SAFETY SIGNIFICANCE OF A TYPE OF SEISMIC INPUT MOTIONS AND CONSEQUENCES ON NUCLEAR INDUSTRY PRACTICE

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ABSTRACT :
The fact that, in nuclear industry, usual practices of earthquake engineering widely overestimate the damaging effects of near-field input motions generated by low–medium magnitude earthquakes was identified in 1997 by the OECD. This issue was addressed by the IAEA in a Coordinated Research Project (2002-2005). The project included a large benchmark, based on experimental data provided by France (relating to a concrete wall subjected to different seismic input motions on a shaking table) and seismic input motions provided by Japan. A major conclusion is that the root cause of the identified issue is relating to the fact that seismic input motions are conventionally regarded as force controlled loads, while, due to their high frequency content, input motions under consideration should be regarded as displacement-controlled loads, so as to take benefit of the fact that structural margins are much larger under displacement controlled loads than under force controlled loads. However such margins are accessible only when modelling the non-linear behaviour of structures. Therefore the IAEA recommends that nuclear industry practices evolve so that the dynamic modelling techniques take into account at least small nonlinearities in the models.

KEYWORDS:
nuclear facilities, near-field input motion, non-linear response, damaging capacity

1. INTRODUCTION

The fact that usual practices of earthquake engineering result in a poor estimate of the damaging effects of near-field earthquake input motions generated by low–medium magnitude earthquakes was identified by the Committee on the Safety of Nuclear Installations of the OECD Nuclear Energy Agency, *OECD/NEA(1997)*, as ‘the most significant issue’ in the field of engineering characterization of seismic input motion. To address this issue, the IAEA organized, under the leadership of the author, a Coordinated Research Project (CRP) on the “Safety significance of near-field earthquakes”. This CRP consisted of two main phases:

(a) Carrying out a benchmark exercise on near-field earthquake (NFE) effects:

- In a first step, the benchmark consisted of interpreting existing experimental data, provided by France, relating to a concrete wall, the CAMUS specimen, subjected to different seismic input motions on a shaking table. Participants modelled the experiments with static and dynamic methods;
- In a second step, the participants were invited to carry out numerical simulation of the response of their models of the CAMUS specimen to a set of seismic input motions provided by Japan;
- A third step consisted of carrying out sensitivity studies about the impact of nonlinearity on floor response spectra, with two types of input motions.

(b) Making proposals for evolution of engineering practice:
On the basis of the benchmark results, the purpose was to make proposals for possible evolutions of engineering practices so as to realistically account for the effects of the type of near-field input motions under consideration and their safety significance.

Twenty-two institutions from 18 Member States were involved in the IAEA CRP, which was jointly funded by the IAEA and the European Union (The Joint Research Centre (JRC), Ispra). Processing and synthesizing the benchmark outputs delivered by the participating institutes were carried out by the JRC Ispra.

The IAEA CRP on the “Safety significance of near-field earthquakes”, the lessons learnt about the safety significance of near-field input motions generated by low–medium magnitude earthquakes, as well as about necessary evolutions of the nuclear industry practices are the matter of a IAEA Technical Document (TECDOC) to be published soon. The present paper is a summary of this Technical Document.

2. CONTEXT AND SCIENTIFIC BACKGROUND

The low damaging capacity of the considered type of input motion was early identified by experts such as *Newmark, and al. (1981)* and confirmed by feedback from experience. It was extensively discussed at the occasion of experts meeting either within an *OECD/NEA (1999)* or *IAEA (2003)* framework. It was concluded that both the conventional description of seismic input motions in the form of response spectra and the associated conventional engineering practices were not appropriate to resolve the identified issue.

Significant developments have occurred in the last decade in the field of earthquake engineering for conventional buildings, principally with the development and refinement of displacement based approaches (DBAs). However, it was recognized that the nuclear industry has to resolve specific issues that are not addressed by the conventional building industry, principally:

- The nuclear industry is not only interested in the capacity of buildings but also in the transfer of the seismic input motion to equipment; this is known as the floor response spectra generation issue;
- The nuclear industry is interested in refining the analysis of the structural response, in the range of immediate post-elastic behaviour, limited by the conventional limit states (there is no need to develop tools that would enable a description of the ultimate behaviour of structures in the field of large strains that control the collapse modes). In this regard, the views of the IAEA *(IAEA 2003)* are that “It should … be possible to set-up simple methodologies qualified in the range of small nonlinearity.” Although Japanese practice is based on systematic use of time history analysis, the current Japanese practice, described in this TECDOC, provides elements of such a rather simple methodology, presented in an *NRC (1994)* document.

