Design of test blanket module attachments under electromagnetic loads by using a dynamic amplification factor envelope

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Abstract

European Test Blanket Modules (TBMs) are attached to radiation shields through mechanical joints. The structural integrity of the joints must be ensured under non-periodic dynamic loading caused by accidental electromagnetic events. This requires the transient dynamic analysis of the TBM-Joint-Shield under multiple loading scenarios. As temperatures and dynamic characteristics of the TBM-Joint-Shield system are updated under the course of the ITER project, the design process of the joints can become very time-consuming. This work presents a methodology based on a response spectrum to simplify the design process of the joint under electromagnetic loads. The mechanical system TBM-Joint-Shield was modeled as a single degree of freedom lumped spring-mass-dashpot system. The dynamic amplification was determined for a wide range of frequencies using the Finite Element Method. Eventually, a design envelope for each loading category was obtained, which can be readily used for determining the dynamic amplification factor of any potential new design of the TBM + Joint + Shield system. Results showed that HCLL undergoes higher loads than HCPB, resulting in a dynamic amplification factor which varies from 1.25 to 2.0 for a damping of 4%.

Keywords:
Test Blanket Module, Electromagnetic Loads, Finite Element Analysis,

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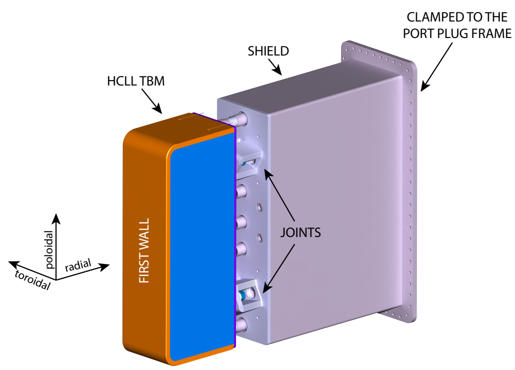
Figure 1: Detail of the TBM-Joint-Shield system.



Response Spectrum

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1. Introduction

European Test Blanket Modules (TBMs) are being developed with the aim of testing two tritium breeder blanket concepts in ITER: the helium-cooled lithium-lead (HCLL), which uses the liquid Pb-16Li as both breeder and neutron multiplier, and the helium-cooled pebble-bed (HCPB) with lithium orthosilicate ceramic pebbles as breeder and beryllium pebbles as neutron multiplier [1]. TBMs will be located inside the equatorial port 16 for testing purposes. The front part is a plasma facing surface (first wall) and consequently, will be exposed to extreme conditions of temperature and radiation.

A neutronic shield, mainly composed of stainless steel and water, is placed behind each TBM to provide protection against fusion plasma neutron flux and gamma radiation. The rear side of the shield is clamped to the port plug frame, whereas the opposite side is attached to the TBM through a metallic joint. The TBM-Joint-Shield system behaves then like a cantilever beam clamped at the rear side of the shield (Fig. 1).

The Joint is particularly critical from the structural standpoint, as it must be capable of withstanding three main loads: (i) the weight of the TBM, (ii) thermal stresses due to the temperature difference that arises between the two plates connected during plasma operation and outgassing; and (iii) the accidental electromagnetic (EM) loads.

The traditional approach to analyze the joint is to generate a detailed 3D Finite Element (FE) and perform a transient dynamic analysis of the TBM-Joint-Shield system. However, the design of the TBMs is still in progress, which makes such procedure unaffordable because every design modification of the TBM would entail the generation of a new 3D FE model and recalculation of the joint for every EM load.

A response spectrum based methodology is proposed here to simplify the analysis of the TBM-Joint-Shield system under transient dynamic non-periodic loading caused by EM loads. The methodology is valid for any mechanical system analogous to a single degree of freedom lumped spring-mass-dashpot system undergoing that specific dynamic loading, regardless of the values of mass and stiffness of the system.

2. Methodology

The TBM-Joint-Shield has been modeled as a single degree of freedom lumped spring-mass-dashpot model, where the TBM and the Joint contribute to the rotational inertia and the rotational stiffness, respectively. The shield is not modeled explicitly, as it is considered perfectly rigid and clamped.

