The ITER EC H&CD Upper Launcher: Seismic Analysis

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The electron cyclotron heating and current drive (EC H&CD) upper launcher (UL) is a component of the ITER tokamak machine devoted to inject localized high microwave power, in order to counteract plasma instabilities (MHD activity). The UL consists of an assembly of ex-vessel waveguides (with diamond windows and isolation valves) and an in-vessel port plug (PP). The PP, with length close to 6 m, is fixed by a support flange into the upper port of the vacuum vessel (VV) as a cantilevered structure and the nominal gap between PP and port is 25 mm only. During an earthquake, accelerations generated by seismic events cause oscillations of the PP which might be amplified in case of resonance with the natural frequencies. A seismic analysis is therefore required in order to check the response of the UL PP to earthquakes.

This paper shows the procedure used for the seismic analysis of the UL PP and results are given in terms of displacements and stresses. The ITER reference earthquake named SL-2 seismic event was considered. The response spectrum method was used in the analysis and floor response spectra (plots of acceleration versus frequency) provided by ITER/F4E at the upper level of the tokamak were applied to the supports as load. A seismic analysis of the UL PP integrated in the upper port is also here reported.

The natural frequencies of the PP are far from the frequencies of the peaks in the applied spectra, so no resonance condition occurs. The obtained displacements and stresses of the PP are relatively small. The maximum total displacement is lower than 2 mm and the maximum equivalent stress is below 30 MPa. Since the highest excitation is the vertical one, most part of the total displacement is in the vertical direction. Afterwards, these results due to the seismic loads must be combined with displacements and stresses due to other loads affecting the PP such as the electromagnetic loads.

Keywords: ITER; Upper Launcher; seismic analysis; response spectrum; Newmark's rule.

1. Introduction and background

The ITER EC H&CD UL is a component used to direct high power microwave beams into the plasma for control of the magneto-hydrodynamic (MHD) instabilities. The UL consists of an assembly of ex-vessel waveguides (with diamond windows and isolation valves) and an in-vessel PP. The UL is part of the first confinement system and therefore it has the most stringent requirements in the ITER safety, quality, vacuum, seismic and tritium classifications. In case of an earthquake, the structural stability and the confinement function of the UL has to be maintained [1, 2].

In this work, the resistance of the UL PP to the seismic events was checked by means of FEM analyses performed in ANSYS Workbench. The seismic analysis of the PP was carried out using the response spectrum (RS) approach and the acceleration floor response spectra (FRS) for the so-called SL-2 seismic event were applied as input. SL-2 event is the reference earthquake in ITER and is classified as a Category IV event, i.e. extremely unlikely loading condition. The damage limit for the UL associated to this category event is the faulted condition [3].

The UL PP is mounted as a cantilever into the upper port of the VV by a support flange at its rear side. The PP has a length of about 6 m and the gap between it and port is 25 mm only. As shown in Fig. 1, it consists of the blanket shield module (BSM) and the mainframe, which are mechanically connected by bolted flanges. The BSM faces the plasma through the first wall panel (FWP). The main internal components are shielding, cooling and mm-wave transmission components [4].

The seismic analysis of the only UL PP was first run and results are given in terms of displacements and stresses. Then, to take account of the port, a second analysis of the PP integrated in the upper port was carried out. Due to the nature of the RS analysis, the results are positive only. However, as the structure is obviously oscillating, the results are amplitudes and so they have to be assumed with the ± sign variations.

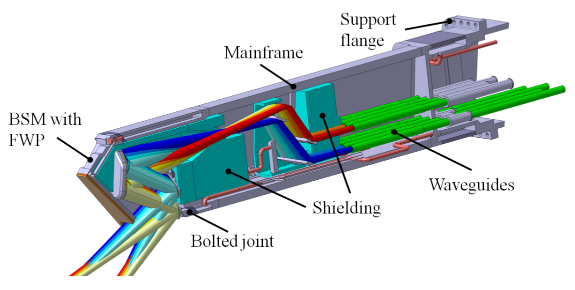

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Fig. 1. Preliminary design of the EC H&CD upper launcher port plug.

It is important to note that, beyond the accelerations due to the seismic events, the UL is subjected to other types of loads such as electromagnetic and thermal loads [5]. Load combinations are thus defined for the UL [6] and so the results reported here will have to be afterwards combined with the results due to the other loads as prescribed in each specific load combination.

Finally, in this work the feasibility of a seismic analysis of the UL PP using a static approach was also investigated. Since the directionality of the responses is not lost in this approach, it would be easier to combine the seismic results with the ones due to the other applied loads.