3. INPUTS FOR THE BENCHMARK

3.1. CAMUS experiment

The CAMUS specimen, presented by *Bisch and Coin (1998)*, consists of two similar parallel shear walls, strongly clamped on a shaking table and subjected in their plane to 1-D horizontal seismic input motions. The specimen is a mock-up at 1/3 scale of typical shear walls of a six level conventional structure. Its total mass is 36 t. The R-bar system was designed in compliance with the French regulation for conventional buildings against a conventional (referred to below as ‘Nice type’) 0.2 g input motion.

The shaking table was activated by input motions representative of far-field (Nice type) and near-field (San Francisco type) cases, scaled to different peak ground acceleration (PGA) values, according to the series presented in the table 1. Recorded top displacements substantiated the fact that a near-field type motion is less damaging than a far-field type at the same PGA value. A key point for the CRP is that design criteria were not exceeded during these tests and that consequently only relatively small non-linearity occurred.

Table 1 : Series of input motions applied to the shaking table

	Run 1	Run 2	Run 3	Run 4
Type of input motion	Nice	San Francisco	San Francisco	Nice
PGA (g)	0.24	0.13	1.11	0.41
Top displacements (mm)	7.0	1.5	13.2	13.4

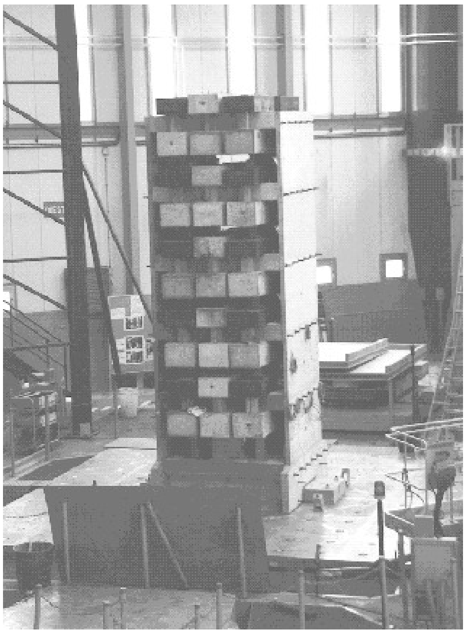

Figure 1 : The CAMUS specimen on the AZALEE shaking table (CEA

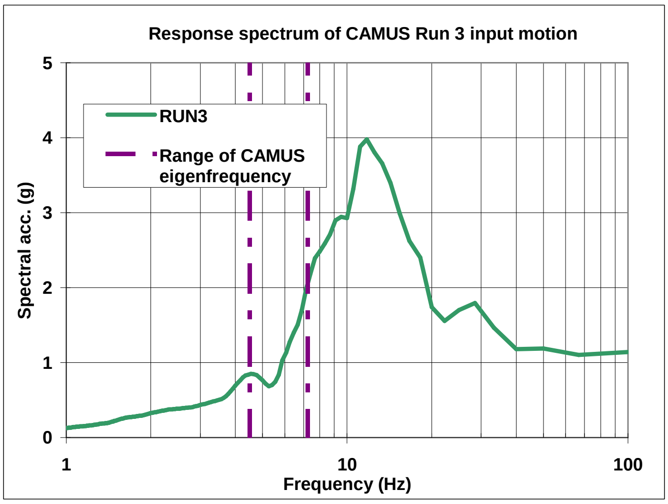

Figure 2 : Run 3 input response spectrum Representative of the high frequency content of the input motions considered in the IAEA CRP

3.2. Japanese input motions

Japan is now equipped with a dense network of about 2600 seismometers, which has provided many records in the recent past. As proposed by the Japan Nuclear Energy Safety Organization, the following input motions were selected from the available near-field record set and the corresponding input motions used by the participants for calculating the response of the CAMUS specimen.

