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Structural analysis and optimization of mechanical multi-pipe connection for DEMO Upper Port

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ABSTRACT

This paper presents the structural optimization of a mechanical multi-pipe connection (MPC), which consists of multi-pipe flange connected with a threaded bolt connection, for use in DEMO Upper Port. Mechanical pipe connections are currently being researched in the fusion context as they offer faster operating time of the pipe connections compared to conventional welded connections. However, the main consideration is that the pipe connection must be sealed against a high vacuum at both room temperature and high temperature. To ensure the necessary tightness during the entire process, the metal seals required must be sufficiently preloaded in all operating conditions. In addition, strict space availability limits the overall shape and dimension of the MPC. For this purpose, a structural analysis and subsequent topology optimization of the flange connection is carried out using the commercially available FEA software Abaqus®. The result of the topology optimization, taking into account suitable boundary conditions, is a design for the flange which, in addition to achieving sufficient deformation of the seals throughout, also smoothed out the stress peaks present in previous designs. However, the design cannot yet be produced in its current form, as cavities have also been created within the flange. The manufacturability of the flange must therefore be investigated in a subsequent second step and the design adapted accordingly. In this paper, a design draft of a MPC for use in DEMO Upper Port is presented, which fulfills all the necessary boundary conditions, but still needs to be revised regarding its manufacturability.

1. Introduction and previous work

For the commercialization of fusion reactors, not only the achievement of scientific but also economic goals is of great importance. The development of a remote maintenance concept plays a crucial role in this, so that maintenance time can be reduced and thus the general downtime of the reactor can be minimized.

In DEMO, it will be necessary to remove and replace the plasma facing components, which includes the breeding blankets (BB) and the divertor cassettes. To access the BB, all cooling and purge gas pipes have to be removed before the BB can be replaced. Currently, these pipes are first cut to access the BB and then welded after the new BB have been installed. As an alternative to cutting and welding, so-called mechanical multi-pipe connections (MPC) have been developed [1]. These MPC allow the connection of multiple pipes within a single manifold system. This means that all pipes connected to a BB segment can be disconnected remotely and simultaneously. Furthermore, this procedure is carried out without removing the pipes and the shielding blocks above the BB, which has a number of advantages. This has the potential to not only reduce operating time, but also to simplify the procedure and increase reliability.

The MPC is generally designed to operate in the upper port section [2,3]. In [1], an MPC concept with clamps as a force distribution tool was initially developed. The clamps achieve a stable connection due to homogeneous force distribution, but this increased the general geometric dimensions. The general design of the clamp concept is shown in Fig. 1. The two flange halves are pressed together by the clamps. The necessary preload force is achieved by means of a tightening bolt and a spring stack. The functional principle of the clamped flange connection is shown in Fig. 2. A more detailed explanation can be found in [1]. This concept was built and tested as a prototype during the FP8 phase of the DEMO development. As a result, it was determined that the general use of the MPC is feasible for upper port maintenance.

Due to the tight space constraints under the shielding block, where the MPC is located, the clamp concept, which is characterized by its geometric size, is replaced in [4] by a concept with two flange halves and directly bolted connections. This allows a significantly more compact design to be developed that better fits the strict geometric constraints for use in the configuration with two cooling pipes and two purge gas pipes. The flange design was further adapted to the constraints during an initial optimization loop. The proposed MPC

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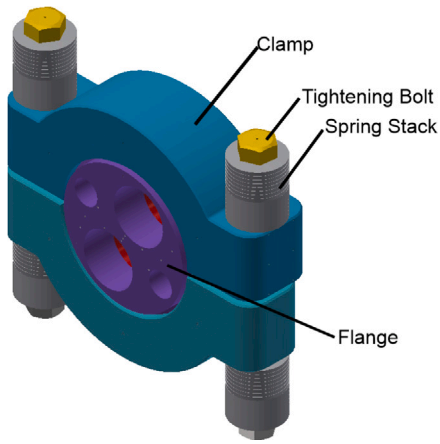

