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Division V

GENERATION OF SEISMIC MOTION FOR SEISMIC QUALIFICATION OF EQUIPMENT

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ABSTRACT

The seismic qualification of active components requires an important input data which is the definition of the seismic motion. The required response spectrum (RRS) shall be deduced from the seismic ground spectra or the spectra transferred to the civil works interface, taking into account the potential local amplifications due to the support of the equipment as well as the multiple positions of the equipment in the facility. This paper will focus on two fundamental needs that are, on one side, the determination of the potential amplification due to the local support and, on the other side, the possibility to re-use easily the tests already done for the qualification of other similar components and/or configurations. The interest of in-situ experimental tests for the determination or the check of the RRS will also be discussed.

INTRODUCTION

The seismic qualification of active components requires an important input data which is the definition of the seismic motion. The required response spectrum (RRS) possibly completed with the relative displacement between supports is generally used. It shall be deduced from the seismic ground spectra or the spectra transferred to the civil works interface, taking into account the potential local amplifications due to the support of the equipment as well as the multiple positions of the equipment in the facility. The different types of uncertainties (uncertainty from modelling, potential design change in supports, etc.) must also be well considered. Previous papers presented in several SMiRT conferences have shown several examples of transfer using simplified formulas or more precise numerical methods (time integration, direct method in the frequency domain in Ezeberry et al., 2015 and Combescure et al., 2022). A method to simplify the calculated spectra and facilitate the propagation of this important input data for the qualification of materials has been applied to the ITER Tokamak buildings in Combescure et al., 2022.

Two fundamental needs are, on one side, the determination of the potential amplification due to the local support and, on the other side, the possibility to re-use easily the tests already done for the qualification of other similar components and/or configurations. The work presented in this paper is aimed at proposing pragmatic solution for fulfilling these two needs. A direct method in the frequency domain has been used to transfer the seismic motion from ground to floor (Floor Response Spectrum) or from floor to component

(Component Response Spectrum). An effort to simplify and identify the driving parameters has allowed to propose a limited number of standardized RRS curves. The interest of in-situ experimental tests for the determination or the check of the RRS will also be discussed in the last part of the paper.

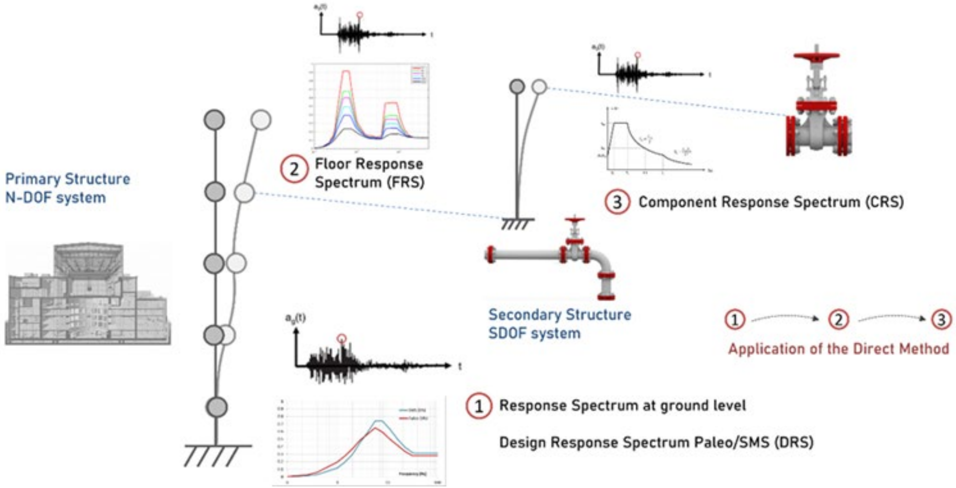


Figure 1. Transfer of seismic motion in the Tokamak building and secondary structures

TRANSFERRING THE SEISMIC MOTION IN THE FREQUENCY DOMAIN

The oscillator spectrum or seismic response spectrum (SRO) and the power spectral density (PSD) are two representations of seismic motion in the frequency domain. The power spectral density (Figure 2a) is less commonly used than the oscillator spectrum (Figure 2b), but it does help to understand that the vibrational energy of seismic motion is limited in the frequency domain. The maximum vibrational energy corresponds to the beginning of the plateau of the oscillator spectrum. Beyond the cut-off frequency, this energy should be negligeable, and the spectral density is virtually zero. This corresponds to the high-frequency asymptote of the oscillator spectrum and the maximum ground acceleration or zero period acceleration (ZPA). The oscillator spectrum is generally calculated by computing the time response of a large number of oscillators, conserving the maximum relative displacement of each oscillator and deducing the spectral acceleration (Figure 3a).

