transport conditions, the purple

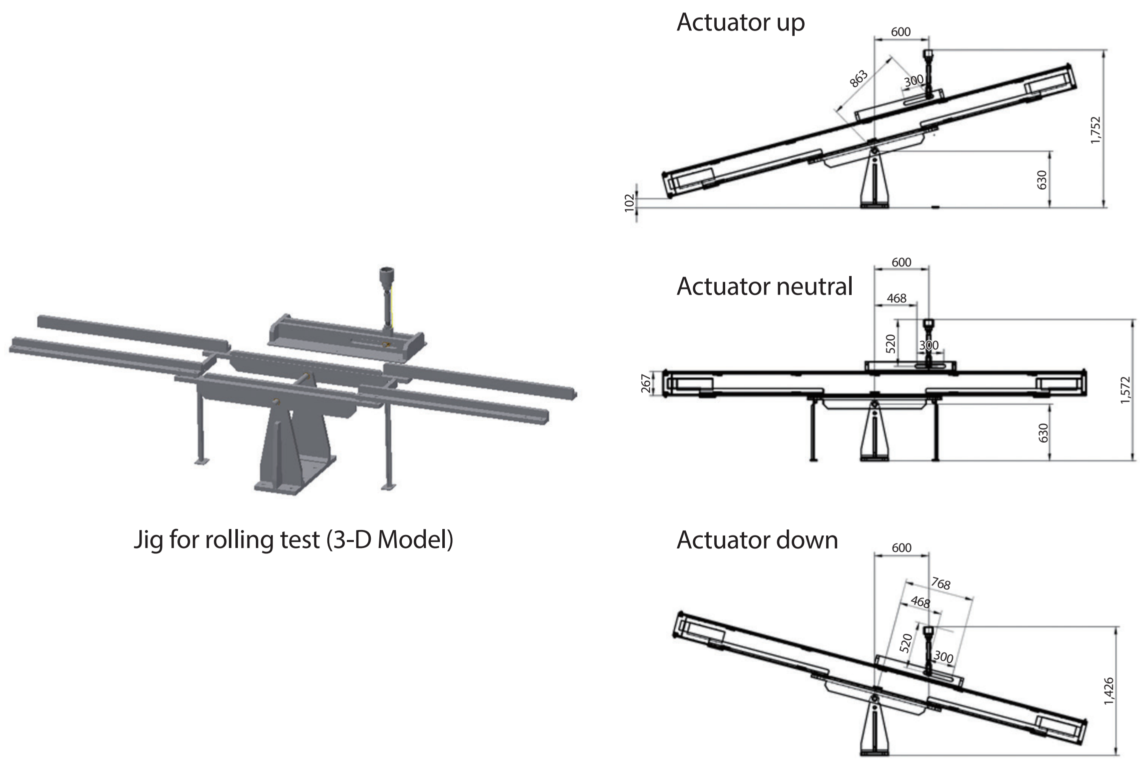


Fig. 7. Jig for rolling test.

region is excluded from the results.

In this study, a separate rolling test was conducted to determine whether the assembly impact event due to slippage can be considered part of normal transport conditions. Additionally, we evaluated the rolling conditions under which the SNF slides as well as the resulting accelerations and strains generated during sliding.

3. Rolling Test to Simulate Sea Transport of Spent Nuclear Fuel Under Normal Conditions of Transport

3.1 Preparation of Rolling Test

A 100 t hydraulic actuator (± 100 mm at 0.2 Hz) from the Korea Institute of Machinery and Materials was used for the rolling test to determine the sliding conditions of the spent fuel assembly. The actuator produces a stroke of ± 100 mm at 0.2 Hz.

As shown in Fig. 7, a jig was designed to convert the vertical motion of the hydraulic actuator to rotation, achieving a rotational motion of approximately ± 15°. The jig includes a support in the center, where the assembly was placed. The actuator and assembly were connected vertically, 600 mm from the center of the assembly. The jig weighed approximately 2 t and included one surrogate fuel assembly.

