Thermo-mechanical analyses of HELICA and HEXCALIBER mock-ups

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ABSTRACT

As benchmark exercises, HELICA and HEXCALIBER mock-ups have been launched in the HE-FUS 3 facility at ENEA Brasimone for investigating the thermo-mechanical behaviour of pebble beds. The present material model of pebble beds, based on the modified Drucker-Prager-Cap model, has been implemented in the commercial finite element package, ABAQUS. The overall behaviour of the lithium orthosilicate cassette (HELICA) and the interactions of ceramic breeder pebble beds and beryllium pebble beds (HEXCALIBER) are studied numerically. The finite element analyses show the temperature distribution of the mock-up experiments, as well as the stress–strain fields. The predictions of HELICA mock-up are compared with the experiments, including the temperature measured by thermo-couples located inside the pebble beds and the lateral deformation of the cell.

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1. Introduction

Working as tritium breeder (i.e. lithium orthosilicate [1]) and neutron multiplier (beryllium) materials in Helium Cooled Pebble Bed (HCPB) blankets in fusion reactors, pebble beds are not only subjected to severe conditions, such as neutron irradiation and high heat flux, but also have complex behaviour due to their discrete nature [2]. Therefore, the thermo-mechanical properties of pebble beds are the mostly concerned in the design of HCPB blankets [3]. To investigate the thermo-mechanical properties of pebble beds under fusion relevant conditions, out-of-pile mock-up experiments are carried out in EU associations, such as HELICA (HE-FUS3 Lithium Cassette) and HEXCALIBER (HE-FUS3 Experimental Cassette of Lithium and Beryllium Pebble Beds) mock-up experiments launched in the HE-FUS3 facility at ENEA Brasimone [4,5]. Thermo-couples (TCs) and linear variable displacement transducers (LVDTs) can be placed to monitor the response of the pebble beds at different loading conditions. To avoid the interference of TCs located inside the pebble layers, the number has to be limited. On the other hand, the stress and strain are difficult to be measured experimentally. Thus, the finite element (FE) simulation using the proper material model is very important to understand the thermo-mechanical behaviour of pebble beds. The comparison between simulation and experiments can be carried out at the points where the measurements are made in experiments. To this end, different EU associations (ENEA, NRG, FZK, etc.) took part in this benchmark exercise, using different constitutive models of pebble beds [6].

In this investigation, the present material model is composed of a non-linear elasticity law, a modified Drucker-Prager-Cap theory and a creep law [7,8]. A method of identification of the temperature dependent material parameters from experimental results (empirical curves for uniaxial compression experiments) is developed, resulting in a thermo-plasticity model [9]. The interface heat transfer between pebbles and structural materials is described by a function of applied pressure and temperature. The material model and the interfacial model have been implemented into the commercial finite element code, ABAQUS, and applied to the fully coupled thermo-mechanical analyses of HELICA and HEXCALIBER mock-up experiments.

2. Material model and validation

To describe the response of granular materials under external excitations, the hydrostatic pressure p and von Mises stress q are often used, and they can be expressed in terms of stress tensor σ_{ij} and deviatoric stress tensor s_{ij} as $p = -\sigma_{ii}/3$ and $q = \sqrt{3s_{ij}s_{ij}/2}$. For pebble beds, even in the elastic region, the material shows strong dependence on the stress state [3], and this is modelled by a non-linear elasticity law. The irreversible strain can be decomposed into the plastic and creep strains. The first part has been modelled by the modified Drucker-Prager-Cap model, consisting of the shear failure surface and cap surface. A non-associated plastic flow theory has also been implemented in this model. Similar to the plastic flow potentials, the creep potentials are used to describe the time-dependent behaviour of pebble beds [8,10].

