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SEISMIC ANALYSIS OF THE TOKAMAK MACHINE AND ITS INTERFACE WITH THE TOKAMAK BUILDING

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ABSTRACT

The ITER Fusion reactor, the so-called Tokamak machine, as well as its connection to the supporting building, the Tokamak Complex, must be designed against seismic loads. Due to its significant size and mass, in the order of 23,000 tons, the determination of the seismic forces developing at the interface with the building and of the floor response spectra defining the seismic environment inside the reactor, poses some difficulties that have been addressed in the work presented in this paper by a one-step approach in the time domain with a coupled dynamic representation of the reactor/building systems.

INTRODUCTION

As all nuclear facilities, the ITER Fusion reactor and its mechanical components have to be designed to sustain seismic forces. An accurate evaluation of the transfer of the seismic accelerations and their spectra from the ground to the components located in the Tokamak machine may be challenging in case of coupling, which may play a crucial role when the interaction between the secondary components and the supporting structure results in a new system whose responses differ from those that would be obtained by considering the two systems as isolated. The determination of the floor response spectra may also become more challenging when the models used for the building and for the machine or the mechanical components are very detailed. The interface between the Tokamak machine and the building structure also represents a critical issue due to the significant mass of the machine and the little space available at the location of the interface. This paper presents a set of seismic analyses performed under F4E supervision in order to determine the floor response spectra inside the machine system and the interface forces with the building structure.

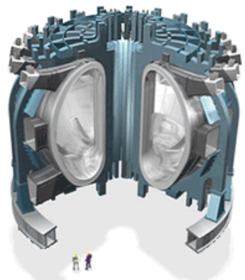
THE ITER TOKAMAK MACHINE

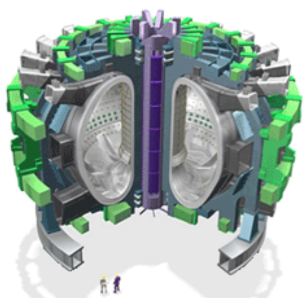
Description of the reactor and its support on the building

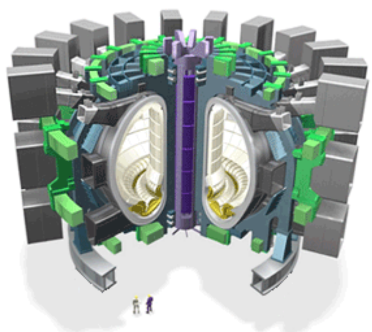
The main components of the Tokamak machine are shown in figure 1. The vacuum vessel (figure 1A) is a central, doughnut-shaped steel container with a weight in excess of 5,000 tons that houses the fusion reaction and acts as a first safety containment barrier. The vacuum vessel is surrounded by 18 superconducting toroidal field coils (figure 1B) and 6 poloidal field coils, a set of smaller correction coils and a central solenoid (figure 1C), that magnetically confine, shape and control the plasma inside the vacuum vessel. The whole magnet system is supported on a steel ring called the pedestal ring (figure 1B) by the so-called gravity supports, located at the base of each toroidal field coil. These supports consist of a set of flexible plates to allow for a free radial expansion of the system under the expected thermal loads. The vacuum vessel is also vertically and toroidally supported at the lower ports (see upper, equatorial and lower ports in figure 1D), by nine special double hinge supports attached to the pedestal ring. These supports also transfer to the pedestal ring any load coming from the in-vessel components (mainly blanket modules, divertor and port plugs, figure 1D). In summary, the reactor is basically supported by the magnets and the vacuum vessel, with their respective supports resting on a common steel ring that is part of the cryostat. The cryostat (figure 1E) is a stainless steel structure surrounding the vacuum vessel and superconducting magnets, which provides a super-cool, vacuum environment.

The support of the Tokamak reactor is provided by a circular reinforced concrete ring going from the pedestal ring to the lower basemat, common to the whole Tokamak Complex, and on a set of radial reinforced concrete walls, as shown in red in Figure 2. 18 sliding based bearings transfer the loads from the pedestal ring to this reinforced concrete structure. The basemat, common to the whole building has a footprint of about 125 x 90 m and it is built with a base isolation system which includes some 500 steel reinforced low damping neoprene pads. The final load path in a seismic event is shown in figure 3.


