Stress Analysis of HCPB BB under Ex-Vessel LOCA Condition

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Abstract. Helium Cooled Pebble Bed Breeding Blanket (HCPB BB) is a kind of concept for the European demonstration fusion reactor (DEMO). The blanket attachment system plays an important role in the mechanical connection of the BB and vacuum vessel. Typically, the mechanical and thermal loads should meet the requirement to avoid collapse of the system with off-normal conditions, e.g., under ex-vessel Loss of Coolant Accident (LOCA). This paper investigates the loading requirement corresponding to the maximum stress that can sustain to avoid the LOCA condition. Firstly, a model of the BB is constructed using SolidWorks. Then, stress analysis is carried out based on the cross section of the blanket. Through simulation, the critical condition for the LOCA case and the maximum stress value for the model are obtained. According to the relevant size dimension from the reference, the blanket's cross section is drawn, and one can get the stress field under the ex-vessel LOCA through stress analysis. The stress distribution under the ex-vessel LOCA condition is simulated to find out the maximum stress field that the blanket can sustain through this paper. The significance is to predict the possible conditions leading to an accident and find possible methods to avoid them.

1. Introduction
Contemporarily, there is an increasing demand for energy sources. However, the supply of traditional energy (e.g., oil and natural gas) is limited, which may only sustain for only hundreds of years [1]. Thus, new-type energy sources (e.g., wind and solar energy) have been developed to solve the crisis. Thereinto, nuclear fusion energy is a kind of new-type energy source, which produces a tremendous amount of energy during the process of compressing hydrogen atoms and heating them into a dense, hot plasma state [2]. The fusion reactor is often applied to control the process of fusion reaction and transfer the energy. One part of it is helium cooled pebble bed (HCPB), a European DEMO reference concept for nearly one decade [3]. Thereinto, Loss of Coolant Accident (LOCA) is one of the important components in the HCPB Breeding Blanket (HCPB BB), which converts heat into useful electrical power [4].

Generally, nuclear reactors generate heat internally, which requires a coolant system removes the heat and turns it into useful electrical power [5]. If the coolant flow is reduced, the nuclear reactor's emergency shutdown system will immediately stop the fission chain reaction. The breakdown of the system may lead to thermal expansion of the whole structure. The unsteady state of the structure is
highly likely to cause dangerous accidents [4]. Thus, the stress analysis of the system is essential to ensure the safety of the nuclear reactor.

In this paper, we present the stress analysis of LOCA in the HCPB BB with ambient temperature. The motivation is to test the structural stability of the whole system before it starts to run, i.e., evaluate the reaction loads to the structure during the accident. Since the normal conditions have been studied a lot, it is more meaningful to make stress analysis under ex-vessel LOCA condition. It is also common in real situations and deserves consideration for further analysis. The rest parts of the paper are organized as follows: Sec. 2 introduces the simulation methods; Sec. 3 demonstrates the results and gives discussions; a brief summary is presented in Sec. 4 eventually.

2. Method
In this paper, SolidWorks [6] is applied to model the stress analysis, which constructs a cross section of the blanket about the global model (Figure 1) and part model (Figure 2). Each module is connected to the so-called back supporting structure (BSS). Each group of modules supported by a BSS forms a segment. The European DEMO segmentation is arranged in 7 outboards (OB) and 7 inboards (IB) blanket modules in each OB/IB blanket segment [7]. The BSS provides the coolant for the FW and BZ of each blanket module by BSS manifold pipes. The FW cooling channels have a cross-section of 12.5 mm × 12.5 mm. The FW front part (plasma side) thickness is 3 mm, resulting in a total FW thickness of 25 mm, which is thin to contribute to a good tritium breeding performance (TBR ~ 1.15) while still satisfying the structural requirement. The CP cooling channels have a rectangular cross-section of 3 mm × 5 mm. The constructed global model is shown in Figure 1.

![Figure 1. Global model of the blanket](image1)

![Figure 2. Part model of the blanket](image2)

Subsequently, stress analysis is carried out for the global model and part model about OB7 in the room temperature. The part model consists of 3 OB blanket segments with their attachments, 2 IB blanket segments with their attachments, the upper port shield plug, and the corresponding VV counterparts, as shown in Figure 2. During modelling, we first select materials (synthetic steel) and fix geometry and actual force surface following Ref. [3]. Then, the simulation is run to obtain the force analysis, displacement change, and strain. Based on the room temperature and LOCA, we pick up the data about the pressure and moment, where one obtains the maximum stress and moment that the blanket can sustain to avoid the LOCA. Figure 1 shows the global model of the blanket.
3. Results and Discussion

