

## 2.15 Tokamak Seismic Analysis

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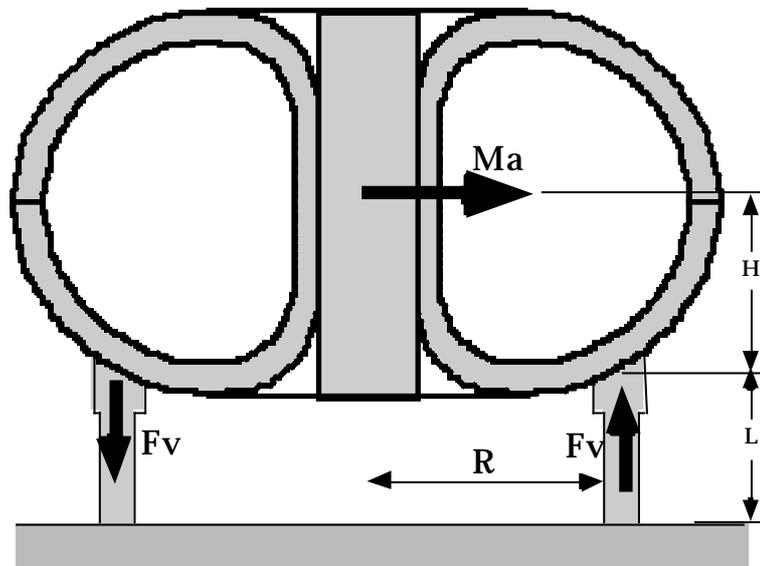
### 2.15.1 Introduction

Even if the ground peak acceleration is a small fraction of gravity (e.g. 0.2g for SL-2) the effects of earthquakes on ITER are significant and have to be carefully taken into account in its design. A seismic event is in fact, in many cases, the most demanding loading condition, in particular for the interface structures (e.g., supports) which must be sized for high strength, and often also for high stiffness.

The two main reasons why these events are of so much importance are as follows.

1. Seismic motion has a relatively broadband spectral content which encompasses the typical natural frequencies of structures (e.g. 1 to 10 Hz) with therefore spectral amplifications likely to take place. Spectral amplification factors are a function of both damping and natural frequency of the structures and are established by enveloping charts, called design response spectra (see paragraph 2.15.2.1). The typical value of acceleration amplification factors (for structures with natural frequency between 1.5 and 10 Hz) is about 3.
2. Structures are usually weaker when loaded by horizontal inertial loads, even when these are a small fraction of gravity.

**Figure 2.15.1-1**  
**Example of Vertical**  
**Reaction Loads at the Main**  
**Gravity Supports when the**  
**Tokamak is Subject to a**  
**Horizontal Seismic**  
**Acceleration**



The response of the tokamak system when loaded by a vertical seismic excitation is fairly easy to consider as a repetitive increase/reduction of the normal gravity load.

However, under horizontal excitations, the ITER global tokamak structure exhibits oscillatory modes which involve horizontal shearing as well as rocking motions around a horizontal axis perpendicular to the direction of the initial excitation.

The rocking motion is determined by the vertical distance from the basement to the centre of gravity of the system. For example, Figure 2.15.1-1 shows a schematic of the magnet system and the main machine gravity supports. The moment originated by rocking mode is reacted by the axial tension/compression of the gravity supports. Since the gravity supports must be radially flexible to accommodate thermal contractions of the magnet, they are able to react a horizontal force only on a line orthogonal to their azimuthal position.

In fact, the rationale for the use of reacting members between VV and magnet, roughly positioned vertically in the plane of the centre of gravity of the VV, is to minimise the relative displacements between VV and Magnet system during both seismic events and VDE's.