A
Vacuum Vessel (VV)


B
VV + Toroidal Field Coils (TFC) + Pedestal Ring (PR)


C
VV + TFC + PR + Poloidal FC (PFC) + Central Solenoid (CS)


D
VV + TFC + PR + PFC + CS + VV ports + in-vessel comps.

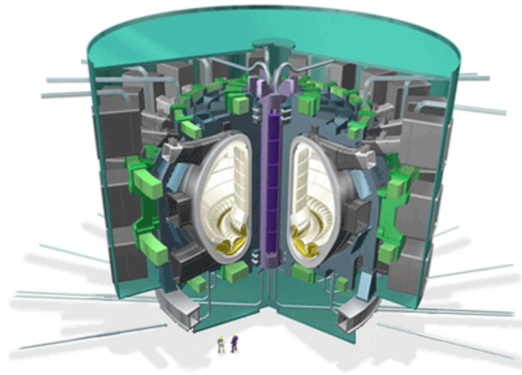

E
VV + TFC + PR + PFC + CS + VV ports + in-vessel components + Cryostat

Figure 1: General perspective of the Tokamak machine (Courtesy of ITER IO & Fusion for Energy).

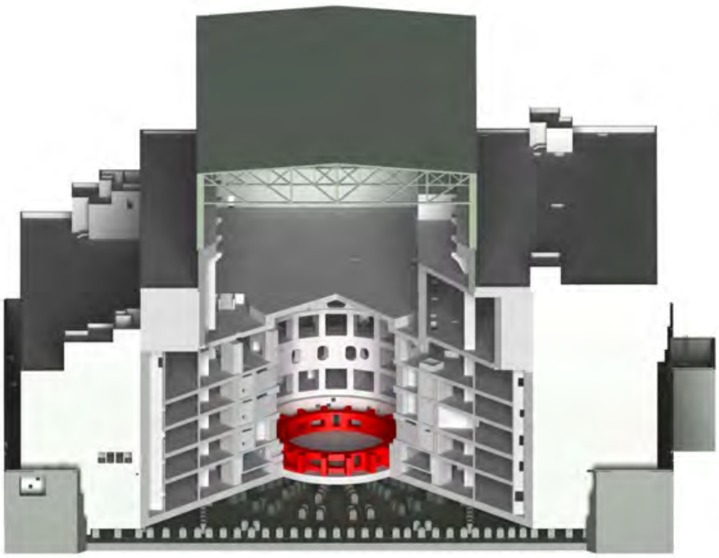


Figure 2: Conceptual design of the reactor supporting structure.

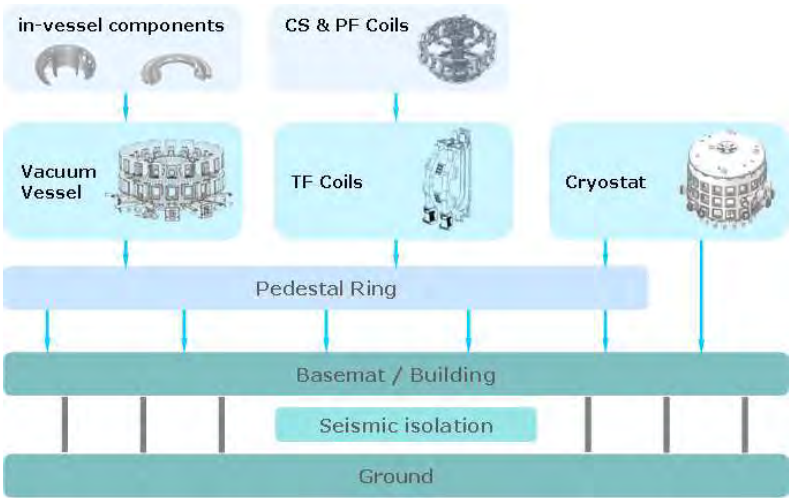


Figure 3: Load paths in the Tokamak machine during a seismic event.

