Effective response spectra for the dynamic qualification of equipment and subsystems

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1 INTRODUCTION

The objective of the Floor Response Spectra (FRS) -and its "raison d'être"- is to serve as a dynamic input for the qualification or design of equipment and subsystems in nuclear power plants. The achievement of this objective has been questioned in practice from different standpoints; it is generally agreed that the conservatism accumulated right through the seismic analysis process is excessive, particularly if the regulatory positions are rigorously followed; additional broadening of the peaks and enveloping of several FRS, in order to cover different equipment locations and equipment groups, introduces additional doses of conservatism.

A significant part of the effort to improve the FRS is oriented towards developing a better analytical tool (1), for instance taking into account structure-equipment interaction, non-proportional damping, tuning effects, etc. Nevertheless, the definition of the real damping mechanism and its effect on system behavior are still to be incorporated from experimental results into the analysis programs.

In this paper, an FRS calculation approach is applied (similar to 2, 3, 5) which takes into account seismic input characteristics, dynamic response of the equipment and criteria for evaluation of its seismic behavior and acceptance.

These Floor Response Spectra which will be called Effective Floor Response Spectra (EFRS), could be more coherent with the original objectives, being a more rational design input. In the following, different approaches are presented, to obtain these types of spectra, and several practical cases of its application are discussed.

2 SEISMIC QUALIFICATION PROCESS

The global process for analysis of qualification of equipment or subsystems is shown in the flow diagram of Fig. 1a. Two main modules of calculation are distinguished; the first one corresponds to the filtering of ground seismic excitation through the soil-primary structure-secondary structure system. ("Secondary structure" refers to a platform, slab or any flexible intermediate structure on which the equipment is supported). The resulting output of this module corresponds to the classical floor response spectra.

The second modulus corresponds to the process of filtering the FRS, through the equipment structure. The result is a response expressed in the form of stresses, forces, deformations or non-structural effects of the equipment. In the event of a postulated earthquake occurring at site, the sequence of the two modules is supposed to model the environment acting upon the equipment.

In continuation of the above modules, the process ends with an evaluation module which evaluates equipment response, comparing it with requirements of regulations and deciding whether it is acceptable.

Requirements for stresses and deformations are generally very conservative and these are evaluated using permanent load criteria, without taking into consideration real failure mechanisms under dynamic actions and additional strength reserve through system ductility, or their capacity for redistribution of stresses and energy dissipation through various mechanisms.

On the other hand, the behavior compatible with the function to be performed by the equipment in earthquake conditions is normally not clearly defined.

In current practice, if the response does not comply with the requirements, it is necessary to:

a. Modify the structure or supports of the equipment or subsystem
b. Attempt to reduce or adjust the FRS

The latter may be done by refining the analysis procedure and reducing conservatism within the narrow margins imposed by regulations in force. This refinement of the analysis has led to the calculation of more complete spectra which take local amplifications into account, and could result in inputs for the equipment or subsystems, even larger than those originally pertaining to the building, with additional shifting in frequencies. This situation in which dynamic inputs are increasingly greater for equipment and subsystems -which makes them vulnerable according to current standards- is not coherent with the results observed in analog system behavior during real earthquakes which, on the contrary, indicate a large inherent capacity during earthquake actions (4).

It is considered, therefore, that it is most important to perform a basic revision of criteria for stress, deformations and suitable behavior during seismic actions.

In the case of EFRS, a definition is made of inputs for the design or qualification of equipment, which takes into account the input dynamic characteristics (module 1 output), structural characteristics and response mechanisms of equipment (module 2), and realistic evaluation and acceptance criteria (module 3). The EFRS, therefore, incorporates aspects of the different modules, transforming them into a design input which is closer to reality and can be put to more effective use. These EFRS, will be oriented towards a specific equiment item or group and, although they cannot be generalized, could lead to a more rational and less conservative qualification.

The unbroken line in Figure 1a indicates the usual corrective actions of classical FRS, geared towards modifying the analysis procedure or equipment or subsystem structures/supports. In the case of EFRS, the modifying actions, depicted by a broken line, are interactively extended to all the modules, incorporating real experiences of equipment during earthquakes.

3 CRITERIA FOR DEFINITION OF EFFECTIVE FLOOR RESPONSE SPECTRA

The diagram in Figure 1b schematically represents some of the parameters to be considered when calculating EFRS. Three main blocks can be distinguished: A) Seismic Input, B) Equipment Response, C) Acceptance Criteria.