The oscillator spectrum from the power spectral density of a seismic signal (ground motion or transferred motion) can be determined by calculating the spectral density of the corresponding spectral quantity (relative displacement, velocity, acceleration, pseudo-acceleration or pseudo-velocity) for a large number of oscillators (Figures 3b and 3c). Let's take the example of an acceleration spectrum. The transfer function between the ground acceleration and the acceleration of the one-degree-of-freedom system has 3 parts: a unit constant function at low frequency, a resonance peak at the oscillator frequency and filtering at high frequencies. At low and medium frequencies, the oscillator will strongly amplify the input spectral density (Figure 3b). At high frequencies, since the vibratory energy is zero, the response will be dominated by the low-frequency content, which is transmitted without amplification by the one-degree-of-freedom system (Figure 3c). This reasoning is also valid for a multi-frequency system (Figure 4).

The determination of the maxima of the physical quantity of the system with one degree of freedom (displacement, velocity or acceleration) requires the recall of two important equations of the theory of random vibrations:

- The integral of the power density function $G(\omega)$ of a zero-mean time signal is equal to the variance of the signal, σ^2.

$$\sigma^2 = \int_0^\infty G(\omega) d\omega \tag{1}$$

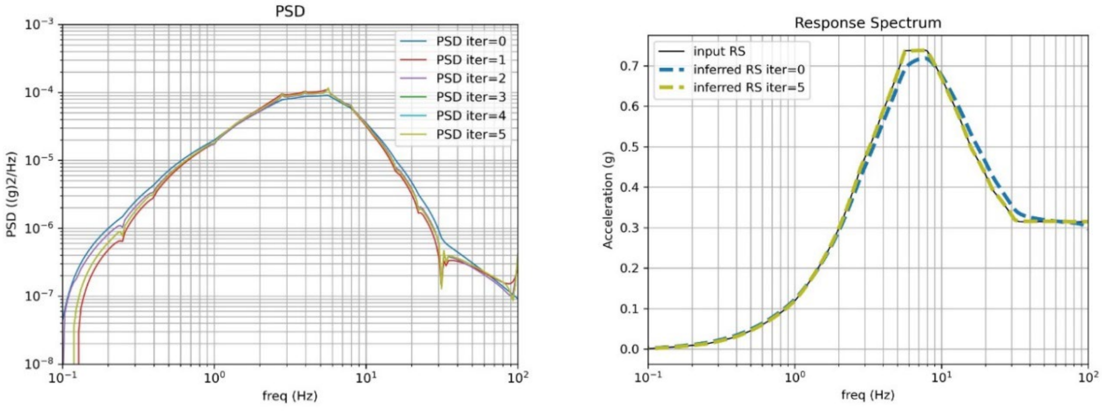
- The maximum response of the physical quantity and the standard deviation are linked by the peak factor $r_{s,p}(\omega_n, s)$ which depends on the frequency content of the signal, which may be broadband (e.g. ground motion) or narrowband (quasi-sinusoidal transferred motion).

$$S_{as,p}(\omega_n, s) = r_{s,p}(\omega_n, s)\, \sigma_{SDOF,a}(\omega_n, s) \tag{2}$$

With:

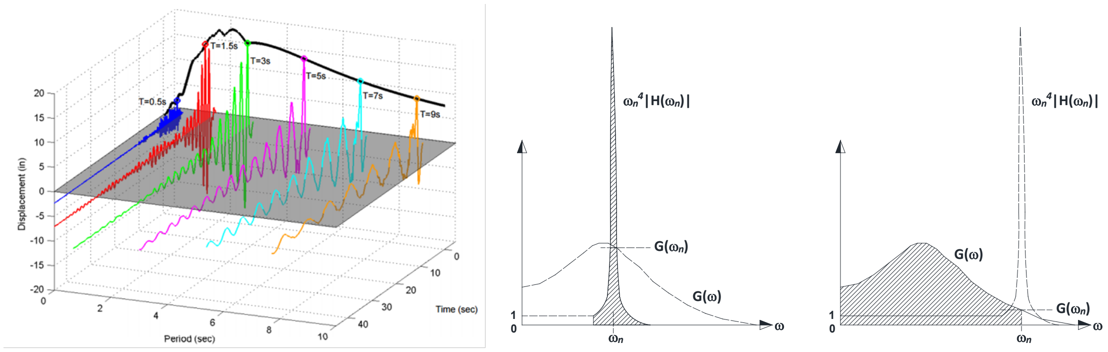
$S_{as,p}(\omega_n, s)$: the pseudo acceleration at the pulse ω_n and s the duration of the signal
$\sigma_{SDOF,a}(\omega_n, s)$: standard deviation of the pseudo-acceleration of the SDOF
$r_{s,p}(\omega_n, s)$: peak factor

The peak factor is determined on the basis of Vanmarcke (1976).



a/ Spectral power density b/ Response spectrum

Figure 2. Equivalence between Power Spectral Density and Response Spectrum



a/ Calculation of a spectrum using the time method b/ Response for a resonant case c/ Response for a rigid case

Figure 3. Calculation of the response of a one-degree-of-freedom structure using the time method (a) and the Power Spectral Density (b) (c)

Once the power spectral density of the input motion has been established (on the ground or at the floor level), the power spectral density of the transferred motion is determined by a simple frequency-domain calculation (convolution of the input motion with the transfer function). The transfer function of the building or support can be calculated on a physical or modal basis. It can also be determined experimentally using in-situ measurement. Figure 5 shows the successive steps to generate the floor response spectrum from the ground response spectrum.