Table 2 : Selected Japanese input motions

	PGA (g)	PGV (m/s)
N-S component, Ito-Oki	0.19	0.25
E-W component, Kashyo dam	0.53	0.51

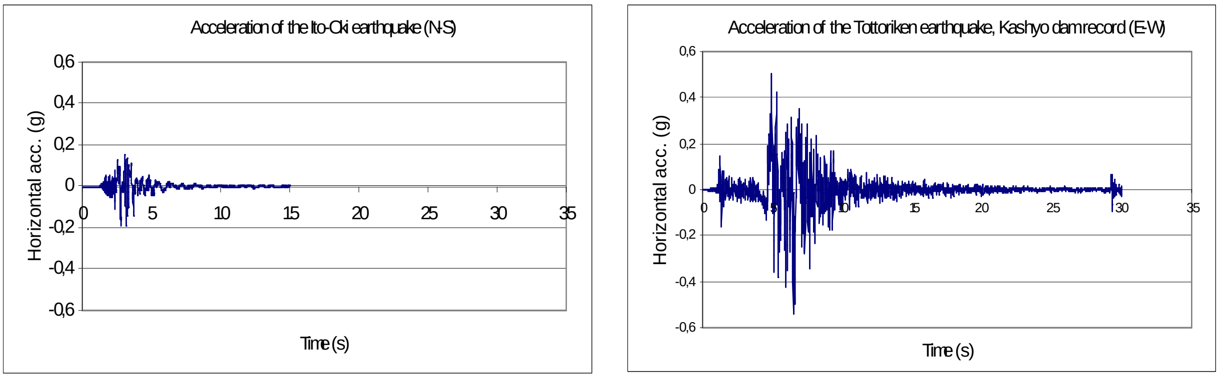

Figure 3 : The two Japanese input motions, plotted at the same scale

4. OUTPUTS OF THE BENCHMARK EXERCISE

As mentioned in the introduction, the benchmark was organized in the form of a three step exercise. It resulted in a series of 34 analyses of the CAMUS specimen that participants were requested to carry out:

- **Step 1**. In Step 1, participants were requested to carry out analyses of the response of the CAMUS specimen according to the spectral method, the DBA method and the time history method. Comparative performance, from processing participants' outputs, is presented in the TECDOC under finalization for top displacement and acceleration of the specimen as well as for bending moment, shear forces and tensile strains in R-bars at the base of the specimen.

Such a comparison is presented on the Figure 3. On the figure, **S** stands for 'Spectral method', **F** for 'FEMA DBA', **A** for 'ATC-40 DBA' and **T** for 'Time history'. For every Run the mean and standard deviation of participants' outputs were calculated and are presented in the figure in the form of vertical bars. The figure clearly exemplifies that the conventional spectral method overestimates internal forces when dealing with high PGA near-field input motion (Run 3). It is not the case when dealing with a low PGA near-field input motion (Run 2) because non-linearity impact on force calculation is then negligible.

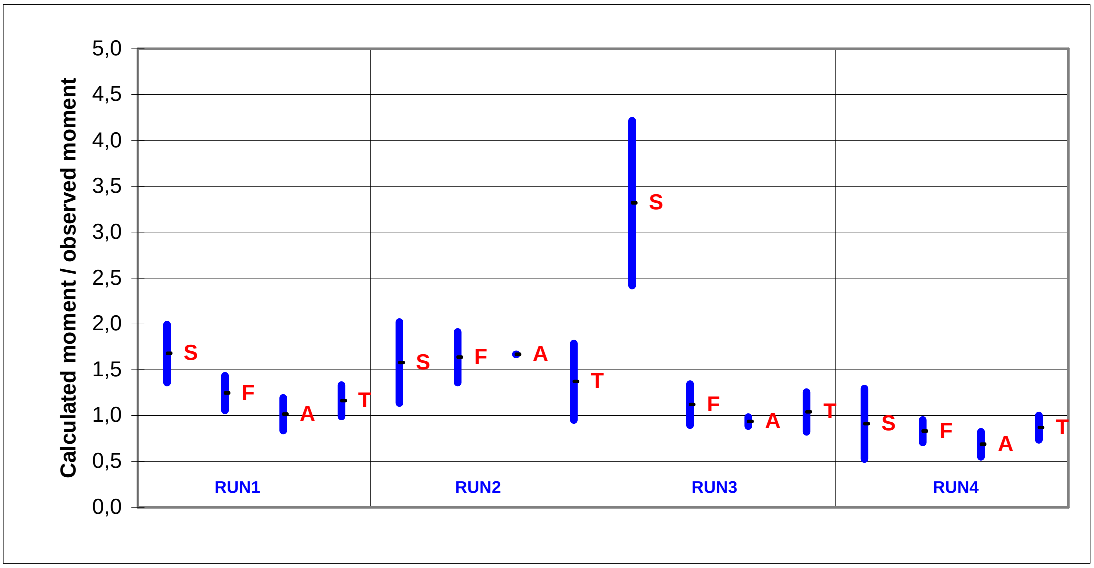

Figure 4 Comparative performance of different methods on level 1 bending moment[1]

The phenomenon is also visible on the Figure 5. It is clear (left) that when dealing with Runs 2 and 3 (same spectral shape with different scaling PGAs), displacements in the specimen are proportional to the PGA. It means that this type of high frequency input motion should be regarded as a displacement controlled load[2].

