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Pre-Conceptual Design of DEMO Upper Port Duct Bellows

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This paper describes the first study on the DEMO upper Port Duct Bellows. It aims at establishing the basis for their pre-conceptual design through available standardized analytical procedures and identify the bellows features where the analytical procedures fail and the detailed finite element (FE) analyses are required. The available analytical procedures have been found insufficient for the specific bellows design, considering the rather challenging size, load cases and non-standard trapezoidal shape of the DEMO upper Port Duct Bellows. Although a properly verified design of the bellows cannot be provided at this stage, an optimization tool has been developed that enables to identify a valid range of bellows parameters that fulfill the design constraints while optimizing their mass or length. The preliminary design results are presented and the shortcomings of the analytical tool identified through FE analyses of bellows performed with the ABAQUS code.

Keywords: DEMO, bellows, expansion joints, design codes, finite element

1. Introduction

The DEMO fusion reactor includes the vacuum vessel (VV) in the core surrounded the cryostat [1]. The connecting structures between these two components should compensate their relative movements during operational and accident conditions, e.g., due to thermal expansion and seismic loads. Bellows expansion joints located at the VV ports are used to connect the VV with the cryostat. They are referred to as Port Duct Bellows. The additional function of the Port Duct Bellows is to seal the cryostat vacuum from the pressure inside the VV port.

The design of standard bellows expansion joints typically follows two main codes, namely the American Society of Mechanical Engineers code (ASME) [2] and the standards for the Expansion Joint Manufacturers Association (EJMA) [3]. These analytical procedures, however, mainly focus on the design of the bellows' convolutions. The limitations of these design codes are typically fulfilled by industrial knowledge. Bellows expansion joints have been designed for fusion reactor applications such as ITER [4-9] and Wendelstein 7-X [10, 11] and for the cryogenic distribution line of the Large Hadron Collider [12].

The pre-conceptual design of the DEMO upper Port Duct Bellows was initiated in 2016 within the "initial definition of cryostat bellows" task of the EUROfusion WPPMI work package. This paper describes the work performed within this task [13]. This includes the initial geometry definition and interface identification given in Section 2, the identification and verification of load cases in Section 3 and Section 4 presents the initial analysis and sizing of the bellows through the available analytical procedures and the finite element (FE) analyses. The development of an optimization tool has been moreover initiated to determine valid ranges of bellows parameters that fulfill the design constraints while optimizing their mass or length. The conclusions of the work performed and open gaps are given in Section 5.

2. Initial geometry definition and interface identification

The space envelope and boundaries on which the bellows geometry can be defined is obtained from the 2015 global DEMO CAD model shown in Fig. 1, left. The bellows shall be placed in the space between the VV upper port extension and the cryostat, as shown in detail in Fig. 1, right. As can be seen in this figure, the cross section of the port extension is bigger than the port. The port cross sectional area is thus extended until it effectively passes through the available opening hole in the cryostat. In this way, the space between the VV upper port extension and the cryostat, assuming the cross section of the VV upper port, is initially identified as the available space for the bellows placement. The dimensions of this space and of the VV upper port cross section are given in Fig. 2.

In order to maintain the available space for instrumentation and accessibility along the port, it is reasonable to assume that the inner dimensions of the bellows and of the port shall be the same. Thus, as a first approximation, the bellows shall have a trapezoidal cross section and a maximum length of about 4.7 meters.

3. Identification and verification of load cases

The upper port duct bellows shall be designed considering the design concept of the ITER rectangular bellows [4-7, 9]. A comprehensive list of load conditions for the ITER upper port duct bellows can be found in [5]. Design loads under normal operation for the DEMO upper port duct bellows, as defined in the task specifications [14], are listed in Table 1.

