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DEVELOPMENT OF IN-VESSEL RAIL DEPLOYMENT AND CONNECTION METHOD FOR ITER BLANKET REMOTE MAINTENANCE

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Abstract

The paper presents a novel rail deployment method for the maintenance of ITER Blanket Modules. Aiming to develop a reliable mechanical system for remote maintenance in the high-radiation environments of fusion reactors, this study conceptualizes and validates feasibility of the methodology. Unlike the previous single-port rail deployment method, the proposed In-Vessel Rail Connection (IVRC) design approach involves extending rails from two ports and connecting them within the vacuum vessel. The new method addresses the limitations of the previous rail deployment method, including challenges in recovery from equipment failures. Through a series of tests, including vibration tests using a scaled-down model and evaluation of structural strength using a partial mock-up, together with Finite Element Method (FEM) analyses, the paper verifies the structural integrity of the overall IVRC rail design.

1. INTRODUCTION

Deployment of robotic systems into the workplace is not only a prerequisite but also a key element in the development of remote handling operations in challenging environment of fusion device. In the context of ITER[1,2], remote handling systems must perform demanding tasks requiring careful consideration of both environmental conditions such as gamma-ray irradiation and operational complexities. A fundamental constraint is that all deployment and withdrawal of equipment must be performed through the vacuum vessel ports. These ports are, by necessity, made narrow due to the requirement of arrangement of magnets around the vacuum vessel. Over the years, methods for reliably deploying a robotic system inside the ITER vacuum vessel have been developed to ensure successful operation of ITER Blanket maintenance [3]. Beyond basic functionality, it is important to ensure that these systems are also recoverable, capable of responding to unexpected failures as much as possible and restoring functionality without leading to operational deadlocks.

This paper presents a novel deployment method for the rail-based remote maintenance system, aiming at enhancing the recoverability in case of failure of remote maintenance system. The ITER maintenance scheme involves deploying circular rail inside the vacuum vessel to replace the Blanket Modules. A Vehicle Manipulator traveling on the deployed rail performs the replacement of the (FW), weighing up to 1 t, and the Shield Block, weighing up to 4 t (Fig. 1) [4]. The previously developed method for rail deployment has taken the approach to deploying the rail from a single port, but devising an effective recovery scenario is challenging under scenarios in which the rail connection device fails and becomes stuck. The newly developed rail deployment strategy is based on extending rails from two access ports of the vacuum vessel and connecting their endpoints within the vacuum vessel—a technique referred to as In-Vessel Rail Connection (IVRC)[5]. This method allows development of recovery scenario by the introduction of a light-weight manipulator to access the failed equipment for rescue operations.

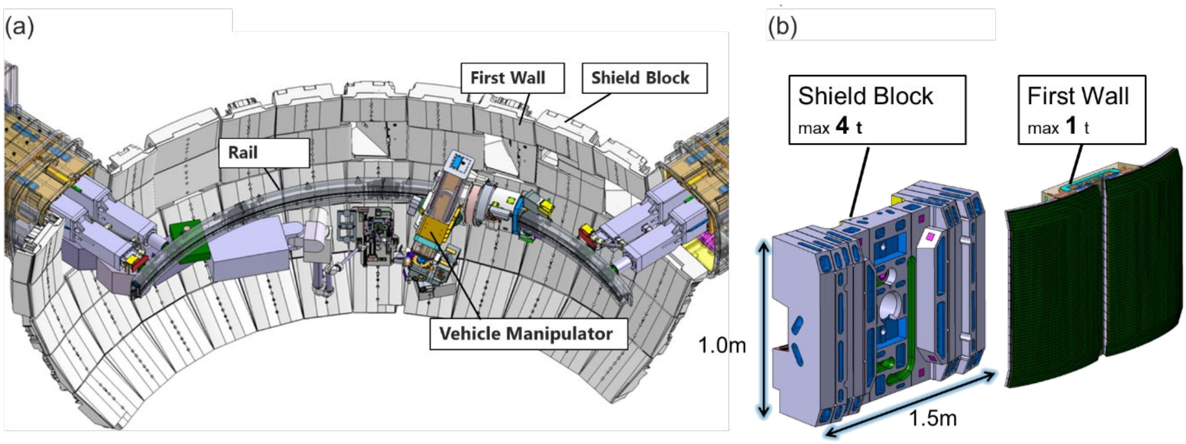

FIG. 1. (a) ITER Blanket Remote Handling System deployed within the vacuum vessel for in-vessel maintenance operation (b) The Blanket Module composed of the First Wall and Shield Block (adapted from [6]*).*