Conversely, due to non-linearity, internal forces are not proportional to the PGA (right). As compared to what is observed on the specimen, the non-linear effect is properly captured by both DBA and time history analyses, and totally ignored by the spectral method.

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[1] Outputs of the Run 4 should be considered with caution because of the pre-damaging effect of the Run 3 that was disregarded by most participants.

[2] This point was already stressed by *Newmark (1978)* when he derived the inelastic response spectrum : He observed that for low frequency oscillators the margin is equal to the available ductility, revealing a displacement controlled input. Later *Labbé and Noé (1992)* put forward the fact that, in order to decide whether the seismic input should be regarded as displacement controlled or force controlled, the relevant parameter is the ratio between the central frequency of the input motion and the major eigenfrequency of the structure.

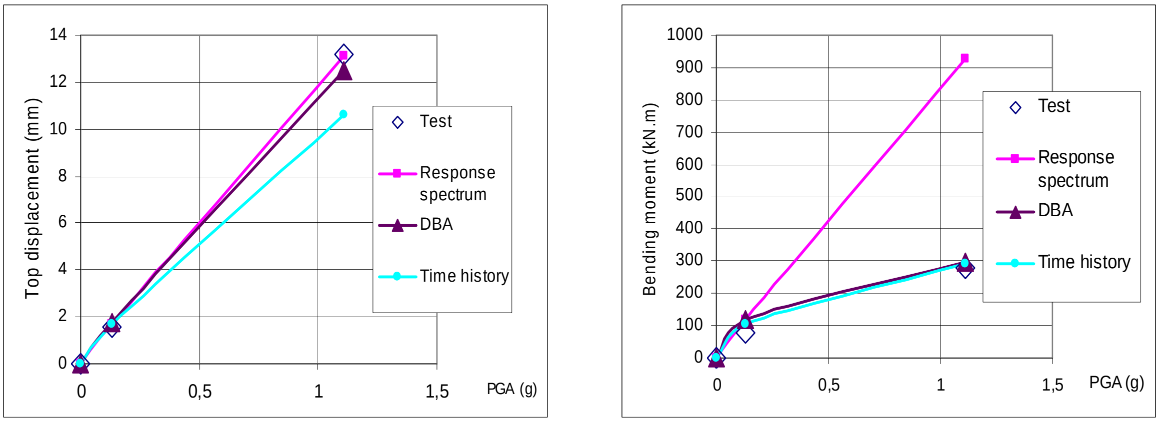

Figure 5 Comparison of Runs 2 and 3 outputs: Top displacement (left) and level 1 bending moment (right).

- **Step 2.** A major interest of Step 2 was that (as opposed to Step 1) participants could not calibrate their respective outputs against experimental results. Step 2 could be regarded as a type of 'blind prediction exercise'. Examining the coefficient of variation (COV) of participants' outputs and comparing it to the COV for Step 1 led to the interesting conclusion that COV did not increase and was not larger for high level input motions than for low level inputs.

Table 3 Mean/Standard deviation/ COV of level 1 shear force and bending moment for the two Japanese input motions

	Ito-Oki	Kasho Dam
Leve 1 Shear Force (kN)	53.7 / 16.8 / 0.31	117.2 / 22.5 / 0.19
Leve 1 Bending moment (kN.m)	158.8 / 51.7 / 0.33	308.3 / 39.1 / 0.13

- **Step 3.** A major output of Step 3 was to reveal the extreme sensitivity of floor response spectra to small nonlinearity. To a large extent, issues posed by floor response spectra generation are not comparable to issues posed by displacement and/or forces assessment, and are certainly more complicated. For displacement and/or forces evaluation, assumption of linear or quasi linear behaviour may lead to acceptable outputs, while the nonlinear effect can hardly be neglected when dealing with floor response spectra generation.