The commonly used experiments to characterize pebble beds are uniaxial compression tests (UCT, [11]). Empirical curves can be extracted from the measurements. For Li_4SiO (diameter: 0.2–0.4 mm) and beryllium (diameter: 1 mm), pebble beds used in

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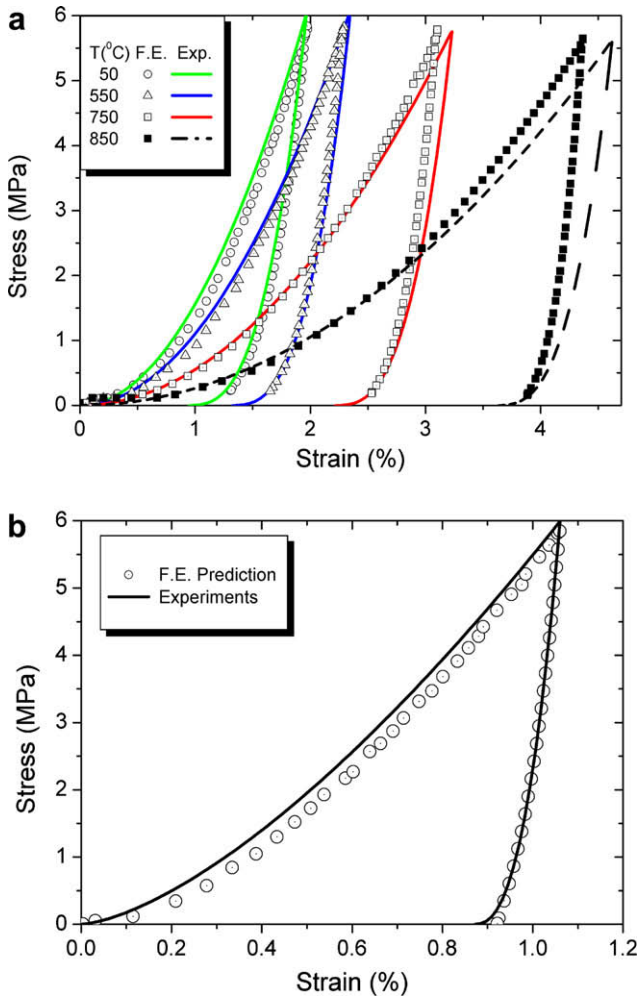*E-mail address:* yixiang.gan@imf.fzk.de (Y. Gan).

Fig. 1. The uniaxial compression of (a) lithium orthosilicate under 50–850 °C; (b) beryllium pebble beds. Dots, prediction of FEA; lines, empirical curves.

Fig. 3. (a) Temperature changes over time during one loading cycle: 100 mm to FW. Dots, experimental data; solid lines, FE calculation (unit: °C). (b) Displacement of HELICA (unit: mm), comparison between LVDTs' measurements (dots) and calculated value (the solid line).

HELICA and HEXCALIBER are qualified by FZK and the corresponding empirical curves can be found in Ref. [12]. By analyzing the stress state in these type of experiments, the identification method of the material parameters has been studied [9]. The present material model has been implemented in ABAQUS. For validation purpose, the comparison between the prediction of UCT and the experiments is shown in Fig. 1. Although the temperature of ceramic breeder material varies from 50 to 850 °C, the prediction of the present model is well consistent with the experimental observation.

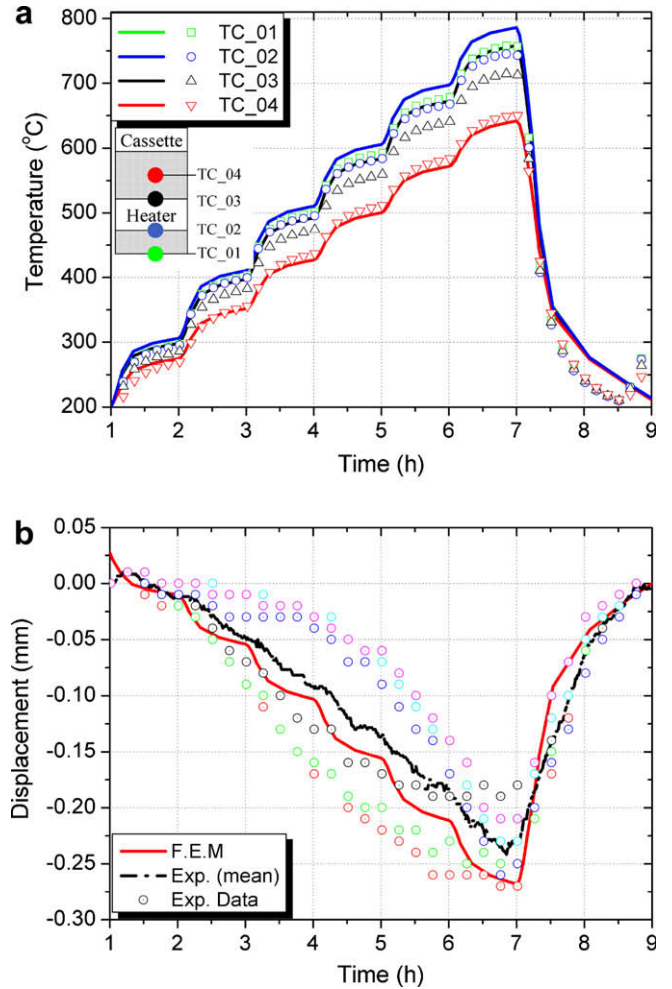Furthermore, in the interfacial region, a thermal contact conductance model is used to represent the changing of the heat trans-fer coefficient (HTC) in dependence on both the applied pressure and temperature. The relation can be expressed explicitly, taking into account the Hertzian contact law and the heat transfer through the interfacial gas.