The ITER reference design considers seismic ground motion up to 0.2 g. The design, however, is such that if ITER is sited in a region with higher seismicity, the pit can be seismically isolated. The use of horizontal seismic isolators would effectively lower the peak acceleration, lower the frequency of seismic oscillations, and increase the motion and deflection of the tokamak and other isolated components relative to the non-isolated structures and the earth. The isolation schemes that would be considered utilise horizontal isolation pads made of alternating layers of steel plate and rubber. The tokamak and tritium buildings would be isolated to minimise the services that must cross the gap between isolated and non-isolated buildings. All services and plant systems which cross this gap would be designed to accept the consequences of relative motion of this gap, either by flexing or by failure and repair for non-safety-related items.

During the course of the EDA, several seismic analyses have been performed on the various design evolutions in order to always maintain and often improve the support scheme and to guarantee the required structural performance both from the displacements and stresses points of view.

The analysis summarised in this section has been performed by using the response spectrum method which has been chosen owing to its simplicity in comparison with a full dynamic analysis (time history method). According to this method a response spectrum at the tokamak anchor points, called the floor response spectrum (FRS), is utilised. It has been a priori assumed that the FRS is the same at all the anchor points of the machine, namely the basement, the cryostat skirt base, and the pit at the cryostat cover lid elevation.

The specific effect of soil-structure-interaction (SSI) is therefore neglected in this analysis. An SSI analysis is site specific as it strongly depends on geological data with its effects being of particular importance, together with the effect of excavation and embedment, for foundations on soft soils. The main effect of taking SSI into consideration is that the seismic input motion acting on the structure-soil system will change. On the other hand, SSI results in the radiation of energy of the waves propagating away from the structure which will result in an increase of the damping of the final dynamic system.

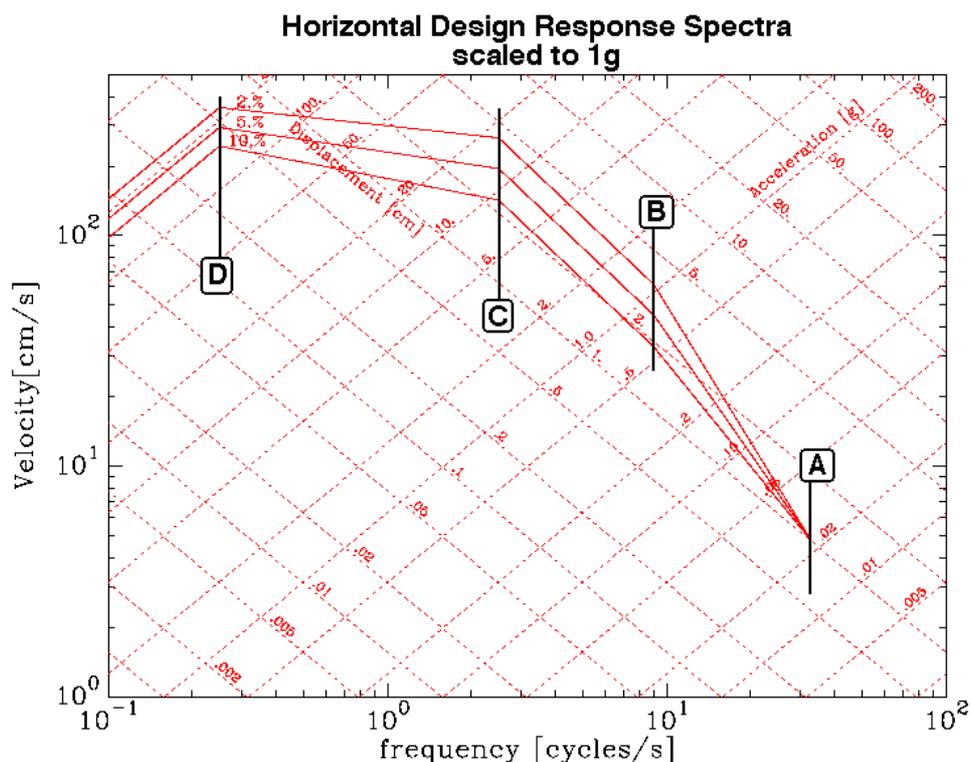
The design response spectra employed in this analysis, described below, has been specified by the U.S. Nuclear Regulatory Commission (NRC) in a Regulatory Guide<sup>1</sup> with the objective to be applicable to a wide range of sites, with the exclusion of those with unusually soft soils.