2. Methods

2.1 Response spectrum approach

The RS analysis is based on the modal analysis of the UL PP and the FRS, that are plots of acceleration versus frequency, provide the excitation. For given geometrical configuration (i.e., PP or PP plus port), three separate RS analyses were run in correspondence to three directions of excitation: radial, toroidal and vertical. Modal and spatial combination rules were applied to obtain the final results.

The results based on a modal analysis are accurate only if more than 90% of the total mass of the structure in each excitation direction is involved in the number of considered modes [7]. This results in calculating more than 100 modes for the PP. However, most of these modes fall in the high frequency region, i.e. beyond the FRS frequency range, where the spectral acceleration is constant. It is therefore sufficient to calculate few modes only (the ones with frequency within the FRS frequency range) because an accurate and computationally efficient method can be used to determine the contribution of the modes beyond the range. This method uses exactly the constant spectral acceleration beyond the FRS range and so it allows not calculating the more difficult higher frequency modes. The mass associated to the not calculated modes is named *missing mass*.

2.1.1 Geometry

In the frame of the grant F4E-2010-GRT-161 between Fusion for Energy and the ECHUL-CA consortium for the development of the EC H&CD UL, the geometry of the UL PP at the design version *zero* (preliminary design shown in Fig. 1) and the geometry of the upper port provided in the baseline documentation of this grant were used in the analysis [8].

The geometrical configurations PP and PP plus port are shown in Fig. 2. In the PP, the double wall section of the mainframe was modelled as a single wall and there are no cooling pipes in the BSM and FWP. The copper and stainless steel layers of the FWP were modelled as a single body. Three point masses account for the inertial effects of the internal shield, mirror box and auxiliary shield. Each point mass was located at the barycentre of the specific UL internal component and mass and inertia moments were assigned.

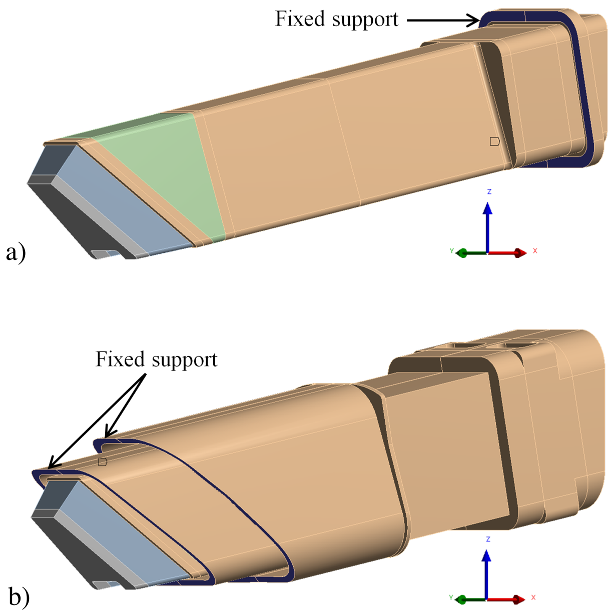

Fig. 2. UL PP (a) and UL PP plus port (b) geometrical configurations used for the seismic analysis of the PP. Internal components were modelled by point masses. The different colours at the tip of the PP indicate the regions where equivalent densities were applied. Fixed supports were applied to the dark violet surfaces indicated by the arrows.

2.1.2 Mesh and materials

A mesh with 437k/254k nodes/elements was used for the PP configuration and a mesh with 745k/389k nodes/elements for the PP plus port one. The element size ranges between 5 cm (global setting) and 5 mm (in the regions where the highest stresses were found).

The stainless steel 316L(N)-IG was used as material [9], but equivalent densities were applied to the double wall section of the mainframe, BSM and FWP, as the details of the inner cooling channels were still missing. Such densities were calculated as weighted averages of the densities of the different involved materials according to their volume fractions. The working temperature was set to 130°C.

2.1.3 Boundary conditions and loads

In the PP configuration, a fixed support was applied to the support flange as boundary condition while in the PP plus port one the fixed support was applied to the surfaces of the inner and outer shells of the port which face the VV (Fig. 2).

The FRS to be used as load in the seismic analysis of the UL PP are defined in [10]. FRS were calculated at several points along the VV perimeter for the SL-2 triaxial earthquake, a 4% damping ratio with 254 frequency points from 0.1 to 33.9 Hz. Per each point, three FRS are given in correspondence to the radial, toroidal and vertical direction. The FRS defined at the points *UPP_flange* and *VV_D* were respectively used for the PP and the PP plus port configurations. Such spectra were taken as text files from [11] and are reported in Fig. 3. They were applied to the fixed support of the configurations. Note that the seismic excitation in the vertical direction is much higher than the one in the other two directions.