Seismic design basis

Seismic load excitation corresponds to the specific selected site for the ITER construction (Cadarache). For buildings and equipment that have safety importance or whose failure impact on reparation or operational costs/time, three levels of ground motion, SL-2, SMHV (Séismes Maximaux Historiquement Vraisemblables = Maximum Historically Probable Earthquakes), and SL-1, are considered (Ref. [4]).

SL-2 corresponds to the seismic level required by French nuclear practice. According to the Ref [3], it shall be demonstrated in this event that releases are under the General Safety Objectives in accidental situations. For ITER site (Cadarache) the SL-2 (also called SSE – Safe Shutdown Earthquake) Design Response Spectra is defined by two spectra: SMS and PALEO spectra. Either types of spectra (or their envelope) need to be analyzed. In the specific context on the work described in this paper, six artificial signals of horizontal acceleration, representative of the design response spectra (three for the SMS and three for the Paleo-earthquakes) have been also given as part of the design input data.

SMHV is the most severe earthquakes liable to occur over a period of about 1000 years.

SL-1 corresponds to an event with a probability in the order of 10^{-2} per year and represents an investment protection earthquake level. The facility has to be designed to restart and operate after an SL-1 event without any special maintenance or test.

PROBLEM STATEMENT – SIMPLIFIED ANALYSES

In order to understand the potential coupling effects between the supporting structure and the equipment when the later is large compared to the former, as well as to assess the potential implications of floor response spectra (FRS) broadening, several time-history analyses have been conducted with a set of 2 degree-of-freedom (2 dof, hereinafter) elastic systems.

On paper, the seismic analysis of any heavy mechanical component such as the Tokamak machine can be performed in two ways:

- One-step approach: the ground seismic motion is directly applied to a model with a simple representation of the building and a more detailed representation of the equipment.
- Two-steps approach: the seismic motion calculated with a detailed model of the building and a very simplified representation of the equipment (transferred motion) is applied at the base of a more detailed model of the equipment.

The seismic motion can be represented either by a set of acceleration signals or by a set of FRS.

Simplified 2 dof systems

Two types of configuration for the 2 dof system have been studied (Figure 4), the first dof representing the support (K1 and M1) and the second dof representing the equipment (K2 and M2):

- Heavy equipment on a light support (case of the Tokamak machine in the vertical direction): M1=1 000 tons and M2=23 000 tons.
- Same equipment on a heavy support (case of the Tokamak machine in the horizontal direction): M1=230 000 tons and M2=23 000 tons.

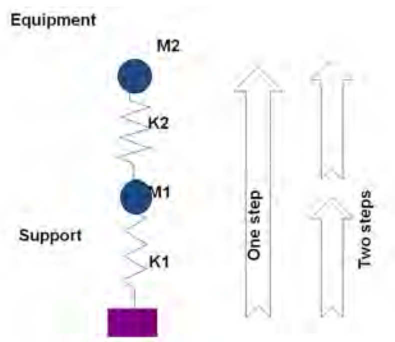


Figure 4: Presentation of the 2 dof system and the analysis.

In both cases, the frequency of the equipment with fixed boundary conditions at its support (isolated equipment) is set to 9 Hz, representative of the isolated machine main vertical mode. Sensitivity analyses have been conducted on the stiffness of the support, K1 (3 cases per system). For the two-steps approach, the response at the base of the equipment from the 2 dof analysis has been applied to the isolated equipment. The spectral accelerations on the support and the maximum acceleration (ZPA) on the equipment have been analyzed and the results from the one-step and the two-steps approach have been compared. The responses of the simplified 1 dof or 2 dof systems (displacement, velocity and acceleration) and the response spectra have been calculated by time integration. The FRS on the two masses have been compared to the ground response spectra (Figure 5).