Fig. 1. Clamped MPC concept from previous iteration [1].

design with bolted connections is shown in Fig. 3. In this concept, the two flange halves are pressed together using four Superbolts [5], which are designed to provide the necessary pre-tensioning force for the metal gasket consisting of HELICOFLEX® [6] seals. The gasket layout is such that each pipe is sealed with a separate seal, and one seal is placed around all the pipes. Accordingly, a total of five seals are used for each flange. The exact layout can be seen in [4]. Since the bolts of the MPC must be tightened remotely, it is important that the two flange halves are aligned against each other. The aim is to ensure this with the help of passive elements, such as grooves. These possibilities are available because the two flange halves are placed vertically on top of each other. However, the alignment of the two flange halves is a complex topic in itself and is not yet part of the current work, but it is planned as a future task.

However, simulations in [4] have shown that the previous concept does not provide a uniform seal deformation, therefore a further shape optimization to improve the overall sealing force distribution is required. For this reason, a dedicated structural analysis and a subsequent structural optimization are carried out and described in this paper.

2. Structural analysis and design adaptation

The following section provides an overview of the material selection and boundary conditions to be considered, as well as a structural analysis of the initial situation and subsequent initial design adaptations.

2.1. Material selection and design constraints

Since the pipes in the BB concepts are made of SS316L [7], the same steel is used for the flange. This improves material compatibility and simplifies the welding process required to connect the pipes to the flange. The BB is made of Eurofer97 material, which is intended to be used as structural steel in DEMO [8]. Inconel718 is chosen as the material for the bolts because it provides high tensile strength not only at room temperature but also at high temperatures. This is necessary because the bolts have to apply the forces necessary for sufficient deformation of the HELICOFLEX® seals, which are in the mega newton range. HELICOFLEX® seals are metal seals that have been rated and certified for use in a nuclear grade installation.

In addition to the aforementioned dimensional restrictions in the area below the shielding block, further design constraints must be taken into account. On the one hand, there are design challenges such as the requirement for remote access and the risk of cold welding. On the other hand, there are extreme environmental influences such as a design pressure of 18.6 MPa or a design temperature of up to 400 °C (HT). In addition, the MPC must be sealed against ultra-high vacuum [9] and must have a helium leak tightness of at least $10^{-8}\ \frac{\text{Pa m}^3}{\text{s}}$ [10]. This corresponds to a minimum residual deformation of the seals of 0.7 mm. However, the deformation must not exceed a value of 0.8 mm according to the manufacturer [6]. These gaskets are also used for ITER and for the previous iterations of the MPC [4]. These are selected for the gasket model and, as the main mechanical property of the gasket, the gasket deformation is modeled. In addition, the maximum stresses must not exceed the material properties of the materials used.

In terms of design constraints, two different positions for the MPC can be considered. As shown in Fig. 4, the flange can either be placed directly on the BB or the connection is made using two flange halves, with one of them being firmly attached to the BB. Both positions will be considered and analyzed in the following.

2.2. Analysis of the initial situation

First, the initial situation is considered and analyzed, i.e. the positioning with two flange halves is assumed. For the simulation, only a quarter of the flange is considered. This is possible for reasons of symmetry and leads to a significant reduction in computing time. To do this, the movements in the normal direction and the rotations around the other two axes must be fixed at the two cut edges. In addition, the areas on the bottom side where the pipe ends are located are fixed in vertical direction at the lower flange. A force of 1.58 MN is applied via the bolts and ABAQUS® offers the gasket element type to simulate the seals. The pressures inside the pipes are then applied and the flange and BB are heated up to 400 °C.