In the following sections, we first provide an overview of the design of the previously developed rail deployment method and the challenges associated with its recoverability. We then describe in detail the In-Vessel Rail Connection (IVRC) method that has been developed to address these issues, including the equipment configuration and operational sequence. A series of verification tests are presented, encompassing vibration tests using scaled-down models, structural integrity assessments with full-scale partial mock-ups, and finite element method (FEM) analyses. Through these investigations which are detailed in [5], we demonstrate both the structural soundness of the rail design under the IVRC concept and the feasibility of the IVRC deployment strategy itself.

This paper reports on the verification of feasibility of this IVRC concept by following verifications:

- Vibration tests using a 1/5 scaled-down model of the entire rail: Understanding the dynamic behavior of the rail structure is essential for the establishment of the rail design of the IVRC. A 1/5 scale model was fabricated to perform dynamic behavior verification tests on the entire rail structure.

- Evaluation of seismic strength using a partial, full-scale mock-up of the rail connection section only and Finite Element Method (FEM) analysis: Based on the dynamic behavior of the rail captured through the scaled-down model, an FEM model was created to define the load conditions on the rail connection section and conduct strength evaluations. A full-scale mock-up of the rail connection section, accurately simulating the structure, was created to conduct strength validations.

Subsequently, Section 5 describes the preparations underway for the full-scale mock-up of the entire rail connection equipment.

2. CHALLENGES OF RAIL DEPLOYMENT FROM A SINGLE PORT

Before presenting the concept and features of the new rail deployment method, this section describes the previously developed method of deploying and connecting rails inside the vacuum vessel from a single port, along with its technical challenges. When introducing remote handling equipment into the ITER vacuum vessel, the available access points are limited to the remote handling ports. After being transported through these ports, the rails must form an arc inside the vacuum vessel.

The approach to achieve this involved assembling the rails from interconnected multi-joint links. During introduction through the port, the rails were transported in a nearly straight configuration, and subsequently inside the vacuum vessel, the links were adjusted into a prescribed arc shape and their joints were locked. After multiple rail links transported in a cask from the storage building to the vacuum vessel were connected inside the cask, they were deployed into the vacuum vessel through the port (see Fig. 2). Therefore, this rail connection method is referred to as In-Cask Rail Connection (ICRC).

However, in this method, if a failure occurred in the remote handling equipment during rail connection inside the cask, access to the failure location would be extremely difficult, raising concerns about recovery operations. Even if one attempted to access the rail connection point using a manipulator during a failure in the rail deployment process, the spatial constraints would make this impractical, and thus the recoverability of failures was a major concern.

Consequently, although rapid recovery from equipment failure during rail connection is essential to secure the operational availability of the fusion reactor, it is difficult to establish an effective recovery scenario if the rail connection device becomes immobilized due to a malfunction. This is because access from behind the cask is physically blocked by the rails themselves, leaving only the option of accessing from the port front (vacuum vessel side). Even if one devised an approach using a long manipulator extended from an adjacent remote handling port, its feasibility would remain very limited.

In such a radiation environment inside the vacuum vessel where human entry is impossible, eliminating these risk factors associated with remote handling equipment failure is regarded as of utmost importance.

