COUPLED SEISMIC ANALYSES OF THE ITER TOKAMAK COMPLEX BUILDING AND TOKAMAK MACHINE

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Abstract

ITER is probably the most ambitious energy project in the world today, whose main objective is demonstrating the scientific and technical feasibility of nuclear fusion as an energy source. 35 nations are collaborating to build the world's largest tokamak fusion reactor, a magnetic fusion device that has been designed to prove the feasibility of fusion as a large-scale and carbon-free source of energy.

The ITER design must face a large variety of potential threats and complex loads, including seismic events. These are a design driver for many of the ITER buildings and main mechanical components, including the Tokamak machine and the building that supports it: the Tokamak Complex. The Tokamak Complex is a reinforced concrete building that houses the 23000-ton Tokamak machine, where the fusion reaction will take place. The Tokamak Complex is more than 70 m high, its plan dimensions correspond to those of a standard football stadium and it will become one of the largest seismically isolated structures ever built.

As a nuclear facility, the seismic design of ITER must ensure the corresponding seismic safety requirements are met according to the French regulation. On the other hand, too conservative approaches may have important technical and financial consequences.

This article provides a global summary of the latest works carried out by the European Domestic Agency, Fusion for Energy (F4E), for the definition of the seismic environment within the ITER Tokamak Complex, including the derivation of seismic floor response spectra as well as the characterisation of the complex interface seismic forces between the Tokamak machine and the building, which are critical for a correct design of the corresponding supporting elements. A part of the transient calculations has been performed with non linear models of mechanical components using condensation techniques (sub-structuring).

Keywords: Modelling; Non linear transient analysis Mechanical components; Floor response spectra.

1. Introduction

ITER is probably the most ambitious energy project in the world today, whose main objective is demonstrating the scientific and technical feasibility of nuclear fusion as an energy source. 35 nations are collaborating to build the world's largest tokamak fusion reactor, a magnetic fusion device that has been designed to prove the feasibility of fusion as a large-scale and carbon-free source of energy based on the same principle that powers our Sun and stars. The experimental campaign that will be carried out at ITER is crucial to advancing fusion science and preparing the way for the fusion power plants of tomorrow. ITER will be the first fusion device to produce net energy, maintain fusion for long periods of time and test the integrated technologies, materials, and physics regimes necessary for the commercial production of fusion-based electricity. The ITER Members—China, the European Union, India, Japan, Korea, Russia and the United States—are now engaged in a 35-year collaboration to design, build and operate the ITER experimental device, and together bring fusion to the point where a demonstration fusion reactor can be designed. ITER is currently under construction in the south of France. The completion of the construction works of the Tokamak complex is scheduled for the end of this decade, so that the scientific experimental campaign can start around 2025.

The ITER design must face a large variety of potential threats and complex loads, including seismic events. These are a design driver for many of the ITER buildings and main mechanical components, including the Tokamak machine and the building that supports it: the Tokamak Complex. The Tokamak Complex is a reinforced concrete building that houses the 23,000-ton Tokamak machine, where the fusion reaction will take place. The Tokamak Complex is more than 70 m high, its plan dimensions correspond to those of a standard football stadium and it will become one of the largest seismically isolated structures ever built. As a nuclear facility, the seismic design of ITER must ensure the corresponding seismic safety requirements are met according to the French regulation [1]. On the other hand, too conservative approaches may have important technical and financial consequences.

This article provides a global summary of the latest works carried out by the European Domestic Agency, Fusion for Energy (F4E, [2]) in collaboration with IO-CT [3], for the definition of the seismic environment within the ITER Tokamak Complex. This includes the derivation of seismic floor response spectra as well as the characterisation of the complex interface seismic forces between the Tokamak machine and the building, which are critical for a correct design of the corresponding supporting elements.

2. GENERAL DESCRIPTION OF ITER TOKAMAK COMPLEX AND SEISMIC REQUIREMENTS

2.1 The ITER Tokamak Complex

The ITER Tokamak Complex (see Fig. 1) is a rectangular reinforced concrete building, roughly 125 m long and 90 m wide, partially embedded in an excavation, called the seismic pit, supported by reinforced concrete lateral walls and a 1.5 m thick basemat. The foundation is on a fairly compact and homogeneous rock, limiting the potential significance of soil-structure interaction effects. The building structure is seismically isolated from the seismic pit basemat by 493 anti-seismic bearings (ABSs) which support the bottom basemat of the entire building. The ASBs are 900x900 mm2 pads mounted on top short columns (“plinths”) that come out the seismic pit basemat. The lower basemat of the building is a 1.5 m thick reinforced concrete slab locally strengthened at the centre of the Tokamak building to support the Tokamak machine, which is surrounded by a thick cylindrical wall: the bioshield wall. The whole Tokamak Complex reinforced concrete structure rests on this basemat.

