20th International Conference on Structural Mechanics in Reactor Technology (SMiRT 20)
Espoo, Finland, August 9-14, 2009
SMiRT 20-Division 5 Paper 1683

Safety Significance of a Type of Seismic Input Motions and Consequences on Nuclear Industry Practice

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

1 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 non-linearity.

2 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, with the support of the European Community, 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 non-linearity 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 inputs under consideration.

Twenty-two institutions from 18 Member States were involved in the 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 non-linearity.” 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.

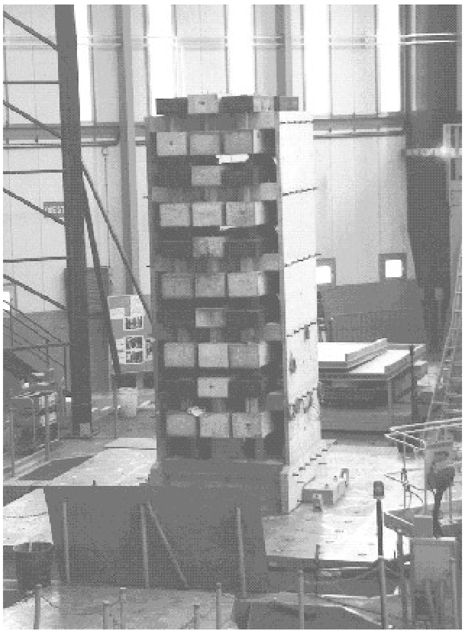

Figure 1. The CAMUS specimen on the AZALEE shaking table (CEA Saclay)

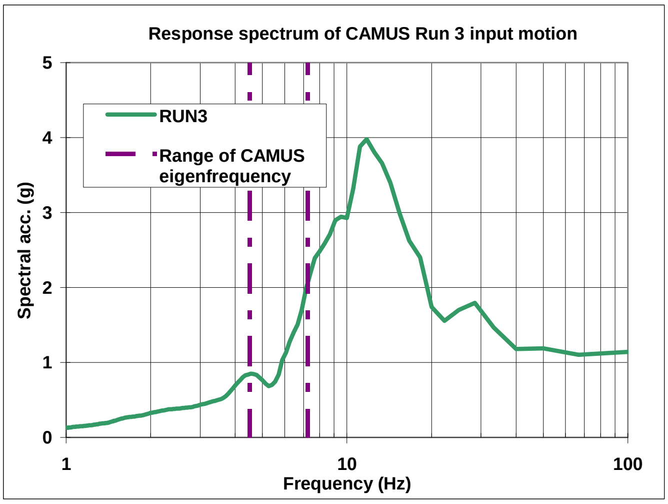

Figure 2. Run 3 input response spectrum Representative of the high frequency content of the input motions considered in the IAEA CRP

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

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

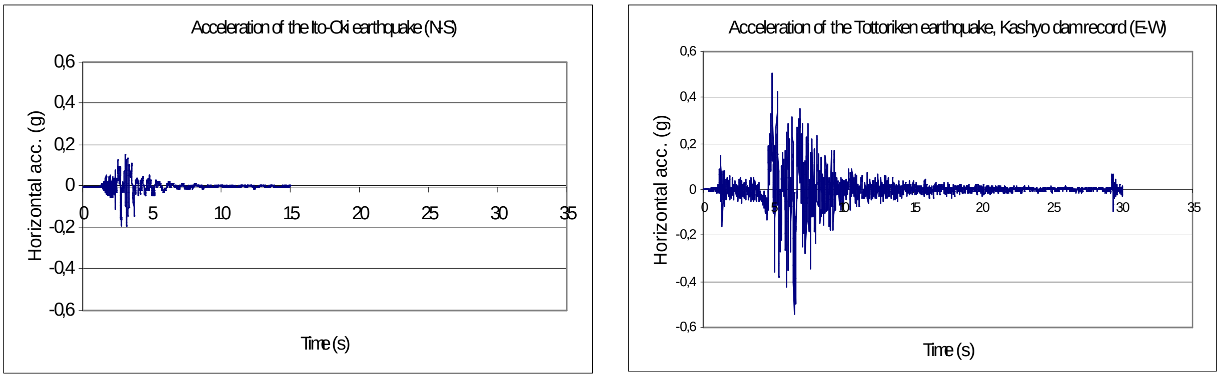

Figure 3. The two Japanese input motions, plotted at the same scale

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. Compared 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 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.