Results for the light support case

This case is aimed at representing the behaviour of the Tokamak machine in the vertical direction: the mass of the concrete slab supporting the machine is small compared to the mass of the machine.

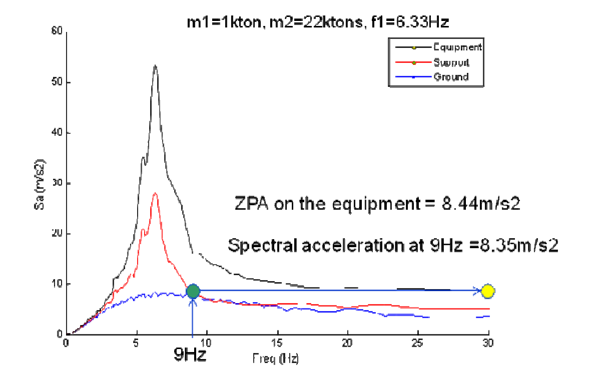
Three different values of stiffness K1 have been considered. The corresponding frequencies of the fundamental mode of the 2 dof system (with coupling) to be compared to the 9 Hz of the isolated machine with fixed boundary condition are:

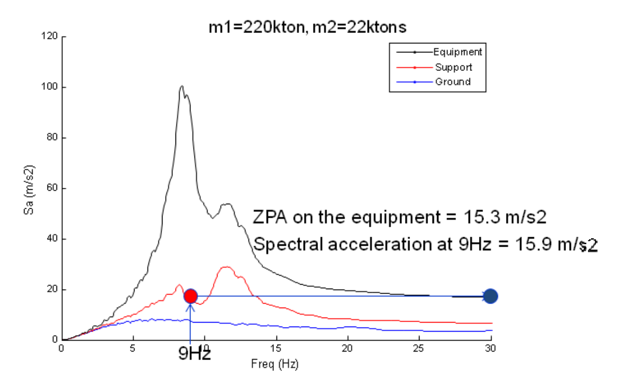
- Case 1a: 6.33 Hz. The support stiffness has a relevant influence on the fundamental eigenmode of the machine (Figure 5, left hand side). The ZPA and the spectral accelerations of the equipment support have a value between the ZPAs and the FRSs of the ground motion and the machine motion.
- Case 1b: 8.50 Hz. The support has a limited influence and the motion of the support is similar to the ground motion. The effect of the machine on the support FRS is visible only around the frequency of the machine.
- Case 1c: 3.62 Hz. The support has a strong influence and the main part of the deformation for the main mode of the system corresponds to the support. The motions of the machine and the support (ZPAs and FRSs) are very similar.

Results for the heavy support case

Similar analyses have been performed but with a very heavy support having a mass ten times the mass of the equipment. This is representative of the response of the machine and the building in the horizontal direction. Because of the mass of the support, the 2 dof system has really two eigenmodes:

- Case 2a: The stiffness of the support is assumed to be very low. It is representative of an isolated building such the Tokamak complex. The benefit of the seismic isolation is clearly put in evidence and the fundamental eigenmode has a much lower frequency than the second eigenmode (0.5 Hz vs 9.4 Hz). The support and the machine behave as a rigid body and the FRSs on the support and the machine are very similar. Above 1 Hz, the FRSs show a very flat plateau and the ZPA of the machine is close to the spectral acceleration on the support at 9 Hz.
- Case 2b: The stiffness of the support is adjusted to get a fundamental eigenmode with an eigenfrequency lower than (but closer to) the one of the fundamental eigenmode of the machine (f_1= 5.30 Hz vs f_2=9.66 Hz with coupling and 9Hz without coupling). The value of 9 Hz is not anymore in the flat plateau of the FRS of the support but the corresponding spectral value is again similar to the ZPA of the machine (11.5 m/s^2 vs 11.6 m/s^2).
- Case 2c (Figure 5, right hand side): The stiffness of the support has been adjusted to obtain very similar eigenfrequencies of the support and the machine in order to maximize the effect of coupling between the machine and the support. The coupled 2 dofs system has two very similar eigenfrequencies (f_1= 8.36 Hz and f_2=11.86 Hz) and the mass of the support is sufficient to impose its motion at the base of the machine which again amplifies the motion. Also in this case, the spectral acceleration at 9Hz (15.9 m/s^2) is similar to the ZPA of the machine (15.3 m/s^2). The FRS on the support strongly varies around 9 Hz and a small imprecision on the frequency of the machine can significantly change the value of spectral acceleration.