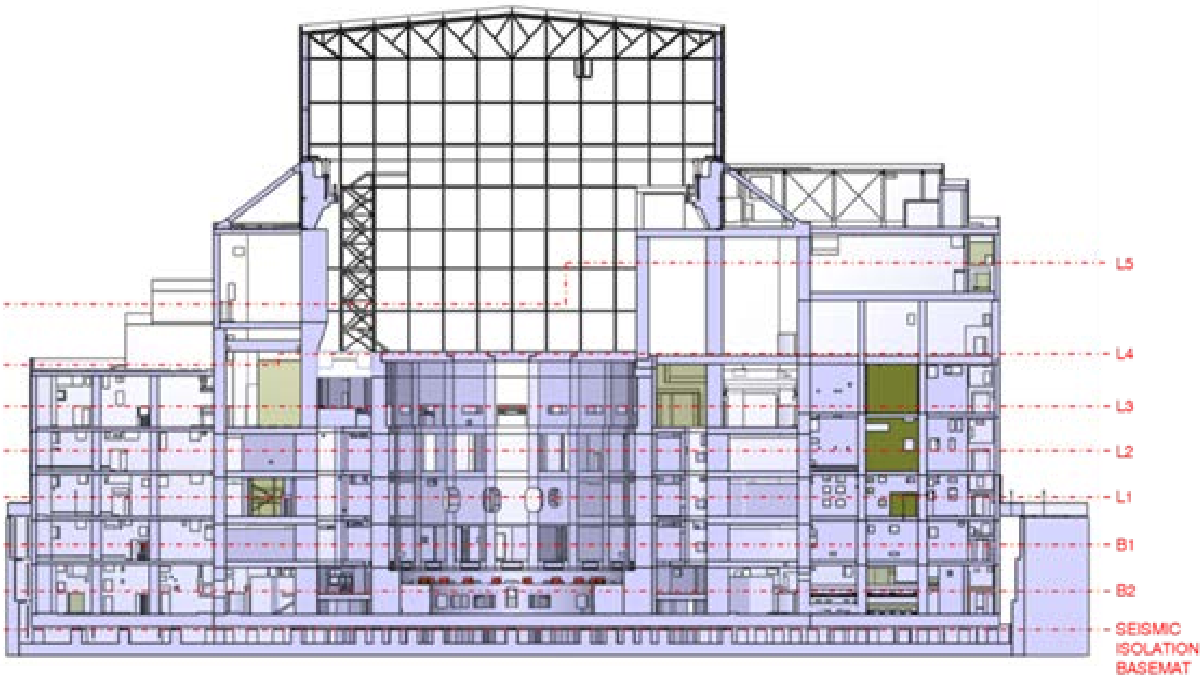


Fig. 1- ITER Tokamak Complex cut view.

2.2 The ITER Tokamak Machine

The ITER experiment builds on the concept of the tokamak, a torus continuous double-wall vessel surrounded by coils that produce a magnetic cage to confine the high-energy plasma. The ITER Tokamak machine (see Fig. 2) will be 24 metres high, 30 metres wide and weight around 23,000 tons. The most relevant components of the Tokamak machine from a global dynamic point of view are:

- The 10,000 tons superconducting magnets in charge of producing the magnetic fields to initiate, confine, shape and control the plasma.
- The Vacuum Vessel, a 8,000 tons stainless steel chamber that houses the fusion reactions and acts as main first safety containment barrier.
- The 3,800 tons cryostat, a stainless steel chamber (29 x 29 m) surrounding the vacuum vessel and superconducting magnets to ensure a cryogenic high vacuum environment.

2.3 Definition of the Seismic Action

The design earthquake for ITER (Safe Shutdown Earthquake –SSE or SL-2-) is generated as the envelope of two seismic events: the “Seisme Majore de Securite” (SMS) and the paleoseism. Figure 3 shows the horizontal SL-2 response spectra, both for SMS and Paleo earthquakes, at the control point (ground surface level). The Zero Period Acceleration (ZPA) is equal to 0.315g. The vertical motion is derived by multiplying the horizontal motion by 2/3. Six artificial signals (three for the SMS and three for the Paleo) for the horizontal accelerations are also shown in Fig. 3, which are representative of the design response spectra and meet the statistical independence requirements of the ASN Guideline [1].

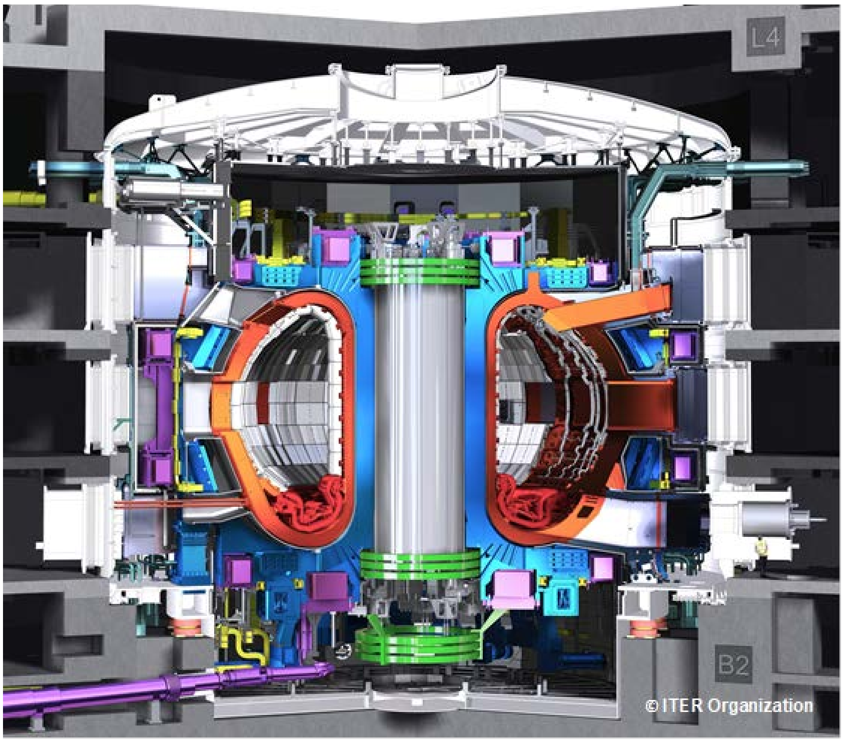


Fig. 2- ITER Tokamak machine (https://www.iter.org)

