13th International Conference on Applications of Statistics and Probability in Civil Engineering, ICASP13
Seoul, South Korea, May 26-30, 2019

Issues in Harmonization of Seismic Performance via Risk Targeted Spectra

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ABSTRACT: Current seismic design code provisions are mainly based on checking structural performance at a single seismic intensity associated with a pre-defined return period. For instance, in EN1998, a ground motion with 10% probability of exceedance in 50 years is used for design. This design procedure, with the inclusion of partial safety factors, is assumed to provide sufficient safety margin against earthquakes for newly designed buildings. Nevertheless, it does not specifically determine the expected seismic risk related to any performance level or limit state. Therefore, it may result in non-uniform risk for buildings located in different sites within a region (or country), even for places with identical design intensities. Instead, ASCE 7-10 incorporates Risk Targeted design maps that suggest the application of suitable spectra adjustment factors, in order to ensure a reasonably low uniform collapse risk. Making use of simplified single degree of freedom structures defined in several configurations of period and ductility, our aim is to test the effectiveness of the adjustment factors computed under different assumptions. It is shown that, although matching is not practically possible, harmonization remains a viable target, offering insights for possible future adoption of Risk Targeted Spectra in forthcoming seismic codes.

1. INTRODUCTION

Seismic design provisions are invariably based on a single ground motion intensity measure (IM) value associated with a constant seismic hazard level. For example, this would be the peak ground acceleration (PGA) at a 475 year return period for EN1998 (CEN 2005). Then every structural performance level, e.g., Damage Limitation or Life Safety, is checked using intensities associated to this predefined hazard. For instance, in EN1998, a ground motion with 10% probability of exceedance in 50 years is used for verification of the Life Safety limit state. This design procedure, which includes partial safety factors that increase actions and decrease material resistances, is assumed to provide a sufficient safety margin against loss of life due to earthquakes for newly designed buildings. Still, it does not determine the expected seismic risk related to any limit state. This approach, therefore, results in non-uniform risk for buildings located at different sites having identical values of ground motion design intensity.

The reason behind this discrepancy can be best explained by considering the approximate formula of Cornell et al. (2002) for determining the MAF, λ_{LS}, of exceeding (or violating) a limit-state LS:

$$\lambda_{LS} \approx H(IM_{c50\%}) \exp\left(0.5k^2\beta^2\right) \qquad (1)$$

$IM_{c50\%}$ and β are the median and dispersion (standard deviation of the log) of the system fragility function for LS. $H(\cdot)$ is the site hazard function for the IM, locally approximated via a straight line of slope k in logarithmic coordinates, $H(IM) \approx k_0 \cdot IM^{-k}$ (Figure 1). Eq. (1) clearly states that the slope of the hazard and the dispersion of the capacity introduce an amplification factor that increases the MAF of the LS vis-à-vis the MAF of $IM_{c50\%}$.

Arguably the most comprehensive approach to tackle this issue is to introduce risk at the output level of the response, rather than at the input level of (design) spectral acceleration. This means designing for λ_{LS}, rather than $H(IM)$. This is performance-based design, and it requires a paradigm shift. Still with this objective in mind, Luco et al. (2007) proposed instead staying within the confines of current design practice by modifying the input design spectral acceleration to a 'risk-targeted' (RT) value that indirectly accounts for the effects of hazard and fragility. This entails modifying the seismic design maps of the ASCE 7-10 (ASCE 2010) provisions by means of Spectrum Adjustment Factors (SAFs) to target a uniform mean annual frequency (MAF) of collapse. These maps are derived for spectral acceleration (S_a) at two periods, namely 0.2s and 1.0s, that are the primary inputs needed to build the ASCE 7-10 design spectrum. The adjustment factors result from a risk analysis involving the definition of a *generic* collapse fragility curve. Keeping constant its assumed variability, the generic fragility curve is shifted, by means of adjusting the S_a at 10% collapse probability, until it produces the target MAF; the ratio between the "shifted" S_a and the original one defines the SAF for the given period. In line with this idea, Douglas et al. (2013) and Silva et al. (2016) proposed the adoption of risk targeted maps for Europe by adjusting PGA, which is the single intensity parameter required to define EN1998 design spectra, to deliver the required risk performance.