Heavy equipment and light support with intermediate stiffness (f_1=6.33Hz)	Equipment and heavy support with high stiffness (f_1= 8.36Hz/f_2=11.86Hz)

Figure 5: Seismic response of 2 dof systems

Conclusions for the use of one-step or two-steps approaches

The effect of coupling between any equipment similar to the Tokamak machine and its support such as the Tokamak Complex structure has been investigated with the help of different 2 dof systems. For each system, the one-step coupled approach and the two-steps approach yield identical dynamic responses of the Tokamak machine under seismic motion: the equipment acceleration. Therefore, the force in the K2 spring can be well estimated with the acceleration or the FRS on the support (provided these are calculated with coupling) and considering the natural frequency of the equipment with fixed boundary conditions (neglecting the coupling for the determination of the natural frequency).

Nevertheless the applicability of this simple principle to complex systems such as the Tokamak machine and its interaction with the building, which require several levels of modelling (simplified model embedded in the building and more refined model with fixed boundary conditions for detailed seismic analyses) forces to check the consistency of the different modeling levels: the models need to have the same dynamic behaviour and so the same fundamental modes and corresponding frequencies.

A particularly interesting issue is whether the FRS has to be broadened for a system with coupling. Such a broadening might introduce excessive and non-uniform margin in case of coupling (Figure 6). Furthermore the margins may depend on each individual case. This broadening by +/-15% of the FRS is aimed at taking into account the approximation on the natural frequencies of the support and the equipment. So, for the analysis with coupling, sensitivity analyses have to be conducted on the relative characteristics (support vs equipment), as will be described next. A similar approach is presented in Ref [1].

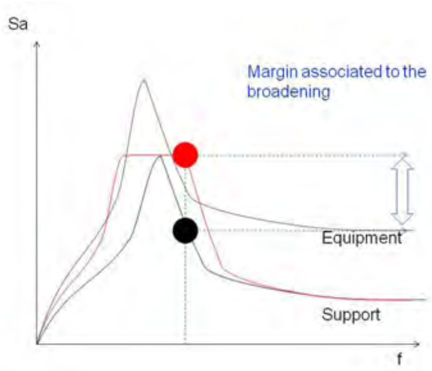


Figure 6: Potential margin associated to the use of the two-step approaches with broadened spectra

COUPLED SEISMIC ANALYSES IN THE TIME DOMAIN

Global coupled finite element model

According to the conclusions derived from the simplified analyses described previously, several seismic analyses of the Tokamak machine have been carried out based on the one-step approach methodology. In order to properly take into account the dynamic coupling in the vertical direction between the Tokamak machine and the supporting structure, two relatively detailed finite element models representing each part have been assembled together into a single unified model, which is shown in Figure 7. This global FE model has been generated in ANSYS.

