3rd EUROPEAN CONFERENCE ON
EARTHQUAKE ENGINEERING & SEISMOLOGY
BUCHAREST, ROMANIA, 2022

A comparison of three scalar intensity measures for non-structural component assessment of nuclear powerplants

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Abstract: Three candidate intensity measures are compared in terms of efficiency and sufficiency for assessing the non-structural performance of nuclear powerplant components. These are the peak ground acceleration, the spectral acceleration at the fundamental period of the structure, and the average spectral acceleration in the range of short periods. To do so, single-degree-of-freedom non-structural components of different periods and capacities are considered at different locations within an AP 1000 reactor model. Incremental dynamic analysis is performed for a set of 30 records. The spectral floor accelerations of each SDOF component are monitored and capacity exceedances are recorded to assess the lognormal parameters of component fragility curves. The numerical results demonstrate that average spectral acceleration would be the most useful intensity measure in both efficiency and sufficiency, regardless of location, period or capacity, with the obvious exception of the ground surface. Nevertheless, the conventional choice of the peak ground acceleration remains a very close contender, as it leads to results of low dispersion and little bias for such stiff structures and short-period components.

Keywords: seismic intensity, fragility assessment, peak ground acceleration, average acceleration

1. Introduction

The seismic fragility evaluation of non-structural components is a critical step in the seismic risk assessment of nuclear powerplants (Zentner et al. 2011). Fragility curves express the conditional probability of failure for a given intensity measure (IM), while failure probabilities of components are used in fault trees to estimate the overall probability of failure of a Nuclear Powerplant (NPP). As a result, the more reliable the evaluation of seismic fragilities, the more accurate the overall estimated risk becomes.

One of the main challenges of fragility analysis is the selection of an appropriate ground motion intensity level (IM). By an appropriate IM choice, the uncertainty due to seismic hazard can be significantly reduced. According to Luco and Cornell (2007) or Kazantzi and Vamvatsikos (2015) a good IM should be efficient, sufficient and practical. Practicality refers to the existence of corresponding Ground Motion Prediction Equations (GMPEs) for the IM. Ordinarily, one would consider the existence of one GMPE to be enough, but in real life case studies, several are required to build a proper logic tree for handling uncertainties in probabilistic seismic hazard analysis. Efficiency provides low dispersion in the conditional distribution of the Engineering Demand Parameter (EDP) selected to measure the response given the IM. Finally, an IM is sufficient when the distribution of EDPs conditioned on the IM is independent of other ground motion properties such as the magnitude of the earthquake, the distance from the site, etc.

While several studies have appeared in the literature concerning the suitability of different IMs (De Biasio et al, 2015; Kazantzi and Vamvatsikos, 2015; Kohrangi et al, 2016b), they almost universally concern ordinary structures of moderate to long periods with some nonlinearity in their response. NPPs are in a category of their own, having purely linearly elastic behaviour and truly short periods, as well as a long history of using Peak Ground Acceleration (PGA) as the one and only IM. Our primary objective is to use contemporary tools to evaluate the performance of PGA and compare it against competing upstarts by performing a parametric seismic fragility analysis of the components of a nuclear powerplant.

Three candidate scalar IMs are considered. The first is obviously the old faithful of PGA, this being the primary option of the nuclear industry (Zentner et al, 2011). Also, spectral acceleration at the fundamental period of the structure, Sa(T_1), is examined as it is considered a good index for first-mode-dominated linear or nonlinear structures and acceleration-sensitive components (above the ground floor). Finally, the average spectral acceleration (AvgSa) in a range of short periods is the upcoming contender as different variants of it have been shown to offer good performance for a multitude of structures (Vamvatsikos and Cornell, 2005; Bojórquez and Iervolino, 2011; Eads et al, 2015; Kazantzi and Vamvatsikos, 2015; Kohrangi et al, 2016a; Adam et al, 2017). There is no question that practicality is ensured for these IMs, even for AvgSa that due to its unique form leverages all GMPEs available for Sa(T_1). What remains is to discern whether they also efficient and sufficient enough to be reliably used for the seismic safety evaluation of a nuclear powerplant according to modern concepts.