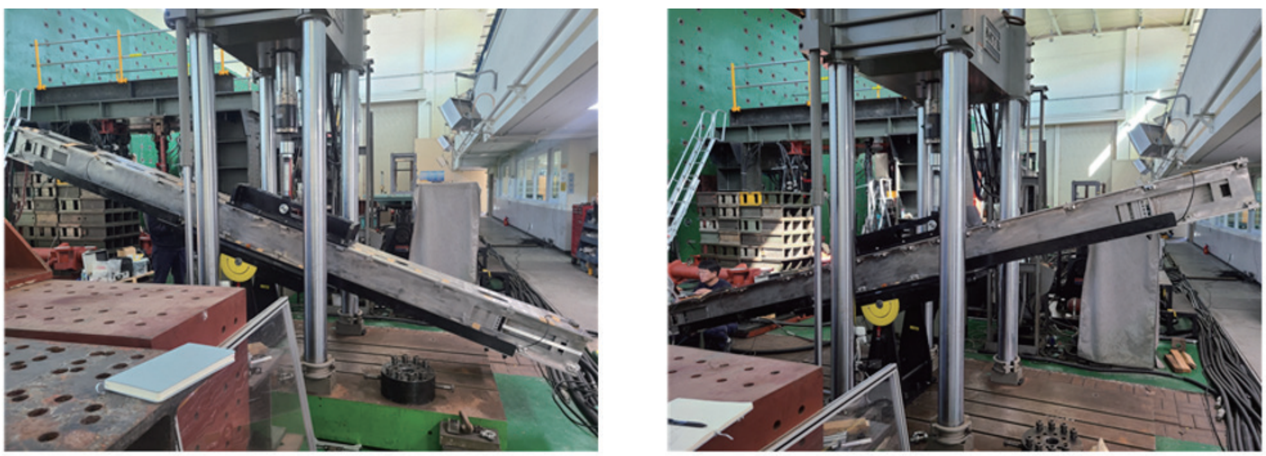
Tables 1 and 2 present the relationship between the hydraulic actuator's vertical displacement and rolling angle, as determined in a preliminary test in which the actuator operates at the lowest speed. The positive direction of the rolling angle is defined as the direction in which the basket housing rotated clockwise from the center when observing the yellow goniometer installed in the center of the assembly test piece (Fig. 8).

Table 1. Relationship between actuator displacement and rolling angle (ACE7)

Angle (°)	Displacement (mm)	Angle (°)	Displacement (mm)
+5	−24.07	−5	27.69
+10	−45.15	−10	57.91
+12.5	−52.03	−12.5	75.73
+13	−53.76	−13	79.59
+13.5	−55.31	−13.5	83.21
+14	−57.02	−14	86.62
+15	−62.61	−15	92.87

Table 2. Relationship between actuator displacement and rolling angle (PLUS7)

Angle (°)	Displacement (mm)	Angle (°)	Displacement (mm)
+5	−24.07	−5	27.69
+10	−44.50	−10	59.48
+12.5	−53.55	−12.5	77.02
+13	−53.76	−13	79.59
+13.5	−55.31	−13.5	83.21
+14	−57.02	−14	86.62
+15	−61.56	−15	95.71



Positive (+) rolling angle   Negative (−) rolling angle

Fig. 8. Positive and negative rolling angles during rolling tests.

Rolling tests were conducted using the ACE7 and PLUS7 assemblies, which were also used for the transportation tests. After completing the sea transport tests, rolling tests were conducted without changing the sensor location. Consequently, the acceleration and strain were measured at the same location as in the sea transportation test.

3.2 Rolling Test Results

Rolling tests were conducted on both the ACE7 and PLUS7 assemblies while varying the rolling angle and frequency, with the results listed in Tables 3 and 4. Among the various SNF assemblies stored at nuclear power plants in Korea, the surrogate SNF assemblies used in this test are not likely to be the most conservative assemblies with the lowest friction coefficient; however, the difference in the friction coefficient according to the type of nuclear fuel is not expected to be large, and hence, is not expected to affect the conclusions of this study.