3. Thermo-mechanical analyses

HELICA (one Li_4SiO_4 layer) and HEXCALIBER (Li_4SiO_4–Be–Li_4SiO_4–Be layers) mock-ups are heated by two electrical heaters located inside each pebble layer, from 0 to 42 kW/m^2 in six 1-h subsequent steps, and helium is used as both coolant and purge

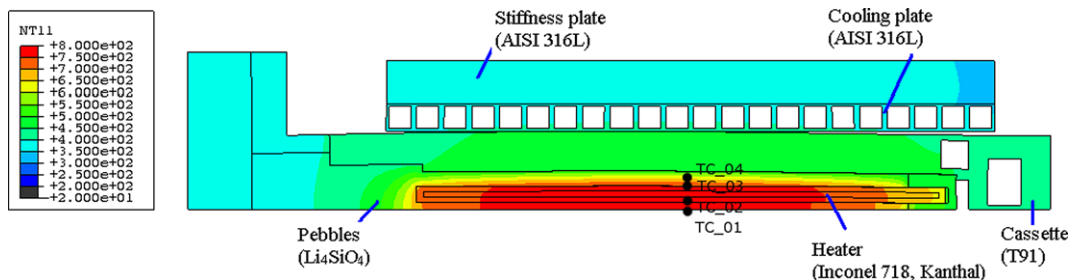**Fig. 2.** Calculated temperature distribution at the maximum electrical load (unit: °C), with deformations at a scale factor of 5.
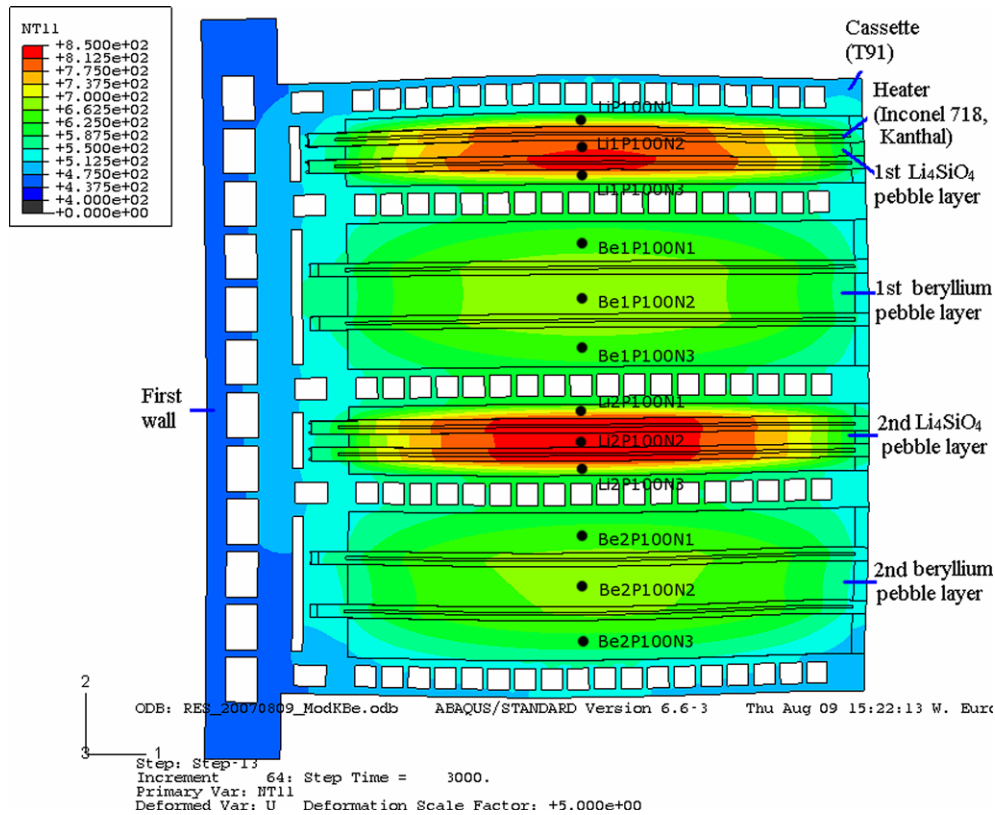
Fig. 4. Temperature profiles of HEXCALIBER at the maximum electrical load (unit: °C), with deformations at a scale factor of 5.