The TBM-Joint-Shield may be subjected to the 15 time-dependent EM loads collected in Table (8 for HCLL and 7 for HCPB), where the category refers to the likelihood of occurrence defined by IO.

Loads can be resolved into toroidal, vertical and radial components. As shown in Figure 2, toroidal and vertical forces are negligible, whereas the radial force works in tension, which may have a favorable effect; likewise, as indicated in Figure 3, toroidal and vertical moments are much smaller than the radial moment. Hence, the radial moment (i.e. twisting moment) has been the only load component considered in the analysis.

As EM loads are non-periodic and suddenly applied (time duration of approximately 50 ms), the equation of motion of the TBM-Joint-Shield system has been solved numerically using the Finite Element Method. The main output of simulations is the reaction to the input load.

The Dynamic Amplification Factor (DAF) is an indicator of how much the dynamic response of the system is amplified. It was determined as the ratio of the maximum reaction $M_{dynamic}$ and the maximum input moment M_{static} in the radial direction, equation (1).

$$DAF = \frac{M_{dynamic}}{M_{static}} \tag{1}$$

Figure 2: Resultant forces acting on the HCLL due to a magnetic disruption event of category II. Note that radial force Fx separates the TBM from the Shield.

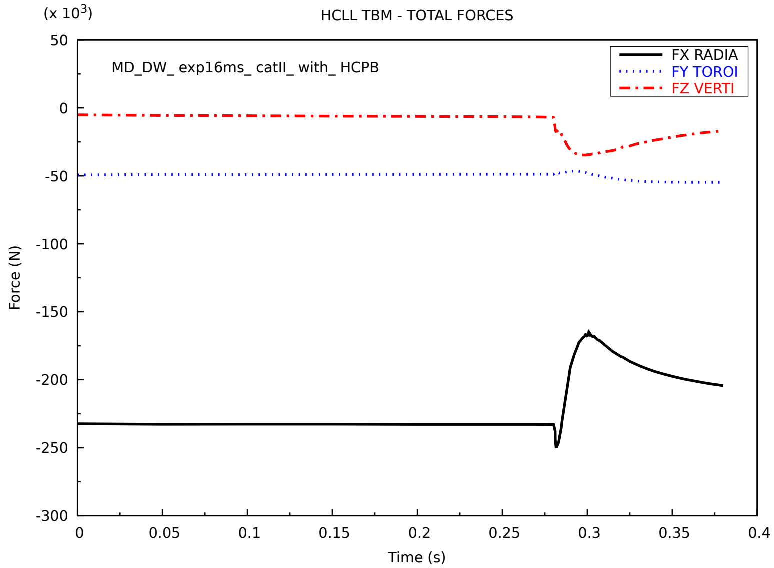
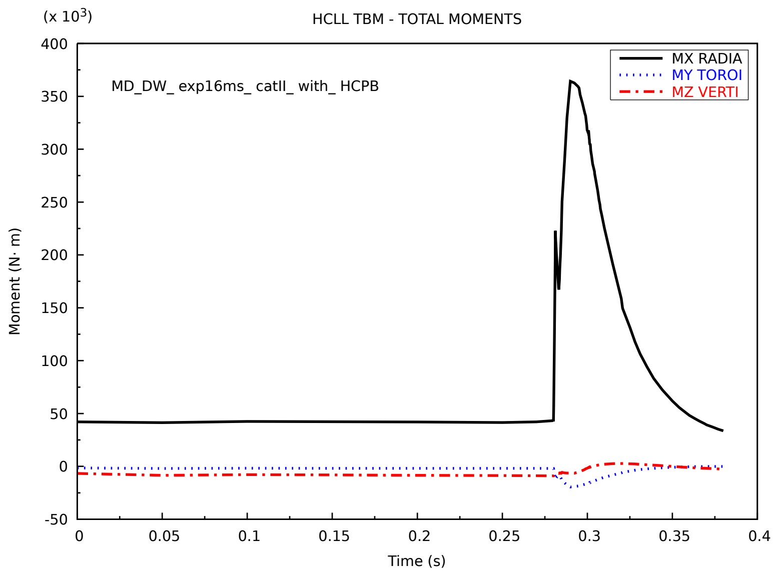


Figure 3: Radial, Toroidal and Vertical moments acting at the center of gravity of HCLL during MD_DW_exp16ms_CatII_with_HCPB_316LN loading.