In block A, three excitation levels can be perceived; a first level which corresponds to low-seismicity areas and which would, in extreme cases, be translated into a zero input for the equipment, complemented by recommendations of a constructive nature regarding equivalent static actions; a third level which corresponds to high-seismicity areas and which will be more rigorously processed, and an intermediate level of medium to low seismicity which corresponds to the majority of sites and whose processing, with regard to EFRS, considers:

a. Variations in the content of site spectra frequencies based on the type of earthquake, epicentral distance, local geological conditions, etc.
b. Effects of soil-structure interaction which influence the variability of the frequency and broadening content

Particular effects such as nearby earthquakes of low-intensity which may occur within tectonic provinces, could give rise to spectra with high-frequency content which, however, produce results of insignificant structural effects (modules 2 and 3), and may be treated as effective reduced spectra. In this case, it is evident that besides the input, other structural effects must be considered (blocks 2 and 3).

In the 2nd block which refers to the filter through the equipment structure, the following should be considered in determining its response: (a) layout of equipment support points, the floor response spectra may be different at each point (multisupported system); (b) physical characteristics of the support (fixed, sliding, gaps, etc.), these characteristics could influence the excitation that "filters" through to the equipment; (c) dominant equipment frequencies and their participation coefficients; (d) dynamic coupling, function of effective masses between both systems; (e) non-lineal behavior due to local plastification or formation of plastic hinges or to large deformations in thin-walled structures.

The acceptability criteria are indicated in the 3rd block: (a) admissible stresses, (b) particular and general deformations, (c) operating conditions. The former are quantifiable and the latter require a parameter equivalent in loads or stresses, or structural criteria such as crack growth, leakage ratio, opening time in electrical contacts, etc.

The evaluation of this 3rd block is essential, since the ultimate aim of the whole chain of activities is to reach this goal. It would be most difficult to disassociate it from real equipment behavior during actual earthquakes (as indicated in the previous point) or its complementary experimental studies.

The following are typical cases of Effective Floor Response Spectra used in practical applications.

1. For the design of an HVAC duct system and its support, an FRS had to be defined. The HVAC system layout was most irregular and passed through building zones of different structural flexibility. As a result of the 1st module, floor response spectra were obtained for rigid and flexible zones, according to the location of the supports (see Fig. 2a)

With respect to the 2nd block, Support Layout, different floor response spectra have to be associated with them depending on whether the support is located in a rigid or flexible zone. Instead of using an envelope response spectrum as usual, the following was studied:

a. The probability of the support being within the range of the flexible zone, taking into account the separation between supports defined by construction or mounting criteria.

b. In the case of different floor response spectra (multisupported system), the spectral loads, if they originate from different floor response spectra, are conditioned by the influence coefficients and participation factors which can be combined to deduce an equivalent mean floor response spectrum. This would be an EFRS, closely adjusted to reality.

To obtain a floor response spectrum for the qualification of equipment supported by the ducts themselves, consideration was given to the above mentioned probability of flexible or rigid zones coupled with the conditionality that the sections also contained equipment. It was also considered that the interaction between the equipment mass and the effective modal mass of dominant modes reduces equipment response.

The foregoing facilitated the obtainment of more-reduced effective floor response spectra for the qualification of equipment resting on the ducts.

Due to regulatory requirements, it was not possible to consider the effects of the 3rd block.

2. In the following cases, criteria from the 3rd block are used and some more general EFRS are defined.

In the case of certain HVAC ducts, such as those indicated in the 1st case, which are subject to seismic excitation simultaneous with high-frequency loads caused by thermohydraulic phenomena, the floor response spectrum is of the kind indicated in Fig. 2b.

With respect to HVAC ducts with gaps in their supports, the slippage effects which limit high-frequency excitation transmission were evaluated. On the other hand, slippage and bumping against the supports can generate local high-frequency loads, but with a low-energy content which is dissipated through local deformations in the duct (6).

The resulting effective floor response spectra for high-frequency evaluation are considerably reduced (see Fig.2b). In the seismic frequency zone (of low to medium value), the duct itself has considerable reserves if one considers its post-buckling behavior, limiting its response, its joint movements and leakage problems.

The effective floor response spectrum will be controlled by the support design and will vary according to the type of support, possibly experimenting incursions in the plastic domain. An effective floor response spectrum can also be defined for different types of anchorages. In all cases, the input must be indicated (wide-band or narrow-band), along with the corresponding increase in amplitudes and the probability of narrow-band spectral ordinates coming within range.

The floor response spectrum might become transformed upon application to practically equivalent static loads weighted by the frequency zone where the equipment responds or is excited.

3. Lastly, special consideration should be given to the case of 3rd

level floor response spectra (structure-equipment-component) where, for example, to qualify a component the spectrum has to be filtered through the component support racks. With the usual dynamic process, high-amplitude spectra can be obtained (see Fig. 2c). If, on the other hand, one considers the conditional probability that the structure(S)/equipment(E) (P[E/S]) frequencies are in resonance, significant reductions can be achieved if the variabilities of the 1st block are also considered.