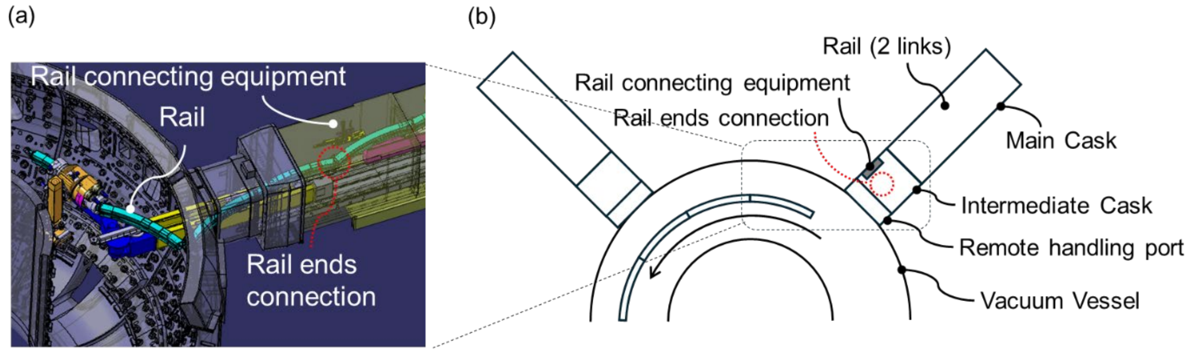

FIG. 2. Overview of the In-Cask Rail Connection in (a) CAD image (b) Schematic diagram (adapted from [5]*).*

3. RAIL DEPLOYMENT PROCEDURE AND CHALLENGES OF STRUCTURAL INTEGRITY

In the newly developed In-Vessel Rail Connection (IVRC) method, the rail is introduced from two adjacent remote handling ports. These are subsequently connected within the vacuum vessel, forming arc-shaped rails. Among the two remote handlings ports involved in the IVRC process, the port for the introduction of the Vehicle Manipulator is termed the Vehicle Fixing Arm (VFA) port, while the other port is designated as the Rail Fixing Arm (RFA) port. The end of the rail links deployed from the VFA port is equipped with a pin, whereas the opposite end of the rail links features a claw hook structure. After the claw hook and pin are engaged, the rail links are connected by the rail connection mechanism rotating the link mechanism inside the rail, which retracts the claw hook. Fig. 3 displays the names of equipment involved in the rail deployment process.

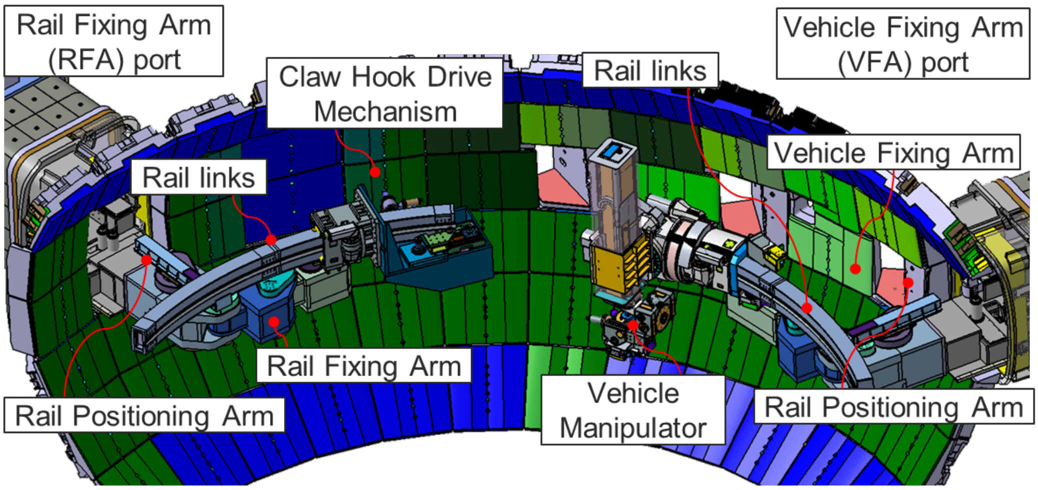

FIG. 3. Overview of the equipment involved in the In-Vessel Rail Connection process (adapted from [5]*).*