gas. Additional details can be found in Ref. [6]. In this investigation, generalized plane strain elements are used in the fully coupled thermo-mechanical analyses, and the out-of-plane strains accounts for the thermal expansion of the cassette to avoid enormously high non-physical stresses.

3.1. HELICA

In the analysis of HELICA, two cycles of loading and unloading have been simulated. The coolant temperature varies from 200 to 300 °C during the loading. Fig. 2 shows the temperature distribution at the maximum heat flux. The predicted temperature, located at TCs at 100 mm to the first wall (FW), and the lateral displacements of the cell in HELICA are compared with the available experimental data for a cycle in Fig. 3. The predictions coincide well with the experiments. The maximum temperature reached is 780 °C in HELICA, and there is nearly no cyclic effect in the temperature field over two loading cycles. At the maximum loading, the hydrostatic pressure in the pebble layer reaches around 4.9 MPa, in the region close to the FW; the von Mises stress reaches 1.5 MPa. The stresses decrease in high temperature regions, due to the increasing creep strains. After unloading, the hydrostatic pressure reduces almost to zero, but no tensile stress is present. The inelastic strain, consisting of the plastic and creep parts, accumulates during loading; it is partially recovered due to the interfacial friction force while unloading. A gap between the pebble layer and the container wall, with a width of 0.29 mm, is found at the side of FW.

3.2. HEXCALIBER

In the analysis of HEXCALIBER, the fully coupled analysis of one loading and unloading cycle is performed. The coolant temperature is set to 450 °C according to information from ENEA Brasimone,

and the maximum temperatures reached in ceramic and beryllium pebbles are 835 and 680 °C, respectively. Fig. 4 shows the temperature distribution at the maximum heat flux, and Fig. 5 shows the changing of temperature over time at each centre of the sub-cells, 100 mm to FW. The positions of TCs have been shown in Fig. 4. The hydrostatic pressure in ceramic layers reaches a maximum value of 6.2 MPa, located in the corresponding position of HELICA, however here it has a larger magnitude. In the beryllium layers, the maximum value saturates near 2.5 MPa. After unloading, the hydrostatic pressure in each material reduces to the minimum value of almost zero, as shown in Fig. 6. The ceramic pebble layers have, on average, lager volumetric inelastic strain than the beryllium ones, and the maximum value reaches 3.8%. During unloading, it is partially recovered, and the remaining part has significant influence on the effective thermal conductivity of the beryllium pebble layers. Furthermore, gaps during unloading are formed in the ceramic pebble layers close to FW, and the width is in the range of 0.25–0.38 mm.