For no amplification, the value of DAF is 1. This procedure was repeated for a wide range of frequencies spanning from 0 to 500 Hz of each EM load and considering two values of damping separately: 4% and no damping. A total of 15,000 simulations were conducted. The process was parametrized using python scripts.

After that, the DAF were grouped by EM load categories I&II, III and IV. Note that categories I&II were included in the same group because they are assigned the same structural service level (Level A).

An envelope curve of the maximum DAF values for each category was generated afterwards. Each envelope represents the TBM response spectrum for accidental EM loads. The spectrum is used for structural analysis under transient EM loads in the same way as response spectra are used for seismic analysis. This curve will be called Dynamic Amplification Factor Envelope (DAFE).

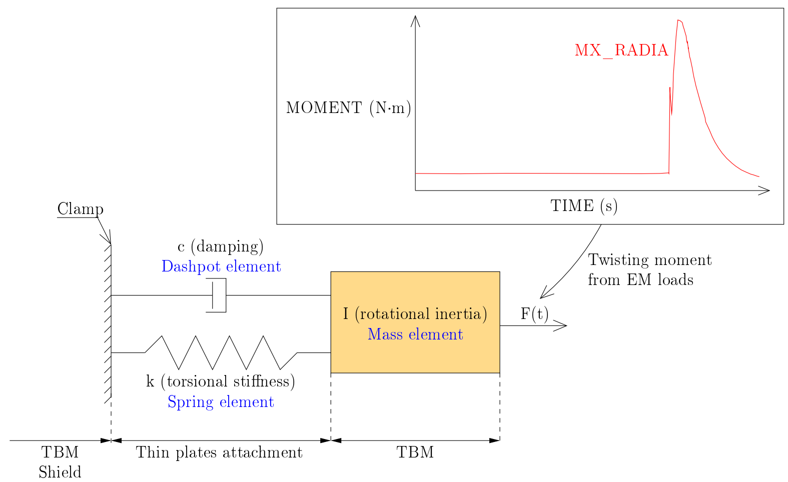
Given the natural frequency of our system, the design moment M_{design} can be readily determined by using the DAFE of that specific EM load, equation (2).

$$M_{design}^{category} = M_{static} \times max(DAF) \tag{2}$$

In summary, the procedure of determination of the design moment is the following:

- Calculate the reactions of the simplified TBM-Joint-Shield model to each EM loading scenario.
- Calculate DAF for each frequency, EM load and damping value of interest.
- Group DAF by categories and plot the envelope curve.
- Given the natural frequency of the system, make use of the envelope curve to calculate the design moment.
- Validate the structural integrity of the system by using the design moment.

Figure 4: Schematic of the lumped mass-spring-dashpot system clamped at one side and subjected to a time-dependent load on the other side.



3. Description of the Finite Element Model

3.1. Modeling approach

A Finite Element (FE) model of the TBM-Joint-Shield system was created in the finite element software Abaqus Standard 6.13. The FE model aims at calculating the reaction forces of the TBM-Joint-Shield system due to the dynamic application of EM loads.

The FE model includes three Abaqus elements: mass, spring2 and dashpot2, which represent the rotational inertia of the TBM, the torsional stiffness of the joint and the damping of the system, respectively. The dashpot and the spring are clamped on one side and attached to the mass on the other side. This system has only 1 dof, and is subject to the time-dependent radial moment of the EM loads included in Table 1. The model is illustrated in Figure 4.

To get equally spaced values of the natural frequency f_n, mass was kept constant, whereas the stiffness was varied according to equation (3):

$$f_n = \frac{1}{2\pi}\sqrt{\frac{K}{I}} \tag{3}$$

where K is the torsional stiffness of the joint and I the rotational inertia of the TBM around the radial axis [2].