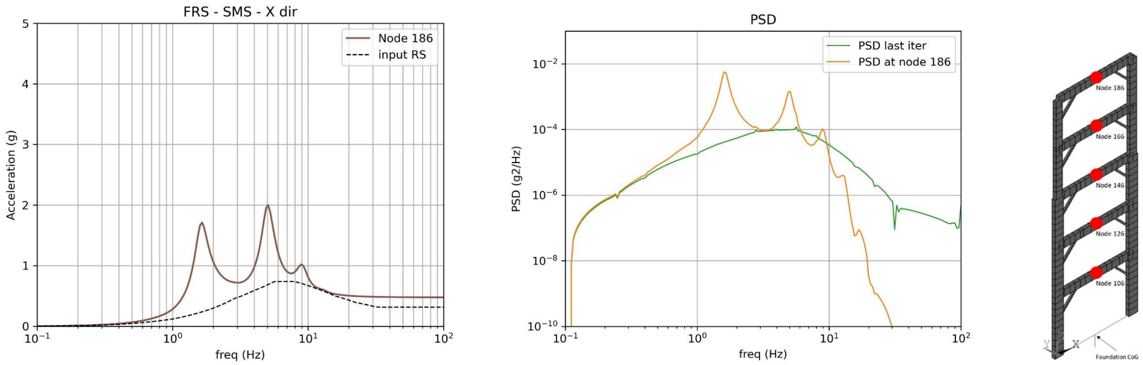


Figure 4. Comparison of seismic ground motion and transferred motion for the portal structure of the AFPS (2013) ICPE Structures support guide (main modes: 1.57Hz and 4.85Hz)

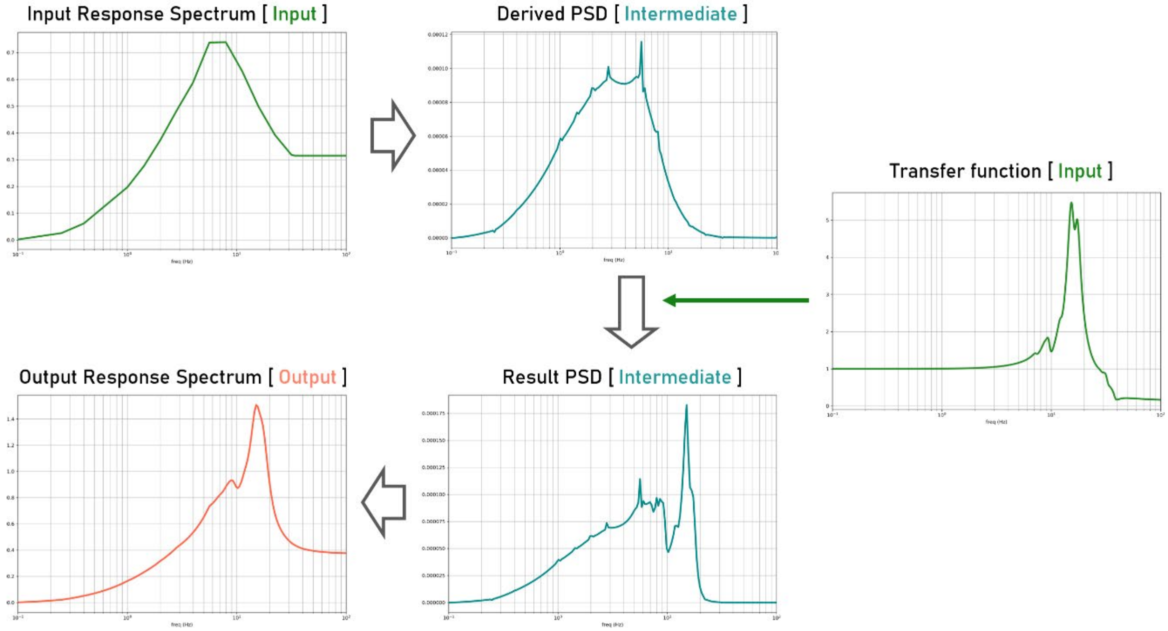


Figure 5. Response spectra and power spectral densities for a structure

SIMPLIFYING THE SEISMIC MOTION TO STANDARDIZE THE INPUT DATA FOR SEISMIC QUALIFICATIONS

The experimental seismic qualification of Safety Important active Components requires the determination of the RRS (Required Response Spectrum). The propagation of this input data for the qualification should be properly controlled and the information well stored in the qualification database. A seismic FRS (Floor Response Spectrum) or CRS (Component Response Spectrum) is a curve, and so a complex mathematical object. It is important to characterize the seismic input for the seismic qualification through, if possible, few physical parameters. An easy and practical way to consider the potential flexibility of the support is also a key-element for reducing the cost and limit of risk of underestimation of the seismic input for qualification.