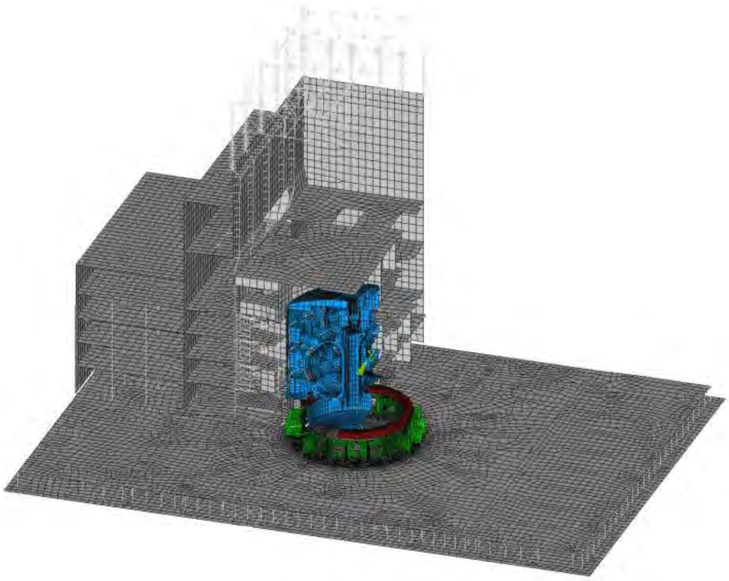


Figure 7: Coupled Tokamak machine – Tokamak building finite element model for seismic analyses.

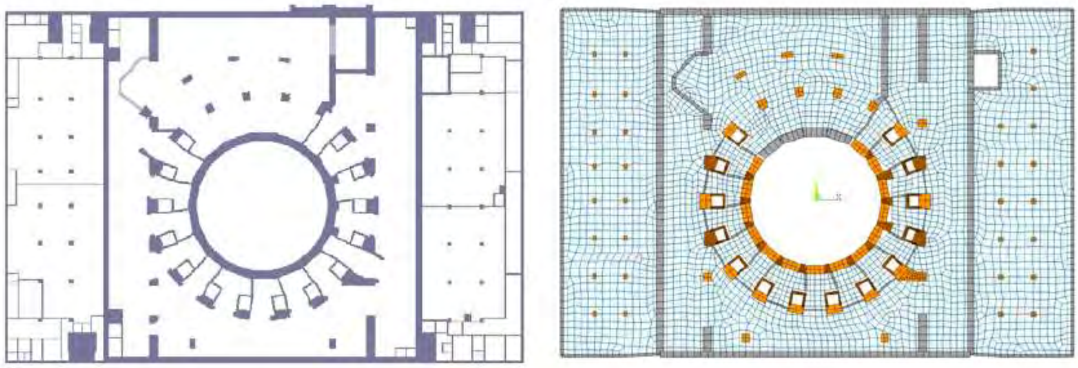
As far as the building is concerned, the spatial distributions of mass and stiffness have been reproduced with great care. Average mesh size and key structural elements that are generally represented in the FE model are shown in Figure 8, which portrays a typical representation of a Tokamak Complex floor on both Catia v5 and ANSYS models as well as the layout of seismic pads, which are represented in the finite element model by a set of five springs per pad.

As for the Tokamak machine, the finite element model developed by ITER IO and presented in Figure 9 has been assembled in the global model for seismic analysis. This finite element model reproduces with a significant level of detail from a global perspective the main characteristics of the machine in terms of mass and stiffness. The double steel wall design of the vacuum vessel is represented by an equivalent one-layer-layout of shell elements, whereas beam elements are most commonly used to represent the TF and PF magnets. A combination of shell and beam elements are used for the cryostat plates and corresponding stiffeners. A thoughtfully tuning process has been carried out by ITER IO so that these more simplified models closely match the mechanical responses obtained with local, more detailed finite element models of each isolated component. Special attention has also been paid to the shell-element-based representation of the pedestal ring supporting the main machine components.