All such reincarnations of RT spectra invariably accept a compromise between simplicity and accuracy, by virtue of defining a single design spectrum at each site, and employing a 'structure-agnostic' generic fragility function to describe the behavior of all structures of similar period. Selecting the fragility function, the IM, the LS and the associated risk value to target, a wealth of options becomes available, each producing different output RT spectra. To understand the implications of such options for design, we shall discuss the elements required to define and apply RT-spectra and investigate the effect of different associated options for a potential EN1998 application.

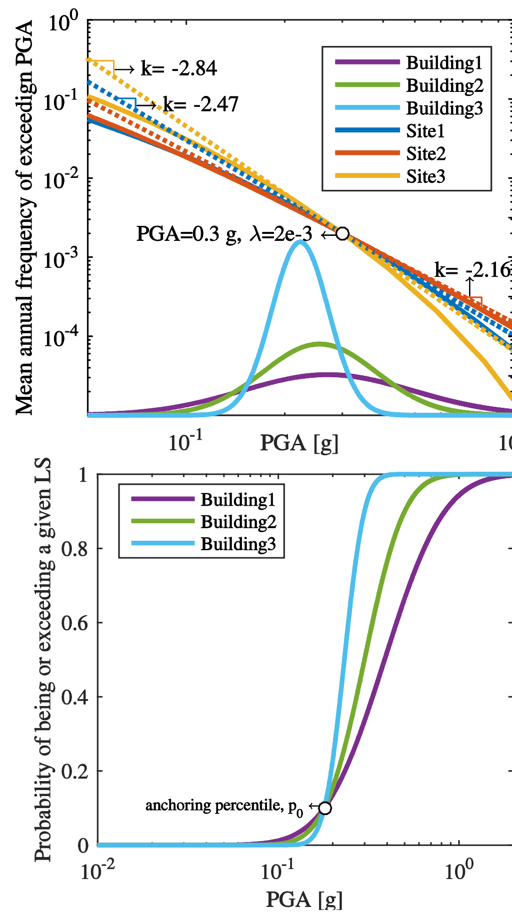

Figure 1: (top) Hazard curves for three sites having the same design PGA at 10% in 50 years but different slope, and (bottom) three different fragility curves to be employed for risk harmonization, each representing a different weighting of the importance of the shape/slope of the hazard curve.

2. RISK-TARGETED SPECTRA ELEMENTS

2.1. Fragility function

The first element in RT spectra application is the definition of the fragility function(s) that describe the performance of the building stock. It is well known that actual fragility curves are building specific, meaning that they are dependent on the structural type, the ductility characteristics and natural period of the structure. In addition, recently they have been shown to also be site dependent, i.e. the building response statistics are a function of the seismological characteristics of the site of interest (see Kohrangi et al. 2017). Nevertheless, the application of site and building specific fragility curves to derive design maps would be too complex and computationally expensive. Therefore, the currently preferred approach is to adopt a generic fragility curve definition for all building types and all sites within the region of interest and to modify it by shifting its central value (or median IM capacity) to reflect the difference in design intensities from site to site