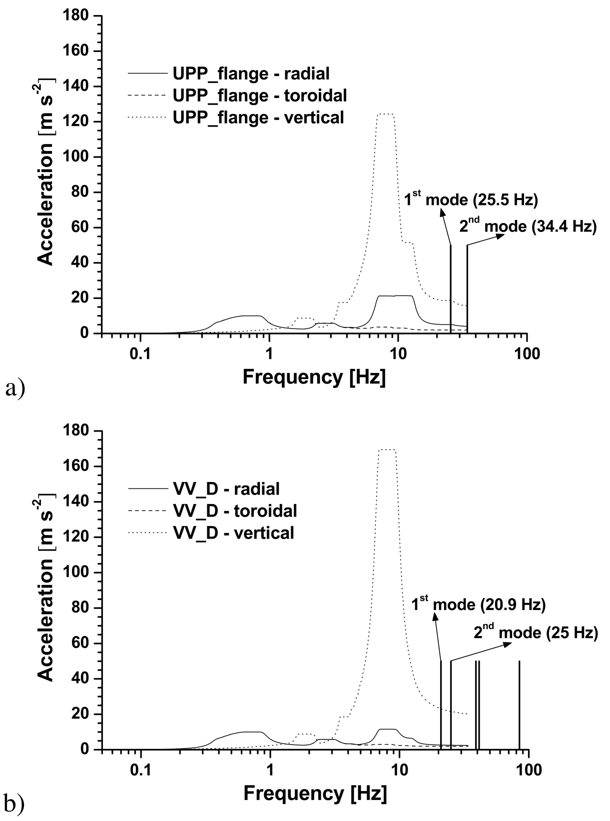

Fig. 3. FRS used as excitation in the RS analysis of the PP (a) and PP plus port (b) geometrical configurations. The natural frequencies of the configurations less than 100 Hz are also reported. The f_{ZPA} is 33.9 Hz. ZPA in radial, toroidal and vertical direction are respectively 4.08, 1.95, 15.7 m s^{-2} for the PP configuration (a) and 2.42, 1.92, 20.2 m s^{-2} for the PP plus port configuration (b).

2.1.4 Missing mass correction

The modal analysis was run by specifying 10 vibration modes to be calculated. Only the first 2 modes fall in the frequency range of the applied FRS and thus were considered in each RS analysis. As anticipated in §2.1, the missing mass correction method of ANSYS was activated in each RS analysis to obtain accurate results.

In a generic spectrum, at high frequencies there is a point beyond which the spectrum curves for several damping ratios converge to the same spectral acceleration. In Fig. 3, this point is the last frequency point of the FRS with acceleration named zero period acceleration (ZPA) and frequency called f_{ZPA}. Beyond this point, the modes are rigid (i.e., their responses are in-phase with the ZPA and so with each other) and since the period of the high frequency modes is very short, their responses are essentially static.

The responses of the modes with frequency higher than f_{ZPA} (i.e., the missing mass response) are thus determined by a static analysis: the structure is subjected to a load that equals the missing mass multiplied by the ZPA. The appropriate ZPA was so specified in each RS analysis to calculate such missing mass contribution.

2.1.5 Modal and spatial combination rules

The RS analysis records only the amplitudes of the responses for each mode. As the phase angles among the modes are not known, a combination rule among the modes has to be thus adopted to obtain the final results of each analysis. The square root of sum of squares (SRSS) rule was used as modal combination rule in each RS analysis.

For each geometrical configuration, three separate RS analyses were made for the three directions of excitation. A further and last combination rule was thus applied to the results of the three RS analyses to obtain the final results, i.e. the directional displacements and the equivalent stress. Newmark's rule was adopted as spatial combination rule [12, 13]. For a given variable S, such a rule is written as:

$$S = \max(\pm S_x \pm 0.4 S_y \pm 0.4 S_z;\ \pm 0.4 S_x \pm S_y \pm 0.4 S_z;\ \pm 0.4 S_x \pm 0.4 S_y \pm S_z)$$

where S_x, S_y and S_z are the maximum responses of that variable (e.g., radial displacement) respectively due to the seismic excitation in radial, toroidal and vertical direction, while S is the resulting maximum response due to all three excitations. Being S_x, S_y and S_z results from the three RS analyses, they are positive values and so this rule is reduced to only 3 of the foreseen 24 combinations. Then, the maximum is taken with the ± sign variations for the directional displacements and obviously positive for the equivalent stress.