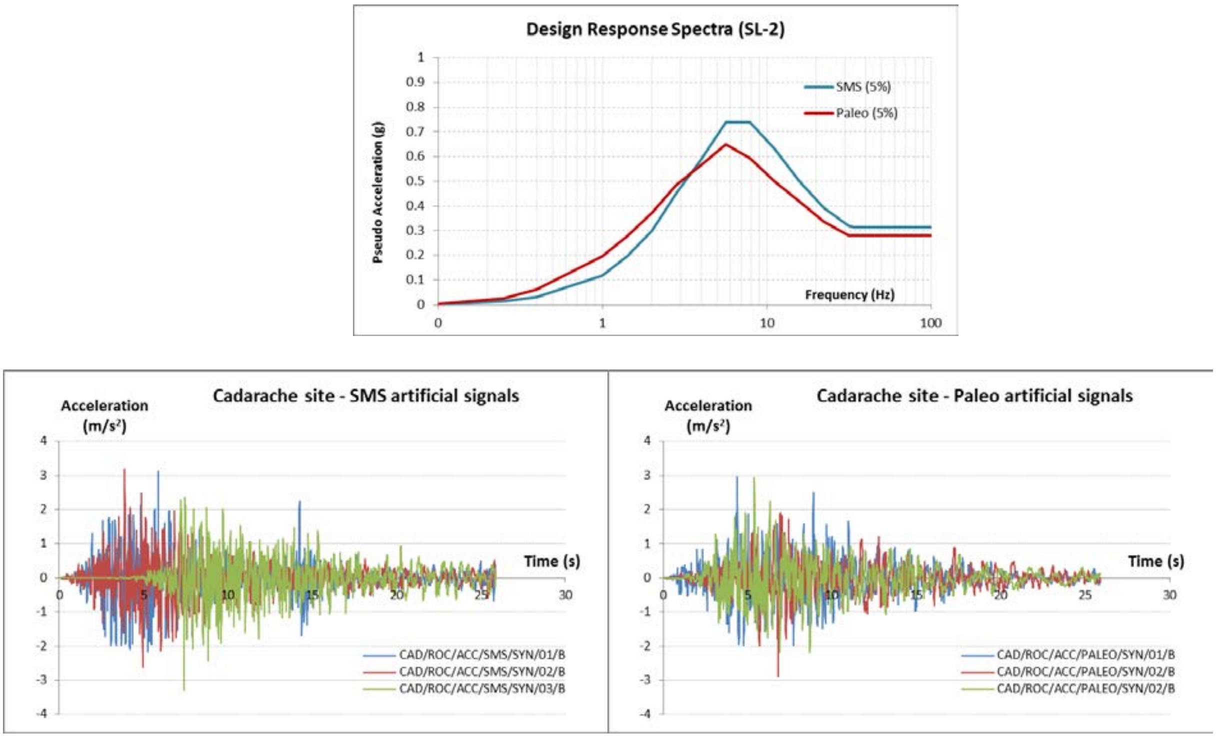


Fig. 3- Design response spectra and artificial acceleration signals for SL-2 (horizontal)