This rail deployment procedure begins once ITER plasma operation has stopped, air or inert gas has been introduced into the vacuum vessel, and remote handling equipment transported from the storage building by a cask has arrived at the port. The rail deployment process begins with two rail links introduced from the RFA port and positioned in an arc by the Rail Positioning Arm(RPA). Similarly, two additional rail links are introduced from the VFA port, positioned in an arc. The VFA-side rail links are then fed counterclockwise by the Vehicle Manipulator until the rail ends reach the connection position, where height and radial alignment adjustments are made to engage the pin and claw (Fig. 4 (a)). The rail ends are connected by retracting the claw hook, with the toggle mechanism securing the joint against tensile forces (Fig. 4 (b)). Next, the Vehicle Manipulator feeds the rail clockwise to detach it from the RFA-side equipment. The rail is subsequently supported by dedicated support equipment fixed at the remote handling port, with its arm inserted and rotated to lock the rail in place. Finally, with the rail fully deployed, the Vehicle Manipulator can travel along it to perform maintenance tasks inside the vacuum vessel.

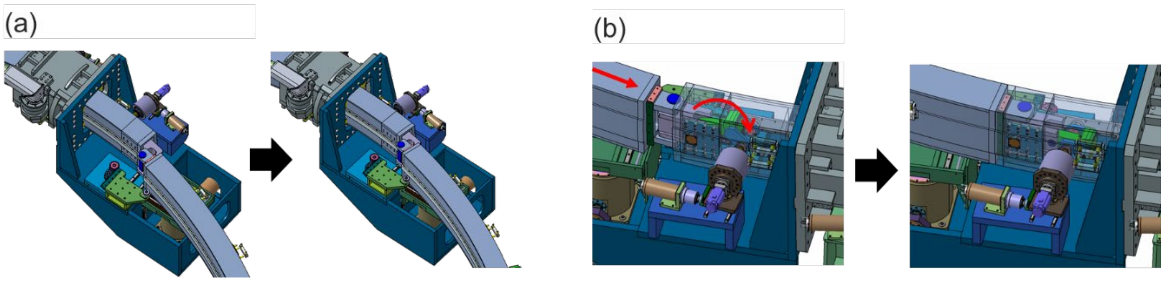

FIG. 4. Rail connection procedure (a) engagement of the rail ends (b) locking operation of the rail ends (adapted from [5]*).*

With the adoption of the IVRC method, the design of rail connection parts suitable for remote operation becomes necessary, requiring tolerance to positional deviations at the rail ends. Unlike the ICRC method, the IVRC method introduces rails from two ports, thereby increasing the cantilevered distance of the rail. As a result, the positioning accuracy of the rail ends decreases, necessitating greater tolerance to misalignments during rail-end engagement. This may lead to increased rail deflection when the vehicle manipulator travels along the rails. Therefore, while the introduction of the IVRC method does not require design modifications to the vehicle manipulator or the external rail geometry, it is essential to verify that both the rail connection and the entire rail structure possess sufficient strength and stiffness to ensure structural integrity. In the early study phase of the IVRC method, technical concerns arose regarding the reduction of stiffness in the redesigned rail connection, as well as the effects of gaps and friction within the connection on system-level modeling. To address these concerns, a 1/5 scale model was constructed and vibration tests were carried out to verify the dynamic behavior of the entire rail system, followed by a full-scale mock-up of the rail connection part to measure stress conditions and assess structural strength.

4. VERIFICATION TESTS OF STRUCTURAL STRENGTH

In this section, we describe the verifications conducted to address the technical concerns discussed in the previous section, including vibration tests using a scaled model, structural strength evaluation with a full-scale partial mock-up of rail connection parts. The evaluation results confirmed the practical strength of the rail connection parts.

4.1. Verification of Dynamic Characteristics Using a Scaled Mock-up

This section describes the setup of the 1/5 scale vibration test and presents its configuration and results. A 1/5 scale model, encompassing the rail, part of the rail support equipment, and a simplified vehicle manipulator (see Fig. 5(a)), was constructed and subjected to experimental modal analysis by hammering the midpoint of the rail. Accelerometers were attached at four points along the rail model to measure accelerations, enabling evaluation of natural frequencies and vibration mode shapes. Excitation was applied by hammering the rail at its midpoint.

