

Structural Design Assessment of the HCCP TBM-set Attachment

Seong Dae Park^a, Suk-Kwon Kim^a, Dong Won Lee^a, Jae-Sung Yoon^a, Hyoseong Gwon^b

^bKorea Atomic Energy Research Institute, Daejeon, Republic of Korea

^bKorea Institute of Fusion Energy, Daejeon, Republic of Korea

*Corresponding author: sdpark@kaeri.re.kr

***Keywords** : RCC-MRx, TBM, attachment, EUROFER 97, RAFM steel

1. Introduction

The HCCP (Helium-Cooled Ceramic Pebble) TBM-set installed in ITER consists of the TBM-box, TBM-shield, and their connecting attachment structures, and is derived from the European HCPB TBM development program [1–3]. The attachment serves as a primary structural component that transfers mechanical loads from the TBM-box to the TBM-shield. At the same time, it must accommodate relative deformation induced by thermal expansion during operation, which has been identified as a key thermo-mechanical design issue in HCPB TBM systems [2,4,8]. Therefore, the attachment is required to simultaneously satisfy load transfer capability and thermal compliance.

The current attachment configuration was developed by referencing the HCPB TBM-set design [1,3]. Thin plate elements were introduced to enhance structural flexibility and to mitigate excessive constraint forces caused by volumetric thermal expansion at elevated temperatures, consistent with previous thermo-mechanical assessment approaches [2,4]. Although this concept effectively reduces thermal stress concentration, it increases the total usage of RAFM steel (EUROFER97), which is the reference structural material for HCPB blanket systems [5–7].

According to the TBM-set design criteria, the total allowable mass of EUROFER97 is limited to 1.3 tons. The present thin-plate-based attachment exceeds this mass constraint, making geometric redesign necessary. This study evaluates the structural behavior of the current attachment configuration through finite element analysis and discusses design considerations for a lightweight attachment concept that satisfies both thermal expansion requirements and mass limitation, in line with ongoing TBM structural evolution efforts [3,9].

In addition, the structural assessment was performed in accordance with the stress evaluation philosophy of RCC-MRx, considering primary and secondary stress components under normal operating (Level A) loading conditions to ensure consistency with nuclear design requirements.

2. Design Requirements and Analysis Method

The thermo-mechanical design of HCPB TBM structures has previously been assessed with respect to codes and standards [2,4], and similar principles are adopted in this study.

The attachment must satisfy the following design requirements:

- Transfer operational loads, including self-weight and reaction forces,
- Accommodate thermal expansion of the TBM-box,
- Maintain acceptable stress levels at connection regions,
- Ensure EUROFER97 mass \leq 1.3 tons.

More specifically, the attachment design aims to (i) prevent excessive constraint forces at the TBM-shield back plate interface, (ii) limit peak stress at welded or contact regions, and (iii) maintain sufficient stiffness along the primary load transfer direction while allowing directional flexibility in the thermal expansion direction.

Thermal loading was defined based on the steady-state operational temperature distribution, consistent with thermo-mechanical analyses performed for EU-HCPB TBM systems [4,8]. Mechanical loading included self-weight and design reaction forces. Linear static finite element analysis was performed using a global TBM-set model, and deformation and stress distributions in the attachment region were evaluated.

The maximum von Mises stress and total deformation of the attachment were extracted from the global model and compared with the allowable stress limits defined by RCC-MRx for the corresponding material category.

3. Structural Behavior of the Thin-Plate-Based Attachment

Previous thermo-mechanical investigations of HCPB TBM structures have shown that structural flexibility is essential for mitigating thermal stress concentration [2,4]. In the present study, the thin-plate-based attachment demonstrated sufficient flexibility under thermal loading. The global model results showed that thermal expansion was partially accommodated by bending deformation of the thin plates, and the overall constraint forces remained within acceptable limits.

The maximum von Mises stress in the thin-plate configuration was 786 MPa, corresponding to approximately 170% of the allowable stress defined by RCC-MRx under Level A conditions.

The increased plate area resulted in a significant contribution to the total EUROFER97 mass, exceeding the 1.3-ton limitation. From a materials perspective,

EUROFER97 has been extensively characterized for fusion blanket applications [5–7], but its efficient structural utilization remains a design challenge. In addition, localized stress concentration was observed near connection regions and plate edges (Fig. 1).

These results indicate that while the current concept is structurally feasible from a thermal compliance perspective, it is not optimal under the imposed mass restriction.

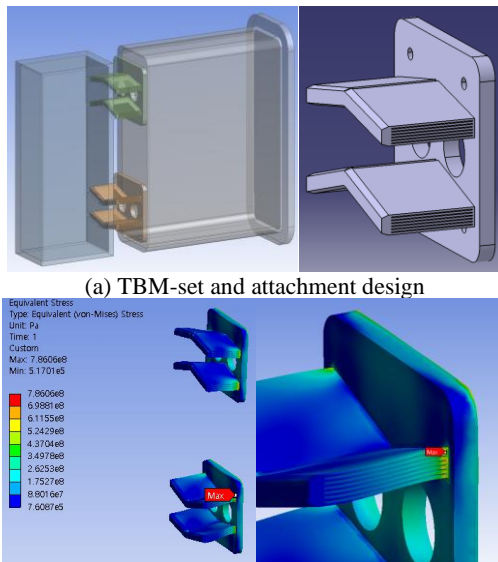


Fig. 1. Geometry design and stress distribution of thin plate model

4. Design Improvement Strategy for the Attachment Structure

Design activities of EU-TBM systems have continuously aimed at improving structural efficiency while maintaining thermo-mechanical integrity [3,9]. To satisfy both structural integrity and mass limitation, a redesigned attachment geometry should focus on structural efficiency and directional flexibility.