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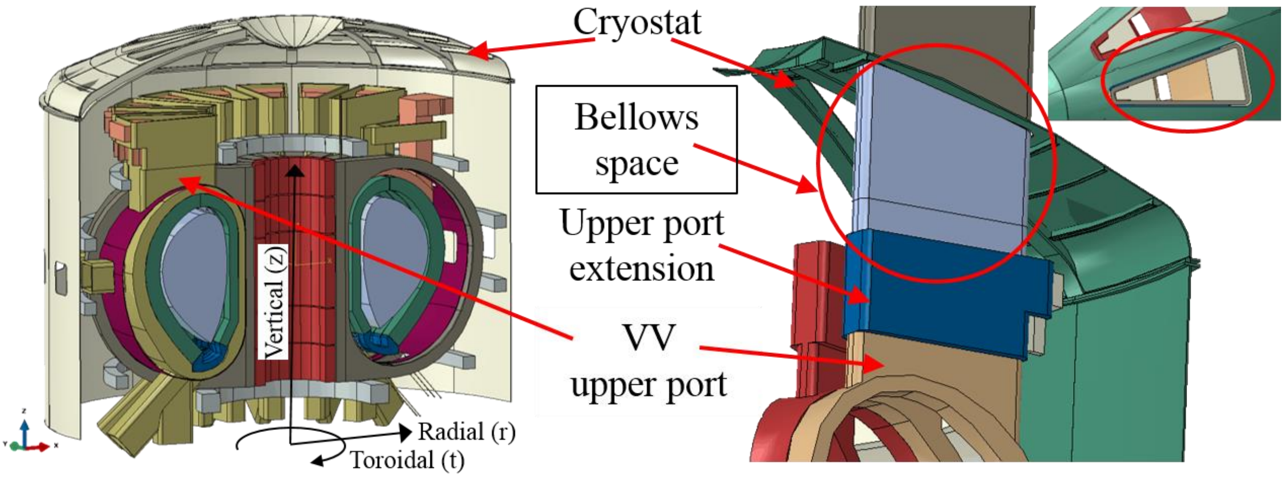

Fig. 1. The 2015 global DEMO CAD model and coordinate system of displacements (left). Definition of the space available for the bellows (right) and its top view (inset).

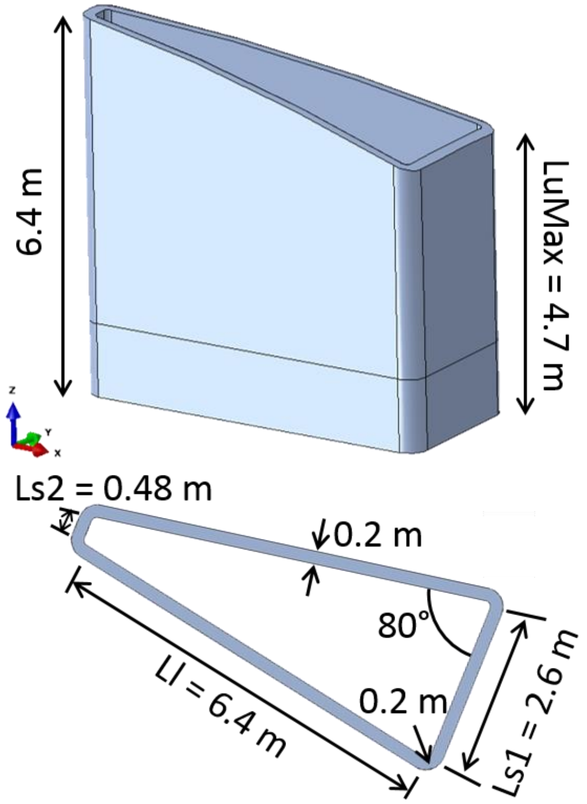

Fig. 2. Dimensions of the space available for the bellows (top) and of the VV upper port cross section (bottom)

The loads include the maximum pressure difference (P) between the inner and outer side of the VV port and the relative displacements between the VV port and the cryostat. The relative displacements are defined in the cylindrical coordinate system of the tokamak shown in Fig. 1 and include the radial (U_r), vertical (U_z) and toroidal (U_t) displacements. Additionally, Table 1 also includes the working temperature (T) of the DEMO VV [15] and the required cycles ($Ncyc$) following ITER example [5]. The cryostat is at room temperature.