Such generic curves, which are typically derived assuming a lognormally distributed IM capacity, are broadly defined by four parameters: (a) The IM type, (b) an anchor "acceptable" probability of limit-state (typically collapse) exceedance, p_0, at (c) a value of the selected IM with an anchor MAF value, λ_0, which is typically chosen to be the one corresponding to the hazard level of the uniform hazard design spectrum, and (d) the uncertainty in the limit-state capacity, represented by the dispersion, β. For instance, Luco et al. (2007) used a generic fragility function based on $S_a(T)$ at a given fundamental period T, anchored at collapse probability of $p_0 = 0.1$ for an IM value with MAF of 2% in 50 years, and a capacity dispersion of $\beta = 0.6$–0.8. Douglas et al. (2013), aiming at a EN1998 application, anchored the fragility curve at a much lower collapse probability $p_0 = 10^{-5}$ in correspondence to a more frequent PGA associated to 10% of exceedance in 50 years, characterized by a less uncertain capacity described by $\beta = 0.5$. More recently, Silva et al. (2016) while generating risk-targeted maps for Europe, investigated the impact of different combinations of generic fragility curve parameters, showing large variations in the SAFs by even minor alteration of these parameters. They employed PGA as the IM, with p_0 ranging from 10^{-2} to 10^{-5}, at λ_0 of 10% in 50 years, with a dispersion of $\beta = 0.5$–0.7. For the same λ_0, the Implicit Risk Project (Iervolino et al. 2018), which examined EN1998 buildings designed for Italy, suggests $p_0 < 0.005$ for collapse and $0.1 < p_0 < 0.2$ for onset of damage in reinforced-concrete frame buildings. A summary of such characteristics appears in Table 1.

The choice of the IM in the aforementioned cases is dictated by the characteristics of the design spectrum implemented in the code of reference. However, sufficiency of the IM, i.e., independence of the response conditioned on the IM from other ground motion characteristics, is required for accurate risk assessment. PGA is not a sufficient IM for predicting the response of any but the shortest period buildings. Building-specific IMs, such as the spectral acceleration at the first mode of vibration of the building, $S_a(T_1)$, or, better, the more advanced average spectral acceleration, *AvgSA*, considerably reduce bias (Kazantzi and Vamvatsikos 2005). Hence, selecting a suitable IM for a risk-targeted approach that works for most if not all buildings may not be straightforward.

The generic fragility curve can be considered as a mechanism for weighting the effect of the hazard curve shape (or its local slope) when estimating the targeted risk. The anchor p_0 and MAF values determine the central point, $IM_{c50\%}$, of the fragility curve and, essentially, identify what part of the hazard curve one wants to emphasize in the risk computation. The dispersion, β, selects how broad or narrow the area of the hazard curve accounted for in the risk calculations will be. Figure 1 presents an example of the PGA hazard curves from three different sites, all having the same intensity value at the 10% in 50yrs level, but different shapes, here characterized by the tangent slope.

According to Eq. (1), each site will yield a different MAF for any of the three fragility curves shown. We can choose to harmonize the risk estimated at each site for any given fragility curve by appropriately shifting up or down the 10% in 50yrs value used for design. If $\beta = 0$, then the hazard shape (or slope) becomes irrelevant and no adjustment shall take place. Then the collapse is certain for that IM value and the risk is coincident with the hazard. The larger the β value, the stronger the emphasis on the hazard curve shape (or the steepness of its slope), which translates into larger adjustments in terms of the SAF to match a target risk.

2.2. Performance objective.

The targeted performance objective is a limit state (LS), such as global collapse or life safety, coupled with a target MAF of exceedance, λ_{tgt}. Many past earthquakes, however, have shown that in modern societies buildings designed only by limiting the chance of collapse without consideration to their operability after more frequent ground motions are neither a desirable nor a sustainable option. The original proposals for RT spectra were mainly devised for design of new structures by still focusing on the collapse limit state. Nevertheless, current codes include also provisions to control damage to structures for relatively low ground motion intensities. Less severe LSs, such as those connected to the onset of damage, are much more influential if we are dealing with loss estimations rather than collapse performance. The choice of the LS to be targeted also influences the anchoring percentile, p_0, to be employed on the fragility curve, as it should correspond to the probability of exceeding the selected LS given the occurrence of a design code intensity anchored at a specified MAF.

2.3. Design spectrum shape

The design spectrum shape and its flexibility is the degree to which one can alter the shape of code-spectra at different periods to achieve the target risk. Seismic design codes typically provide a design spectrum whose intensity is defined by anchoring it to one or two spectral ordinates extracted from hazard maps (i.e., defined either by seismic zonation maps or a web-based tool), while its shape is adjusted by the soil type, vicinity to the faults, etc. For instance, EN1998 uses PGA as anchoring point, while ASCE 7-10 employs two spectral ordinates at 0.2 s and 1.0 s. Obviously, the rigidity of the spectrum shape curtails the capability of an RT-spectra approach to harmonize risk across structures with different fundamental periods located at any given site.