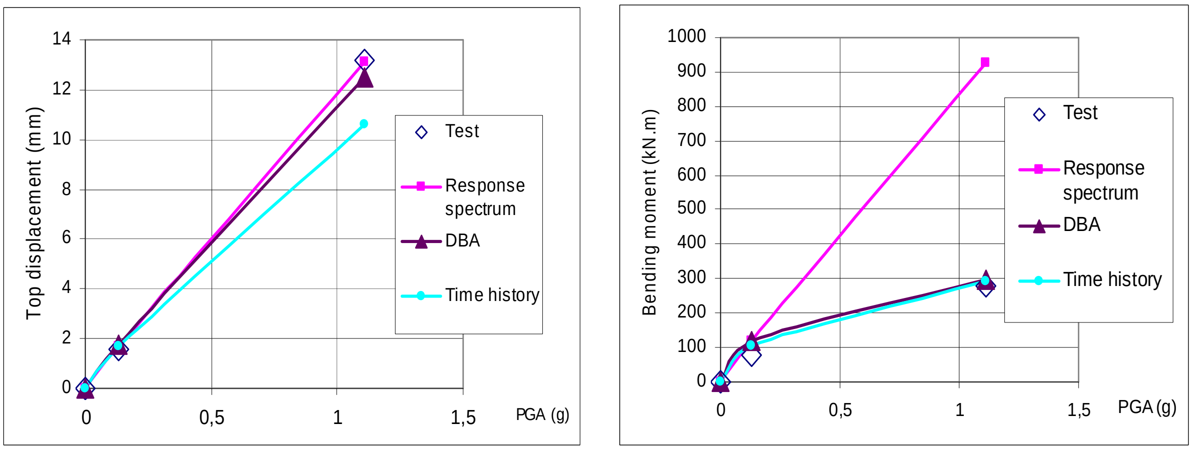

Figure 5. Comparison of Runs 2 and 3 outputs: Top displacement (left) and level 1 bending moment (right).

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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.

- **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.