Newmark's rule is preferred to the SRSS rule for the spatial combination because it is more conservative. The modal combination is performed directly by ANSYS code, but Newmark's rule is not given among the options.

2.2 Static approach

Since most part of the vibration modes falls in the region of the FRS where the behaviour is static, a seismic analysis of the UL PP was also performed directly using a static approach. For each configuration, three ZPA are given for the three directions of excitation. These ZPA have to be considered with the ± sign variations and so eight sets of load combination are obtained. Eight structural analyses for each geometrical configuration were run by applying the sets of ZPA and using the boundary conditions described in §2.1.3. The directional displacements and the equivalent stress resulting from the most severe load combination were compared with the ones obtained from the RS analysis.

3. Results and discussion

3.1 Response spectrum approach

Fig. 3 reports the applied FRS together with the natural frequencies up to 100 Hz for both geometrical configurations. First, it can be seen that only the first two modes are below the f_{ZPA} and therefore were used in the RS analysis (the second mode for the PP case is indeed beyond the frequency range, but it is very close to the f_{ZPA}). Then, such natural frequencies are far from the frequencies of the FRS peaks, so no resonance condition occurs for the UL PP. Of course, the natural frequencies of the PP plus port configuration are lower than those of the PP configuration because of the increased mass and decreased stiffness when the port is included.

Since the PP is a cantilevered structure, the first two modes correspond to the first order toroidal and vertical bending of the PP. Considering the radial, toroidal and vertical direction, they account only for 1.90%, 53.3%, 53.9% of the total mass in the PP configuration and 0.74%, 25.6%, 23.3% in the PP plus port configuration. As a consequence, the missing mass correction method was used to obtain accurate results.

Table 1 reports the maximum directional displacements and equivalent stresses obtained in the UL PP from the RS analyses of both geometrical configurations. Fig. 4 shows typical plots of results given by one RS analysis. The seismic analysis of the UL PP has led to relatively small displacements and stresses. As expected, when the port is included in the analysis, greater displacements and stresses are obtained in the PP.

Since the highest seismic excitation is the vertical one, it gives the most important contribution in the spatial combination for the stress and furthermore, considering that the PP is inclined with respect to the radial direction, this excitation also rules the spatial combination for the radial displacement. The combination for the toroidal and vertical displacements is normally ruled by the toroidal and vertical excitations.

The maximum stress of the PP is less than 30 MPa and is located at the corners of the transition plate from the rectangular to trapezoidal PP cross section. Due to the very high vertical excitation, the UL PP oscillates mainly in the vertical direction during the seismic event with amplitude anyway less than 2 mm. A total displacement of the PP might be calculated using the values reported in Table 1 and it would amount to 0.63 mm for the PP case and 1.49 mm for the PP plus port case.

It is important to note that the displacements obtained for the PP plus port configuration are de-facto the relative displacements between PP and port, since the attachment to the VV is the fixed support. They can, in turn, be compared with the size of the gap between the UL PP and the port (i.e. 25 mm, of which 13 mm only are allowed for the PP deflection). By comparison with the displacements due to electromagnetic loads affecting the UL PP during plasma disruptions [14], it is possible to conclude that the seismic contribution is generally low.

Table 1. Maximum results in the UL PP obtained from the RS approach applied to the two configurations. Newmark's rule was used as spatial combination rule.

Config.	Rad. displ. [mm]	Tor. displ. [mm]	Vert. displ. [mm]	Equiv. stress [MPa]
UL PP	±0.162	±0.141	±0.588	21
UL PP plus port	±0.388	±0.204	±1.43	27.8

3.2 Static approach

The maximum directional displacements and equivalent stresses given by the static approach are shown in Table 2 for both geometrical configurations. They can be compared with the results obtained by the RS approach and reported in Table 1. It is possible to observe that for the PP configuration there is a very good agreement while it is not anymore the case when the port is included. In fact, the static approach gives displacements smaller than the ones obtained from the RS approach by 15-24%.

This can be explained considering that in the PP plus port configuration the first two natural frequencies fall inside the FRS range and have spectral accelerations higher than the ZPA, while in the PP configuration, this happens only for the first frequency. If mass is added to the PP model, the natural frequencies become lower and other modes could fall in the FRS range increasing thus the difference among the results of the two approaches (see Fig. 3-b). It can be concluded that the RS approach has to be used for the seismic analysis of the PP plus port configuration and for homogeneity reasons such approach is also extended to the PP configuration.