Fig. 5 shows the von Mises equivalent stress distribution in the two flange halves based on the finite element method (FEM). Stresses ranging from 0 MPa to 500 MPa are displayed in the color code from blue to red. Regions where the stresses exceed 500 MPa are displayed in gray. At both temperatures, the maximum stresses are below the tensile strength of SS316L, which is approximately 500 MPa at RT and 450 MPa at HT. By using Inconel718 for the bolts, this also results in a sufficiently high yield strength there.

Fig. 6 shows the residual deformations of the seals achieved with this configuration. The residual deformations in millimeters are color-coded from a minimal deformation in blue to a maximal deformation in red. Fig. 6 also shows that the necessary deformations cannot be achieved in either room temperature (RT) or HT. For this reason, it is necessary to further adapt the flange design, which is discussed in Section 2.3.

2.3. Design adaptation

In the following, the positioning is considered in which the flange is attached directly to the BB. Furthermore, the flange is configured in a stepped design so that the forces in the center of the flange are better directed to the seals. The resulting model can be seen in Fig. 7. In addition, the pipes welded to the flange are also modeled with a length of 1000 mm to simulate additional rigidity of the flange. The BB is simulated as a cut quarter-block with a width and length of 800 mm each in the cut state, a height of 1000 mm and with the material properties from Eurofer97. The cutting conditions as already described in Section 2.2 apply again to the two cut edges. The BB is also fixed on the underside. Otherwise, the conditions as in Section 2.2 apply.

Fig. 8 shows the stress distribution for this flange design at RT and HT. The stresses for the flange are within the range of the material properties for both RT and HT, although a stress peak occurs in the blanket at HT that requires more in-depth analysis. However, it is planned that Eurofer97 will be used as the material for the blankets, which has a higher tensile strength than SS316L, and the blankets are replaced during the maintenance phase, so that small plastic deformations may also be permissible.

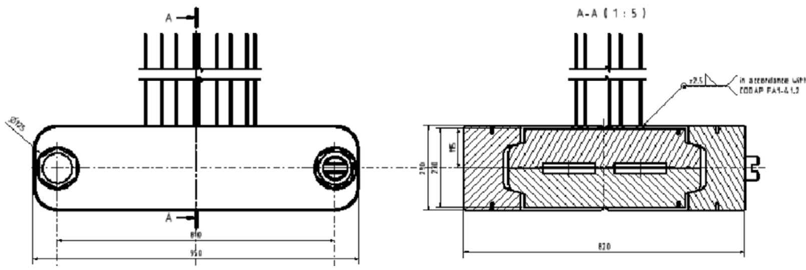

Fig. 2. Functional principle of the clamped flange connection [1].

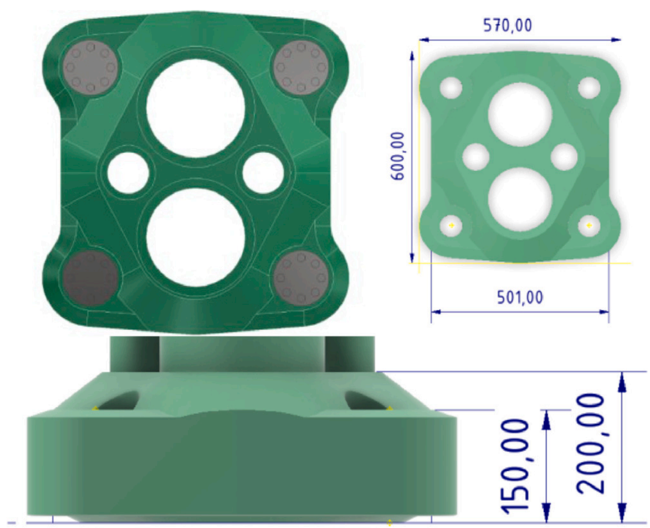

Fig. 3. Design of MPC with bolted connections [4]. The dimensions are given in millimeters.