During the sea transportation rolling test, the impact event occurred at a rolling frequency of approximately 0.15 Hz, maximum acceleration of approximately 4.1 g, and maximum strain of approximately 73.6 με. When the rolling angle is relatively small, such as ± 5° or ± 10°, the test

Table 3. Results of rolling test (ACE7)

Case	Angle (°)	Frequency (Hz)	Test time (s)	Slide or not	Max. acceleration (g)	Max. strain (με)
Case 1	±5	0.1	60	X	-	-
Case 2		0.2	60	X	-	-
Case 3		0.3	60	X	-	-
Case 4		0.4	60	X	-	-
Case 5	±10	0.1	60	X	-	-
Case 6		0.2	60	X	-	-
Case 7		0.3	60	X	-	-
Case 8	±15	0.1	60	O	3.6	57.5
Case 9	±12.5	0.1	60	X	-	-
Case 10	±13	0.1	60	X	-	-
Case 11		0.2	60	X	-	-
Case 12	±13.5	0.1	60	X	-	-
Case 13	±14	0.1	60	O	1.4	33.4
Case 14	±15	0.15	60	O	3.9	50.0
Case 15	±15	0.175	60	O	1.4	29.1

Table 4. Results of rolling test (PLUS7)

Case	Angle (°)	Frequency (Hz)	Test time (s)	Slide or not	Max. acceleration (g)	Max. strain (με)
Case 1	±10	0.1	60	X	-	-
Case 2	±10	0.2	60	X	-	-
Case 3	±10	0.3	60	X	-	-
Case 4	±12.5	0.1	60	X	-	-
Case 5	±12.5	0.2	60	X	-	-
Case 6	±15	0.1	60	O	13.3	49.5
Case 7	±15	0.15	60	O	15.3	35.3
Case 8	±15	0.2	60	O	1.9	15.1

can be conducted by increasing the rolling frequency up to 0.3–0.4 Hz. However, when the rolling angle reached ± 15°, the rolling frequency was limited to a range of 0.15–0.175 Hz owing to the constraints of the actuator capacity. For the actual sea transport test, which operates at a rolling cycle of 0.15 Hz, the test was feasible up to approximately ± 15°.

The test results for the maximum acceleration and strain values are listed in Tables 3 and 4, respectively. The ACE7 assembly did not experience slippage at angles of ± 5°, ± 10°, ± 12.5°, ± 13°, and ± 13.5°. However, slippage occurred at angles exceeding 14°; in addition, the maximum acceleration and strain generated at this point were considerably smaller than those measured during the rolling test of the sea transportation test.