For simplicity here we shall categorize the different design spectra based on the number of spectral ordinates that are employed for their parameterization. A *flexible* shape is the ideal case where any spectral ordinate can be individually adjusted for a particular site. This may make for a highly discontinuous shape, thus some flexible non-parametric function can be fitted to restore continuity. Instead, a *semi-flexible* shape, based on the ASCE 7-10, is characterized by two anchor points, typically $S_{ds} = S_a(0.2s)$, and $S_{d1} = S_a(1.0s)$. The first ordinate defines the start and height of the horizontal plateau while the second anchors the constant velocity part. Finally, the *rigid* shape of an EN1998-type spectrum is defined by a single pivot point, the PGA.

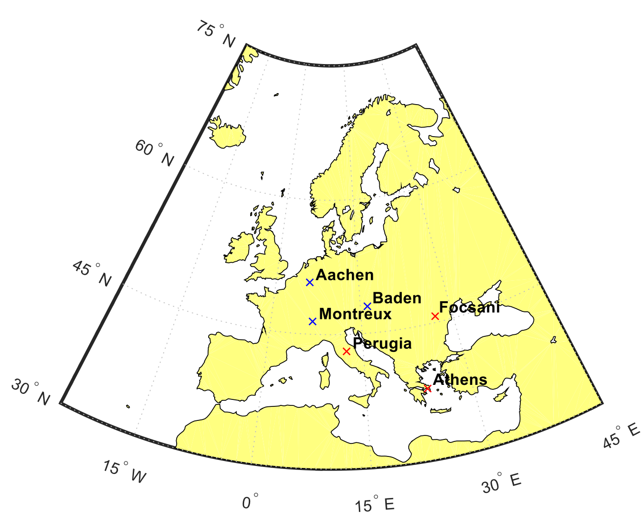

Figure 2: Map of cities chosen as representative of high (red) and medium (blue) hazard zones.

Table 1: Different definitions of RT-Spectra determination approaches as adopted in the literature.

Method	Anchor percentile, p_0	Anchor IM MAF, λ_0	Dispersion β	Target LS and MAF, λ_{tgt}	IM	Spectrum shape	Spectral ordinates optimized
Luco et al. (2007)	0.1	2% in 50yrs	0.6 – 0.8	Collapse 1% in 50 yrs	$S_a(T_1)$	Semi-Flexible	$S_a(0.2)$, $S_a(1.0)$
Douglas et al. (2013)	10^{-5}	10% in 50yrs	0.5	Collapse 0.05% in 50yrs	PGA	Rigid	PGA
Silva et al. (2016)	$10^{-2} – 10^{-5}$	10% in 50yrs	0.5 – 0.7	Collapse 0.25% in 50yrs	PGA	Rigid	PGA

Table 2: Behavior factor and over-strength assumptions.

Ductility class	Behavior factor q	Overstrength OS	Ultimate ductility μ_u
DCH	$q = 4.5 \cdot a_u / a_1 = 4.5 \cdot 1.3 = 5.85$	2.0	5
DCM	$q = 3.0 \cdot a_u / a_1 = 3.0 \cdot 1.3 = 3.90$	1.5	7

Table 3: Limit state definitions.