Rail
The rail was fabricated using the same material as the actual design, faithfully reproducing the geometry of a 100-degree rail at 1/5 scale. Elements that could not be precisely scaled, such as bolts, were modified as necessary. The rail connection structure replicated the actual mechanism, incorporating claw hooks to grip pins and a toggle mechanism for rail locking.

Vehicle Manipulator
For the purpose of understanding the dynamic behavior of the rail, it was not necessary to reproduce the detailed structure of the Vehicle Manipulator. Instead, weights were used to simulate the manipulator's mass and the moments acting on the rail. The mock-up manipulator contacted the rail through multiple guide rollers and could be manually moved along the rail.

Partial Model of Rail Support Equipment
Rather than fabricating the entire rail support equipment, only the connection point with the rail was modelled. This choice was made because the support equipment is rigidly attached to the vacuum vessel port and its stiffness is considered significantly higher than that of the rail itself.

The comparison between natural frequencies obtained from hammering tests and those derived from FEM analysis focused on the fundamental vertical mode, which is critical during earthquakes, as shown in Fig. 5 (b). The results revealed substantial agreement between the experimental outcomes and the FEM analysis, validating the appropriateness of linear models for analysis. In the FEM modelling of the rail connection points, the rigid connection at the rail connection section ensured that the natural frequencies and the mode shapes match that of the 1/5 scale model. It is noted, by similarity laws, that comparing the natural frequencies obtained from a 1/5 scale model requires scaling the frequencies by a factor of 1/5 when compared to full-scale results.

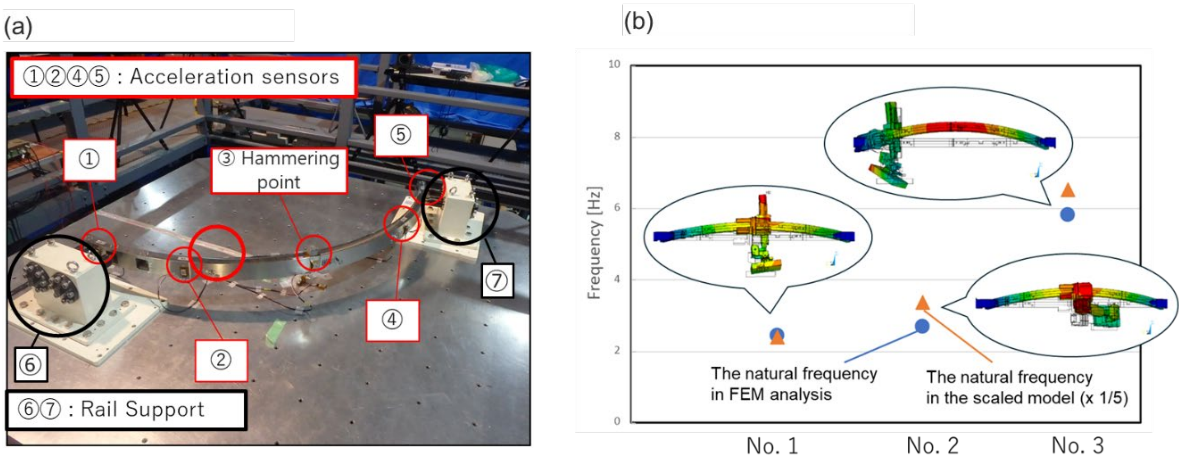

FIG. 5. (a) Experimental set-up of the vibration test with scaled mock-up (b) Comparison of the main natural frequency between the experimental results and FEM analysis (adapted from [5]*).*

4.2. Strength Evaluation of Rail Structure with Full-Scale Partial Mock-up

This section discusses strength verification of the rail connection part. Small gaps and frictional contact behavior at the connection are difficult to reproduce accurately using FEM analysis alone. Therefore, a full-scale partial mock-up of the rail connection and its adjacent structure was fabricated, and load tests were performed to validate the analysis. Based on these tests and FEM results, design improvements were implemented.