## 2.15.2 Input Conditions

### 2.15.2.1 Design Response Spectra

The ground motion DRS to be used for seismic analyses is specified in accordance with the guidelines of ASME<sup>2</sup> and NRC<sup>3</sup>. The primary scaling parameter used in the construction of this spectrum is the design maximum ground acceleration. The horizontal component ground DRS for both SL (seismic level)-2 and SL-1 can be linearly scaled from the DRS shown in Figure 2.15.2-1, which corresponds to a maximum ground acceleration of 1 g and accompanying peak ground displacement of 91.4 cm. A slightly different DRS spectrum is utilised for the vertically directed component of the seismic excitation.

The DRS curve shows the peak response of a single-degree-of-freedom oscillator of a given resonant frequency and damping coefficient excited by the ground motion as a function of the oscillator's resonant frequency. Different curves are given for different damping coefficients.



**Figure 2.15.2-1 Horizontal Ground Acceleration DRS Scaled to 1 g at point A. The points A, B, C, D are reference frequencies defined in the NRC guides.**

<sup>1</sup> NRC Guide 1.60

<sup>2</sup> ASME III Appendix N- Dynamic Analysis Methods

<sup>3</sup> NRC Guide 1.92, NRC Guide 1.60, NRC Guide 1.61

### 2.15.2.2 Damping Coefficients

The energy of a vibrating system is dissipated by various mechanisms. In materials, these include plasticity, thermal effects of repeated elastic strain, and internal friction. In structures, other effects can contribute to energy absorption such as friction at mechanical connections. For analysis convenience, damping is generally assumed to be viscous in nature.

The damping values in Table 2.15.2-1, expressed as a percentage of the critical damping coefficient, are the ones recommended by the NRC. The lower levels of the values given for each item are generally considered to be nearly lower bounds and highly conservative.

Considering that an SL-2 earthquake is to be analysed and that the ITER tokamak structure is built by a composition of both welded and bolted components, a single realistic damping ratio of 5% is used for the main calculations. However, different damping coefficients for each component of the Tokamak were also used for comparative calculations to check the sensitivity of the results<sup>1</sup>.

**Table 2.15.2-1 Damping Factors for Seismic Analysis**

	SL-0/SL-1	SL-2
Welded steel	2%	4%
Bolted steel	4%	7%
Reinforced concrete	4%	7%
Large diameter piping D>12in	2%	3%
Small diameter pipes D ≤12in	1%	2%

### 2.15.3 Model Overview

The reported analysis has been performed using ANSYS and a global 3-D finite-element beam-shell model which, while being sufficiently simplified to allow the execution of the model, is sufficiently detailed to properly model stiffness, deflections, and forces.

Due to cyclic symmetry of the system, one 20° sector of the tokamak with symmetric boundary conditions has been used for the modal and spectrum analyses for vertical (Z-directed) seismic excitation.

Under horizontally directed seismic excitation, in light of the double-symmetry of the system, a model of 1/4 of the tokamak may be used with the boundary conditions of symmetry in the ZX - plane and anti-symmetry in the ZY - plane. However, if the cyclic symmetry of the structure and sinusoidal distribution of the horizontal response in the toroidal (azimuthal) direction are taken into account, the model dimension may also be reduced to 1/18 of the tokamak. This model would require the use of so-called harmonic boundary conditions which allow only the modes with one nodal diameter to develop.