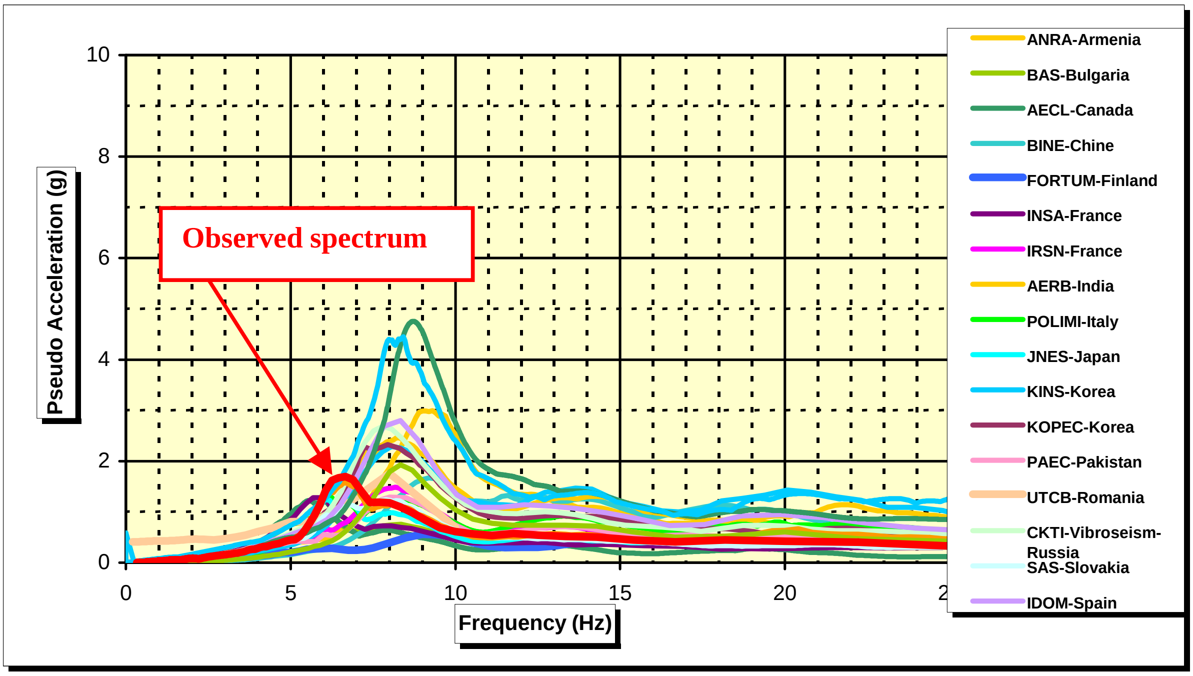

Figure 6. Top response spectrum (5% damping) for Run 2.

5. ANALYSIS OF THE BENCHMARK OUTPUTS

On the basis of the conventional reinforced concrete (RC) approach, the {level-1 moment / curvature} relationship was established and compared to the average relationship established by the Participants. An excellent consistency was achieved. Concurrently, every time-history analysis results in a set of {top displacement / level-1 bending moment} couples (one per Participant). The {mean top displacement / mean level-1 bending moment} couples are plotted in Fig. 7 (left). On this basis, an output of the analyses carried pout by the authors is the following: assuming that the conventional limit state corresponds to a 1% strain in R-bars, then the CAMUS wall conventional limit state is characterized by a 396 kN.m level-1 bending moment and a 27 mm top displacement.

In numerous countries, the nuclear industry practice consists of i) assuming that structural response is linear and governed by the initial stiffness of the virgin structure, ii) computing this response according to the conventional response spectrum method, and iii) verifying that internal forces and moments do not exceed conventional limit values. On the Fig. 7 (right), the straight line from the origin to the triangle mark (abscissa 6.25 mm) illustrates this practice. On the same figure, the doted line from the triangle mark to the square mark represents the ductile capacity of the structure, which is disregarded by the nuclear industry practice. In the case of the CAMUS specimen, this ductile capacity is equal to 27 / 6.25 = 4.3.