Table 1. Normal operation loads of the DEMO upper port duct bellows [5, 14]

U_r (mm)	U_z (mm)	U_t (mm)	P (MPa)	T (°C)	$Ncyc$
35	73	0	0.15	200	300

*Effect of gravity is considered

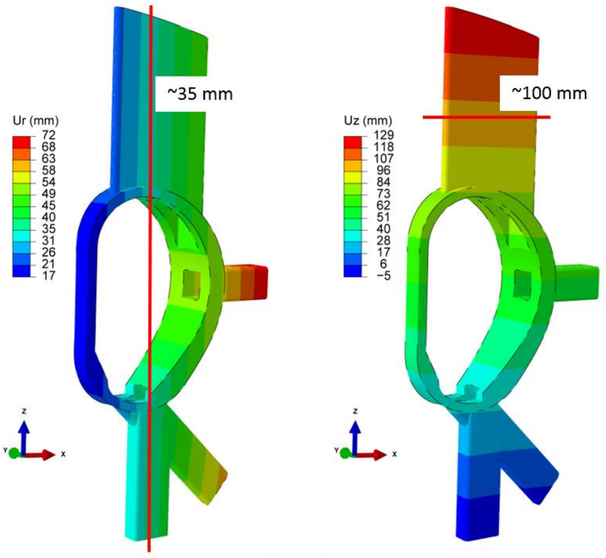

Fig. 3. Results of the 2015 DEMO VV thermal expansion analysis and expected displacements near the bellows position [15].

The verification of load cases is performed by comparing the relative displacements in Table 1 with the results of the 2015 thermal expansion analysis given in Fig. 3 [15]. The expected thermal displacements of the VV upper port near the position of the bellows are about 35 mm in the radial direction and 100 mm in the vertical direction. This analysis assumed a static cryostat. Therefore, the VV thermal displacements are directly comparable to the relative displacements in Table 1. It can be seen that the radial displacement clearly matches the input value while the vertical displacement from the thermal expansion analysis is higher. In the 2015 analysis, the elevation of the VV vertical support was considered rather low for conservatism since it is not defined yet (see U_z=0 in Fig. 3). The actual vertical expansion of the VV at the upper port bellows could be lower than 100mm. Additionally, the effect of gravity on thermal expansion was not considered in the 2015 analysis. Therefore, the loads presented in Table 1 are employed for the pre-conceptual design of the DEMO upper port duct bellows.

4. Pre-conceptual bellows design

The ASME code provides rather basic design rules only for circular and single ply bellows [2, 16]. The more extensive EJMA standard provides additional design rules for multiply, reinforced and unreinforced circular bellows and single ply unreinforced rectangular bellows [3]. The design concept of the ITER uses multiply and unreinforced rectangular bellows [5]. One of the goals of this study is to evaluate possible designs of the DEMO bellows through available procedures. Thus, the pre-conceptual design is performed assuming the rectangular shape, single ply and unreinforced bellows following the EJMA standard. The design procedure for conditions below the creep limit is also assumed. Note that the working temperature of the VV (200 °C) is well below 450 °C were the creep damage for typical stainless steels becomes significant [17].

The EJMA analytical procedure mainly focuses on the design of the bellows' convolutions. The parameters of the "U" shape convolution, also selected for the ITER bellows [5], are depicted in Fig. 4, top. These include the thickness (*t*), pitch (*q*), height (*w*) and mean radius (r_m). Together with the number of convolutions in one bellows (*N*) and the connector length (L_c), these parameters define the total length of the bellows expansion joint (L_u) as shown in Fig. 4, bottom. The length of additional material that connects the components, named as tangent (L_t), is neglected in this work. The cross sectional dimensions of the bellows are defined, as shown in Fig. 4, bottom, by the inner dimensions of the long (L_l) and short (L_s) sides.