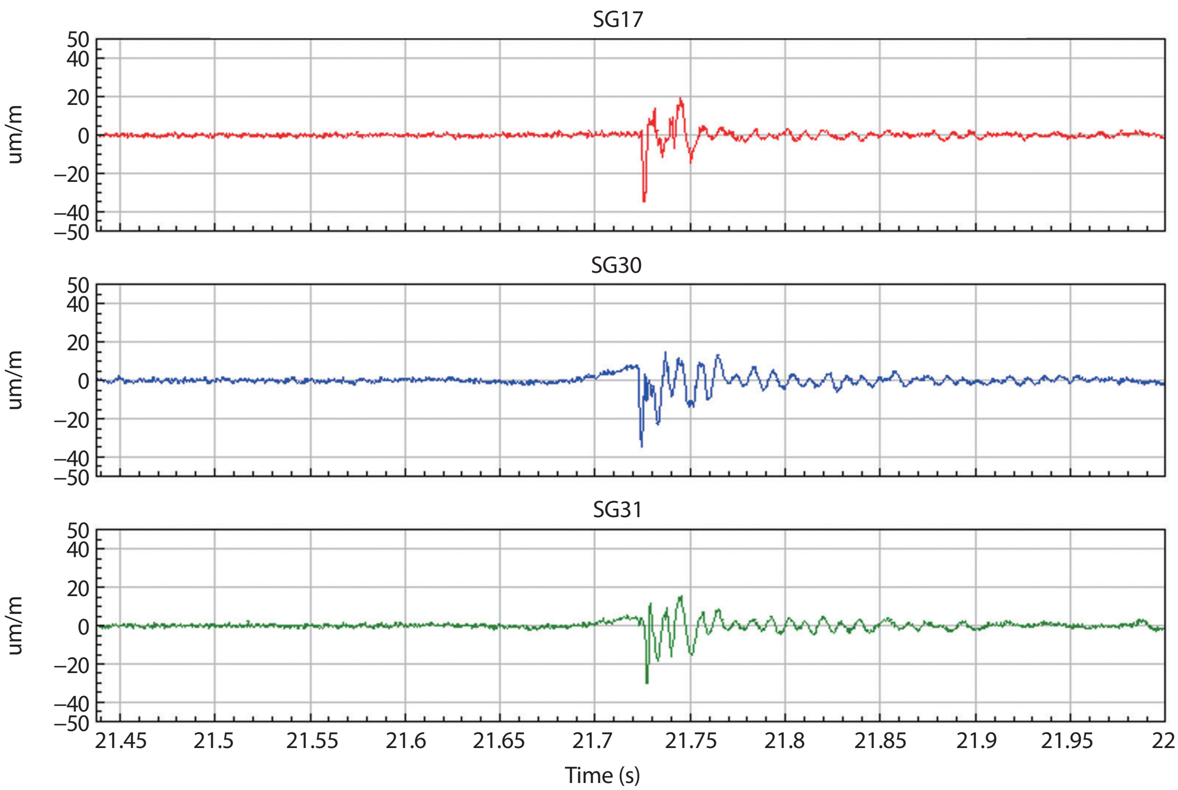


Fig. 9. Measured strain during rolling test.

During the rolling test of the PLUS7 assembly, slippage occurred at ± 15° and the assembly moved. Furthermore, the maximum acceleration and strain generated at this point were significantly lower than those obtained in the sea transportation test.

Fig. 9 shows the strain measured during the rolling test. The strain–time history graph is similar to that shown in Fig. 4, which represents the impact load generated in the rolling test of the sea transport test.

Notably, the slipping phenomenon was more affected by the angle than the frequency. During the preliminary test, slip occurred at an angle of 14.3° for the ACE7 assembly when moving at a slow speed, consistent with the dynamic sliding angle observed in the current test.

In this test, converting the result of starting to slide on an inclined surface at an angle of approximately 14–15° to friction coefficient resulted in an approximate value of 0.2–0.23. As both the surrogate fuel assemblies and basket structures were machined smoothly, the assemblies have a low friction coefficient.

Although the test was conducted repeatedly under the same conditions, there were instances where the assembly slipped but remained stable and did not move in subsequent tests because the friction coefficient increased as the stainless-steel grid structures and the upper and lower nozzles of the assemblies wore down owing to friction with the stainless-steel basket structure.

The condition that yields the lowest friction coefficient during the lifetime of a nuclear fuel assembly is expected to be when the fuel is new. The minimum friction coefficient can be estimated if tests are conducted on a new fuel assembly.

Therefore, the slipping phenomenon caused by the rolling motion does not improve with an increase in the repetition; instead, it becomes less slippery over time. Therefore, the phenomenon of the assembly sliding further with repeated sliding will not occur. In summary, when the rolling angle reaches approximately 14° or higher, the spent fuel assembly may experience slip owing to the rolling motion, potentially leading to an impact event. However, this condition exceeds the criteria for domestic coastal voyages and deviates from the normal transport conditions for SNF.

4. Conclusions

In this study, a separate rolling test was conducted using two different surrogate fuel assemblies while varying the rolling angle and frequency to determine the angles and frequencies at which slippage of the assemblies occurred. The test results show that slippage of SNF assemblies can occur at angles of approximately 14° or higher because of rolling motion, possibly generating impact loads. Moreover, slippage was more affected by the rolling angle than the rolling frequency. However, this outcome exceeds the conditions under which a vessel can be permitted to depart for coastal navigation in the Republic of Korea. Consequently, it deviates from the normal conditions for the transport of SNF and surpasses the criteria set for domestic coastal voyages.

Conflict of Interest

No potential conflict of interest relevant to this article was reported.

Acknowledgements

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