2. Case study: Stick model of an NPP

The nuclear powerplant under study is a stick model of the main containment/auxiliary building based on the AP 1000 advanced reactor design. It consists of three concentric sticks (Fig.1), representing the Coupled Auxiliary and Shield Building (ASB), the Steel Containment Vessel (SCV) and the Containment Internal Structure (CIS). The modelling data are taken from EPRI (2007).

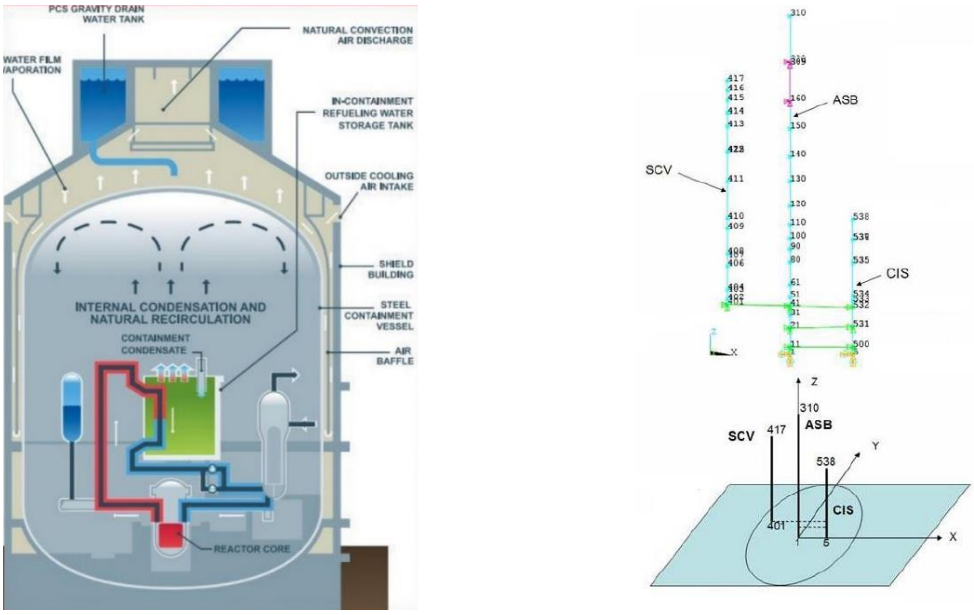


Fig. 1 – Original reactor design (left) and simple stick model (right) per EPRI (2007)

The structure is modelled using the open-source structural analysis program OpenSees (OpenSees 2006). In the first step, a modal analysis was performed. The first mode period is equal to 0.26s, while subsequent ones range from 0.19s and downwards. Incremental Dynamic Analysis (IDA, Vamvatsikos and Cornell 2002) was performed using a suite of 30 two-component ground motion records, selected to be consistent with the seismic hazard of a hypothetical site in Southern Europe.

Per current loss assessment standards (e.g. FEMA P-58) structural, non-structural components and contents located in a structure are sensitive to different engineering demand parameters (EDPs), typically either interstory drift or peak floor acceleration (PFA) response. Typical examples of acceleration-sensitive non-structural components are piping systems and (un)anchored equipment (D'Angela et al, 2021). Their assessment for ordinary buildings involves the analysis of the supporting structure, the determination of the distribution of PFA, and the assessment of fragility given said EDP. In other words, their fragilities are expressed in terms of the EDP rather than the IM.

On the contrary, for the evaluation of NPPs, non-structural component fragilities are usually directly expressed in terms of the IM rather than the EDP. By virtue of being an extremely stiff structure akin to a monolith, an NPP is implicitly considered to transmit PGA nearly unchanged to the different levels within the structure. Were our forefathers right in this assertion? Can indeed PGA be the one and only IM that one needs to consider in lieu of the elaborate IM-to-EDP dance that modern guidelines prefer? To answer these questions, we will assess the fragility of (fictitious) anchored components that are located at different levels of the three NPP sub-structures (ASB, CIS or SCV). Focusing on the suitability of the different IMs for this purpose, we will also be looking for discrepancies in discarding the "classic" use of an EDP for non-structural component assessment.