The design constraints defined by the EJMA standard are based on geometrical, limit stress and fatigue criteria [3]. The displacements and stresses of the convolutions, as defined by the standard [3], have to fulfill these criteria for the selected set of bellows' parameters and input loads. These have been implemented in an in-house tool to optimize the bellows' mass or length based on sets of parameters that fulfill the criteria. To this end, it is convenient to define the mean radius and the height of the convolutions as:

$$\begin{gathered} r_m = K_{rm} t \\ w = K_w r_m \end{gathered} \tag{1}$$

The constraint $K_w \geq 2$ is based on purely geometrical basis and $K_{rm} \geq 3$ is set according to the ASME code [16]. The bellows material Inconel 625 is assumed in this study with properties from [17]. The fatigue curve expression for circular bellows has been taken from the ASME code [16]. The reason for this choice is twofold: it is conservative compared to the EJMA curve for circular bellows and because the general EJMA fatigue curve depends on specific fatigue test parameters currently not available. Thus, the ASME fatigue curve is used in our analyses only for the purpose of demonstrating the complete procedure. Finally, Ll and $Ls1$ dimensions of the trapezoidal cross section (Fig. 2) are assumed to represent the sides of the rectangular bellows.

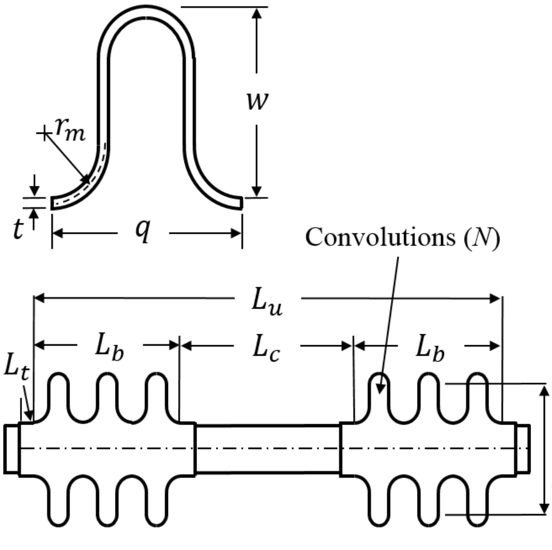

Fig. 4. "U" shape convolution parameters (top) and length dimensions of the rectangular bellows (bottom).

4.1 Analytical results

Examples of the results obtained with the in-house tool can be seen in Fig. 5. These represent the regions, within the three dimensional space designated by K_{rm}, K_w and *N*, where the design constraints are fulfilled for the given thickness *t* = 5 mm and total length L_u = 4,7 m. Additionally, the colors in individual plots represent either the mass or the connector's length, L_c, for a selected set of parameters and assuming the typical material density for steels of 8,000 Kg/m^3. The results show that the region of available parameters is rather large for both K_{rm} and K_w. For low K_{rm}, a wide range of K_w and *N* may be chosen with bellows masses ranging from 5 to 25 tonnes, the connector length L_c may range from very short to more than 3 m. For increasing K_{rm}, the possible range of K_w and *N* values is much smaller. This last observation is even more pronounced for increased *t*, as seen in Fig. 6. In this case the bellows mass may become too high and therefore not necessarily optimal from the material and fabrication costs point of view.

4.2 FE simulations

Dedicated FE simulations of trapezoidal bellows have been performed to evaluate the bellows features that the analytical procedures may fail to identify. The FE simulations of trapezoidal bellows with one convolution have shown that the corner effects on the short inboard side of the bellows may force its inwards deformation against the pressure force, as shown in Fig. 7. This is not necessarily a feature of trapezoidal bellows only, but of short sided bellows. The equations of convolutions' stresses provided by the EJMA standard are indeed valid only for *L*/*w* >10, condition that may avoid this issue.