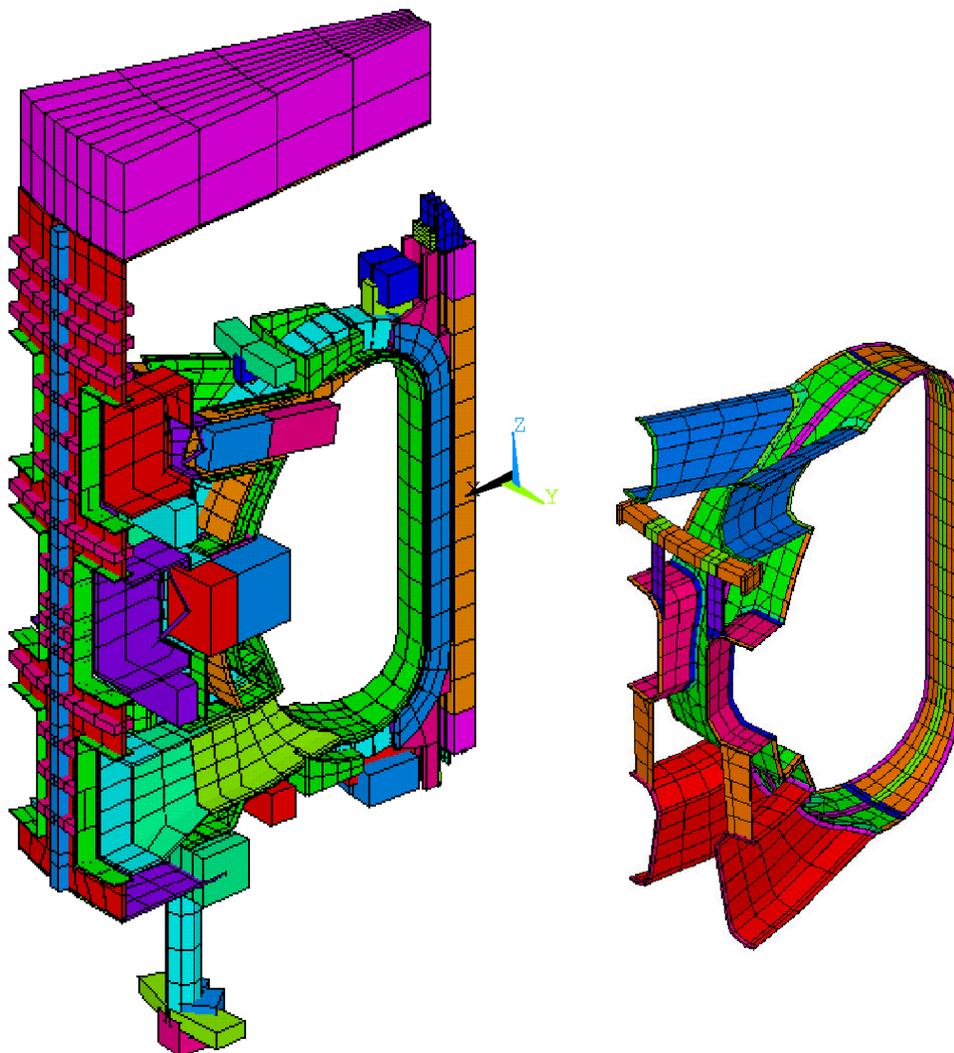
To obtain the mutual (relative) displacements between the major tokamak parts with the same degree of accuracy and reliability as for usual displacements several "key" pairs of nodes have been chosen where mutual displacements are to be determined. Then special additional

<sup>1</sup> V Sorin *et al.*, Seismic Response of the tokamak ITER updated model under combined loads, Plasma devices and operations, 1999, Vol. 7, pp267-291