Table 1: Load cases analyzed separately for HCLL and HCPB

Category	EM load
I	md_dw_exp22ms
II	vde_dw_lin36ms
	md_dw_exp16ms
	md_dw_exp16ms_with_hcpb_316ln[1]
III	vde_up_exp16ms
	vde_down_exp16ms
	vde_down_lin36ms
IV	md_up_slow_fast

[1] This load case is only applied to HCLL

Likewise, the damping ratio ξ was kept constant for each natural frequency f_n. The damping parameter c was modified for each input file according to equation (4).

$$c = 4\pi I f \xi \tag{4}$$

3.2. Solver and time integration

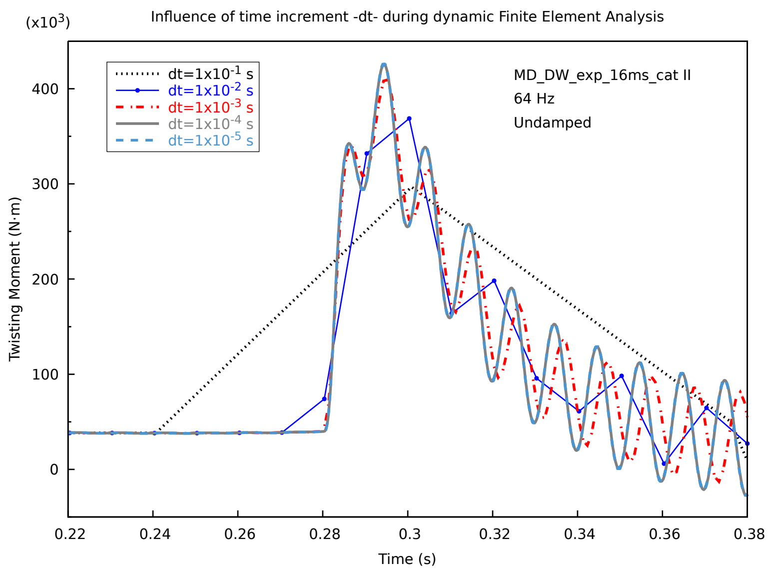
A direct-integration transient dynamic analysis was conducted for each EM load. The solver uses the implicit Hilber-Hughes-Taylor time operator, which has the advantage of being unconditionally stable for linear systems while keeping at a minimum the amount of numerical damping [3].

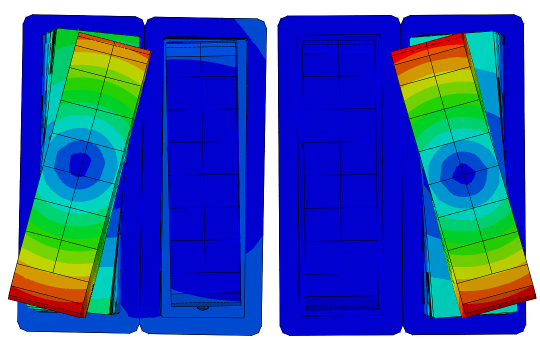
The time integration dt was determined from a sensitive numerical analysis in which the reaction force history was plotted for decreasing values of dt until the outcome does not change. The time integration selected was $dt = 0.0001s$ (Figure 5).

3.3. Torsional natural frequencies of HCLL and HCPB

The natural frequencies of the HCLL and the HCPB are required to obtain the dynamic amplification factor and, subsequently, the design moment. They were previously determined in a detailed 3D FE model. As indicated in Figure 6, results showed that the first torsional natural frequencies corresponding to HCLL and HCPB are 64 Hz and 96 Hz, respectively.

Figure 5: Influence of the time increment on the reactions of the TBM-Joint-Shield system against the EM load MD_DW_exp_16ms_cat_II