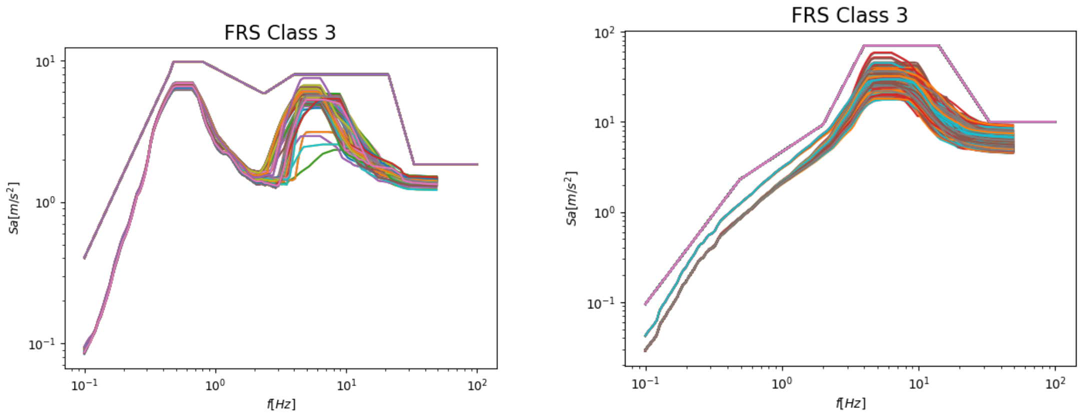
Reducing curves into a limited number of parameters

The idea is to simplify the RRS curves into a set of parameters in order to ease their propagation to the experimental facilities in charge of the seismic qualification in a similar way than the RRS proposed by the French standard RCC-E. In Combescure et al. (2022), a method has been proposed to identify the main physical parameters of the FRSs and calculate easily envelops. Because of the seismic isolation in ITER, the horizontal FRSs have a specific shape with two peaks and low values of ZPA but high values of spectral displacement. The automatic generation of the simplified RRS is based on the determination of local maximum values of spectral quantities and values of frequency such as the cut-off frequency or the limits of the plateau. statistical studies were carried out on the floor spectra of the ITER Tokamak building.

Statistical studies to determine the key parameters identified the following properties:

- Below 2Hz, the spectra are very similar for all points and a single envelope curve can be taken for each direction (enveloping the first peak for horizontal spectra and close to ground motion for vertical spectra).
- The maximum acceleration (ZPA) and spectral acceleration (Sa) of the second peak of the horizontal spectra do not show a clear correlation and pairs of values (ZPA, Sa) have been proposed for the standardised spectra.
- The maximum acceleration and spectral acceleration of the vertical spectra show a clear correlation and a relationship has been proposed to conservatively deduce the spectral acceleration from the ZPA for standardised spectra (factor 7 for 5% damping).
- Conservative frequency values were easily determined for the pseudo-acceleration plateaux (0.48Hz-0.71Hz for the first horizontal peak, 4Hz-21Hz for the plateau of the second horizontal peak and 4Hz-14H for the plateau of the vertical spectrum).

Table 1, Figures 6a and 6b show the proposed standardised spectra and a comparison between the standardised spectra and the floor spectra. In the ITER Tokamak building, maps giving the class to be considered for the horizontal and vertical FRS are available and ease the determination of the input RRS for the systems directly fixed onto the building or on a rigid support.

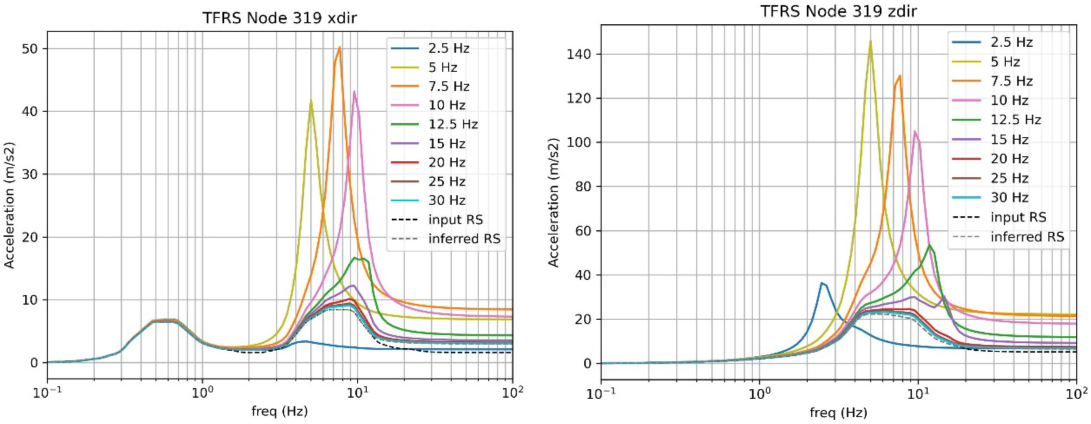


a-Horizontal b- Vertical

Figure 6. Proposal of standardised required response spectra in the ITER Tokamak building