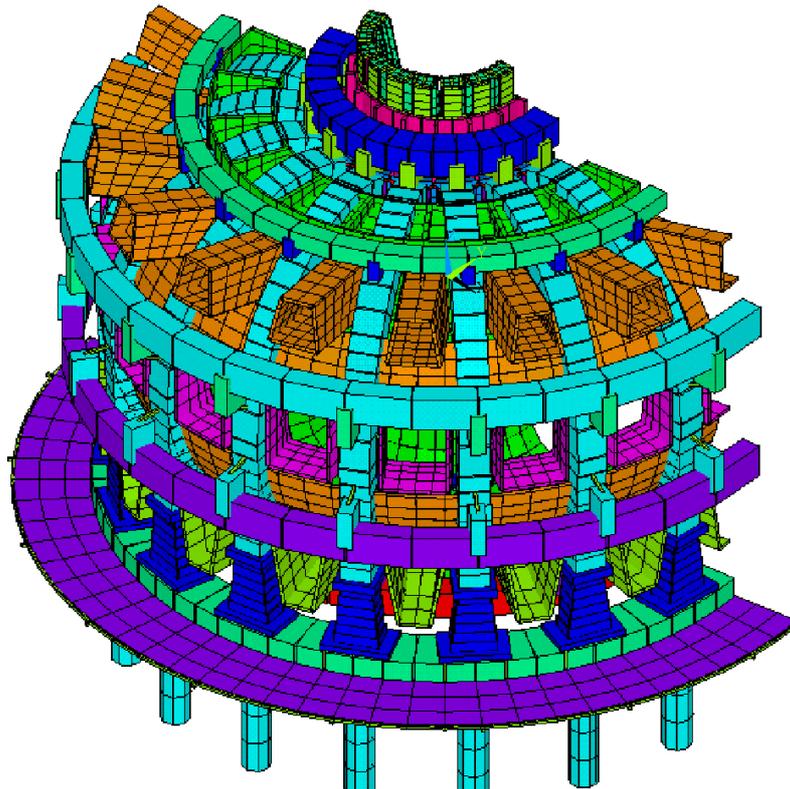
indicative nodes are introduced in the model where, by means of constraint equations, the displacements of these indicative nodes are set to be the difference between corresponding displacements of initial "key" nodes.

The one sector model is shown in Figure 2.15.3-1. For clarity, the vacuum vessel thermal shield model is shown separately. A 180° model is shown in Figure 2.15.3-2, whose mesh has also been used to verify the validity of the one sector model with harmonic boundary conditions.

The model includes a) the TF magnet with intercoil structures, b) the central solenoid together with its supports and preloading structure, c) the complete set of poloidal field coils with their radially flexible supports, d) the vacuum vessel also supported to the magnet by means of radially flexible supports, e) the VV thermal shield, f) the divertor cassette, g) the gravity supports, g) the blanket modules modelled as distributed masses and the port plugs, h) the lower set of supports consisting of vertical columns and radially directed "washer" shaped lower part of the cryostat, i) the VV port extensions and port plugs, and j) the cryostat.



**Figure 2.15.3-1 Finite Element Model Used for the  
DRS Seismic Analysis of ITER FEAT.  
Thermal Shield Model Shown on the Right Side.**



**Figure 2.15.3-2 Seismic Model of the Tokamak Extended to 9 Sectors.**

#### 2.15.4 Main Results Under SL-2 Seismic Excitation

In the modal analysis ten natural frequencies have been extracted both for a horizontal and a vertical seismic excitation. In both cases these frequencies model the movement of more than 95% of the total mass.

The first most significant four natural frequencies obtained for both horizontal and vertical seismic excitation are shown in Table 2.15.4-1.

**Table 2.15.4-1 First Four Eigenvalues for Both Vertical and Horizontal Excitation of the Tokamak.**

	Horizontal excitation	Vertical excitation
1 Frequency	2.82 Hz	8.10 Hz
2 Frequency	3.40 Hz	8.54 Hz
3 Frequency	5.37 Hz	9.90 Hz
4 Frequency	6.56 Hz	11.2 Hz

The first horizontal eigenvalue of about 2.8Hz corresponds to a mode where the entire tokamak rocks on top of the gravity support and is responsible for a large fraction of the overall effective modal mass. In this mode the supports aligned with the direction of the earthquake are loaded axially whereas the supports whose radial flexibility is normal to the earthquake direction react the horizontal inertial load by means of shear and bending.