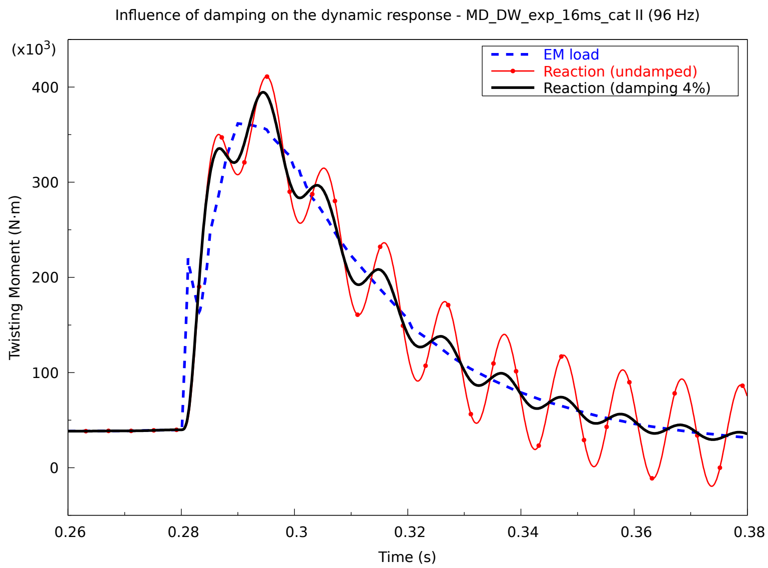




(a) HCPB (96 Hz) (b) HCLL (64 Hz)

Figure 6: First torsional modes of TBMs viewed from plasma.

Figure 7: Influence of damping on the dynamic response at a frequency of 96 Hz. Only the relevant time interval is displayed.



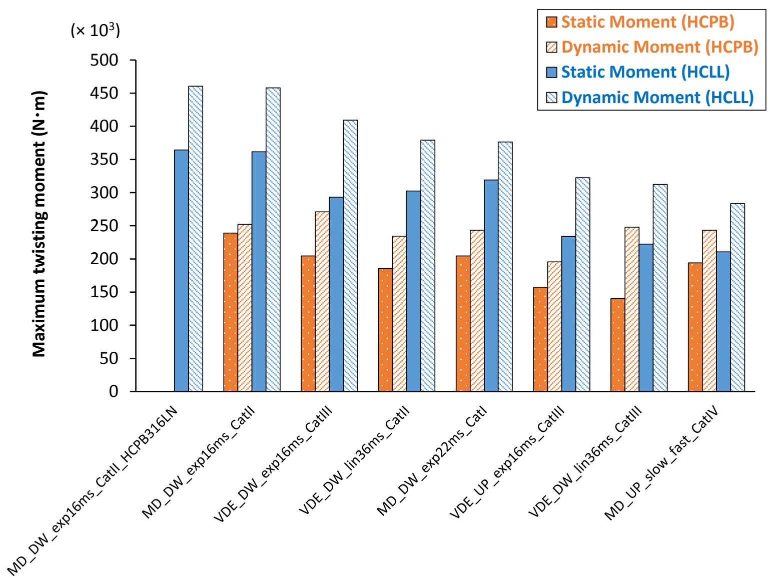
4. Results and discussion

4.1. Dynamic response of the system

As shown in Figure 7, the TBM-Joint-Shield system amplifies the input EM load. As expected, damping attenuates progressively the oscillations.

The maximum value of each EM load and the corresponding reactions are depicted in Figure 8. Values were obtained with a damping of 4% and for frequencies of 64 Hz and 96 Hz, which correspond to the first torsional natural frequencies of the HCLL and HCPB, respectively. Interestingly, radial moments are much higher in HCLL than in HCPB due to the presence of the PbLi in the HCLL. The highest EM load acting on the HCLL corresponds to the EM load MD_DW_exp16ms_CatII_with_HCPB_316LN (Figure 8), whereas in the case of HCPB the highest input corresponds to the MD_DW_exp16ms_CatII. It is worth noting that, as the dynamic amplification depends on the frequency content of the input load and the dynamic characteristics of the TBM-Joint-Shield system, the highest input load acting on the HCLL does not lead to the highest reaction.

Figure 8: Input radial moment and corresponding amplified dynamic reaction. HCLL is subjected to higher moments than HCPB.



4.2. Dynamic Amplification Factor Envelope

The DAFE of the EM loads corresponding to the HCPB and category III is shown in Figure 9. The curve is plotted by joining the maximum values of the DAF generated for each EM load of this category. By using an envelope curve, this design approach becomes more conservative, because the design moment is always equal or higher than the resultant reaction. For example, although the DAF obtained for the EM load MD_DW_exp16ms_CatII at 96 Hz was lower than that of the VDE_DW_lin36ms_CatII(1.25 vs 1.80), the design moment was calculated from equation 3 with the highest value (1.80).