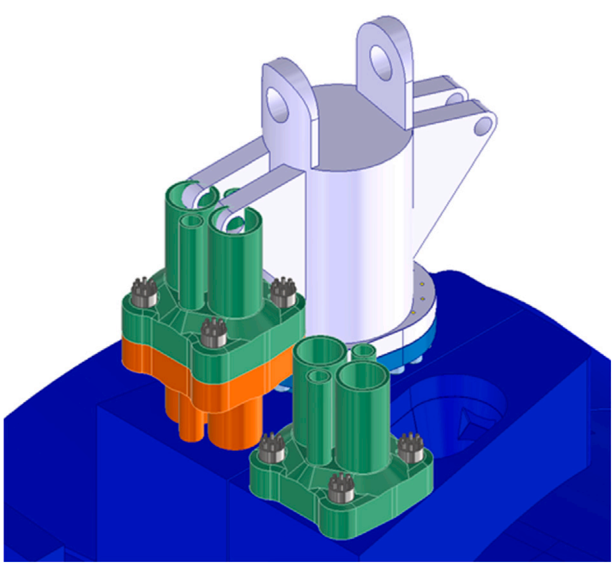

Fig. 4. Possible positions of the MPC on the BB [4].

Regarding the residual deformations of the seals, Fig. 9 shows that the minimum seal deformation is still not reached at either RT or HT, even though they are significantly higher than in the previous iteration. The maximum residual deformation of the seals is limited by means of the groove in which the seals are placed on the blanket side, so that no further deformation beyond the maximum expansion is possible. For this purpose, a height of 3.48 mm is selected for the groove.

Even with the adapted design, the necessary residual deformations of the seals are not achieved at all points. With the aim of achieving the most uniform distribution of the deformation of the seals, a structural optimization is carried out subsequently.

3. Structural optimization of the flange design

Structural optimization is a computer-aided optimization process for mechanical components and structures. Optimization makes it possible to modify the examined structure so that it satisfies the defined constraints. In addition to the form, the topology can also be optimized. A special structural optimization method – topology optimization – is used here.

Topology optimization is an iterative process that initially requires to specify a design domain. In this domain, the material is distributed step by step in such a way that the specified objective function is optimized while also adhering to the defined constraints.

In commercial software such as Abaqus®, the so-called SIMP (Solid Isotropic Material with Penalization) method is usually implemented, which was first described in [11]. This method is based on the finite element method and was further developed by [12–14].

The SIMP method is based on the ersatz material approach, where constant material properties are assumed for each discrete element. The relative density of the respective elements is used as the design variable, whereby the range of values $0 < x \leq 1$ applies to the density. By varying the parameter, any structures can be modeled on the fixed finite element discretization. The material properties within an element are defined as the product of the relative density raised to a value and the material properties of a solid element. If a suitable value is chosen for the power, physically permissible structures are obtained. In [15], Ole Sigmund presents an exemplary implementation of the SIMP method in Matlab®.

3.1. Definition of the optimization problem

To perform a topology optimization in Abaqus®, it is first necessary to define the area to be optimized, the so-called design domain. Here, the flange is selected as the design domain, whereby the pipes welded to the flange are not taken into account. In addition, the areas on which the seals are located are considered fixed, i.e. no material is allowed to be removed at these points. This ensures that there is always enough material around the seals. The areas where the forces are applied are also fixed so that enough material is always there to absorb the forces. The target function is to minimize the maximum von Mises equivalent stress in the flange, where, in addition to a maximum stress limit, the minimum residual deformations of the seals are also defined as boundary conditions.

The SIMP method is used as the material interpolation technique in sensitivity-based topology optimization in Abaqus®. A value of 3 is used as the penalty factor, since numerical experiments show that good results can be achieved with this value. In addition, the Abaqus® sensitivities are used wherever possible, so that the von Mises equivalent stresses can be used as the target function and for the boundary condition. As a design variable, the relative density in the elements can range from 0.001 to 1.