This point is illustrated by the Figure 6. Top floor response spectra calculated by the participants for the Run 2 are plotted and compared to the top response spectrum observed on the specimen at the occasion of this Run 2 (in bolt). It is clear that, in spite it is a very low level input, generating only small non-linearity in the structure, this small non-linearity has a significant impact on the top floor response spectrum and should not be neglected when dealing with floor response spectra computation. On the one hand, neglecting this effect could lead to an undue overestimate of floor response spectra in the frequency vicinity of the eigenfrequency of the structure, but on the other hand it could lead to a non-safe underestimate in the low frequency domain. It means also that deciding whether non-linear effect can be neglected should be discussed carefully. In the case of Run 2, it is clear that it can be disregarded when items of interest are outputs such as maximum displacements or forces, but not when they are floor response spectra.

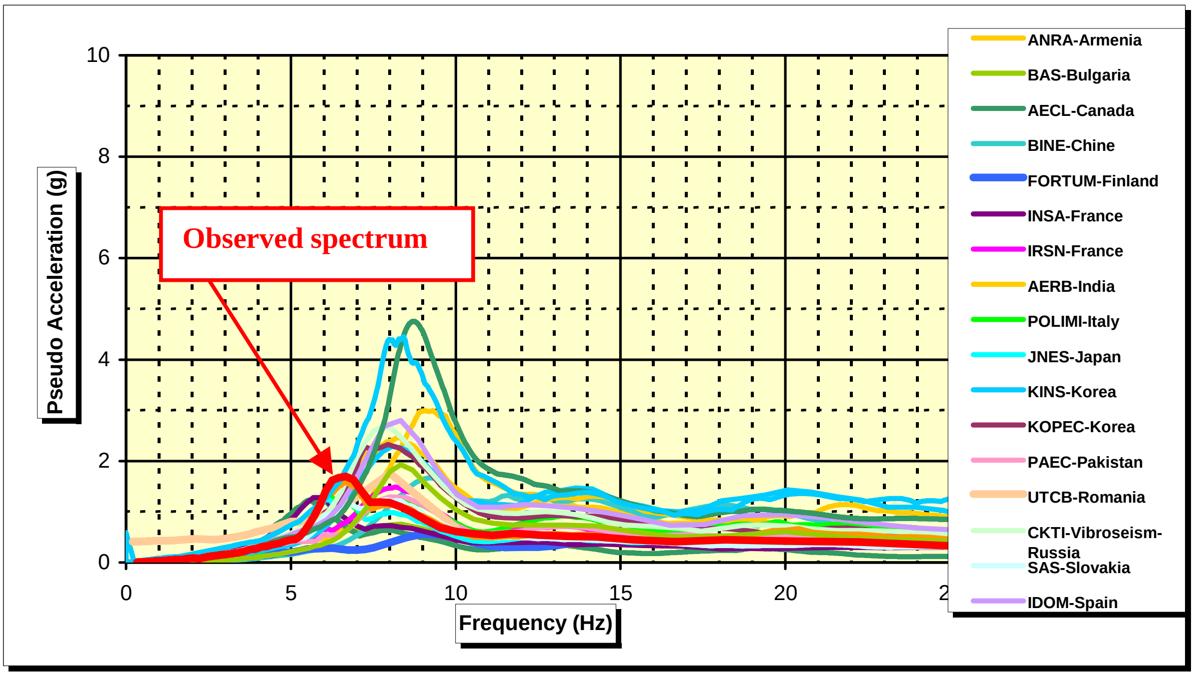

Figure 6 Top response spectrum (5% damping) for Run 2.

5. STRUCTURAL ENGINEERING PRACTICES AND THEIR POSSIBLE EVOLUTIONS

The available engineering methods are presented in the IAEA TECDOC under finalization in the form of a selection of six typical methods, from the simplest (linear spectral approach) to the more sophisticated (time history analyses). An outline and the major features of each method are presented with comments. Comments focus on the philosophy of the method: Does it imply static or dynamic equilibrium? Is the input motion implicitly regarded as force or displacement controlled?

The introduction and summary of available methods is followed by a discussion of DBAs, which are becoming more and more popular for the design and evaluation (i.e. the verification of the design) of conventional buildings. Codified methods developed in Europe, *Eurocode 8 (2008)*, New Zealand, *NZNSEE (2006)* and the USA, *ATC-40 (1996)*, *FEMA (1997)* and *SEAOC (1999)* are presented and compared. The possible application of these methods to nuclear buildings is discussed, addressing, in particular, the complexity of nuclear structures, the soil–structure interaction issue and the acceptance criteria.