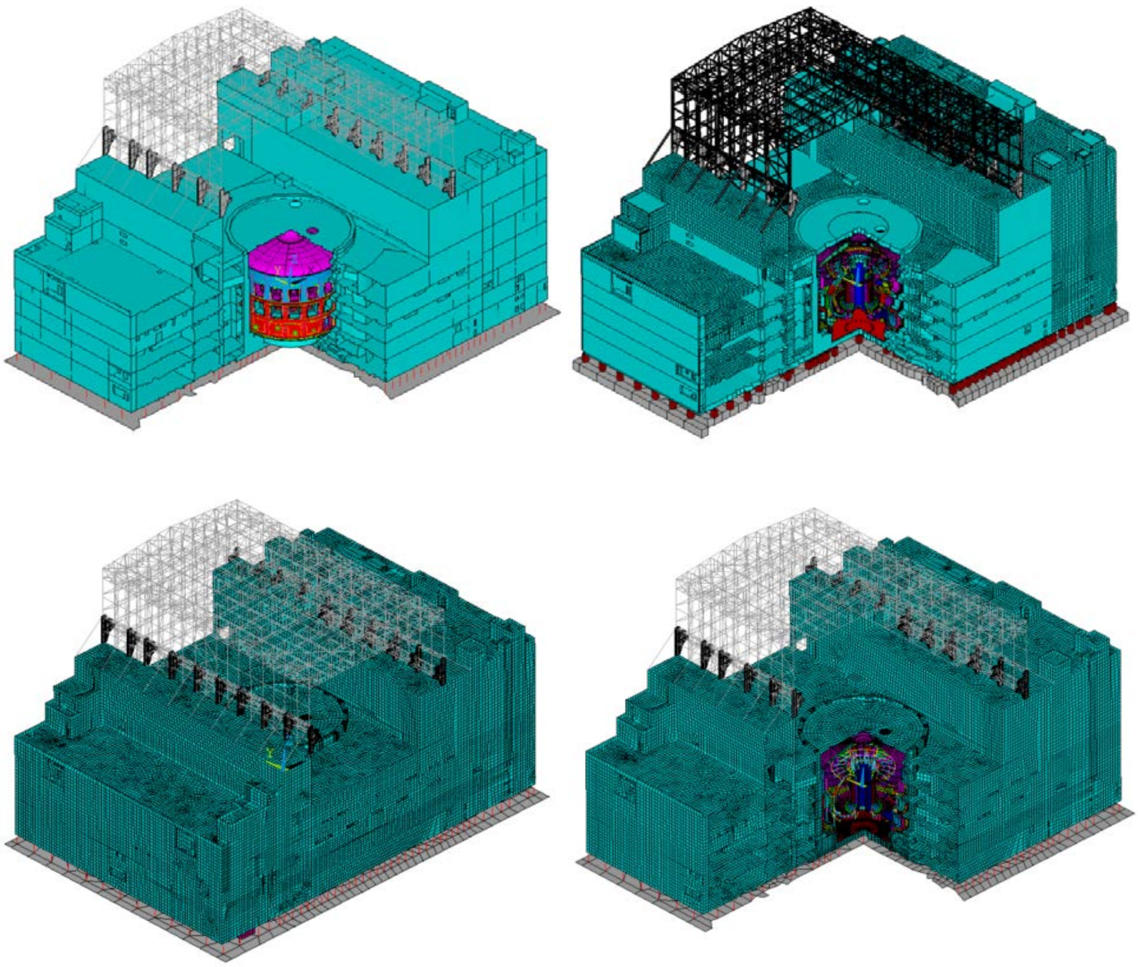


Fig. 4- Independent dynamic FE model of the ITER Tokamak Complex – Esteyco

3. OVERVIEW OF SEISMIC ANALYSES

3.1 Dynamic Representation of the Structures and Components Involved

Relatively detailed Finite Element (FE) representations of the Tokamak Complex, created with both ANSYS and ABAQUS commercial packages, have been used for the determination of its seismic response. On one side, the most updated version of the official ANSYS FE model developed by the ITER Architect Engineer (The Engage Consortium) has been used as the reference building FE model for the derivation of the seismic floor response spectra (FRS). On the other side, a new independent dynamic FE model of the Tokamak Complex has been developed by ESTEYCO (Fig. 4), both in ANSYS and ABAQUS, for the cross-check of the reference FRS within the building and for an independent assessment of the in-machine seismic FRS and the seismic interface forces between the Tokamak machine and the building. This new independent FE model of the Tokamak Complex includes a detailed, solid-element based representation of the Tokamak machine supporting structure (the so-called concrete crown and the bioshield wall), which is further connected to a relatively detailed FE representation of the Tokamak machine developed by the ITER Organization Central Team (IO-CT). Significant efforts have been devoted to entirely base this new independent dynamic FE model of the Tokamak Complex on completely up-to-date design information, since the tracking of the latest design and configuration management changes, especially regarding mass control, has been given the highest priority in such a complex and multidisciplinary project.

Additionally, a global dynamic FE representation of the Tokamak machine developed by ITER Organization has been assembled to the independent Tokamak Complex FE representation described above. This is shown in Fig. 5, where specific machine parts are depicted, namely, cryostat (2*), central solenoid, poloidal and toroidal field coils (3*), and vacuum vessel and the extension ports (4*).

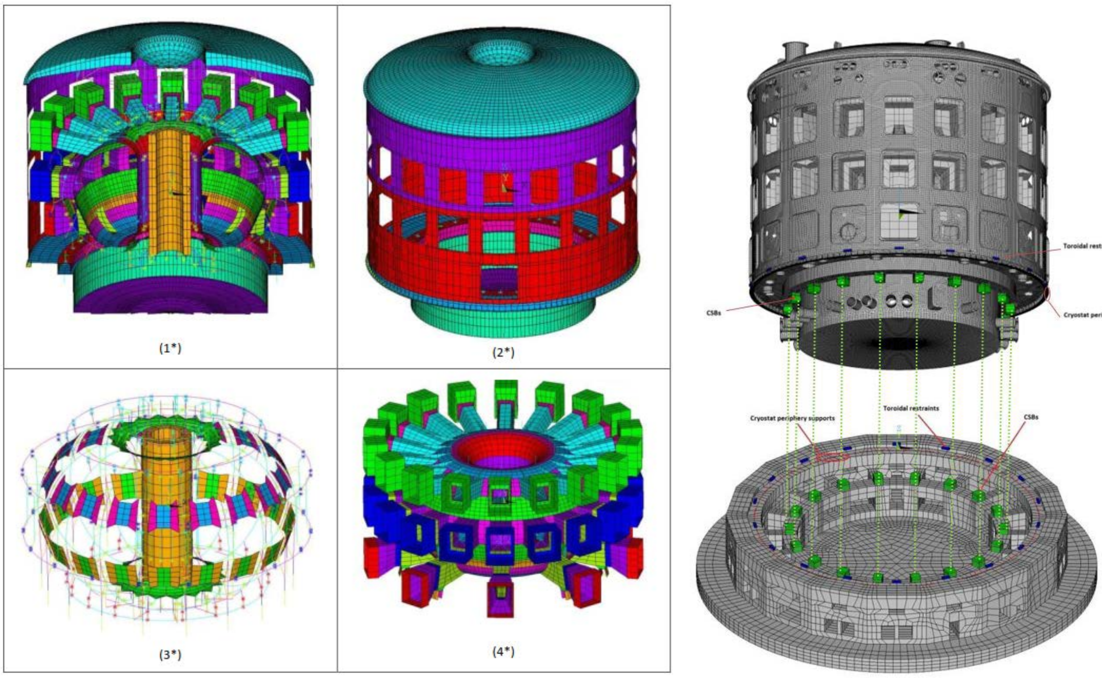


Fig. 5- Global dynamic FE model of the ITER Tokamak machine – ITER Organization
(1) VV and cryostat (2) Cryostat (3) Magnet (4) Vacuum Vessel (Left)
Solid element FE representation of the biowall & Tokamak machine to building structural interfaces (Right)

In addition to the reference elastic models developed at F4E and ITER IO, a global nonlinear FE model of the Tokamak Complex and the Tokamak machine has been developed in ABAQUS by Esteyco under an F4E contract for non-linear static and dynamic transient analyses in the time domain.

The development of the global nonlinear representation has been based on:

- Dynamically condensed representations of the main Tokamak machine components (VV, magnets and Cryostat) and the Tokamak Complex (Fig. 5).
- Specifically developed simplified (in terms of size), nonlinear FE models of the main supporting interfaces for the Tokamak machine, whose response is known to be inherently nonlinear: the Cryostat Support Bearings (CSBs) and the Vacuum Vessel Gravity Supports (VVGSs), whose development has been in turn based on the outcome of extensive testing campaigns as well as detailed and specific non-linear FE models (Fig. 6). These nonlinear interfacing elements have been designed as nonlinear for various reasons mainly related to the significant thermal variations the Tokamak machine is expected to experience during operation, abnormal and accidental conditions, and are recognized as one of the main sources of nonlinearity in the global static and dynamic response of the Tokamak machine.