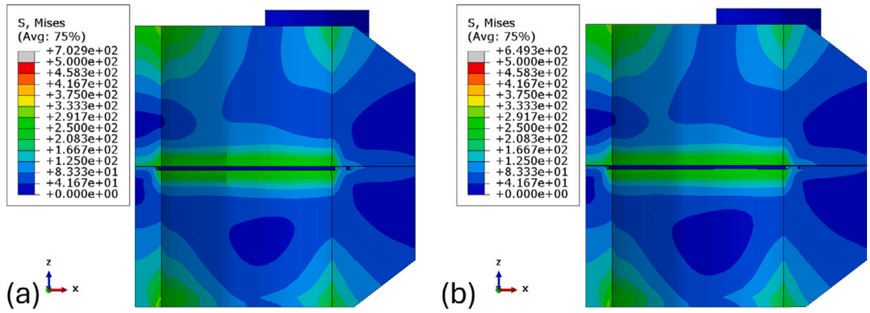

Fig. 5. Stresses in the initial flange design at (a) RT and (b) HT.

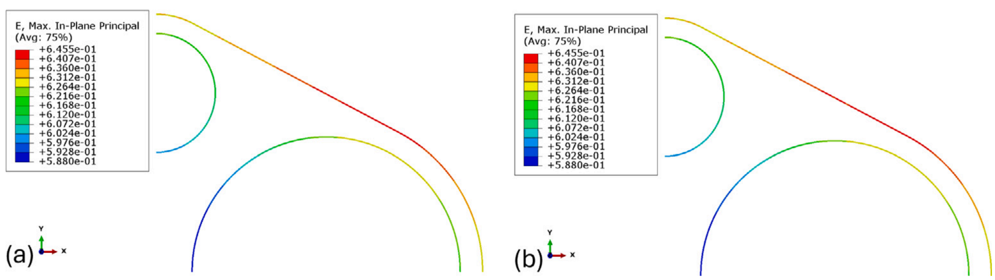

Fig. 6. Residual deformations of the seals in the initial flange design at (a) RT and (b) HT.

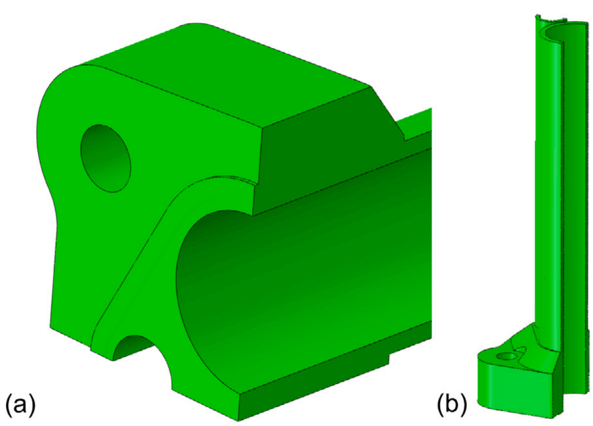

Fig. 7. Model of the design adaptations of the MPC flange: (a) view from underneath and (b) side view.

3.2. Results

The flange design obtained from the optimization is shown in Fig. 10. The material removals on the bottom side of the flange are of particular interest, since the interactions with the seals take place there. The area circled in red is especially interesting because the material removal adjusts the flow of force to the seals with regard to the defined boundary conditions. The change in the flow of force affects both the distribution of stresses in the flange and the deformation of the seals.

The stresses remain in similar areas as in the previous iteration, as can be seen in Fig. 11. In addition, a stress distribution that is as homogeneous as possible is achieved in the upper flange for both RT and HT. The stress peaks occurring again on the blanket side require, as already mentioned in Section 2.3, further analysis. However, the top side of the BB is also not part of the scope.