Table 2. Maximum results in the UL PP obtained from the static approach applied to the two configurations. The percentages into brackets are the relative differences with respect to the correspondent results shown in Table 1.

Config.	Rad. displ. [mm]	Tor. displ. [mm]	Vert. displ. [mm]	Equiv. stress [MPa]
UL PP	±0.163	±0.132	±0.586	22.3
	(0.7%)	(-6.1%)	(-0.3%)	(6.4%)

UL PP plus port	±0.295	±0.173	±1.14	28.8
	(-24%)	(-15%)	(-20%)	(3.4%)

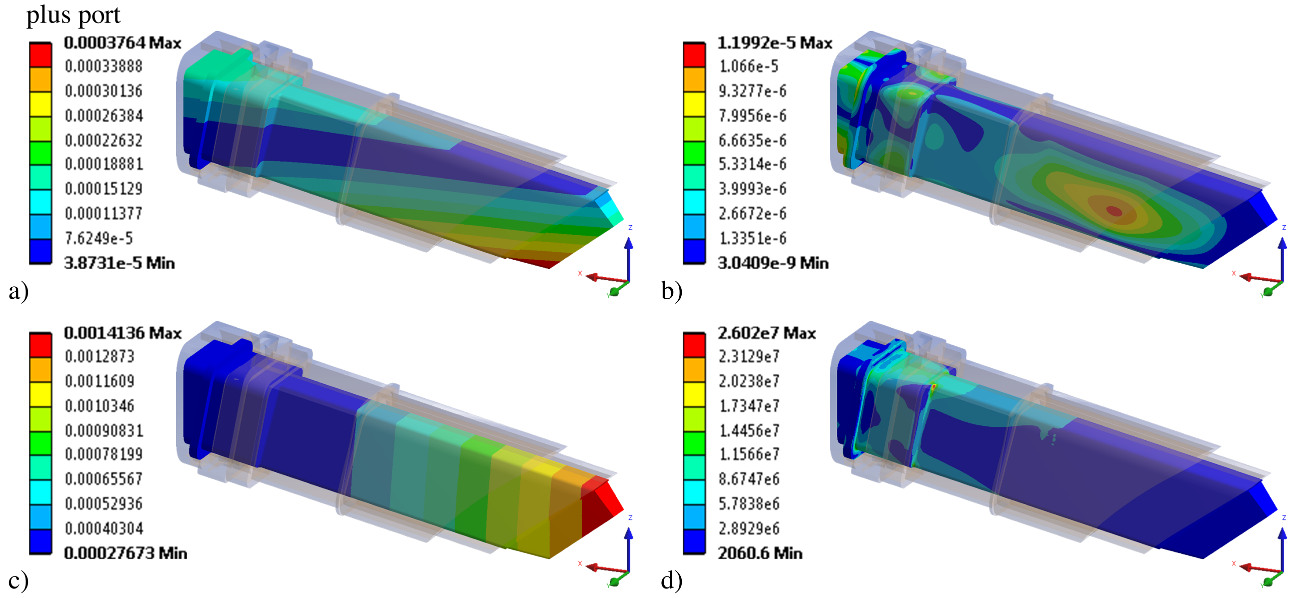

Fig. 4. Results of the RS analysis for the PP plus port configuration with the FRS applied in the vertical direction (the results are only positive). Displacements of the PP are shown in radial (a), toroidal (b) and vertical (c) direction with values in m. The distribution of the equivalent stress in the PP is reported in (d) with values in Pa. Each maximum directional displacement and the maximum stress were combined with the correspondent ones obtained from the other two RS analyses (radial and toroidal excitation) by Newmark's rule in order to calculate the final results reported in Table 1. Note that the RS analysis in the vertical direction plays in general a major role in the combination of the results.

4. Conclusions

A seismic analysis of the ITER EC H&CD UL PP was carried out for the SL-2 seismic event using the RS approach. The effect of the upper port was also taken into account and then the feasibility of a static approach was investigated too.

No resonance condition occurs for the UL PP during the ITER reference seismic event. The maximum equivalent stress is lower than 30 MPa and the PP oscillates mainly in the vertical direction with amplitude less than 2 mm. Looking at the UL load combinations, the seismic contribution can be generally considered low. When the port is included in the analysis, the static approach cannot be used anymore because more natural frequencies fall in the FRS range. The RS approach has to be used for the PP plus port configuration and it is also extended to the PP one. The seismic analysis of the UL PP will be afterwards updated accordingly to the design development of the PP.

Acknowledgments

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