Table 1. Reaction forces and moments at attachments acting upon VV (F-force, M-moment)

|        | Fx (MN) | Fy (MN) | Fz (MN) | Mx (MNm) | My (MNm) | Mz (MNm) |
|--------|---------|---------|---------|-----------|----------|----------|
| OBR Key Bottom | 3.2     | -6.4×10^{-2} | 5.7     | -5.9×10^{-2} | 0.13     | -7.5×10^{-3} |
| OBR Pad       | 3.7×10^{-4} | -2.5×10^{-8} | 5.2×10^{-3} | -5.6×10^{-8} | 6.3×10^{-6} | -4.7×10^{-8} |
| OBC Key Bottom | 3.1     | -2.7×10^{-2} | 5.7     | 0.18       | 0.13     | 3.4×10^{-2}  |
| OBC Pad       | 1.7×10^{-13} | 3.8×10^{-15} | 5.4×10^{-3} | -2.1×10^{-8} | -2.5×10^{-6} | 2.3×10^{-10} |
| OBL Key Bottom | 3.2     | 5.0×10^{-2} | 5.7     | -9.1×10^{-2} | 0.13     | -4.2×10^{-2} |
| OBL Pad       | 5.1×10^{-4} | -1.6×10^{-8} | 5.2×10^{-3} | -5.5×10^{-8} | 9.9×10^{-6} | 1.0×10^{-7}  |
| OBR Key Extens | 0.62    | -9.4    | -2.6×10^{-2} | 0.77      | 4.7×10^{-2} | 0.57     |
| OBR Top       | 2.7     | -0.22   | -4.2    | 0.26       | -0.96    | 0.23     |
| OBL Key Extens | 0.64    | 9.6     | -3.1×10^{-2} | -1.4      | 8.3×10^{-2} | -1.3    |
| OBI Top       | 2.7     | 1.5×10^{-2} | -4.5    | -0.33      | -0.93    | -0.2     |
| IBR Key Bottom | 0.87    | 2.8×10^{-2} | 3.7     | -1.4×10^{-2} | 7.4×10^{-3} | 1.5×10^{-2} |
| IBR Key Mid-1 | 2.3     | 1.5×10^{-2} | 3.4×10^{-2} | -2.5×10^{-3} | -0.19    | 2.8×10^{-3} |
| IBR Key Mid-2 | 5.7     | -0.17   | -0.25   | 2.0×10^{-2} | 0.57     | -7.7×10^{-3} |
| IBR Key Top   | -0.25   | 0.14    | -2.7    | 3.7×10^{-2} | -0.22    | 6.2×10^{-3} |
| IBL Key Bottom | 0.78    | 5.4×10^{-2} | 4.7     | 1.9×10^{-2} | 4.2×10^{-3} | -2.1×10^{-2} |
| IBL Key Mid-1 | 2.4     | -0.15   | 3.6×10^{-2} | -2.6×10^{-3} | -0.20    | -1.4×10^{-2} |
| IBL Key Mid-2 | 6.1     | 0.32    | -0.27   | -5.7×10^{-2} | 0.70     | 1.7×10^{-2} |
| IBL Key Top   | -0.3    | -0.21   | -3.7    | -5.9×10^{-2} | -0.36    | -0.17    |

Note: OBR/IBR is the right of the out board/in board, OBL/IBL is the left of the out board/in board.

Table 1 summarizes the three-dimensional forces and moment parameters acting on the blanket attachment. Based on this table, the maximum pressure can be acquired. According to the part model, one can find that the stress is lower in the outer plate while higher in the inner plate. In the global model, gravity acts on all objects. The maximum value of the IBLIBL Middle-2 is 6.4 MN. By comparing with the existing literature on stress analysis of HCPB BB in the unloaded state, it is found that the maximum stress is located in the region where the two cladding modules interact. It was found that the HCPB BB and attachment system exhibited sufficient structural strength under selected forward ship LOCA. For better illustration, the pressure and displacement distributions are presented in Figure 3, which further proves the structure is stable at room temperature since the effects are minor. As for the figure3, we first, add the Simulation plug-in. Click Simulation to perform the force analysis. Next, click on the new example in the example consultant and select the static stress analysis. After that, click Apply Materials and select the material. Next click Fixture Advisor, fix the geometry and select the fixed surface. Then, the external load consultant selects the force and surface, that is, the actual force surface, and then inputs the value. Finally, this example is run to obtain the force analysis, displacement change and strain. At last, we got the result of Figure 3.

Even though our estimation is relatively accurate, there are still some drawbacks for improvement. First, we only consider the stress analysis of the HCPB BB under ambient temperature, while high temperature environments might occur during operation. Thus, one ought to estimate the distribution of forces and moments under different temperatures and give a safe temperature range where the HCPB BB can still sustain. Second, we only use SolidWorks as the software to build up the model and stress analysis, i.e., it will be one of the limits about the result. Third, the model is slightly different from Ref. [3, 7], which might result in a little bit of error.
Figure 3. Part model's pressure(left) and displacement(right) distribution under ex-vessel LOCA in the room temperature.

4. Conclusion
In summary, stress analysis has been presented to re-exam the current design of EU DEMO baseline 2015 under an ex-vessel LOCA condition. Base on SolidWorks modelling, the reaction forces and moments at attachments acting on VV under selection accident conditions are obtained. According to our results, the designed structure is stable at room temperature, verifying the structure's stability under certain forces for the state-of-art design. These results will be useful for further improving the design of the HCPB BB and its attachment system.

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