Limit State	DCH		DCM	
	Median, $\hat{\mu}$	Additional Dispersion, β_U	Median, $\hat{\mu}$	Additional Dispersion, β_U
Global Collapse (LS3)	7.0	0.3	5.0	0.3
Severe Damage (LS2)	3.5	0.3	2.5	0.3
Moderate Damage (LS1)	1.5	0.2	1.5	0.2

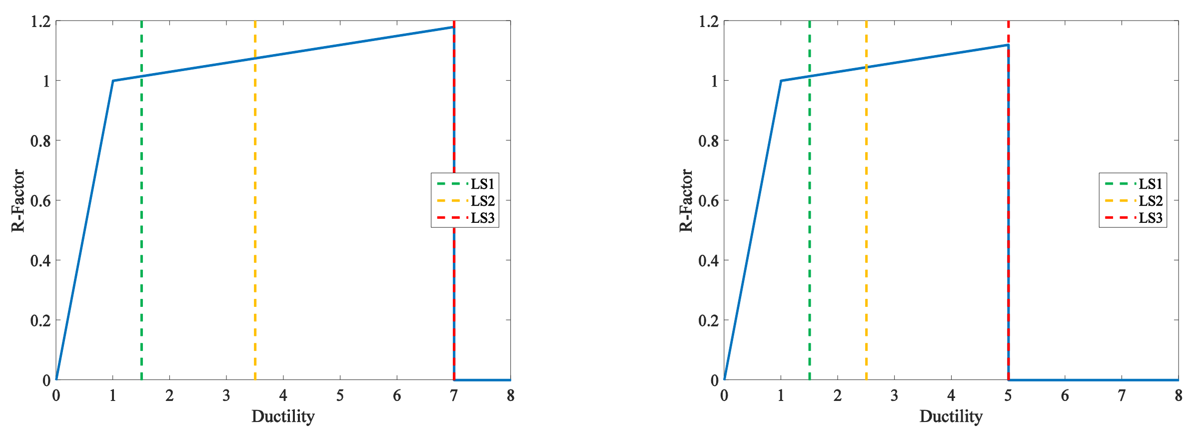

Figure 3: SDoF backbone curves in terms of the ductility and the strength ratio (base shear over yield base shear) and limit state definition according to a building's ductility class: DCH - high ductility (top) and DCM - medium ductility (bottom).

2.4. Optimized spectral ordinates

The final element of RT spectra application is the range of periods and associated spectral ordinates that are optimized, and how these ordinates are weighted when considering a fixed spectrum shape. In the flexible case, all periods in the range of interest need to be employed. For less flexible cases, one may optimize only the spectral ordinates that define the spectrum, e.g. PGA for EN1998. Still, this runs the danger of biasing the result at other periods.

3. SITES, MOTIONS, SYSTEMS

We chose two sets of three case study sites representing medium and high seismicity regions based on the probabilistic seismic hazard assessment (PSHA) model developed for Europe

(Giardini et al. 2013). The cities of Athens (Greece), Perugia (Italy) and Focșani (Romania) represent the high seismicity sites with PGA value on bedrock of about 0.30g for a 475 year return period (i.e. $a_g = 0.30$g in EN1998). The three cities of Baden (Germany), Montreux (Switzerland) and Aachen (Germany) represent the medium seismicity sites with PGA value on bedrock of about 0.15g for a 475 year return period (i.e. a_g=0.15g). Figure 2 shows the locations of the selected sites on map.

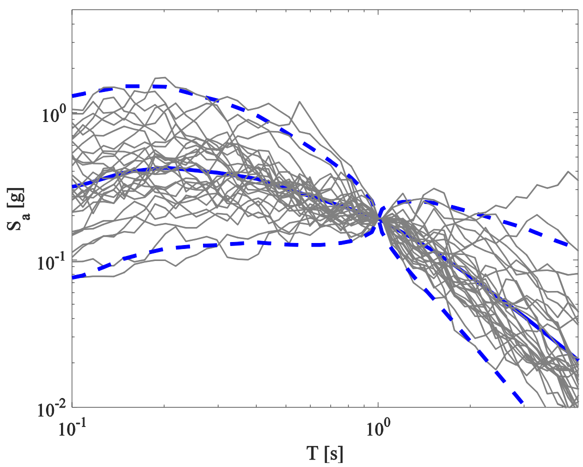

Figure 4: Records selected for Athens and for SDoFs with T_1=1s using $S_a(T_1)$ as conditioning IM.