Considering the potential effect of the supports

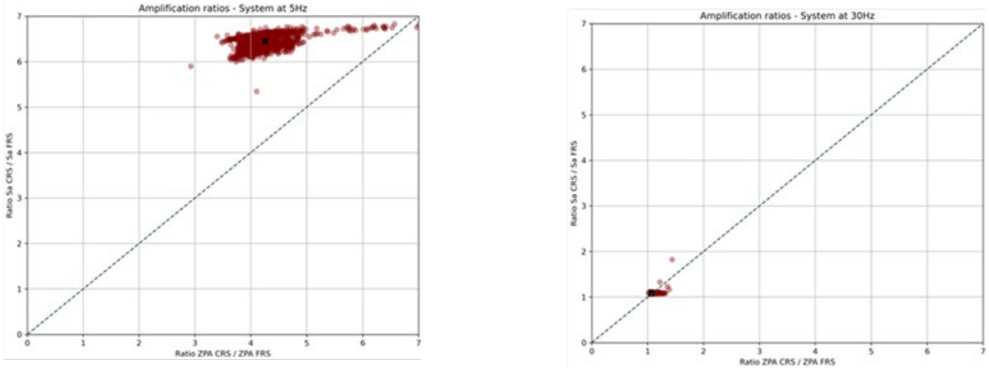
Let now discuss the issue of the potential amplification of the component support. The direct method presented in the first section was applied to a large number of floor response spectra (1118 points) in the ITER Tokamak building for typical support structures with frequencies between 2.5Hz and 30Hz (V. Domingue, 2023). In this study, each support was considered as a SDOF. One of the objectives was to estimate the amplification of non-perfectly rigid supports (f<33Hz). Figure 7 shows comparisons between the input spectra and the spectra transferred by these supports. From 12.5 Hz, amplification is reduced and almost non-existent for 20Hz. In this case, the only effect is often to widen only the plateau of the input spectrum. Very flexible and very stiff supports ensure that the seismic movement is not amplified. Figure 8 shows the maximum acceleration and spectral acceleration amplifications for two values of support frequency. (5Hz and 30Hz). It is interesting to remark that, for the non-rigid or resonant support (5Hz), the amplification of the spectral acceleration is higher than the amplification of ZPA. This property comes from the narrow band nature of the transferred signal. The ratio between spectral acceleration and ZPA is higher for a sinusoidal signal (narrow band signal) than for a random noise (broadband signal).



a/ Horizontal direction

b/ Vertical direction

Figure 7: Modification of the seismic motion by the support structure

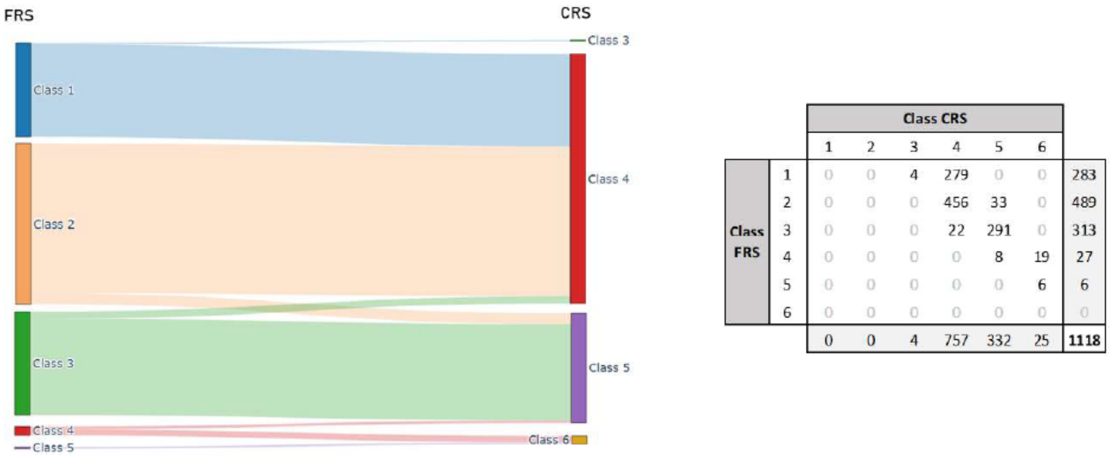


a/ Resonant support (5Hz)

b/ Rigid support (30Hz)