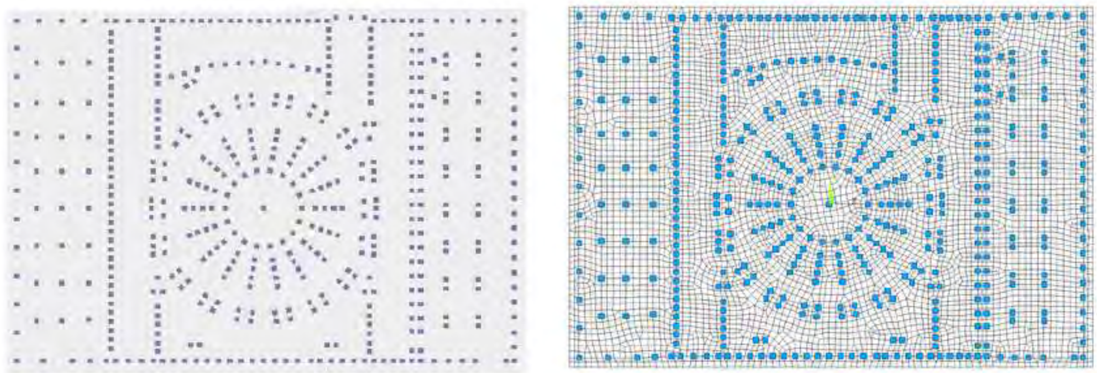
Seismic analyses in the time domain

The analyses of the seismic response of the Tokamak machine have been carried out by applying simultaneously three statistically independent spatial components of the free field acceleration signals at the base of the global finite element model of the machine/building assembly described previously.

Time history analyses have been performed using the integration of the equations of motion by modal superposition, therefore obtaining the time dependant response of the structure as a linear combination of the individual response of its mode shapes. The resulting radial, toroidal and vertical force and acceleration time histories at the elements modeling the interfaces and at other locations of interest have been obtained for further post-processing.



Comparison of typical Tokamak Complex intermediate floor layout in Catia v5 (left) and ANSYS (right) models



Comparison of seismic pads layout in Catia v5 (left) and ANSYS (right) models

Figure 8: Modeling details in the Tokamak building finite element model for seismic analyses.

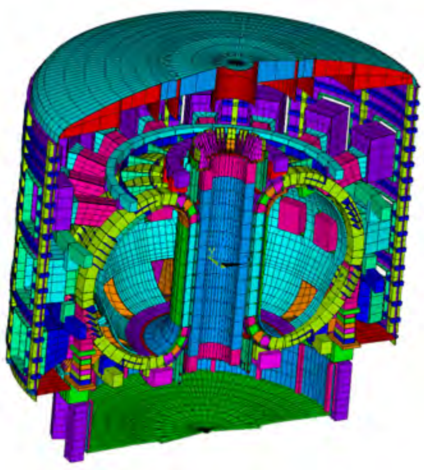


Figure 9: Tokamak machine finite element model for seismic analyses.

Accounting for uncertainties

The implementation of the FRS peak broadening within the two-steps approach into the one-step approach language could be expressed as ‘taking into account uncertainties in the modeling of the support dynamic representation’. From a one-step approach perspective this is the most consistent way to deal with this issue in a coupled system, since, as already discussed in the simplified analyses presented previously, applying broadening in a two-steps analysis of a strongly coupled system may be highly conservative. In the context of the work presented in this paper, accounting for these uncertainties has been accomplished by modifying the mechanical properties of the materials from which the main parts of the system (i.e. soil, seismic pads, building and also Tokamak machine) are made:

- Variability of both soil and seismic isolation stiffness is considered according to the ITER Structural Design Code for Buildings, this is, maximum and minimum stiffness for the soil have been related to the best estimate value of the shear modulus, G_{be}, by: $G_{min}=2/3 \cdot G_{be}$ and $G_{max}=3/2 \cdot G_{be}$, whereas maximum and minimum stiffness for the pads have been selected based on the results of an extensive testing campaign.
- Variability in the material properties of those elements pertaining to either the building or the Tokamak machine is also taken into account by applying a certain factor to the stiffness (i.e. Young’s modulus) of the corresponding materials. This factor accounts for a theoretical variation in the natural frequency of the system modes of ±15%. However, these variations have only yielded small differences in the results, since uncertainties related to the soil and the seismic pads are more relevant, as anticipated in Ref [2]].

Out of all the possibilities resulting from any potential combination of the available sets of properties regarding soil, seismic pads, building and machine stiffness, five bounding combinations have been considered. These combinations cover any reasonable range of variation in the mechanical properties of the global system. For each of these combinations, a different FE model has been generated and run under six different seismic scenarios that combine ground motions corresponding to both the Paleo and SMS earthquakes, resulting in a total of 30 runs in the time domain.