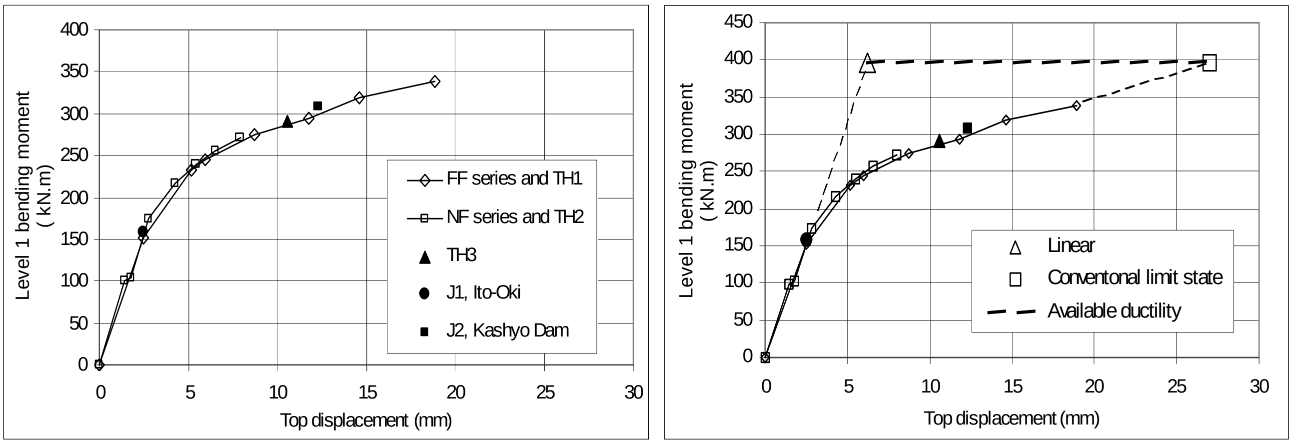

Figure 7.. Push over curve resulting from time history analyses carried out by the Participants (left); ductility of the CAMUS specimen consistent with the conventional limit state (right).

For a given input signal, the conventional limit PGA is defined as the PGA scaling value for which the specimen would reach its limit state. According to the above-mentioned nuclear practice, the conventional limit PGA corresponds to the triangle mark in the Fig. 7 (right) while the best estimate conventional limit PGA corresponds to the square mark. Calculations of these PGA values are detailed in an IAEA document in preparation *(IAEA 2009)* and are summarized in the table 4, as well as the corresponding margin of the nuclear industry practice.

Table 4. Conventional PGAs and associated margins for the Run 1 and Run 2 inputs

Input type	Run 1	Run 2
PGA 1: Response spectrum approach (nuclear industry practice)	0.27 g	0.45 g
PGA 2: Best estimate based on time history analysis	0.86 g	2.03 g
PGA 3: Best estimate based on experimental outputs	0.93 g	2.28 g
Margin = ((PGA 2 + PGA 3) / 2) / PGA 1	3.3	4.8

Authors draw the attention to the fact that margins identified in the table 4 are of the same order as the ductility of the specimen. This is relating to the fact that, due to their frequency content, both Run 1 and Run 2 input motions should be regarded as displacement controlled loads and not as force controlled loads. It is clear that the identified margin is not available with those seismic input motion that should be regarded as of the force-controlled type. For a given structure, a seismic input motion should be regarded as a displacement controlled load when its frequency content is higher than the first (or dominant) frequency of the structure, and it should be regarded as a force controlled load in the opposite case.

6. CONCLUSIONS

6.1. 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 this is very low in spite of their possible high PGAs), but rather 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 the actual damaging capacity of this type of input motion.

The poor capability of this indicator is linked to the fact that seismic input motions are conventionally regarded as force controlled loads (or primary loads in mechanical engineering terminology). However, it is well known that high frequency input motions (with respect to the structure frequency) act principally as displacement controlled loads (or secondary loads in mechanical engineering terminology) *(IAEA 2003).* Consequently, this overestimate resulted from ignoring the favourable combination of the high frequency content of this type of input motion and the ductile capacity of structures. This high frequency content was first identified as generated by NFEs, but the NFE origin is not really pertinent to this analysis. What is pertinent is the frequency content, irrespective of the so called far- or near-field origin.

The conventional nuclear approach should be amended, at least, when dealing with this type of input motion, especially when evaluating existing facilities, to avoid unduly overestimating their damaging capacity, such as illustrated by the CRP outputs. It is expected that a reasonable evolution of nuclear power plant engineering practices (also desirable for other reasons) will eliminate this artificial issue