4 CONCLUSIONS

1. The seismic input for the qualification and design of equipment and subsystems defined as effective floor response spectra (EFRS) should simultaneously consider the seismic input characteristics, equipment response and behavior evaluation criteria.

2. The EFRS facilitate a more balanced design by making the seismic environment more coherent with the actual behavior expected.

3. Engineering judgment should be applied in each case for each equipment item, weighing up all aspects of the process and promoting control mechanisms which guarantees that the hardware corresponds to its assumed behavior.

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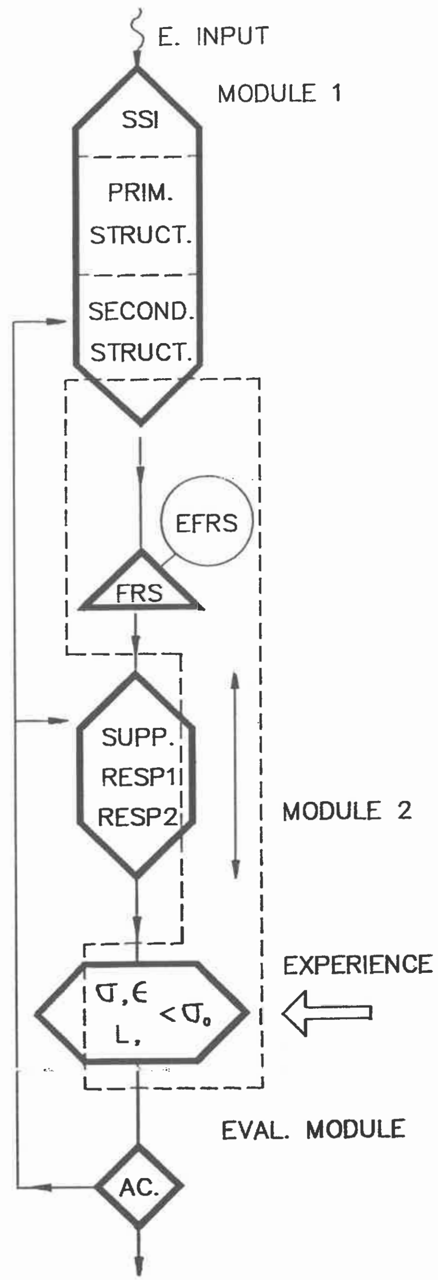

FIG. 1a
SEISMIC PROCESS.

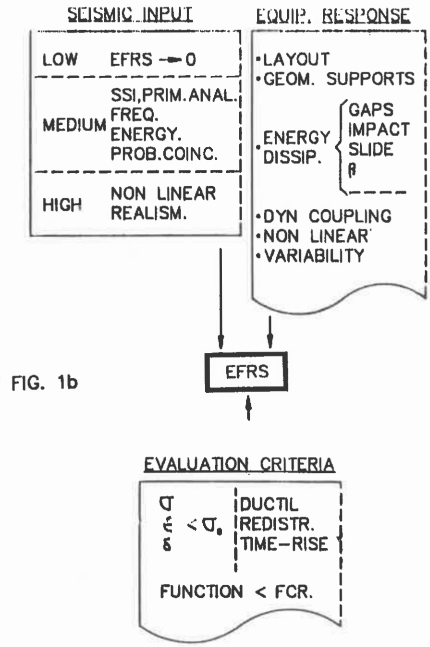

FIG. 1b

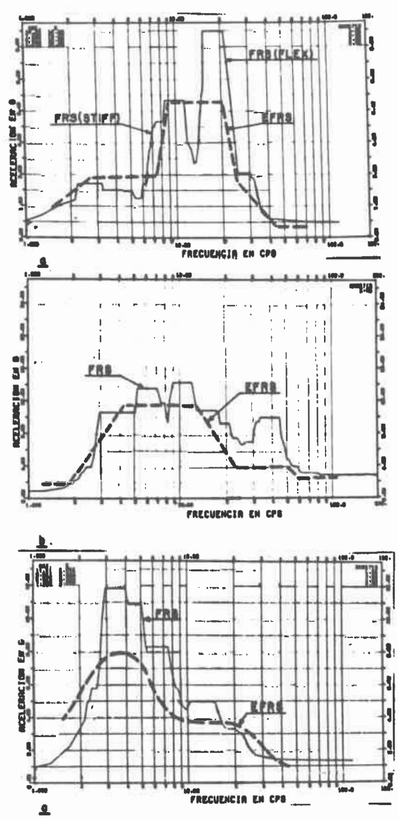

FIGURE 2