The residual deformations of the seals are within the specified range for HT, but for RT the minimum deformation is still not quite achieved. This can be seen in Fig. 12. However, this is only a small area of the seal for the cooling tube. This area is located near the center of the flange. This means that even more minor adjustments to the design have to be made so that all areas of the seals are sufficiently deformed at RT. To do this, it is necessary to make further modifications in order to keep the flange stiffer in the center at RT, so that a greater deformation of the gasket is achieved in these areas.

4. Conclusion and outlook

In this paper, the structural analysis and optimization of the MPC for use in a configuration with cooling and purge gas pipes in DEMO were shown. The MPC designed in [4] was used as a basis for this. The MPC was further developed to achieve the most homogeneous stress distribution possible in the flange and the most uniform residual deformation possible in the seals. It was shown that the maximum material properties were adhered to with regard to the stresses that occur. Regarding the seals, there is only a small area where the residual deformation is just below the minimum limit and further small design adjustments are necessary.

The manufacturability of the flange must be examined in more detail, as this was not considered during the optimization. This has created cavities that cannot be produced in this way. In addition, different material pairings should be tested for the flange, bolts and BB, since the materials used so far have different expansion coefficients, which can cause relative movements during operation that lead to friction and wear. Furthermore, cold welding between the components can occur, which must also be investigated. Finally, a leak test should be carried out to check the tightness of the entire MPC and to validate the theoretical and numerical preliminary studies.

After all structural issues for the MPC have been addressed, it is also necessary to develop and test a detailed alignment concept for the two flange halves.

As already mentioned in Section 2.3, a more in-depth analysis of the blankets is also necessary. For example, it is of interest whether the

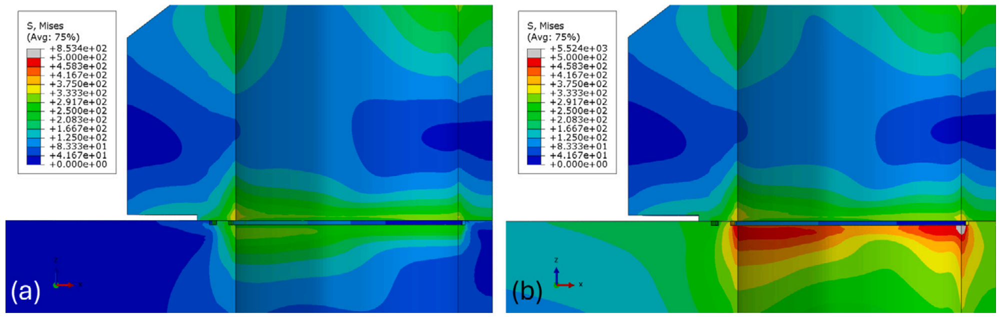

Fig. 8. Stresses in the flange with design adaptations at (a) RT and (b) HT.

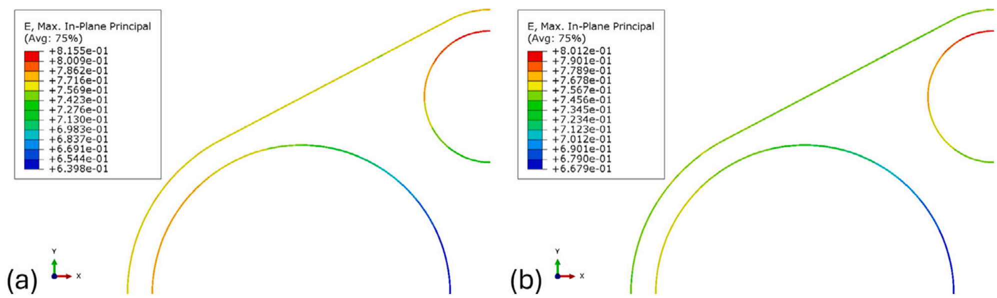

Fig. 9. Residual deformations of the seals in the flange design with design adaptations at (a) RT and (b) HT.