6.2. On challenges to nuclear industry practice

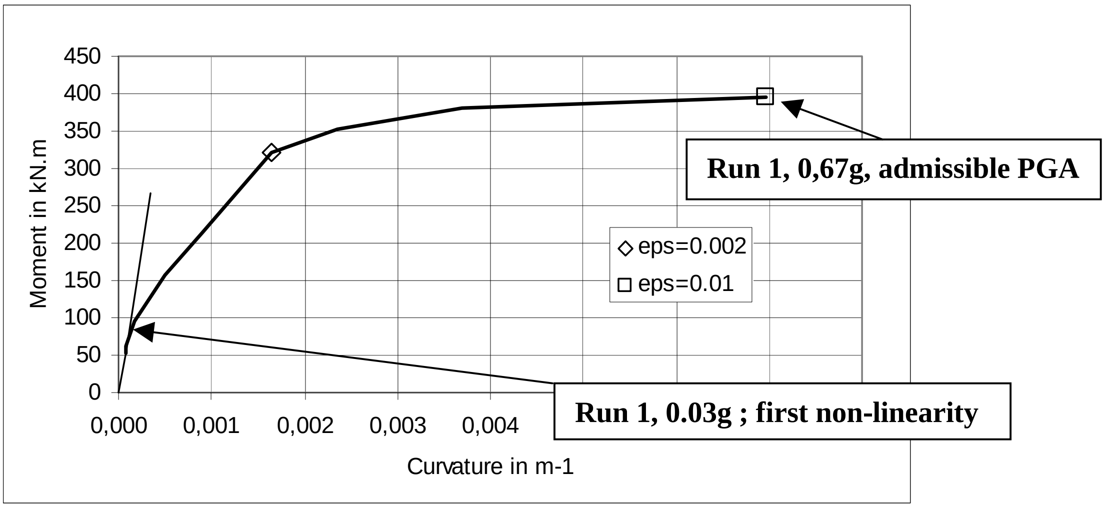

Figure 8. Illustration that non-linear effects might appear for very low PGAs (CAMUS Run 1).

There is a lack of consistency in the conventional nuclear industry approach such as implemented in numerous countries, due to the concurrent following practices and/or requirements: i) Structural responses are calculated on a linear behaviour assumption and ii) Acceptance criteria stipulate that forces and moments should not exceed those corresponding to the conventional limit state. The point is that the second statement does not imply that the structural response is actually linear. On the contrary, significant non-linear effects appear for low PGAs, as exemplified on the Fig. 8 on the basis of the CRP Run 1. Therefore, any concrete structure should be recognized as exhibiting non-linear behaviour under seismic input motion.

To a certain extent, the RC response is similar to the soil response; that is, small non-linear effects appear for low level inputs. Geotechnical engineers and scientists have developed engineering practices (linearisation) that account for this phenomenon and are currently used in engineering, including by the nuclear industry. This is not yet the case for engineers dealing with concrete structures.

Reasonably realistic floor response spectra cannot be computed without accounting for small non-linearity effects. Depending on the circumstances, neglecting these effects may lead either to undue margins or to a lack of margins in the generated floor response spectra. Therefore, an evolution of nuclear power plant engineering practice is highly desirable.

In this regard, it is recommended by the IAEA that the nuclear industry pursues its evolution towards dynamic modelling techniques that match structural behaviour; some countries go in this direction *(ASCE 2005, ASN 2006)*. In particular, it is recommended that small non-linearity be considered in the models and that the nuclear industry work towards a more systematic and codified use of simple non-linear structural analysis, such as linearization techniques, both for design of new facilities and evaluation of existing ones.

Acknowledgements. All the Participants to the IAEA-JRC CRP are kindly acknowledged for their three year effort and contribution to this common research work. Didier Combescure (CEA) is acknowledge for having carefully prepared and provided CAMUS experimental data. Members of the organizing committee other than the authors, namely Antonio Godoy, Polat Gülkan, Yoshio Kitada, Andrew Murphy, Vito Renda , Pierre Sollogoub, are sincerely acknowledged for their advises and support in the conduct of the CRP. A special thought is dedicated to Yoshio Kitada, who passed away in January 2009. He played a major role in the Japanese contribution to the CRP, explaining Japanese practices and reporting on Japanese feedback of experience for the benefit of the Participants, selecting input motions for the CRP Step 2 and leading the Japanese contribution to the benchmark exercise.

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