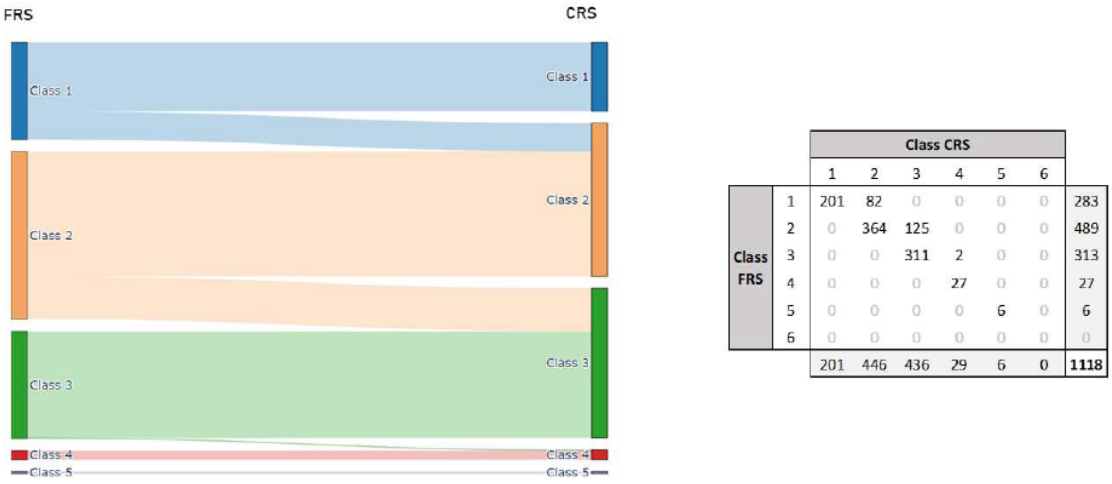
Figure 8: Amplification of ZPA and Spectral acceleration (5% damping) in the ITER Tokamak Complex

When the input data for the qualification of a component is needed, it is interesting to translate the potential amplification factor of a support into an upgrade of class for horizontal or vertical RRS. Figure 9 gives such an indication. For rigid or semi-rigid supports, the upgrade of classes between FRS and CRS is very limited and at maximum by one class. The flexible support has much more impact and an upgrade by 2 or 3 classes should be considered. This result is valid for SDOF support. Real supports are very often more complex with several eigenmodes and coupling between directions (vertical excitation may induce horizontal response and vice-versa). To allow the use of the strategy based on classes, a tool for the engineers in charge of the determination of the RRS for qualification is under development. The tools is aimed at giving access to the input FRSs in the ITER Tokamak complex and other buildings of ITER Facility or other facilties, allowing the possibility to introduce the transfer functions of the component support based on the calculated eigenmodes or the experimental transfer function and providing the numerical tools to simplify the Component Response Spectrum and determine the class of each RRS.



		Class CRS						
		1	2	3	4	5	6	
Class FRS	1	0	0	4	279	0	0	283
	2	0	0	0	456	33	0	489
	3	0	0	0	22	291	0	313
	4	0	0	0	0	8	19	27
	5	0	0	0	0	0	6	6
	6	0	0	0	0	0	0	0
		0	0	4	757	332	25	**1118**

a- Resonant support (5Hz)



		Class CRS						
		1	2	3	4	5	6	
Class FRS	1	201	82	0	0	0	0	283
	2	0	364	125	0	0	0	489
	3	0	0	311	2	0	0	313
	4	0	0	0	27	0	0	27
	5	0	0	0	0	6	0	6
	6	0	0	0	0	0	0	0
		201	446	436	29	6	0	**1118**

b- Rigid support (30 Hz)

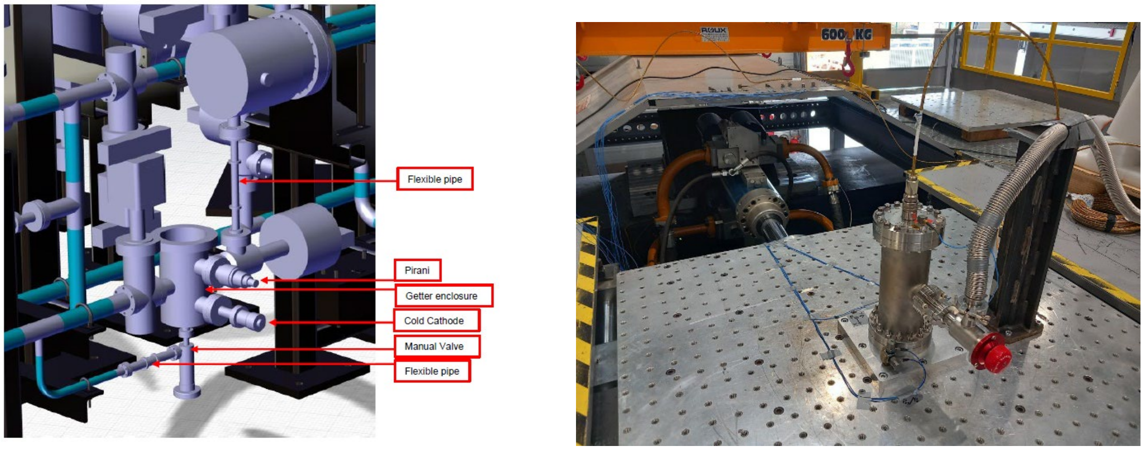
Figure 9: Influence of the support onto the class of RSS to be considered for qualification (FRS: interface with building structure, CRS: interface with supporting structure)