For the derivation and assembly of this global nonlinear FE model, the FE models and substructures originally developed in ANSYS have been converted to ABAQUS and gone through an exhaustive validation process to ensure representativeness is maintained after conversion. Many studies have been already conducted to optimize the selection of retained nodes (number and location), number of modes selected for different components, dynamic condensation technique, number and extent of the substructures selected to reduce the model, type of dynamic analysis (direct full integration with respect to modal superposition) and, in particular, definition of the damping properties of the system, so that consistent comparisons could be made with respect to reference (linear) results. Once this conversion has been successfully completed, the different substructures have been assembled together and the nonlinear discrete links developed specifically for the CSBs and VVGSs used to connect the corresponding interfacing FE models and/or substructures.

This global FE model is fully representative of the global system's response and provides almost identical results to those obtained with currently equivalent complete and heavy FE representations. A two-orders-of-magnitude-reduction has been achieved in the size of the model, which allows to undertake non-linear analyses that were simply prohibitive with original FE models, especially when considering that full non-linear transient analyses of a seismic event require in the order of 40,000 time increments for those scenarios yielding highly non-linear responses at the corresponding interfaces.

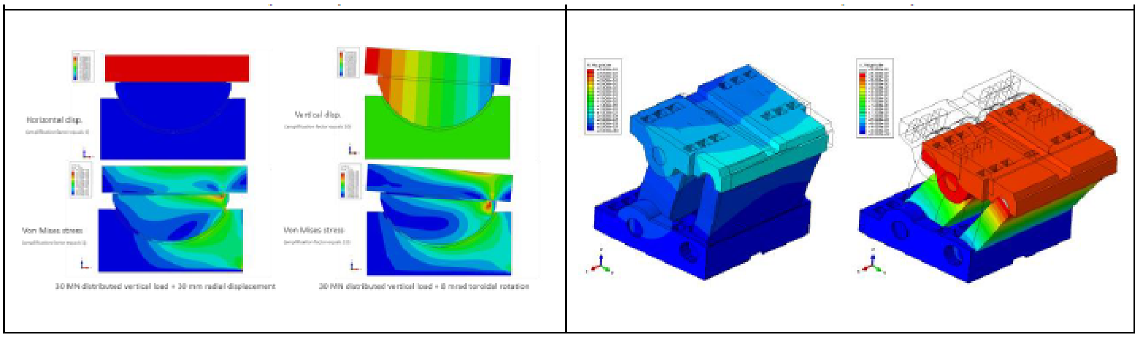


Fig. 6 - Critical nonlinear interfaces for the Tokamak machine – Numerical models

3.2. Reference Methodologies

The seismic response of the Tokamak Complex and the Tokamak machine ha been first obtained using linear FE models (see Fig. 4 and Fig. 5). This first approach is based on time history analyses of the assembled FE representations described in the previous subsection, in which the dynamic response of the system is obtained as a linear combination of its modal responses. That is, the dynamic equations of motions are integrated for the modal coordinates of the system, which is thus assumed to be linear and elastic. The dynamic equations of motion have been integrated using the implicit HHT algorithm with a time step equal to 10^{-3} seconds. The resulting absolute displacements have been stored at every time step and used to obtain the acceleration time histories.

In order to account for uncertainties related to the mechanical properties of the different materials: soil, seismic isolation pads and concrete, lower bound (LB) and upper bound (UB) sets of analyses with different FE models have been carried out. The variability of the seismic signals has been considered by performing the transient analyses with at least three sets of signals. The three available statistically independent artificial signals for each earthquake (SMS and Paleo, see Fig. 3) have been simultaneously combined to generate three different seismic scenarios. A total of six scenarios have been therefore analysed for each LB or UB FE model, which already include the combination of the three spatial directions.

A second set of transient analyses has been undertaken in the non-linear range, in order to assess the local and global significance of non-linear responses at two of the main supporting elements of the Tokamak machine: the CSBs and the VVGSs (see Fig. 6). The non linear model of Tokamak complex and Tokamak machine and the associated analyses have been used to increase the level of knowledge and so reduce the uncertainties.

- First, the response of the assembled nonlinear model has been tested under horizontal loading (push-over analysis). Once equilibrium is reached for vertical gravity load on the Tokamak machine, a horizontal acceleration up to 1.0 g is gradually applied. This is makes active all the non-linearities implemented in the global model under a controlled load pattern, and helped in the understanding of the main non-linear mechanisms involved and load redistribution patterns. The load distribution between the Vacuum Vessel Gravity supports and the Cryostat Spherical Bearings have been analysed in detail, providing meaningful explanations about which portions of the loads were taken by the different (non-linear) mechanisms involved. It should be pointed out that the response of these supports is driven by frictional aspects and, under severe load cases, potential uplift.

- Second, the transient non-linear response of the system under relevant seismic scenarios has been obtained by full integration of the equations of motion, providing valuable information about the extent of both local (at a support level) and global sliding and/or uplifting events.

4. SUMMARY OF RESULTS

4.1 Seismic FRS within the Tokamak Complex (TKC)

A reference set of seismic FRS have been generated by F4E and IO based on the results obtained from the official Tokamak Complex FE representation developed by the Architect Engineer. A relatively large sample of monitoring points has been selected for the determination of seismic FRS, resulting in more than a thousand locations throughout the Tokamak Complex. These constitute a representative sample for the potential statistical treatment of the resulting data or the determination of envelopes room by room or level by level. A full detailed set of FRS has been derived for reference damping levels (2%, 4%, 5%, 7%, 10% and 20%, see Fig. 7), whereas maps of key spectral quantities (peak and ZPA values, see Fig. 8 for one representative floor) have been obtained for all the monitored points and graphically represented level by level for the horizontal and vertical directions. It should be noted that the first peak of the horizontal FRS is roughly constant and determined by the Tokamak Complex seismic isolation.