SDoF systems are used as reference to model multiple buildings and structural systems. This choice allows us to perform a considerable number of dynamic analyses while updating the system characteristics according to the design requirements. To cover a wide range of different structures, each SDoF is defined as an elasto-plastic system with 3% hardening backbone designed for two levels of ductility, namely medium (ductility class medium, DCM) and high (ductility class high, DCH), representing EN1998-compatible characteristics, and having three different fundamental periods of 0.5s, 1.0s and 2.0s. These three first-mode vibration periods encompass the majority of structures in Europe. Associated behavior factor values, overstrength and ultimate ductility characteristics appear in Table 2.

Structural performance is evaluated for three LSs defined in terms of ductility thresholds. In order to include the uncertainty in LS definition, we incorporated an additional dispersion of β_u = 0.2 – 0.3, with larger values employed for the more uncertain LSs (Table 3). Figure 3 shows the backbone characteristics and the LS ductility thresholds adopted for the DCH and DCM structures.

Sets of 30 records have been selected by means of the Conditional Spectrum (CS) approach (Lin et al. 2013) for each site and oscillator period based on the IM chosen to describe the severity of ground shaking (e.g., Figure 4). The record selection has been performed on the basis of the PSHA disaggregation data of the site, as estimated at the 10% in 50yrs hazard level that is associated to EN1998 design. Two types of IMs were employed, namely spectral acceleration at the first modal period of the structure, $S_a(T_1)$, and the geometric mean spectral acceleration, *AvgSA*, evaluated over the period range of [T_1, $2T_1$] with a period spacing of 0.1s.

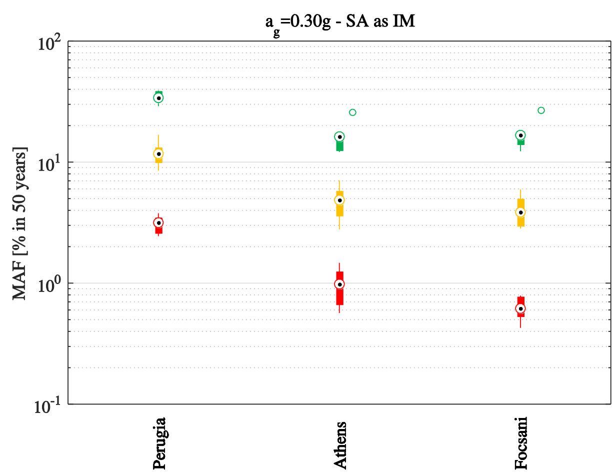

Figure 5: Initial MAF distribution for IM=S_a for LS1 (green), LS2 (yellow) and LS3 (red) differentiated by cities belonging to high hazard zones.

4. INITIAL ESTIMATES

After the definition of the fragility and the integration with the hazard curve we have the initial, un-harmonized cases. A small but representative part of the results appears in Figure 5, showing the MAFs' distribution according to different combinations of city, and

LS for high-seismicity sites. This effectively represents the implicit risk of the SDoFs when designed according to the EN1998 provisions. As expected, the current design provisions lead to evident differences in the achieved performance from site to site for all LSs. Clearly, the need for harmonization is there.

Figure 6 compares the PGA-based results for LS3 and for T=1s, 2s systems with those coming from different record sets selected on the basis of the IM. For most cities, there is a clear conservative bias in the MAFs estimated by PGA versus those based on the other two IMs that, conversely, offer quite similar results. Clearly, despite the robustness of the CS approach, there are limits to its applicability. Therefore, PGA will not be employed here any further.