EXAMPLES OF QUALIFICATION USING RRS CLASSES

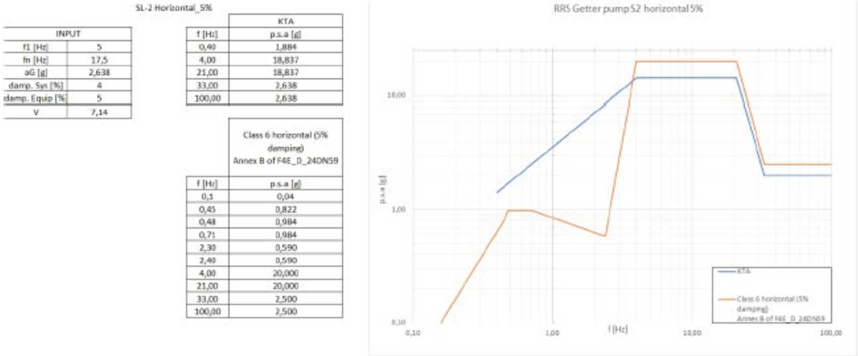
ITER nuclear fusion facility shall qualify many components related to vacuum technology. For instance, Non-Evaporable Getter (NEG) pumps are high vacuum and ultra-high vacuum pumps able to effectively capture the so-called active gases present in vacuum systems. The getter pump consists of two fundamental parts: the mounting flange and the pump cartridge. The mounting flange consists of a high vacuum "ConFlat" base flange of size DN100 with a glass feedthrough to power the built-in heater of the pump cartridge. The cartridge incorporates the ZAO (Zr, V, Ti and Al) sintered disks that perform the chemical processes. The power supply and control of the getter pumps is done by means of a controller connected to the mounting flange connector with cables. These pumps require high temperatures for activation of the pump cartridge in order to perform the physical processes that allow the capture of gases. The pump underwent thus seismic tests while being heated at 550°C.

Figure 10 gives a view of the environment of a getter pump of the ITER Leak Detection System and a picture of the specimen of getter pump that has been seismically qualified.

The RRS considered for the seismic qualification are characterized by their ZPA and a shape in agreement with the KTA German standard. The values of ZPA and the eigenmodes of the piping system have been calculated through a set of response spectrum analysis with FEA models of the process piping system and are reported in the flexibility reports. From the existing ITER seismic classes (see Table 1) an enveloping RRS is chosen to envelope the ZPA and shape defined by KTA.



a- Drawings showing the getter pump environment b- View of a specimen seismically qualified



SL-2 Horizontal_5%

INPUT	
f1 [Hz]	5
fn [Hz]	17,5
aG [g]	2,638
damp. Sys [%]	4
damp. Equip [%]	5
V	7,14

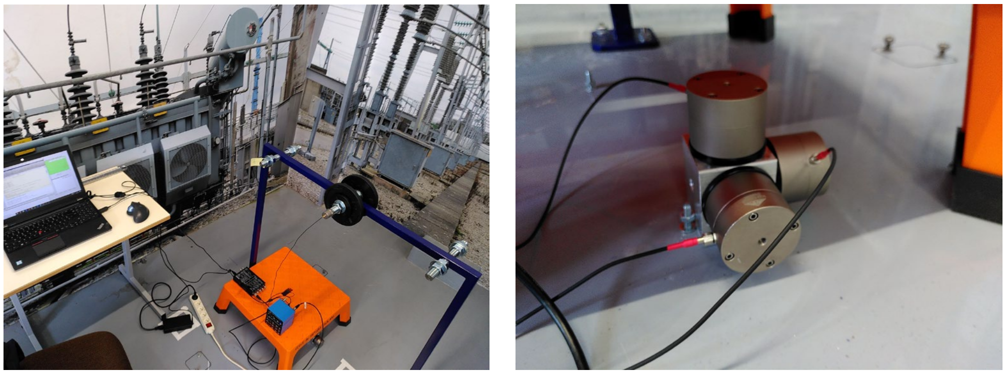
	KTA
f [Hz]	p.s.a [g]
0,40	1,884
4,00	18,837
21,00	18,837
33,00	2,638
100,00	2,638

	Class 6 horizontal (5% damping) Annex B of F4E_D_24DN59
f [Hz]	p.s.a [g]
0,1	0,04
0,45	0,822
0,48	0,984
0,71	0,984
2,30	0,590
2,40	0,590
4,00	20,000
21,00	20,000
33,00	2,500
100,00	2,500