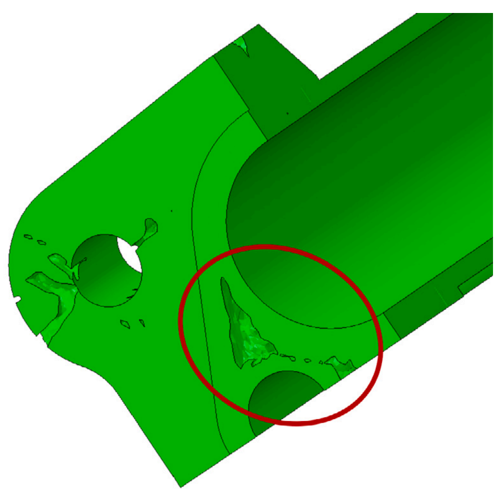

Fig. 10. Optimized flange design with the removed material on the bottom side of the flange as a result of the topology optimization.

occurrence of small plastic deformations is allowed or whether changes in the surface structure are possible to reduce occurring stresses.

CRediT authorship contribution statement

K.J. Büscher: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **A. Azka:** Writing – review & editing, Validation, Software, Methodology, Investigation, Formal analysis, Conceptualization. **M. Mittwollen:** Writing – review & editing, Supervision, Resources, Project administration, Investigation, Funding acquisition, Conceptualization.

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Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Keno Jann Büscher reports financial support was provided by European Consortium for the Development of Fusion Energy. Azman Azka reports financial support was provided by European Consortium for the Development of Fusion Energy. Keno Jann Büscher reports a relationship with European Consortium for the Development of Fusion Energy that includes: funding grants. Azman Azka reports a relationship with European Consortium for the Development of Fusion Energy that includes: funding grants. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

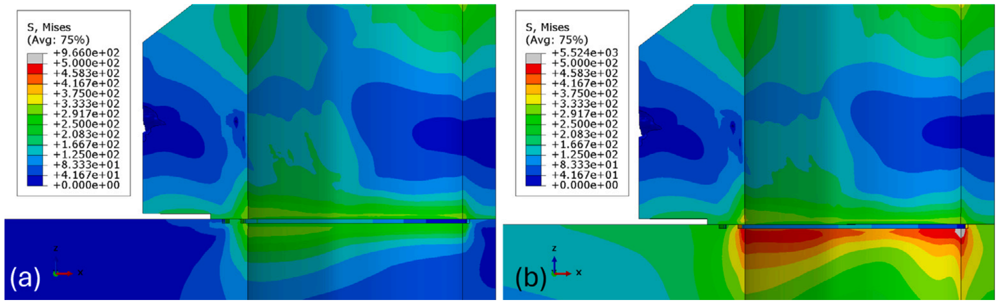

Fig. 11. Stresses in the optimized flange design at (a) RT and (b) HT.

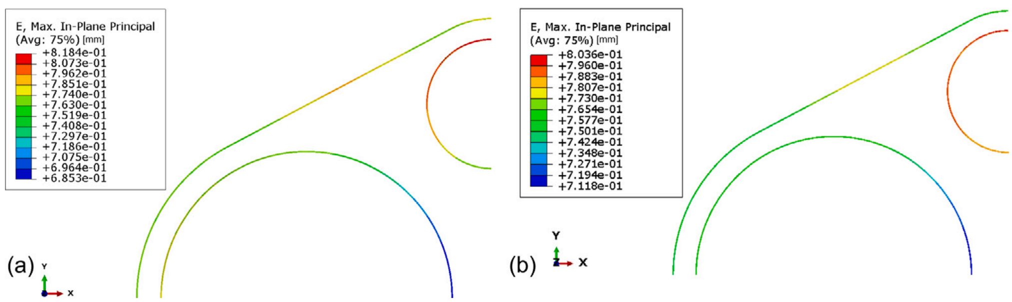

Fig. 12. Residual deformations of the seals in the optimized flange design at (a) RT and (b) HT.

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