3.3. Discussions

For both mock-up experiments, according to the present numerical analyses, following conclusions can be made:

- The maximum temperature will be reached in the middle sub-cells between the two electric heaters, and the maximum value depends on both the heat flux provided by the heaters and the configuration of the cooling channels. Regions of high temperature gradients are located in the lateral sub-cells. The effective thermal conductivity of beryllium pebbles is sensitive to the volumetric inelastic strain, which will bring cyclic effects in the temperature history there, while cyclic effects of ceramic pebbles are negligible.
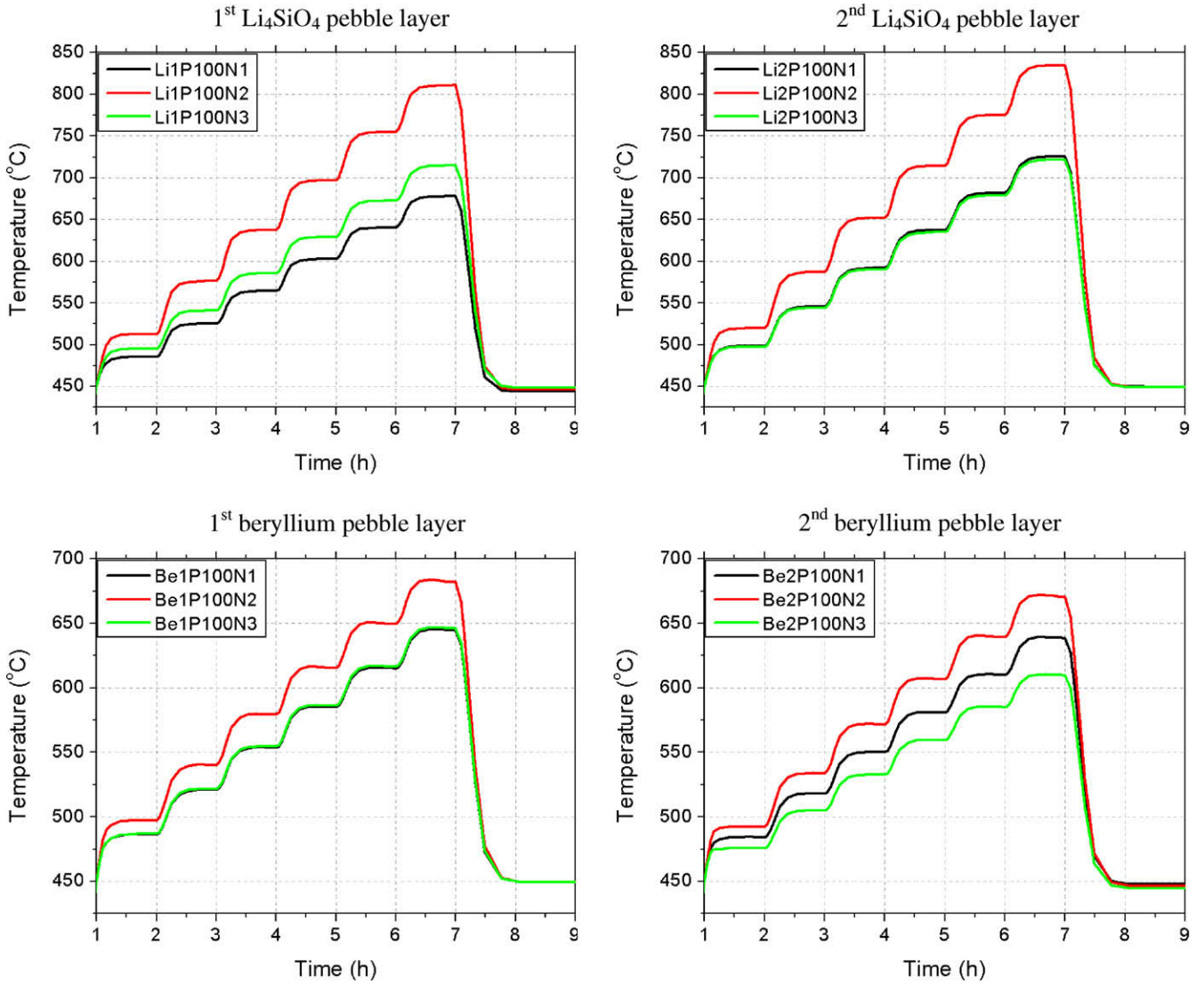
Fig. 5. Temperature changes over time in HEXCALIBER: 100 mm to FW (unit: °C).
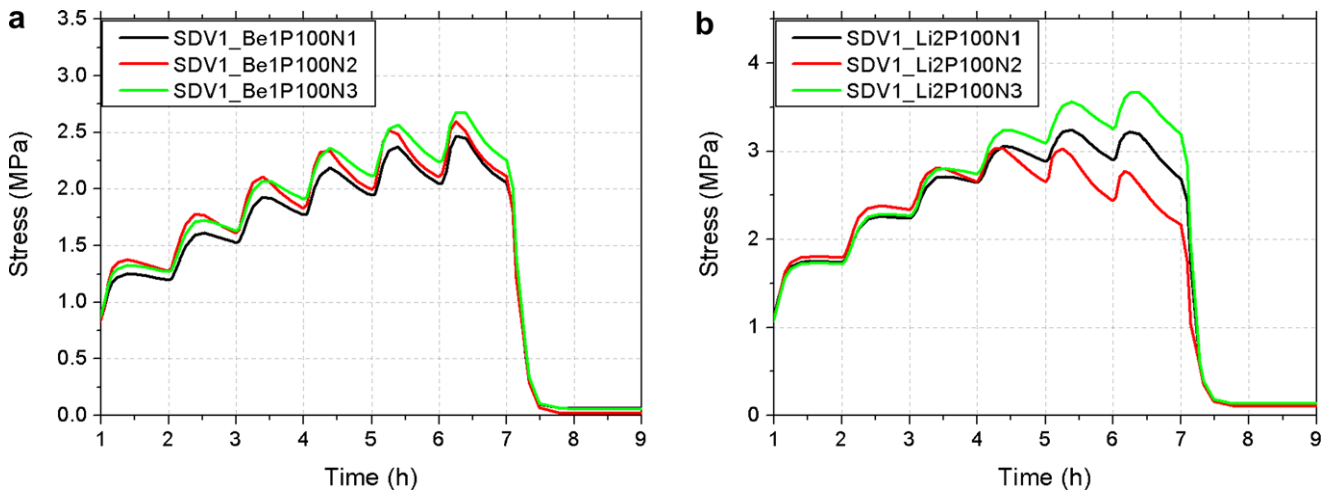