The full-scale mock-up of the rail connection section (Fig. 6) was fabricated and subjected to load tests. Strain gauges were attached to the claw and pin structures as well as to the rail frame near the connection. The strength of the hooks and pins was evaluated under both normal operating loads and seismic loads corresponding to ITER's design basis earthquake (equivalent to a once-in-100-years event).

Comparison between test results and FEM predictions revealed that stresses at the upper part of the rail frame were about 20% higher than predicted. The cause was attributed to local contact at the upper contact pad. Additionally, a parametric survey of FEM analysis was conducted to examine the influence of gaps in the rail connection. The results confirmed that stress is highly sensitive to clearance. For example, when the gap at the claw connection surface increased by 0.5 mm, the stress increased by 40 MPa. This finding suggests that strict control of clearances at contact points is essential. Based on this result, design modifications were implemented, including the repositioning of the upper contact pads and the enlargement of the surface area of the side contact pads as shown in Fig. 7. It was confirmed that the structural strength of the rail connection section is sufficient.

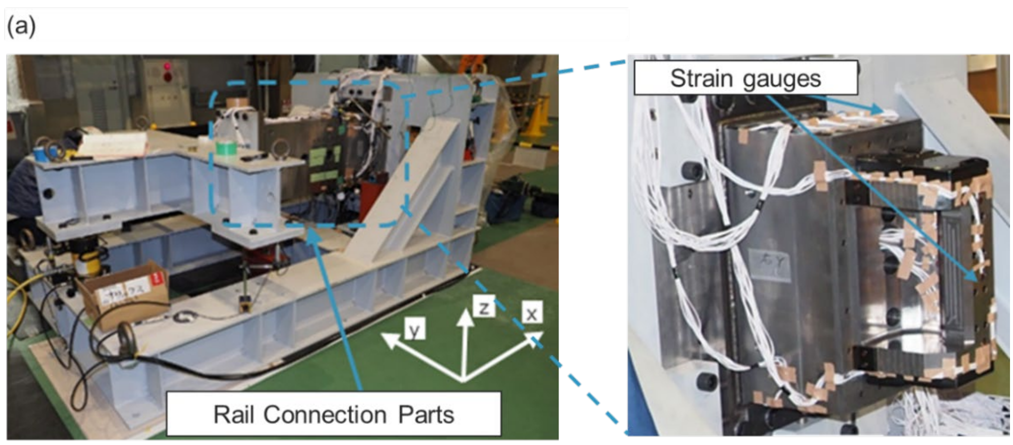

FIG. 6. Set-up of the loading test of rail connection part (a) Test rig overview (b) Rail ends (adapted from [5]*).*

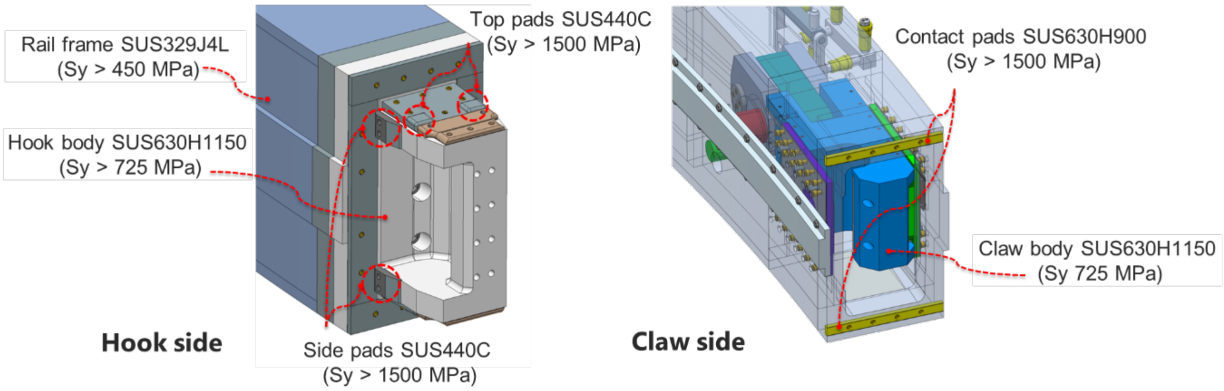

FIG. 7. Reinforced design of the rail connection parts.