Finally, other options for the evolution of engineering practices are explored, including full scope time history analysis and modelling simplification techniques such as the macro-element approach. Based on the feedback of experience of well established geotechnical engineering methods, an equivalent linear analysis method is proposed and its outlines presented. Member States are invited to test and calibrate it.

6. CONCLUSIONS AND PROPOSALS FOR THE EVOLUTION OF ENGINEERING PRACTICE

The conclusion of the CRP and the recommendation for the evolution of engineering practice are organized under the following specific topics:

6.1 Conclusions of the benchmark exercise

6.1.1 On the safety significance of near-field input motions

The root cause of the ‘significant issue’ raised by the low–medium magnitude near-field input motions is not their damaging capacity (there is a consensus that it is very low in spite of their possible high PGAs), but the fact that the engineering community used the response spectrum as an indicator of the damaging capacity of these type of input motions. This indicator significantly overestimates their actual damaging capacity due to the fact that seismic input motions are conventionally regarded as force controlled loads (or primary loads in mechanical engineering terminology), while high frequency input motions (with respect to the structure frequency) act principally as displacement-controlled loads (or secondary loads in mechanical engineering terminology). Consequently the conventional nuclear practice ignores the favourable combination of the high frequency content of this type of input motion and the ductile capacity of structures.

6.1.2. On engineering approaches alternate to the response spectrum method:

DBAs: A drawback of DBAs is that as well as the conventional response spectrum method, they are inherently not appropriate for floor response spectra generation. Furthermore, these methods have been developed for (low frequency) conventional buildings. So far, regarding stiff structures such as nuclear structures, outputs provided by these approaches have not been benchmarked against time history analyses. Nevertheless, the evolution of DBAs should be monitored for possible application to structures typical for nuclear power plants;

Time history analysis: A major conclusion is that, at least in the simple case of the CAMUS experiment, dispersion of the time history outputs was not greater than dispersion of the response spectrum method outputs. Time history analysis appears to be the most robust method regarding the estimate of displacements, accelerations, forces and moments. This method is also the most robust for estimating the acceptable PGA (the PGA value that leads the structure to the conventional limit state) associated with a given spectral shape and, if properly implemented, is the only method for computing reasonably realistic floor response spectra.

6.1.3. On challenges to nuclear power plant engineering practice

There is a lack of consistency in the classical nuclear power plant engineering approach due to the concurrent following of practices and/or requirements: structural responses are calculated on an (equivalent) linear behaviour assumption, and acceptance criteria stipulate that forces and moments should not exceed those corresponding to the conventional limit state. On the contrary, significant nonlinear effects appear for low PGAs (significantly lower than those corresponding to the conventional limit state or leading to plastic yield in R-bars). Therefore, any concrete structure, even if designed according to nuclear standards, should be recognized as exhibiting nonlinear behaviour under seismic input motion. Moreover, reasonably realistic floor response spectra cannot be computed without accounting for small nonlinearity effects. Depending on the circumstances, neglecting these effects may lead either to undue margins or on the contrary to a lack of margins in the generated floor response spectra. An evolution in NPP engineering practice is highly desirable in this regard.

6.2 Proposals for the evolution of engineering practice

6.2.1. Generic recommendations

In order to adequately calculate the dynamic response of a structure, all aspects of input and models need to be capable of representing phenomena observed or expected, including nonlinear behaviour and complex boundary conditions. Acceptance criteria of structures and components should allow inelastic deformations compatible with the required performance and corresponding performance criteria. It is recommended that the nuclear industry pursues the evolution of the dynamic modelling techniques taking into account at least small nonlinearities in the models, such as offered in *ASCE (2005), ASN (2006).*

6.2.2. Accompanying R&D effort

Further R&D effort should focus mainly on theoretical evolution and experimental tests to improve and validate the DBAs and the time history approaches. For the latter approach, standard procedures for design and verification should be implemented and proven to be realistically conservative;

6.2.3. Specific recommendation on strong motion scaling factors

It is expected that in the future more and more high frequency input motions will be recorded, thus resulting in higher and higher PGA values meaningless in terms of input motion damaging capacity to structures. It is therefore strongly recommended that a more relevant and simple indicator be selected and adopted by the structural engineering community as a scaling factor of recorded strong motions, such as peak ground velocity (PGV) or cumulative absolute velocity (CAV), and that a significant R&D effort be carried out to concur on engineering practices incorporating this new scaling factor.

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