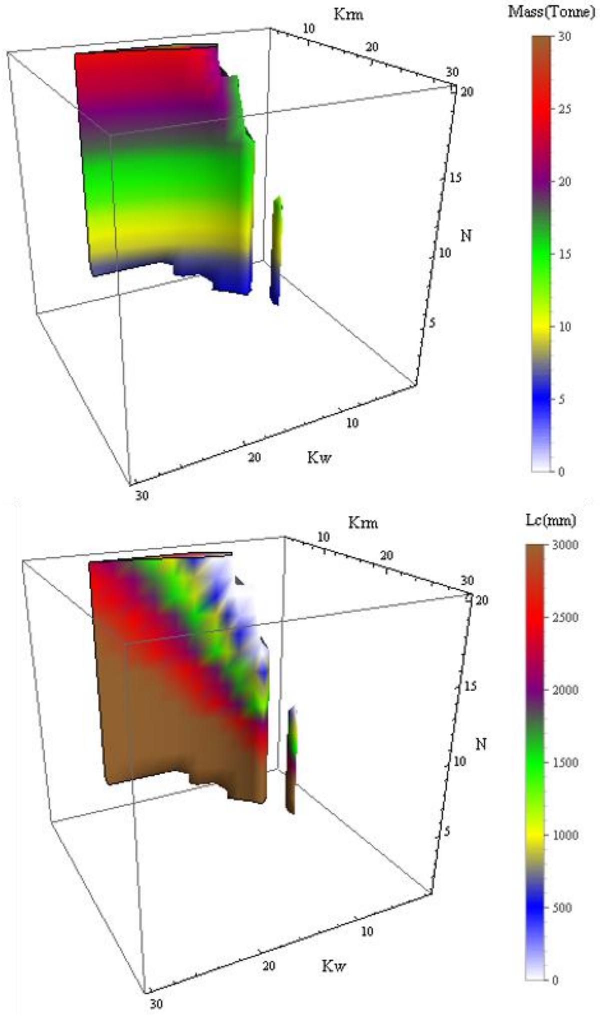

Fig. 5. Parameters space for *t* = 5 mm, L_u = 4,7 m.

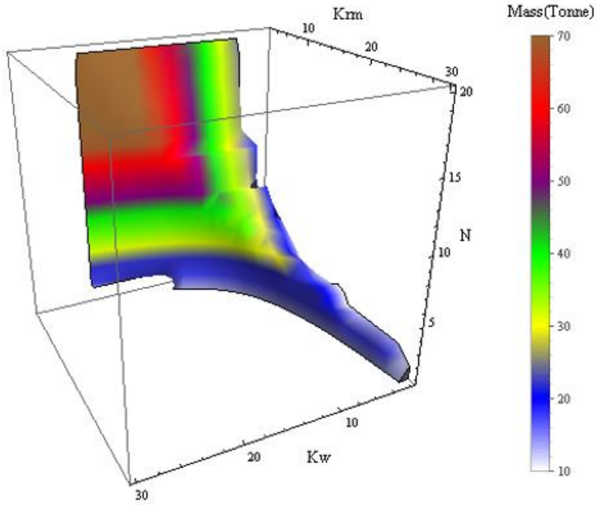

Fig. 6. Parameters space for *t* = 10 mm, L_u = 4,7 m.

The FE results of realistically sized bellows have shown that the connector could deform excessively under pressure loads due to the large dimension of its longer side, see Fig. 8. Additionally, stress concentrations above yield (377 MPa) arise at the corners. The evaluation of corner stresses will require dedicated FE simulations of specific bellows geometries. Nevertheless, the development of FE models and simulations of complex bellows have proven to be a rather time-consuming task. Therefore, it is necessary to improve the available analytical tools for the selection of bellows parameters.