Fig. 6. The hydrostatic pressure changes over time in (a) the 1st beryllium pebble layer and (b) the 2nd ceramic pebble layer.

- A hydrostatic pressure develops during the loading steps, and decreases in high temperature regions. The maximum value is reached near the interface of the FW in the middle sub-cell of the ceramic pebble layers. The value is so high that it is likely to break individual pebbles in these regions. The hydrostatic pressure reduces nearly to zero after unloading, but no tensile stress exists.
- Gap formation is found in the analysis, but the widths of the gaps are mainly in the range of 0.25–0.38 mm. The locations are at the interface of the FW in the middle sub-cell of the ceramic pebble layers.
- Pebble beds and structure materials have tremendously different values of yielding stresses, i.e. a few MPa to hundreds MPa. To both reach convergence and obtain reasonable results, extra controls for convergence have to be made in the finite element analysis, when pebbles are present in the structural analyses.

4. Conclusion

In this paper, HELICA and HEXCALIBER, two out-of-pile mock-up experiments, have been analyzed, using the constitutive model of pebble beds developed in FZK. The model is mainly based on the modified Drucker-Prager-Cap model and it has been implemented in the commercial FE package, ABAQUS. The validation was first made based on the material database. For the structural analysis for TBM-HCPB design, the pebbles have a strong influence on the temperature field. The modified Drucker-Prager-Cap model can more precisely describe the behaviour of pebbles during both loading and unloading. The mechanical variables, in turn, change the temperature distribution, in the fully coupled thermo-mechanical analysis. The present work shows the feasibility of the simulation of large scale experiments, and the capability of the structural analysis to take into account the special features of pebble beds. The thermo-mechanically coupled analysis will be an efficient and important tool for the design of HCPB blankets.

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