5. FULL-SCALE MOCK-UP OF THE ENTIRE RAIL CONNECTION EQUIPMENT

Following the confirmation of the feasibility of the rail connection approach presented in the previous section, efforts have been directed toward the fabrication of a full-scale prototype of the entire rail connection equipment (Fig. 8). The purpose of this development is to establish a framework for verifying the overall rail connection process under representative conditions. Preparations for the planned verification tests are currently ongoing. With the test device, we plan to conduct rail feeding operations with the Vehicle Fixing Arm and Rail Fixing Arm, perform precision alignment measurements of the partially assembled rail, and evaluate the robustness of the rail connection, including the allowable positional error. The results of these investigations are expected to provide critical insights for the implementation of the actual system.

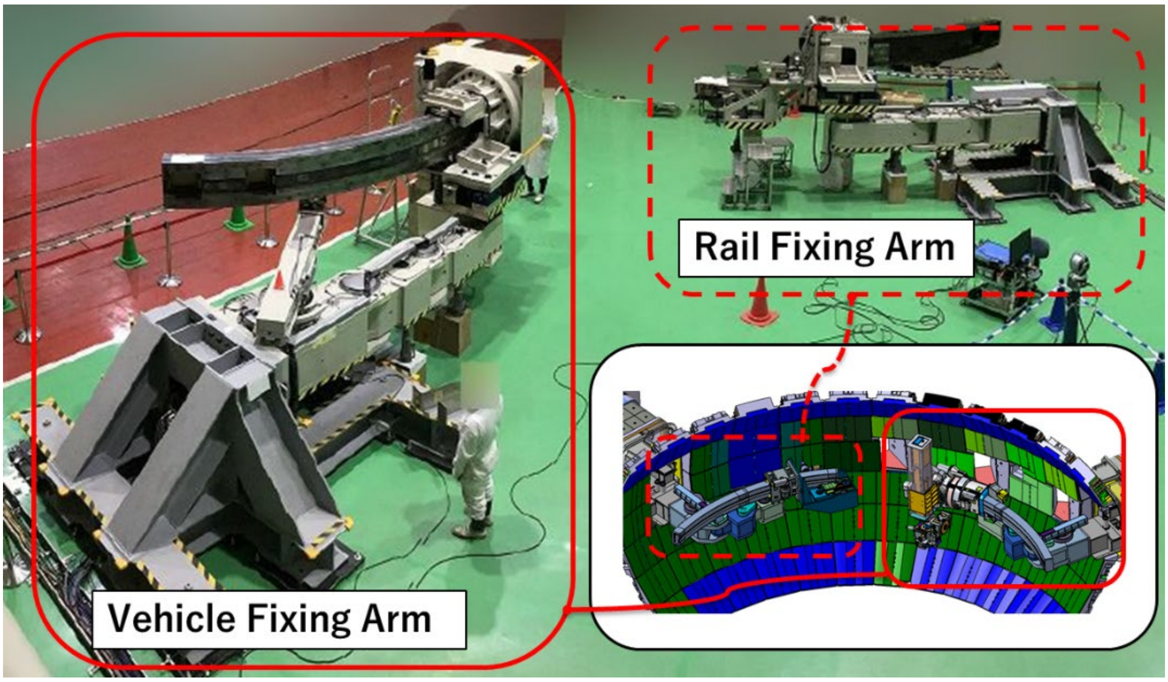

FIG. 8. Picture of the full-scale mock-up of the entire rail connection equipment under preparation.

6. CONCLUSION

This paper presents the In-Vessel Rail Connection (IVRC) method developed for the ITER project and verifies the structural integrity of the entire rail structure by confirming dynamic behaviors through testing of a 1/5 scale model and validating structural integrity through a partial mock-up and FEM analysis. Based on these verifications, we will initiate full-scale tests of rail connection process, toward its application in ITER.

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