Development of in-vessel rail deployment and connection method for ITER Blanket remote maintenance

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This 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 novel rail deployment 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 mockup, together with Finite Element Method (FEM) analyses, this paper verifies the structural integrity of the overall IVRC rail design.

Introduction

Deployment of robotic systems into the workplace is both a prerequisite and a key aspect for remote handling operations in challenging environments reactors. In the context of ITER, remote handling systems must perform demanding tasks requiring careful consideration of both environmental conditions such as gamma-ray irradiation and operational complexities. 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. Beyond basic functionality, it is important to ensure that these systems are also recoverable, capable of responding unexpected failures as much as possible and restoring functionality without leading to intractable 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[1]. 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)[2]. This method allows development of recovery scenario by the introduction of a light-weight manipulator to access the failed equipment for rescue operations.

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 mockup 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 mockup of the rail connection section, accurately simulating the structure, was created to conduct strength validations.

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. 1 displays the names of equipment involved in the rail deployment process.

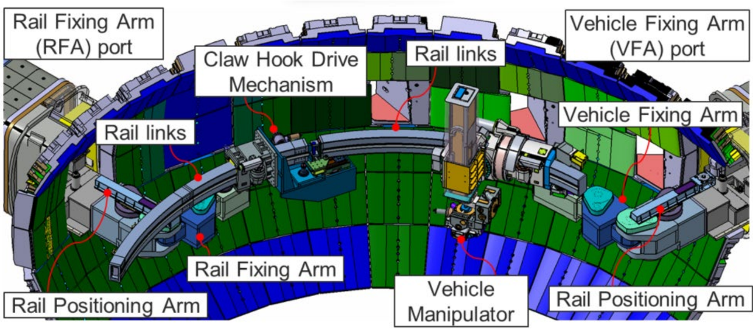

Fig. 1 Overview of the equipment involved in the In-Vessel Rail Connection process[2].

Verification tests of structural strength

A 1/5 scale model, encompassing the rail, part of the rail support equipment, and a simplified vehicle manipulator (see Fig. 2), was constructed and subjected to experimental modal analysis by hammering the midpoint of the rail. The comparison between natural frequencies obtained from hammering tests and those derived from FEM analysis focused on the fundamental vertical mode is shown in Fig. 3. The results revealed substantial agreement between the experimental outcomes and the FEM analysis, validating the appropriateness of linear models for analysis. In the FEM modeling 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.

A full-scale mockup of the rail connection section was then fabricated to conduct loading tests. The mechanical integrity of the hooks and pins was evaluated under conditions of normal operation and with a design seismic loading. The evaluation results indicated that the design criteria are met and confirmed the practical strength of the rail connection parts.

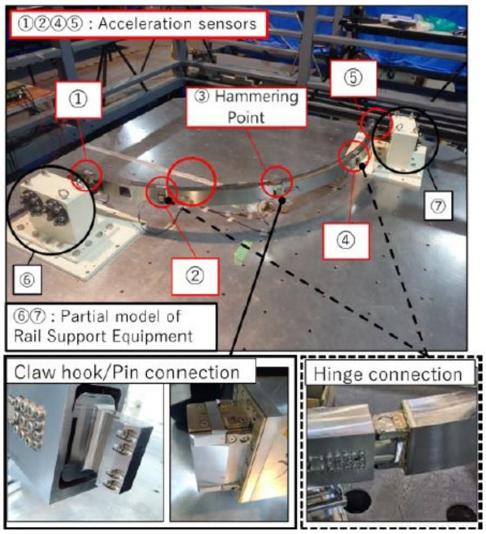

Fig. 2 Setup of the vibration tests with the scaled rail mockup[2].

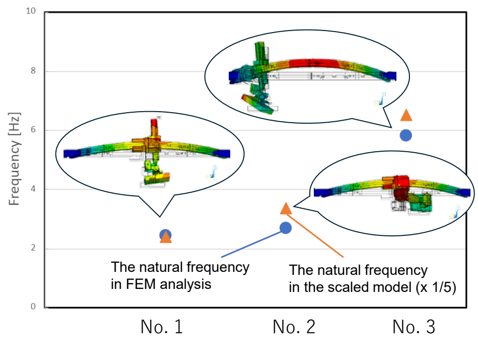

Fig. 3. Comparison of natural frequencies in vibration tests and FEM analysis in thr ee representative postures.

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 mockup and FEM analysis. We establish a foundation for full-scale verification of rail connections, toward its application in ITER.

References

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