3 Fragility curves

The total variability of a component is characterized by the different response, exhibited by the same component under different records and different-capacity versions of the component under the same record; in other words, record-to-record variability and the variability of the capacity, respectively. Deterministic capacities of acceleration-sensitive non-structural components do not consider the main features of the components, including geometry, boundary conditions, dynamic properties and supporting system (ground or structure supported). Herein component capacity is assumed to be deterministic, set at fixed values of 1.0g, 2.0g or 3.0g, in order to clearly see the effect of the record-to-record component.

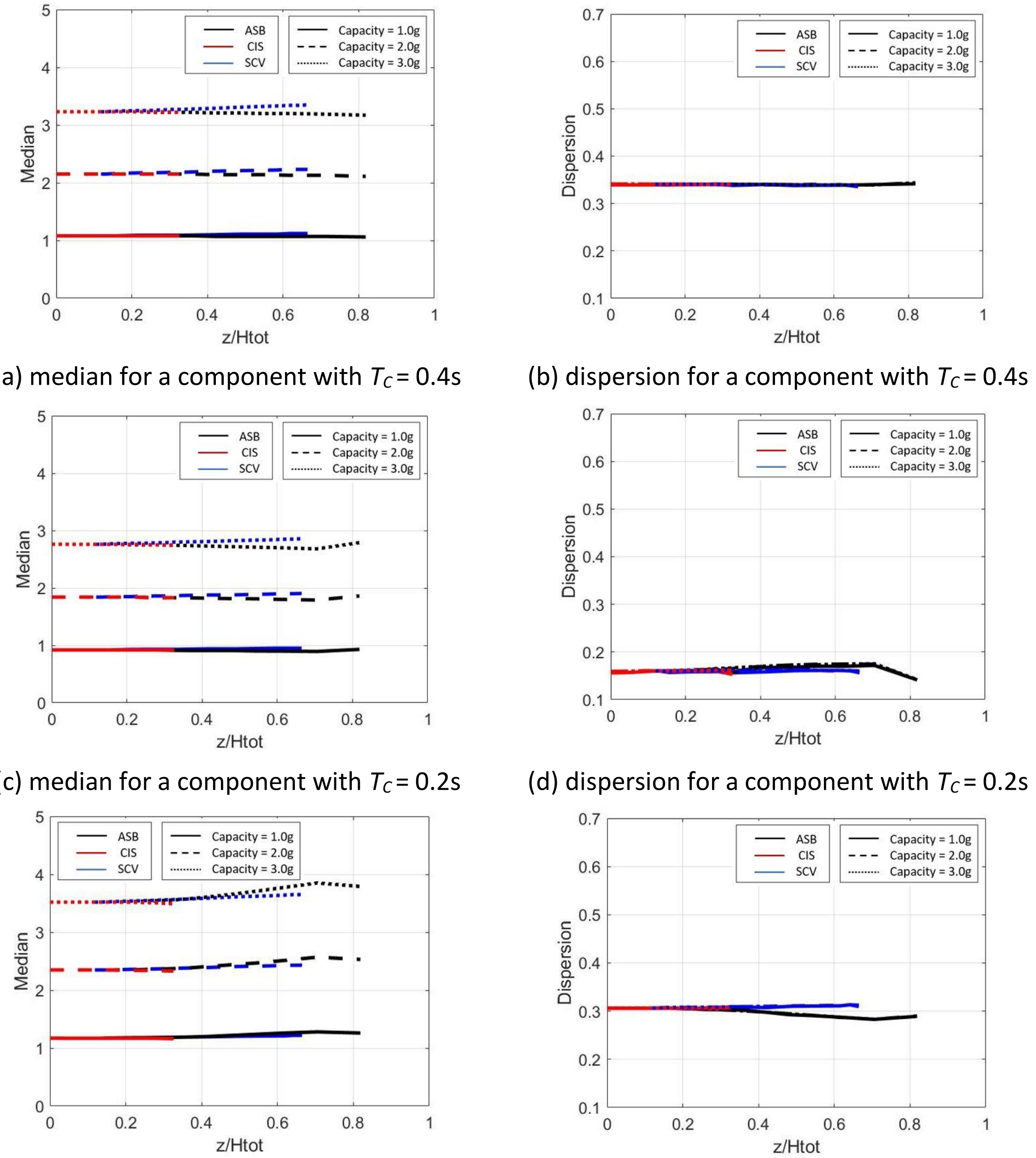
Let us consider a component $C_{Fj}(T_c)$ located at the k-th level of building j, simulated as an SDOF of period T_c. Its seismic demand, $a_{i,j}(T_c)$, is defined as the spectral acceleration of the floor motion spectrum caused by record i at the component's period T_c. It should be noted that each floor motion has two orthogonal components; herein, $a_{i,j}(T_c)$ is calculated as the geometric mean of the two corresponding spectral values. The fragility function utilized to calculate the probability of component $C_{Fj}(T_c)$ to fail for a given $a_{i,j}(T_c)$ value is described by the following function:

$$P\left(a_{i,j}(T_c) \geq C\right) = \Phi\left[\frac{1}{\beta}\ln\left(\frac{a_{i,j}(T_c)}{C}\right)\right] \tag{1}$$

The variable C denotes the (deterministic) capacity of the component. $\Phi(\cdot)$ is the standard normal cumulative distribution function, while β corresponds to the total dispersion, herein equal to the record-to-record dispersion in demand.

4. Analysis results and discussion

The results of fragility curves of non-structural components for three different periods are presented; due to absence of more specific data for nuclear powerplants, the encountered periods are 0.4s, 0.2s and 0.1s. The procedure is conducted for all possible locations of the components along the height of the structure and among the sub-structures ASB, SCV and CIS (Fig.1).



(a) median for a component with $T_C = 0.4$s (b) dispersion for a component with $T_C = 0.4$s

(c) median for a component with $T_C = 0.2$s (d) dispersion for a component with $T_C = 0.2$s

(e) median for a component with $T_C = 0.1$s (f) dispersion for a component with $T_C = 0.1$s

Fig. 2 – Median and dispersion of fragility curves conditioned on AvgSa(0.1s – 0.4s)

Fig. 2 illustrates the distribution of median and dispersion values of component lognormal fragility curves along the height. The intensity measure used in this case is AvgSa(0.1s-0.4s). Figs 2a-b correspond to a component of 0.4s period, Figs 2c-d to a component of 0.2s period and Figs 2e-2f to 0.1s. It can be seen that the fragility of each component is independent of its location on the structure, due to the fact that NPPs are extremely stiff; as expected, the higher the capacity, the higher the median values of the fragility curves are. As for the dispersion, the results are really close for all the locations of the components.

The same procedure is carried out for the structural fragility of non-structural components conditioned on Sa(0.26s) and PGA. The median values for these two IMs show similar behaviour as observed with AvgSa(0.1s-0.4s) in Figs 2a, c and e. Overall, it is concluded that dispersion is independent of the location (sub-structure or height) and the capacity of the components. Still, it will depend on the IM. Actually, the dispersion is what is used to indicate the efficiency of an IM; the lower the dispersion of an IM, the higher the efficiency becomes, or in other words the fewer records one needs to assess the response or the fragility. To aggregate the effect of even the smallest of differences, the comparison of the IMs is based on the average of the fragility dispersion values over height and component capacity, illustrated in Fig. 3. Apparently, AvgSa(0.1s-0.4s) is the most efficient IM regardless of the period of the component; on the other end, Sa(T_1) is the worst, while PGA is somewhat in-between the two, closely matching AvgSa(0.1s-0.4s) for short component periods, and getting closer to Sa(T_1) for longer ones. Still, in absolute terms, the differences are not overwhelming: the lowest dispersion is ~0.15, recorded for AvgSa(0.1s-0.4s) and $T_c = 0.2$s, i.e., for components close to the structure's fundamental period. The largest is ~0.35 for AvgSa(0.1s-0.4s), but up to 0.45 and 0.50 for Sa(T_1) and PGA, respectively.