An additional set of seismic FRS has been derived with the independent FE model of the Tokamak Complex, in order to establish a direct and detailed comparison with the reference seismic FRS previously described. The goal of this independent comparison is to support the validation and approval of the final seismic FRS for design purposes inside the Tokamak Complex. This validation has been based on global statistics for the reference spectral quantities in all directions and building levels.

This comparison has yielded a very good level of correspondence between both sets of FRS, especially when taking into account that both FE models (reference and independent) have been generated by different methods, from different sources, at different times and by different teams. These are quite complex representations and the level of similarity obtained between the reference and independent sets of seismic FRS is believed to provide a good level of confidence regarding the quality of the FE models and the procedures followed to obtain the reference seismic FRS within the Tokamak Complex.

4.2 Assessment on the Seismic Response of the Tokamak Machine

An updated representation of the Tokamak machine seismic response has been based on the same sort of linear dynamic analyses carried out in the time domain through the one-step approach, in which a coupled FE model representation of the Tokamak Complex and the Tokamak machine are assembled together. It should be noted that previous results had demonstrated that there is a significant level of dynamic coupling between both systems. These seismic analyses have been used to update the current estimations regarding two main aspects:

- The seismic FRS generated at different locations within the Tokamak machine, covering the main machine parts, namely Vacuum Vessel, Magnets and Cryostat.
- The seismic forces developed at the interface between the Tokamak machine and the surrounding concrete structure.
- The seismic forces at the main internal interfaces within the Tokamak machine, mainly at the supports of the Vacuum Vessel and the magnet system.

Seismic FRS have been obtained at a total of 620 locations within the Tokamak machine (see Fig. 8), which have been grouped into 31 sets where envelopes for FRS in the radial, toroidal and poloidal directions have been derived. In addition, seismic interface loads between the machine and the building have been obtained in quite a detailed manner, both locally and globally (see Fig. 9), for the three main interfaces involved: Cryostat Support Bearings (CSBs), Toroidal Skirt Supports and Vertical Skirt Supports, as well as for the most relevant supports within the machine. These results based on integrated building and tokamak machine models have provided very useful information for the design of many machine systems and confirmed the conservative nature of previous studies which are based on a two steps methods: first step for the FRS evaluation at the tokamak machine support and the second step for the detail analysis of the tokamak machine alone.

The results of the non linear calculations obtained under SL-2 events confirm some local non-linearities take place, mainly separation of some secondary hinges, rotational sliding of the primary and secondary hinges and toroidal sliding of the secondary hinges. The level of sliding at the primary and secondary siding surfaces of the CSBs is quite limited and no practical uplifting at the interface with the pedestal ring has been identified. The influence of these effects on global and local forces is limited, and results obtained are in very good agreement with previous analyses based on linear models and modal superposition. It has been noticed that sliding events are sudden and take place over very short periods of time, in the order of a few miliseconds. These events trigger local perturbations of a very short duration as well in the analyses whose physical or numerical nature must be investigated further. These perturbations do, however, die out quite rapidly and do not normally affect the results in terms of peak responses. The separation effects at the secondary hinges do not yield significantly high loads in the parts involved though it has been confirmed that this conclusion is highly dependent on the local modelling of the impacting parts.

5. Conclusions

A significant effort has been devoted over the last couple of years to improve the knowledge of the expected seismic response of the two main ITER systems: the Tokamak machine and the Tokamak Complex, the seismically isolated, reinforced concrete structure that houses the 23000 ton ITER fusion reactor.

Many elastic and non linear analyses have been carried out in order to derive a detailed and robust representation of several global and local seismic responses. These have confirmed the conservative nature of previous studies and have provided a significant amount of information that will be used, both in the short and long term, to improve the level of understanding of the dynamic response of such a complex system, to derive a better and more robust design of the facility, to calculate the actual design margin and to support the licensing of ITER.