First, the primary load path between the TBM-box and TBM-shield should be clearly defined. Structural members that do not significantly contribute to load transfer should be minimized.

Second, instead of distributing flexibility over large plate areas, localized compliant mechanisms may be introduced. Directionally flexible regions can allow thermal expansion in specific directions while maintaining stiffness along the main load transfer axis.

Third, mass-efficient structural concepts such as rib-reinforced plates, strut-based members, or hybrid plate-truss configurations may be considered to improve stiffness-to-mass ratio. Such structural efficiency considerations are consistent with blanket optimization efforts toward DEMO-relevant systems [9,10].

Preliminary conceptual comparison of candidate geometries (Model 1–3 in Fig. 2) indicates that structural stiffness can be preserved while reducing total plate

surface area. Among the examined concepts, Model 2 showed improved stiffness-to-mass performance compared with the original thin-plate configuration.

Future work will include comparative finite element analyses of candidate geometries under identical loading conditions to identify an optimized attachment configuration that satisfies both the EUROFER97 mass constraint and structural performance requirements.

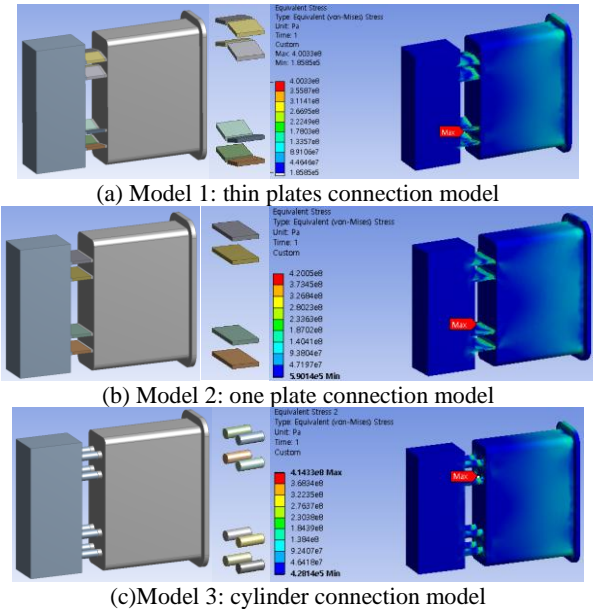


Fig. 2. Comparison of candidate attachment configurations and corresponding maximum stress distribution.

5. Conclusions

This study assessed the structural behavior of the HCCP TBM-set attachment under thermal expansion and material mass constraints. The current thin-plate-based design provides effective thermal compliance but exceeds the allowable EUROFER97 mass limit of 1.3 tons.

A lightweight attachment concept based on clarified load paths, directional flexibility, and improved structural efficiency is therefore required, consistent with the evolution of HCPB TBM structural design frameworks. The proposed design considerations provide a systematic basis for the next stage of attachment geometry optimization and structural verification.

By integrating code-based stress evaluation and mass efficiency considerations, the proposed redesign strategy provides a practical engineering framework for achieving regulatory compliance while meeting system-level material constraints.

REFERENCES

- [1] L. M. Giancarli, et al., Overview of the ITER TBM Program, Fusion Engineering and Design, Vol.87, p.395, 2012.
- [2] F. Cismondi, S. Kecskes, and G. Aiello, HCPB TBM thermo mechanical design: Assessment with respect to codes

and standards and DEMO relevancy, *Fusion Engineering and Design*, Vol.86, p.2228, 2011.

[3] J. Vallory, et al., Design activities toward the achievement of the conceptual phase of the EU-TBM sets, *Fusion Engineering and Design*, Vol.109, p.1053, 2016.

[4] F. Hernández, F. Cismondi, and B. Kiss, Thermo-mechanical analyses and assessment with respect to the design codes and standards of the HCPB-TBM Breeder Unit, *Fusion Engineering and Design*, Vol.87, p.1111, 2012.

[5] P. Fernández, et al., Metallurgical characterization of the reduced activation ferritic/martensitic steel EUROFER97 in as-received condition, *Fusion Engineering and Design*, Vol.58–59, p.787, 2001.

[6] G. Stornelli, et al., Grain refinement and improved mechanical properties of EUROFER97 by thermo-mechanical treatments, *Applied Sciences*, Vol.11, p.10598, 2021.

[7] R. Lindau, et al., Present development status of EUROFER and ODS-EUROFER for application in blanket concepts, *Fusion Engineering and Design*, Vol.75–79, p.989, 2005.

[8] F. Cismondi, et al., Design update, thermal and fluid dynamic analyses of the EU-HCPB TBM in vertical arrangement, *Fusion Engineering and Design*, Vol.84, p.607, 2009.

[9] F. A. Hernández, et al., Consolidated design of the HCPB Breeding Blanket for the pre-conceptual design phase of the EU DEMO and harmonization with the ITER HCPB TBM program, *Fusion Engineering and Design*, Vol.157, p.111614, 2020.

[10] M. Abdou, et al., Blanket/first wall challenges and required R&D on the pathway to DEMO, *Fusion Engineering and Design*, Vol.100, p.2, 2015.