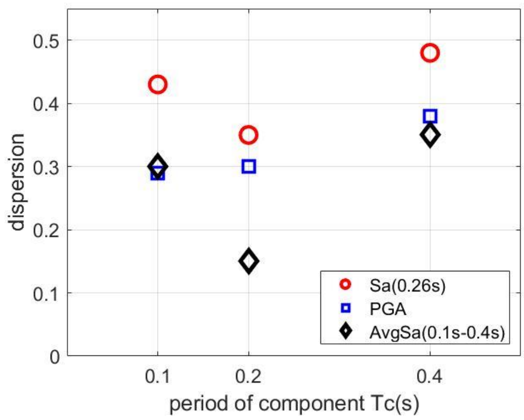
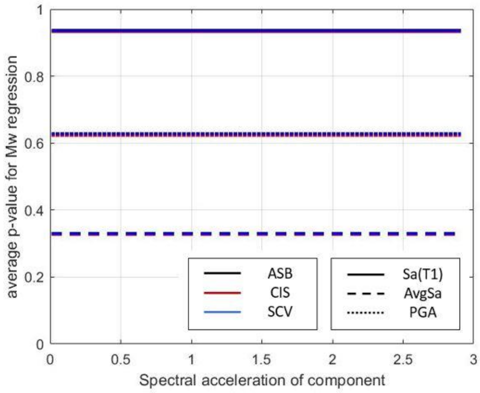


Fig. 3 – Dispersion distribution over component period's range

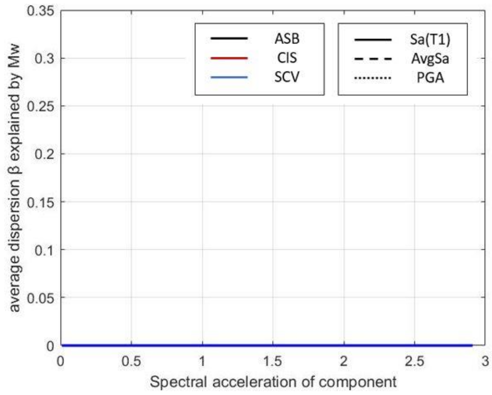
Next, the sufficiency of the considered IMs is tested against the moment magnitude M_w of the records, this being traditionally a stricter test than, e.g., against distance. A linear regression analysis between IM|EDP, or the IM for a given value of the EDP, and M_w is performed as follows:

$$\text{IM}|\text{EDP} = a + b \cdot M_w \tag{2}$$

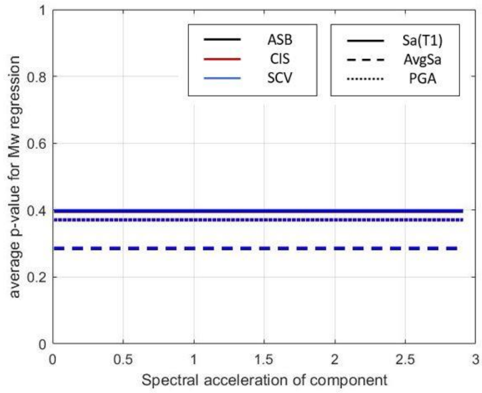
The average p-value and the average dispersion β explained by M_w, along the height of sub-structures ASB, CIS or SCV, are used as metrics to evaluate the sufficiency of the IMs against M_w. The p-value quantifies the statistical significance of the regression coefficient b on M_w; a low p-value, conventionally taken as $p < 0.05$, indicates that the regression coefficient b is statistically significant and implies that the considered IM is not sufficient. Figs 5a, c and e illustrate the p-values for the component response of each sub-structure. First of all, in all cases the components' location does not influence the outcomes. In addition, all tested IMs, especially Sa(0.26s), are considered quite sufficient for components of 0.4s period, although as the period of the component becomes lower, they all become less sufficient.