The second horizontal eigenvalue of 3.4 Hz corresponds to the cryostat horizontal translation /rocking. The cryostat has its own independent horizontal support; and hence its seismic motion is mainly independent from the tokamak.

The third and fourth horizontal modes correspond to the horizontal oscillation of the thermal shield and the vacuum vessel with respect to the magnet system.

Table 2.15.4-2 shows the most important relative displacements between major components for a triaxial earthquake:

**Table 2.15.4-2 Relative Displacements Obtained in the SL-2 Seismic Analysis.**

Name	Radial mutual displac. mm	Vertical mutual displac. mm
VV – TFC, equatorial inboard	6.7	2.5
VV – TFC, top	7.4	2.0
VV – TFC, equatorial outboard	6.9	2.2
CS – TFC, equatorial inboard	1.4	0.7
TS – TFC, equatorial inboard	6.6	1.1
TS – VV, equatorial inboard	1.8	2.8

The relative deflections between TF magnet and vacuum vessel are within the allowable space allocation also in the case of an SL-2. In the inboard region this motion is in fact limited to less than 7 mm with an allowable (radial build allocated) value of 10mm. The TFC-VV and the TFC-TS relative displacements are in large part determined by the first overall tokamak mode and for this reason the relative displacements VV-TS is relatively small.

Table 2.15.4-3 gives the computed reacted loads at the gravity and VV supports under dead weight and SL-2 seismic loads:

**Table 2.15.4-3 Absolute Values of the Reaction Loads in the Main Machine Supports**

	Triaxial Earthquake	Dead Weight	Triaxial and Dead Weight
<b>Gravity Supports Response:</b>			
Axial load, MN	7.8	-10.9	18.6
Toroidal load, MN	12.4	0	12.4
Radial moment (top), MNm	7.64	0	7.6
Radial moment (bottom), MNm	35.4	0	35
Toroidal moment, MNm	0.44	-0.7	1.1
Axial (torsion) moment, MNm	3.0	0	3.
<b>VV Supports Response:</b>			
Axial load, MN	4.6	-6.4	11.1
Toroidal load, MN	9.1	0	9.1
Radial moment, MNm	9.1	0	9.1
Toroidal moment, MNm	0.2	0.11	0.3

### **2.15.5 Seismically Isolated Tokamak**

The above analysis, which shows sound overall tokamak behaviour and has been the basis for the detailed design of the supports, is based on a generic site seismicity where the peak acceleration is assumed to be 0.2g. If ITER is to be sited in regions with higher seismicity, the use of seismic isolation has been foreseen. Its spatial extension would be limited to the tokamak and tritium building, thus encompassing also the primary heat transfer system. An optimisation procedure has been performed to establish the best compromise between isolation pad effectiveness and mutual displacements between the isolated island and ground. The challenge is to design power, signal, and cooling lines to cross the isolation boundary with sufficient compliance.

With the support concept discussed in the previous sections, the ITER tokamak is able to withstand earthquakes up to 0.2g. This makes the required isolation scheme rather straightforward since, for example, a reduction factor of only 2 would be required by the isolation if an SL-2 event if it were raised to a 0.4g specification. A natural frequency of about 1Hz would provide the required reduction in the event of a doubling of site seismicity specification.

If ITER is to be sited in a location with a significantly higher level of seismicity, it will be possible to incorporate seismic isolation at the bottom of the reactor pit. With this concept, the seismic isolation will not change the machine design and general equipment layout, requiring only some structural modifications of the pit and building.

### **2.15.6 Conclusions**

For the employed concept of both magnet and vacuum vessel support design it has been found that the entire tokamak is strong and rigid enough so that the use of seismic isolation can be avoided for the presently specified seismic conditions. The use of a stiff and strong horizontal linkage between magnet structure and vacuum vessel has been shown to be essential and effective to react both horizontal VDE loads and seismic ground motions.