Main results from the dynamic analyses

Forces have been processed for all the interfaces including the nine sectors of the Tokamak machine and used for the determination of load envelopes. The results obtained are, therefore, based on a full and integrated spatial representation of the building/machine systems. In terms of maximum seismic forces developed at the machine/building interfaces, results have been derived at a local and global scale, providing valuable insight into the concomitance in time and space of the main peak responses. Figure 10 presents an example showing the simultaneous distribution of vertical load among the 18 sliding bearings below the pedestal ring at three relevant time instants for one of the 30 scenarios studied.

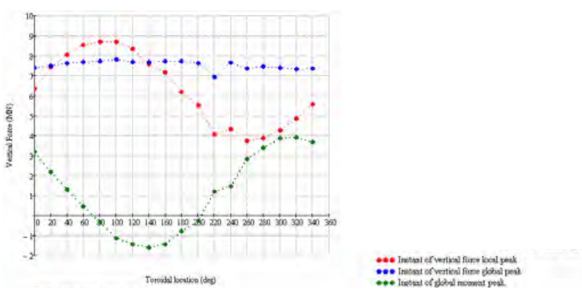


Figure 10: Typical spatial distribution of vertical load among the 18 Tokamak machine sliding bearings obtained at three different time of the simulation (time of maximum vertical force on a single support, total vertical force on the 18 supports, overall bending moment on 18 supports.

Design seismic FRS have been calculated at a number of points within the Tokamak machine. A summary of the points that have been considered in the analyses is presented in Figure 11. The FRS have been calculated for all the monitored points covering the nine machine sectors in the radial, toroidal and vertical directions. The results obtained are, therefore, fully representative of the machine system.

Generally speaking, horizontal FRS present two peaks. The first peak is at a frequency of 0.5 Hz and corresponds to the base isolation of the Tokamak Complex, whereas the second peak corresponds to a coupling between ground vertical motions and a combined horizontal response of the Tokamak Complex due to several rocking and torsional modes in the frequency range between 6.0 and 9.0 Hz. In the vertical direction, neither the building nor the machine systems are seismically isolated and the maximum spectral values are considerably larger. Vertical FRS are single-peak curves at a range of frequencies between 6.0 and 9.0 Hz, also.

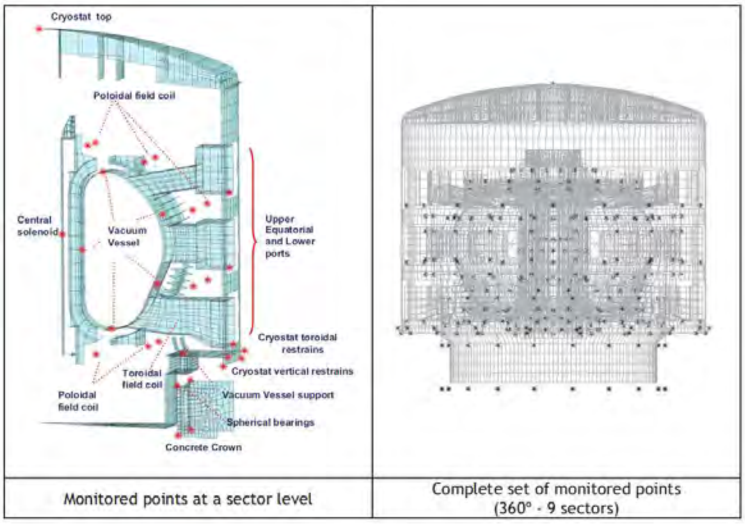


Figure 11: Control points in the Tokamak machine for determination of seismic FRS.

CONCLUSIONS

The seismic response of the Tokamak building and the Tokamak machine has been determined by a one-step approach in the time domain with a coupled dynamic representation of the reactor/building systems. The effects of the coupling between this heavy component and its support have been properly taken into account in the analyses and FRS peak broadening has been replaced by several sensitivity analyses on the main mechanical properties of the machine, the building, and the ground. This approach provides a more accurate evaluation of the seismic response for the coupled system and may eliminate the excess of conservatism introduced with the broadening of the spectra in the two-step approach.

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