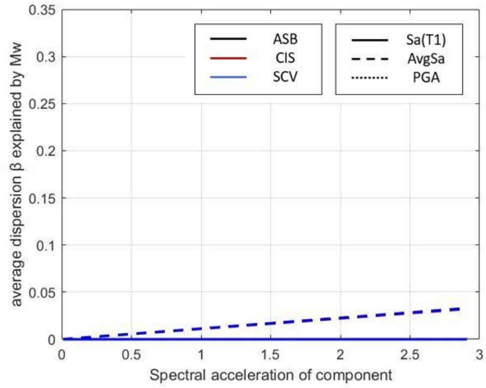
(a) average p-value for IM given $a_j(T_C = 0.4s)$



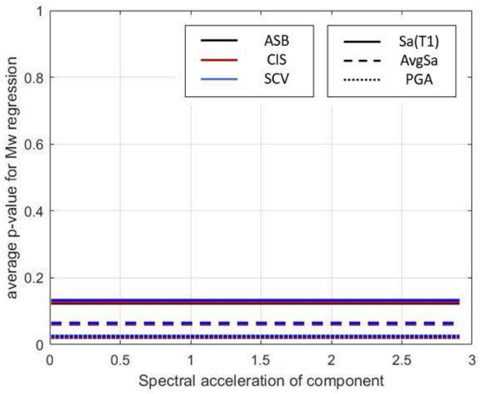
(b) average dispersion β explained by M_w for IM given $a_j(T_C = 0.4s)$



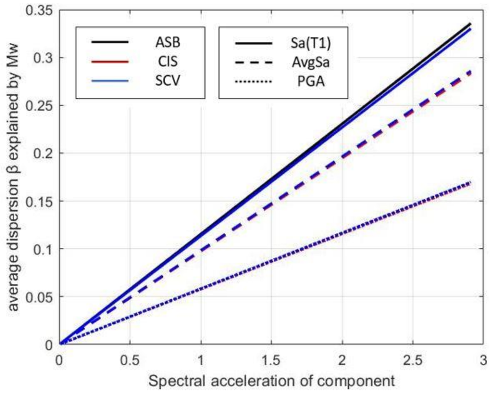
(c) average p-value for IM given $a_j(T_C = 0.2s)$



(d) average dispersion β explained by M_w for IM given $a_j(T_C = 0.2s)$



(e) average p-value for IM given $a_j(T_C = 0.1s)$



(f) average dispersion β explained by M_w for IM given $a_j(T_C = 0.1s)$

Fig. 4 – Statistical metrics for testing the sufficiency of the IMs against M_w for components of different periods and different locations in the sub-structures. In all cases, the location hardly matters.

The p-value should be considered in conjunction with the dispersion β explained by M_w. For "long"-period components ($T_C \geq 0.2$s) the average dispersion β explained by M_w has practically zero values (Figs 4 a-b), this means that M_w does not have any capability of explaining the dispersion of the tested IMs; as a result, they are considered sufficient. On the other hand, for ultra-short-period components ($T_C = 0.1$s), a non-negligible part of the dispersion of Sa(T_1) and AvgSa(0.1s-0.4s) can be explained by M_w; this is somewhat lower for PGA which is the most sufficient IM for these components.

5. Conclusions

The effect of IM selection on the fragility curves have been presented for a number of idealized components of an NPP. Their damage assessment was performed by characterizing the influence of several features: (a) different locations of components in the powerplant, (b) the period of the component, (c) the capacity of the component, and (d) intensity measures (IMs).

First of all, due to the high stiffness of the structure, the same demand is recorded for the anchored components regardless of their location. Thus, employing fragility curves parameterized on the ground intensity measure, rather than the floor acceleration is an acceptable if not highly accurate assumption. Among the tested IMs, AvgSa(0.1s-0.4s) shows the lowest dispersion for all the examined components and as a result the highest efficiency. Furthermore, all IMs are sufficient against the moment magnitude M_w for the specific stick model, with PGA being more appropriate for short period components. Combining all information, AvgSa(0.1s-0.4s) shows in general the best performance. Nevertheless, the efficiency and sufficiency of PGA is not far off, leaving this conventional choice as a viable candidate for NPP assessment.

Acknowledgements

This research has been financed by the European Commission through the Program "METIS – Methods and tools innovations for seismic risk assessment" with Grant Agreement number: 945121 (HORIZON 2020).

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