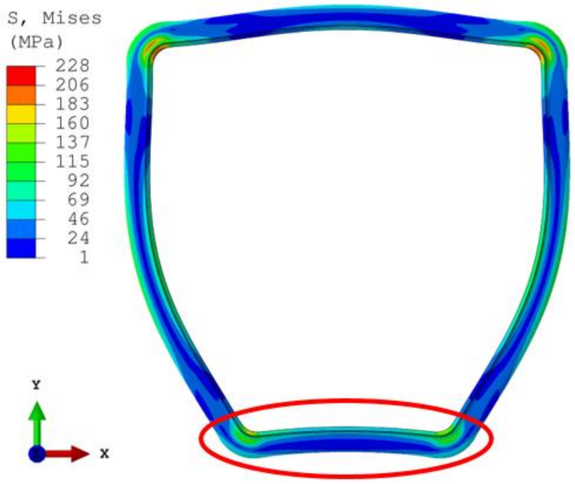

Fig. 7. Misses stresses in trapezoidal bellows with one convolution under pressure load.

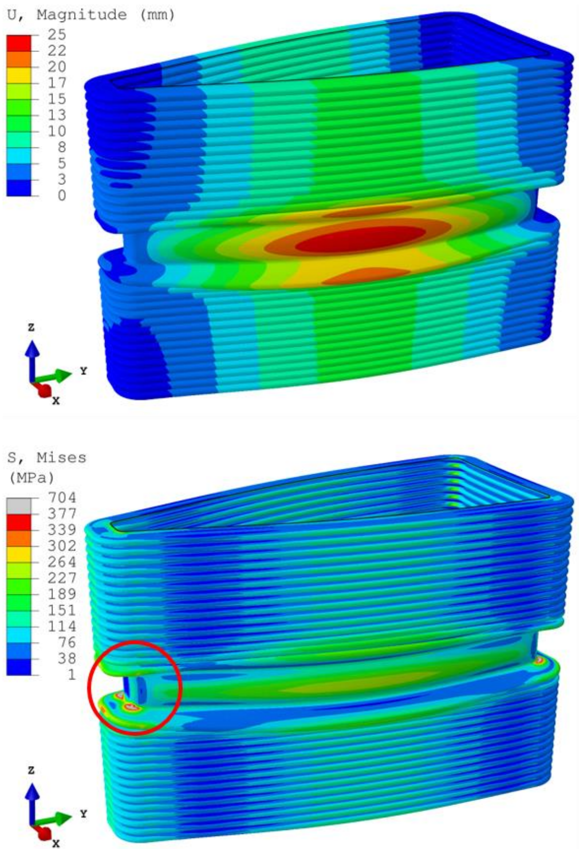

Fig. 8. Bellows with DEMO port sizes, L_u = 4.7 m and *t*=10 mm. Displacements (top) and Mises stress (bottom) due to pressure load.

5. Conclusions

The work performed within the 2016 task "initial definition and analysis of the DEMO cryostat bellows" has established the basis for the pre-conceptual design of the DEMO upper Port Duct Bellows through available analytical procedures. Additionally, the shortcomings of current analytical procedures have been identified through FE simulations. Main outcomes and the remaining open issues are:

Regarding the initial geometry and interface identification:

- The bellows inner dimensions are based on VV upper port dimensions with trapezoidal shape.
- The bellows maximum length is based on the space between upper port extension and cryostat.

Regarding the identification and verification of load cases:

- The loads defined in the task specifications have been shown to be reasonable through FE thermal expansion analysis.

Development of the bellows optimization tool based on the available analytical procedures:

- The available analytical procedures from the codes and standards do not include design rules for bellows of trapezoidal shape. Therefore, a properly verified design of the bellows cannot be provided at this stage.
- The development of the analytical tool has proven to be useful and is a necessary step before building the time-consuming FE models of complex bellows.

FE simulations of simple and complex bellows:

- Corner effects on convolution stresses and deformations may be present in shorter sides of the bellows.
- Corner stresses have to be analyzed by dedicated FE simulations for specific bellows geometries.
- Due to rather challenging dimensions of the DEMO VV ports, the connector may deform excessively under pressure loads.

Acknowledgments

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