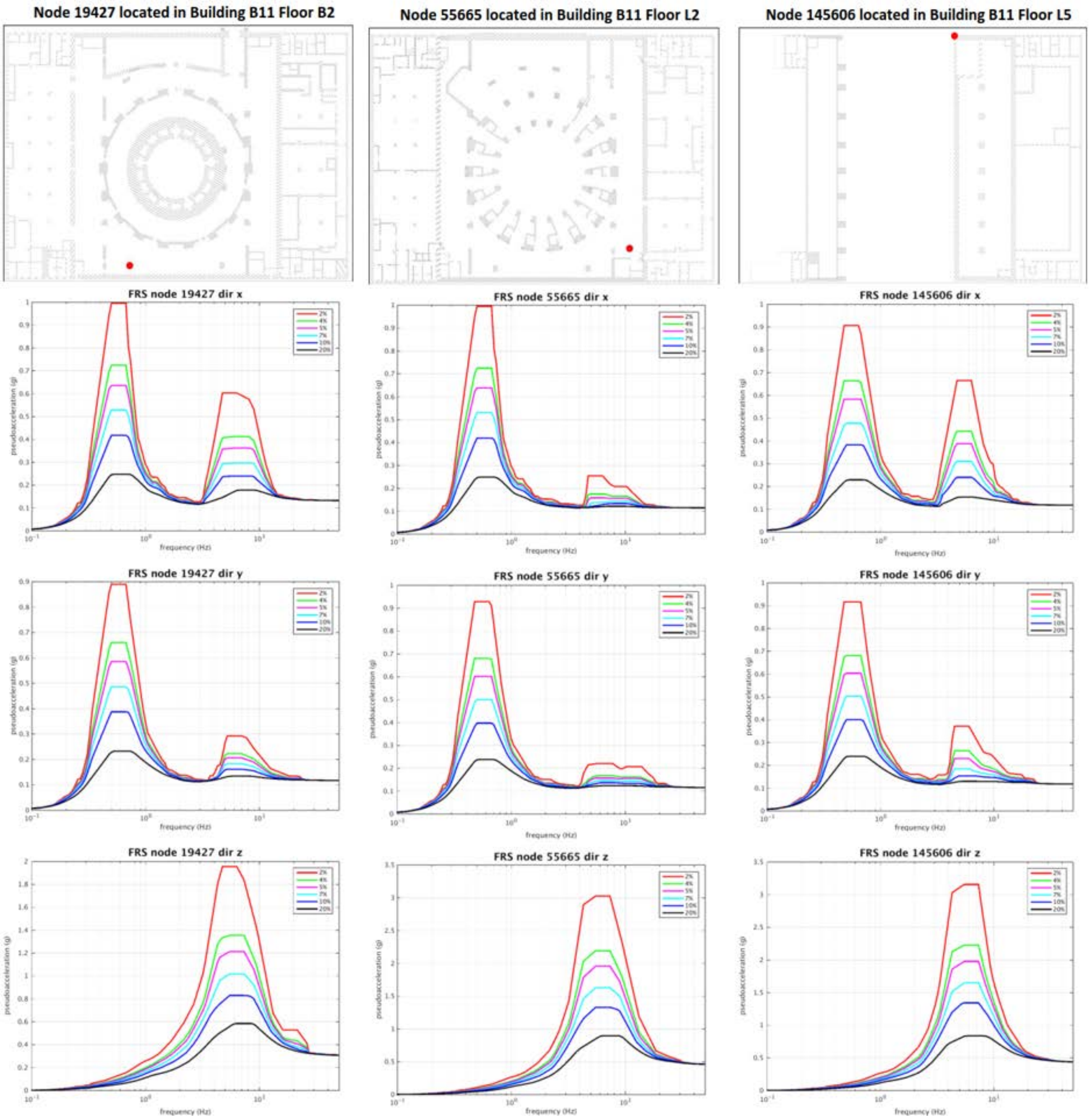


Fig. 7- Examples of seismic FRS at discrete locations within the Tokamak Complex (for 2%, 4%, 5%, 7%, 10% and 20% damping)

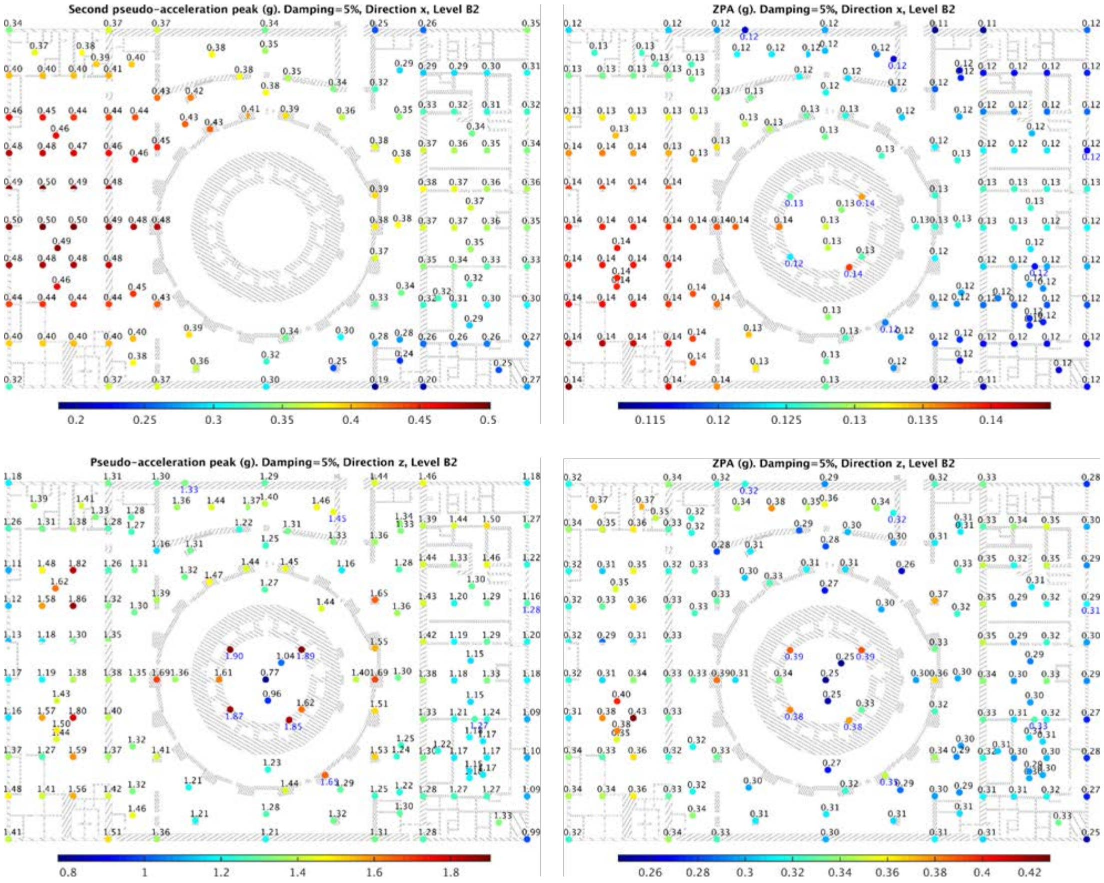


Fig. 8- Maps of FRS key spectral quantities – Example : Level B2 of the Tokamak Complex