The DAFE corresponding to HCLL and HCPB are depicted in Figures 10 and 11, respectively. The maximum amplification occurs in both cases for the Category III, with a value approximately equal to 1.8 for the HCPB case.

The DAF corresponding to categories I&II of EM loads acting on HCLL and HCPB are compared in Figure 12, revealing that the response of the HCPB is more amplified than that of the HCLL. Moreover, as expected, it is shown that amplification is higher when the system is undamped.

Figure 9: Generation of Dynamic Amplification Factor Envelope curve from DAF curves of category III (HCPB).

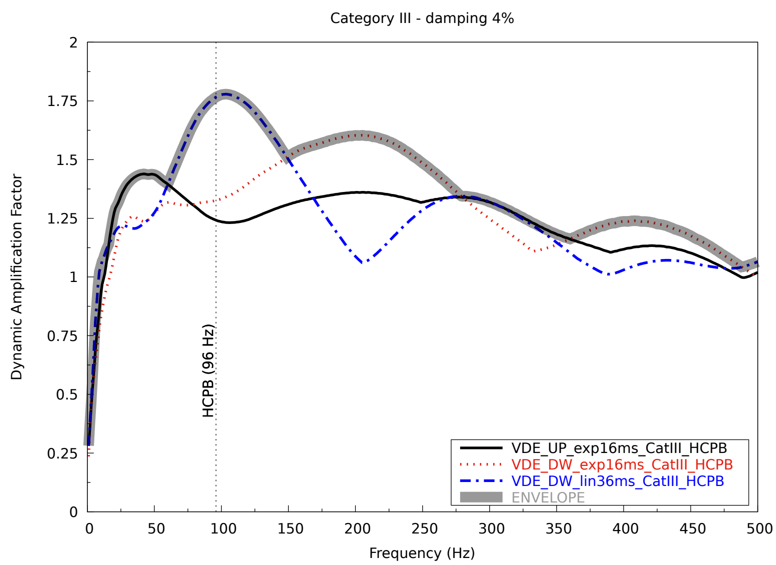


Figure 10: Dynamic Amplification Factor envelopes of HCLL for all categories.

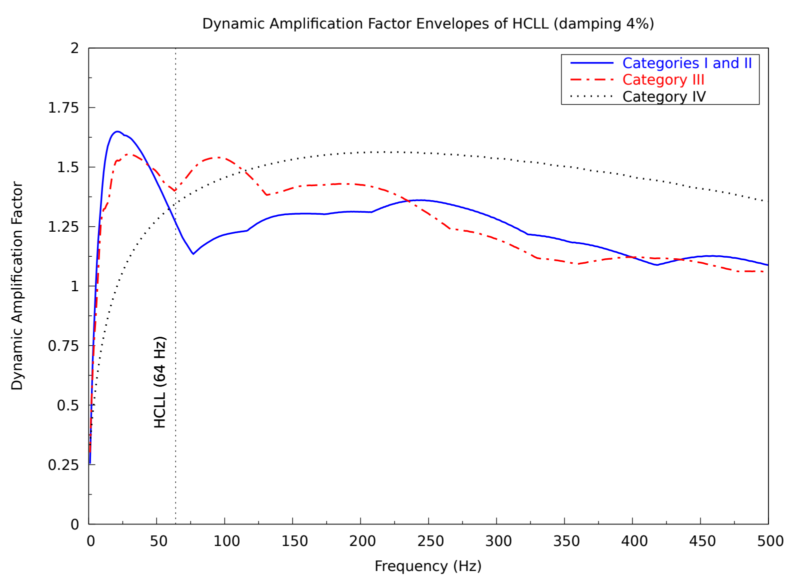


Figure 11: Dynamic Amplification Factor envelope of HCPB for all categories.