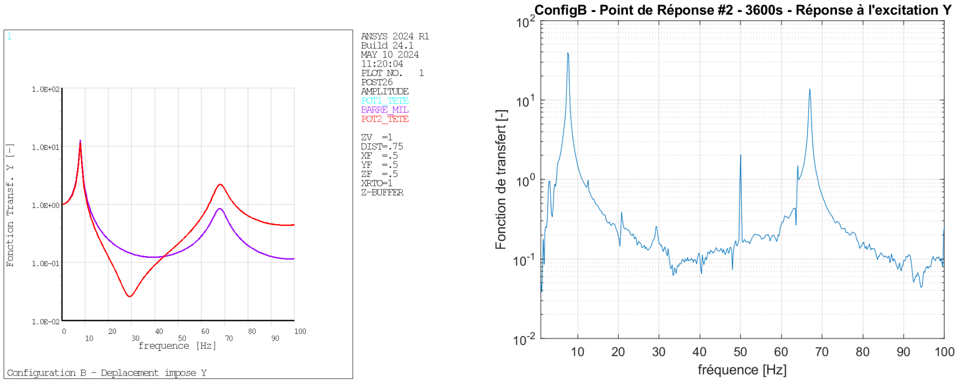
c- Example of RRS class compared to the FRS from the response spectrum analysis
Figure 10: View of a getter pump and the RRS

ABOUT THE USE OF IN-SITU EXPERIMENTAL TESTS

A procedure to determine the transfer function has been developed. It is based on the measurement of the input motion (at the interface with the building structure) and the output motion (at the component location). The experimental measurement is used to estimate the cross-spectral power density matrix for the inputs (G_{XX}) as well as the outputs-inputs (G_{YX}). An estimator ($H=G_{YX}.G_{XX}^{-1}$) based on these measurements is used to obtain the experimental transfer function both in the presence or absence of noise (extraneous noise should be quantified, using the magnitude-squared coherence). Figure 11 shows an application of the experimental method for the determination of the transfer function of a benchmark case (simple frame structure).



a- Experimental set-up



b- Comparison between numerical and experimental transfer functions

Figure 11: Application of the experimental method for the determination of the transfer function of a benchmark case

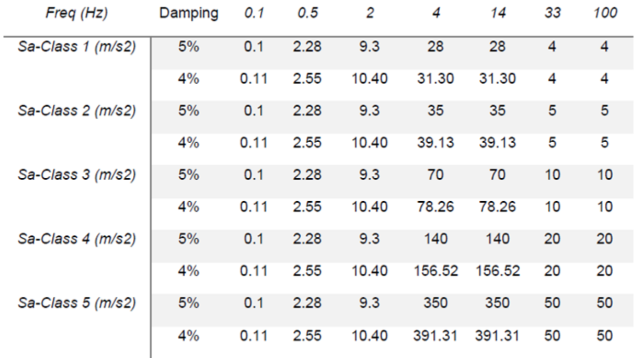
While this procedure in itself is straightforward, it is essential to bear in mind a number of practical limitations, which are absolutely critical with respect to the quality of the results:

- the procedures aims at capturing the motion transfer function for base motion and the structure should not be excited by other sources (wind, fluid circulations, human activity);
- instrumentation should be practically noiseless for the input sensors, since the numerical procedure works under the assumption that they are noise-free. This in turn requires that at least the input signals should be collected using stringent quality control, and sensors installed, protected, and monitored by sufficiently experienced staff
- in most situations the signal/noise ratio will worsen at very low frequencies (around 1Hz) and the input motions cannot be assumed to be uniform in the high frequency range. This imposes a limited frequency range for which the transfer function can be determined experimentally.

CONCLUSION

This paper has focused on two fundamental needs for the seismic qualification of components that are, on one side, the determination of the potential amplification of the seismic motion due to the local support and, on the other side, the possibility to re-use easily the seismic tests already done for the qualification of other similar components and/or configurations. The author is convinced by the importance of proposing practical rules and tools to reduce the cost and secure the seismic qualification of components not only for a single project but also for the reuse of existing qualification for other projects or in other fields.

Table 1: Classes proposed for the RRS for qualification of ITER Components (vertical direction)



Freq (Hz)	Damping	*0.1*	*0.5*	*2*	*4*	*14*	*33*	*100*
Sa-Class 1 (m/s2)	5%	0.1	2.28	9.3	28	28	4	4
	4%	0.11	2.55	10.40	31.30	31.30	4	4
Sa-Class 2 (m/s2)	5%	0.1	2.28	9.3	35	35	5	5
	4%	0.11	2.55	10.40	39.13	39.13	5	5
Sa-Class 3 (m/s2)	5%	0.1	2.28	9.3	70	70	10	10
	4%	0.11	2.55	10.40	78.26	78.26	10	10
Sa-Class 4 (m/s2)	5%	0.1	2.28	9.3	140	140	20	20
	4%	0.11	2.55	10.40	156.52	156.52	20	20
Sa-Class 5 (m/s2)	5%	0.1	2.28	9.3	350	350	50	50
	4%	0.11	2.55	10.40	391.31	391.31	50	50

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