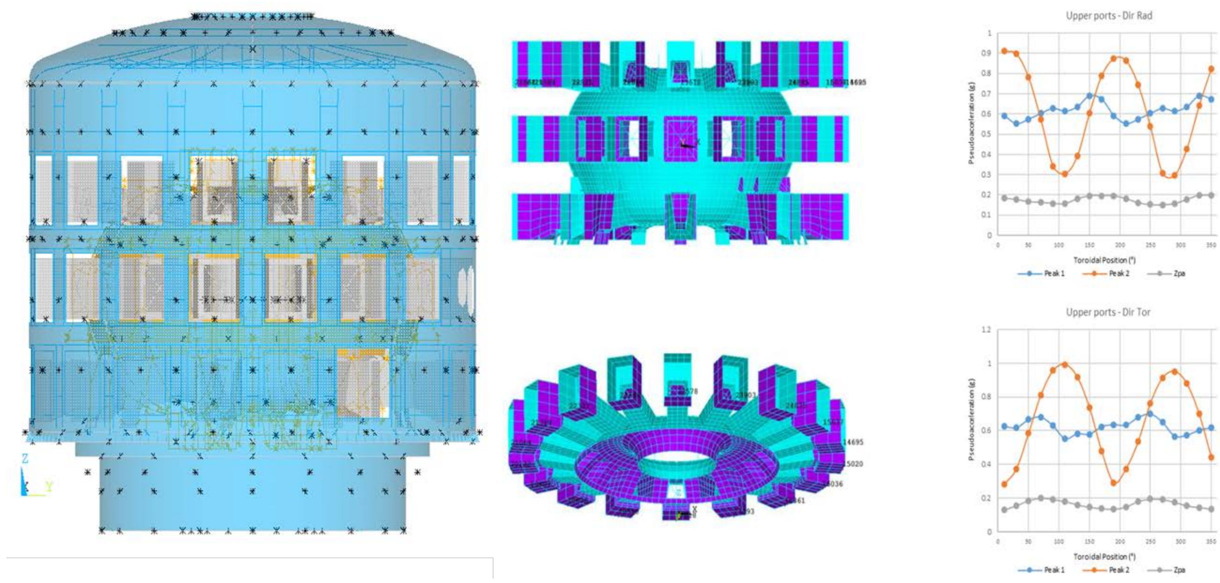
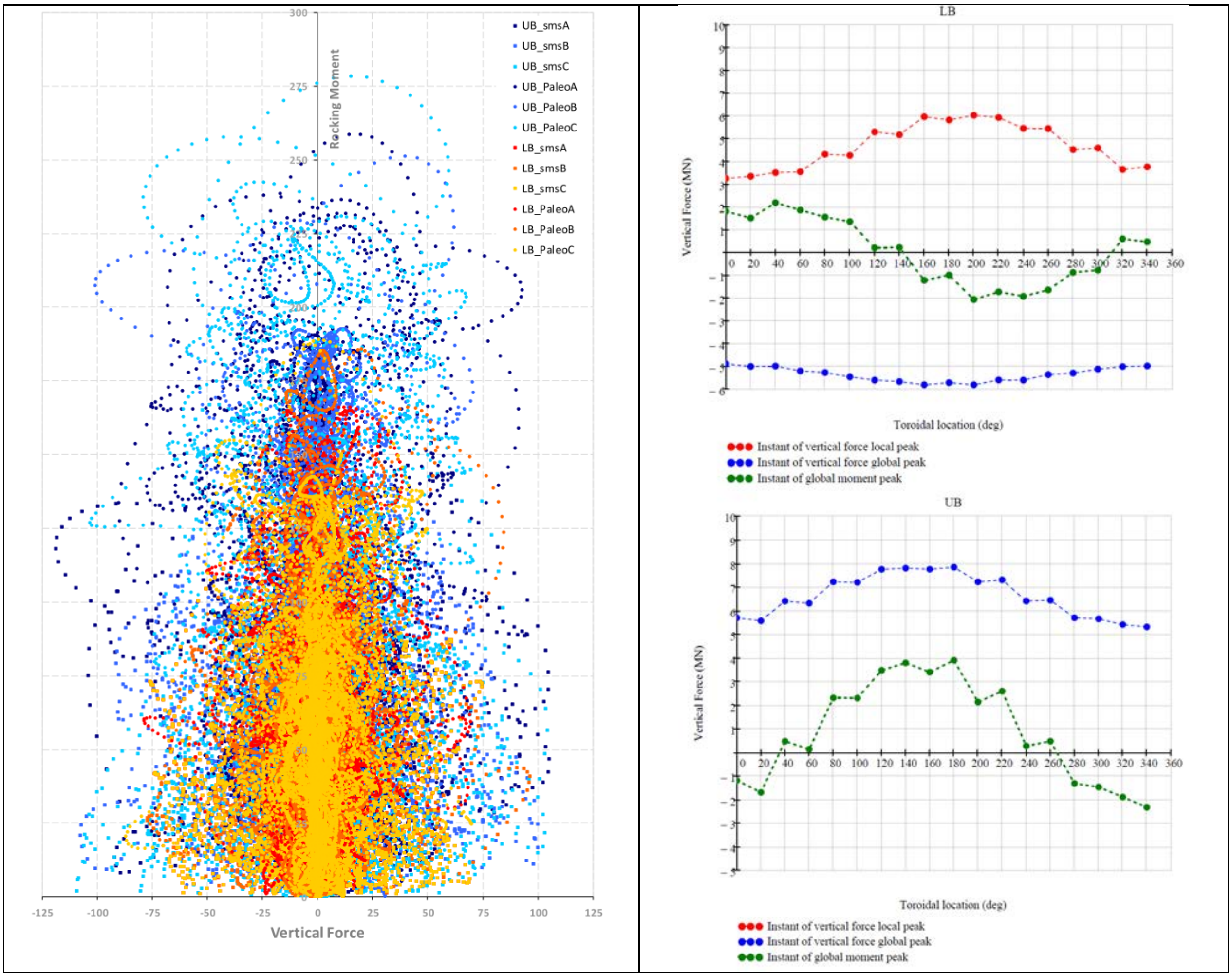


Fig. 9 - Seismic FRS within the Tokamak machine (left: cryostat, center: vacuum vessel, right: distribution of horizontal ZPA and acceleration in the upper ports of vacuum vessel)



N-M interaction diagram-Tokamak machine support	Vertical forces at CSBs – Peak response instants

Fig. 10- Seismic forces at the Tokamak machine / Building interface.

6. References

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[2] http://fusionforenergy.europa.eu/

[3] https://www.iter.org

7. Disclaimers

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