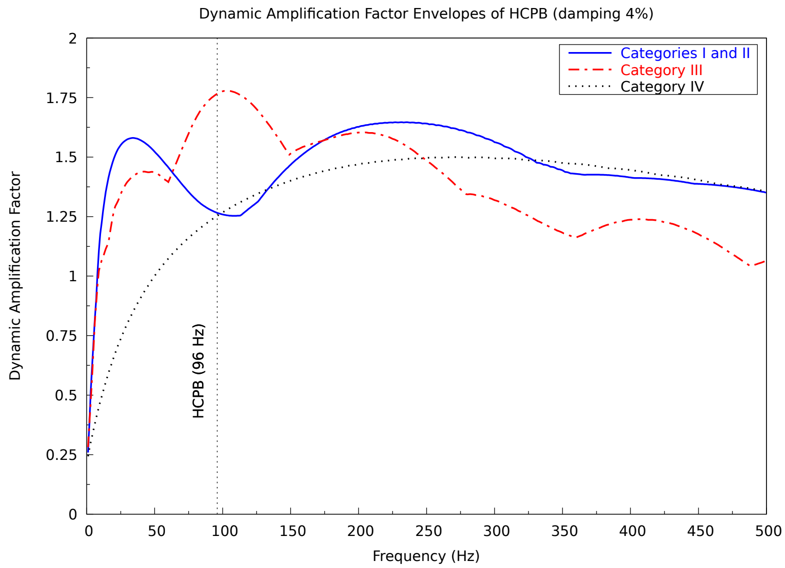
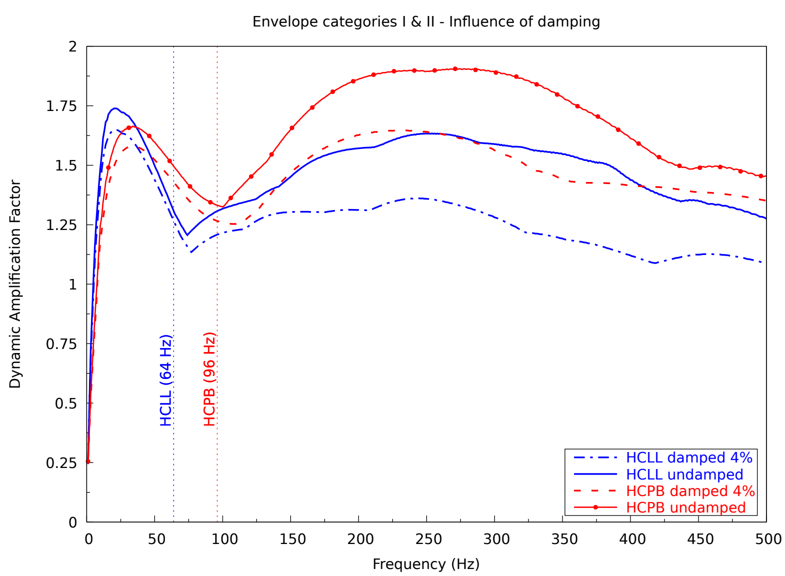


Figure 12: Dynamic Amplification Factor envelope of HCLL and HCPB for category I&II. Damped and undamped values are compared.



5. Conclusions

A response spectrum based methodology has been presented to simplify the dynamic analysis of the TBM-Joint-Shield system under EM loads. Results show that values of the dynamic amplification factor range from 1.25 to 2.0. It can be concluded that HCLL is more critical than HCPB from the Joint prospective. In particular, the design driver of the Joints is the EM load MD_DW_16ms_CatII_with_HCPB_316LN.

References

[1] G. Aiello, J. Aktaa, F. Cismondi, G. Rampal, J.-F. Salavy, F. Tavassoli, Assessment of design limits and criteria requirements for Eurofer structures in TBM components, Journal of Nuclear Materials, 414 (1) (2011) 53-68.

[2] Luisa María Gil-Martín, Juan Francisco Carbonell-Márquez, Enrique Hernández-Montes, Mark Aschheim, M. Pasadas-Fernández, Dynamic magnification factors of SDOF oscillators under harmonic loading, Applied Mathematics Letters (25) (1) (2012) 38-42.

[3] Hibbitt, Karlsson and Sorensen., ABAQUS/Standard User's Manual, 2013.

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