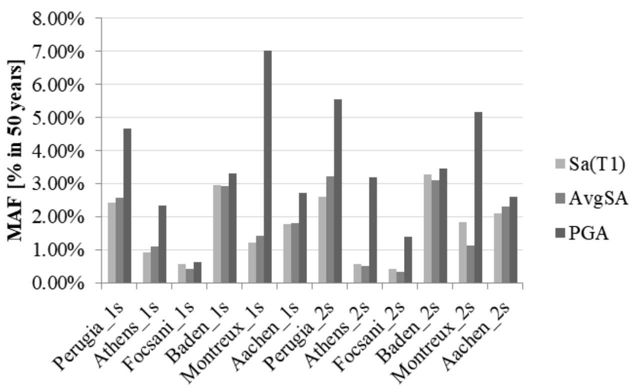

Figure 6: Comparison of MAFs computed using three different IMs: PGA, $S_a(T_1)$ and AvgSA.

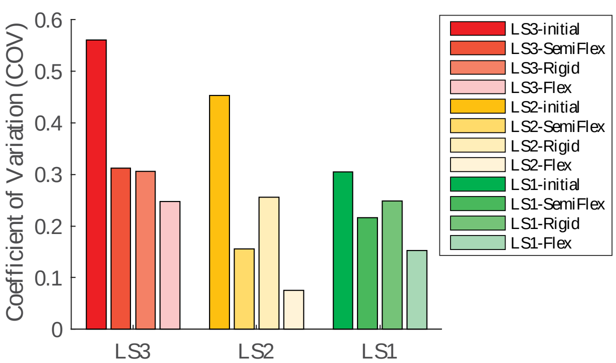

Figure 7: Building-specific fragilities with Rigid/Semi-Flexible/Flexible spectra. Impact of the IM and CS record selection approach for DCM structures when targeting LS2 and employing only the DCH designs to achieve harmonization. Site-specific record selection based on S_a.

5. ESTIMATES WITH RISK TARGETING

Two conceptually different kinds of fragility curves are considered. The first is represented by building-and-site specific fragility curves obtained by means of a PSHA-based record selection applied to the specific SDoF systems. The second kind is defined in line with the currently preferred ‘generic’ fragility approach, disregarding any site and building dependence beyond the design intensity at the site of interest.

Figure 7 depicts the impact of employing building-specific fragility curves with a Flexible shape spectrum. Herein, we target only the SDoFs in the DCH subset and only one of the three LSs at the time while employing S_a as the response predicting IM. Additional results (Spillatura 2018), not shown herein, have been evaluated for different spectrum shapes and using different subsets of the 36 investigated systems to achieve normalization. It can be said that after any kind of harmonization we employ in terms of IM, system subset or spectrum shape, we do observe significant decrease of the variability of the MAF. Given the adopted strategy that targets one LS for one SDoF, the best results (i.e. a perfect match of the target MAF) are obviously achieved for the individual SDoF systems for which the SAFs are computed. Still, to a certain degree the effect spreads also to the other non-targeted LSs. This is especially obvious when employing LS2 that sits in the middle of LS1 and LS3, thus managing to somewhat harmonize their risk as well. Finally, Spectrum flexibility obviously has an impact as well: a Flexible shape generally offers good harmonization, typically on par with the Semi-Flexible, both being better than a Rigid shape.

6. CONCLUSIONS

Risk-targeted spectra can be computed in numerous combinations, targeting different limit-states and corresponding MAFs, employing generic or building-specific fragilities and optimizing different period ranges to adjust design spectra shapes of different parameterization and flexibility. In all cases tested, one single theme seems to emerge: RT-spectra are not a panacea for achieving performance-based design. They simply cannot guarantee risk *matching* for any limit-state across buildings and sites. Risk matching would only be possible with case-specific customized fragilities that have been derived for the building and site of interest. Simply put, a single design spectrum, however adjusted, cannot simultaneously cater to the performance needs of multiple different structures at a given site. On the other hand, RT spectra are a fairly good risk *harmonization* tool. A given risk may not be matched for any specific building, but similar risk values can indeed be achieved across different buildings and sites. This would be already a great improvement over the current design approach.

7. ACKNOWLEDGEMENT

The second author acknowledges the support of the European Commission via the Horizon 2020 Grant No. 769129 “PANOPTIS: Development of a Decision Support System for increasing the Resilience of Transportation Infrastructure based on combined use of terrestrial and airborne sensors and advanced modelling tools”.

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