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PERFORMANCE-BASED NONLINEAR RESPONSE HISTORY ANALYSIS FRAMEWORK FOR THE "PROINDUSTRY" PROJECT CASE STUDIES

Marco Faggella[1], Raffaele Laguardia[1], Rosario Gigliotti[1], Francesco Morelli[2], Franco Braga[1] and Walter Salvatore[2]

[1]Sapienza University of Rome
Via Eudossiana 18
{marco.faggella, raffaele.laguardia, rosario.gigliotti, franco.braga}@uniroma1.it

[2]University of Pisa
Largo Lucio Lazzarino 2, 56126 Pisa, Italy
{francesco.morelli@dic, walter@ing}.unipi.it

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Abstract. *Within the PROINDUSTRY project a Performance-based analysis framework is defined for seismic assessment of industrial structures, based on Nonlinear Response History Analysis (NL RHA) using in particular the Incremental Dynamic Analysis (IDA) method. This paper describes the choice of the PBEE and IDA analysis methods starting from an overview of state-of-the-art methods. The choice is analyzed in relation to: analysis goals for the selected case studies (design-based vs. risk-based), availability of databases/tools for hazard analysis and GMs selection, accuracy of criteria to scale and match GMs to a target spectrum (UHS, CMS, etc.) and treatment of record components. Three possible approaches of GMs selection are described and analyzed: (1) UHS-coherent Unscaled (Design), (2) UHS-coherent GMs scaled to Sa(T1) (Risk/Loss), (3) CMS-coherent GMs scaled to Sa(T1), (Risk/Loss). Within the scopes of PROINDUSTRY, the approach (1) is proposed, as a trade-off between simplicity of conventional PBEE design methods and probabilistic robustness for a heterogeneous portfolio of structures/facilities.*

1 INTRODUCTION

Recent seismic events in Europe have pointed out the importance of assessing, managing and mitigating the seismic risk of industrial plants [1], [2]. The"Seismic PROtection of INDUSTRial plants by enhanced steel based sYstems" (PROINDUSTRY) project aims at developing enhanced seismic protection systems for process plants, process units, storage units, pipeline and pipe systems, through innovative antiseismic techniques: seismic isolation and energy dissipation systems (such as the one described in [3]). The project includesthe definition of a framework for seismic assessment of industrial structures, based on Nonlinear Response History Analysis (NL RHA) using in particular the Incremental Dynamic Analysis (IDA) method. The framework shall be defined to allow not only the assessment of the current case studies seismic vulnerability, but also the comparison between the seismic behavior before and after the application of the anti-seismic systems.

Seismic design provisions for industrial plant structures can be found under the ASCE/SEI 7-10 provisions [1], particularly for the structure types of 'non-buildings similar to buildings', and 'non buildings not-similar to buildings'. Design codes classify structures types and behavior based on q, R factors for use in force-based linear analysis and design. Correspondence between US codes and Eurocode 8 [5] and capacity design rules are described in [6] and [7]. A comprehensive review of NL RHA code procedures for different types of structures is carried out in the NIST GCR 11-917-15 document 'Selecting and Scaling Earthquake Ground Motions for Performing Response-History Analyses', [8]. In general, the different seismic design codes prescribe a reference spectrum and indicate the number of Ground Motions (GMs) needed to perform NL RHA. The general requirement is to use 7 different GMs and process results in terms of best estimates, or use 3 different GMs and the max response values.

A review of current Performance-Based Earthquake Engineering (PBEE) code provisions for NL RHA in terms of their evolution and underlying vision is useful to analyze what is the most appropriate context, what are the objectives of the prescriptions, and what should be the expectations of a chosen protocol of analysis. Two main types of PBEE design and assessment are identified and discussed: (A) 1st Generation PBEE approach, described in the most commonly used codes of practice; and (B) a Next generation PBEE approach, with new performance metrics and a broader vision in terms of risk analysis.

1.1 First Generaton PBEE (Design-based)

1st Generation reference codes/guidelines for design/assessment prescribe force-based linear methods of analysis/design classifying structures based on type (new/existing buildings, bridges, seismically isolated structures, nuclear plants, liquefied natural gas tanks), and define structural performance matching limit states (identification of component damage level) with a probability of exceedance of the seismic intensity (FEMA356/ASCE41). These codes prescribe also methods of NL analysis, both static and dynamic, and rules for RHA and GM selection. The objective of these code provisions is the performance assessment at the component level, checking/comparing member demand with capacity. Assessment/design of industrial structures and their retrofit using innovative devices are covered by the following documents:

- **Eurocodes**:
  - UNI EN 1998-1 (New Buildings)
  - UNI EN 1998-3 (Assessment and retrofit of buildings)
  - UNI EN 1998-4 (Silos, tanks and pipelines)
  - UNI EN 1998-6 (Towers, piles and chimneys)

- **US codes and guidelines**:
  - New buildings, ASCE/SEI 7-05 (2005), ASCE/SEI 7-10 (2010)
  - Existing buildings, ASCE/SEI 41-06 (2007)
  - Isolated and conventional bridges (AASHTO, 2010 a, b)
  - Nuclearfacilities, ASCE/SEI 43-05, (2005)
  - Liquefied natural gas facilities (FERC, 2007)
  - Dams, FEMA 65, (2005)
  - Civil works, EC1110-2-600 (U.S. Army Corps of Engineers, 2009)
  - Department of Defense facilities, UFC 3-310-04, (Dept. of Def., 2004, 2007, and 2010)
  - Storage tanks, API Standard 650 (2007), API Standard 620 (2009)

Whether used with linear force-based analyses or nonlinear procedures, design methods of the first generation contain a number of limitations regarding in particular:

- *Discrete limit states*: the definition of performance, with respect tosingle components or to the structure as a whole, related to the achievement of a certain limit state is still coarse and often involves questionable margins of conservatism.
- *Accuracy and reliability of procedures.*
- *Performance measures:* Engineering parameters used for definition of performances, such as drift, accelerations, stresses, strains etc., are not understood by entrepreneurs, investors, lenders, and decision makers.
- *Deterministic approach:* the assessment of performance is purely deterministic, only the intensity of the seismic action is modeled in a probabilistic way.

Figure 1. PROINDUSTRY project: someof the industrial case study structures.

1.2 Next-Generation PBEE (Risk/loss-based)

To address these limitations the Pacific Earthquake Engineering Research center developed a Performance Based Earthquake Engineering methodology (PEER PBEE, [12]) and tested it on a number of benchmark structures. For building structures these efforts culminated in the release of the FEMA P-58guidelines, which is a fully probabilistic new paradigm for risk/loss based PBEE [13], [14], and of its companion tool for damage-based accumulation of monetary performance/loss at the global level (PACT tool, [15]). Uncertainties are explicitly considered in terms of: human losses (loss of lives, injuries, etc.), direct economic losses (cost of repairs, replacements, etc.), and indirect economic losses (downtimes, Unsafe placarding, etc.).

The methodology incorporates the components of the PEER PBEE approach, namely the Probabilistic Seismic Hazard Analysis (PSHA), the Structural Analysis, the Damage and Loss analyses. The seismic hazard is defined in terms of Uniform Hazard Spectrum (UHS), or alternatively in terms of Conditional Mean Spectrum (CMS) [16] and Conditional Spectrum (CS) [17]. Three main types of assessment are considered: a) Intensity-based, b) Scenario-based and c) Risk/Time-based. At the core of the methodology is the structural analysis module, based on NL RHA with sets of natural GMs.

Analysis of these documents is important to define a protocol for PROINDUSTRY, giving due consideration to the fact that the FEMA P-58 methodology is developed specifically for building structures, and there is no codified reference document on application of complete PBEE risk/loss framework for industrial structures in general. It is also very important to remark that a comprehensive risk-based approach is beyond the scopes of PROINDUSTRY, which foresees a 1st-gen design/assessment approach. Therefore an appropriate, sufficient, and closer reference document for the analysis approach to develop in WP2 is the NIST GCR 11-917-15. This document is intended for practicing engineers and structural analysts, and contains recommendations on NL RHA analysis protocols and ground motions selection/scaling/matching to target spectra.

An important aspect to consider is that the analysis protocol should be aimed at comparing the structural performance and behavior before and after retrofit with innovative protective devices. Since isolation and energy dissipation devices change drastically the structural system and properties, and in particular the parameter $S_a(T_1)$, and modify the system response as a whole as well as the nonlinear interaction with the superstructure [18], it is desirable that the analysis method and the inherent scaling criterion of the input GMs is as much as possible independent on the properties of the structure.

The FEMA P-58 and NIST guidelines would be easy to follow selecting GMs from the PEER NGA database [19], and scaling to the UHS or CMS provided by USGS, using the extensive database and interactive online tools. However this approach may not be consistent with this EU project. On the other hand some difficulties may arise using the currently available interactive tools (INGV-ESSE project, [20], [21], [22], [23], [24], [25]) or those under development [26] from the Italian/EU databases and PSHA. Some limitations may persist if the CMS is used as target spectrum, and if the GMs are to be scaled to this CMS, particularly due to the inherent type of the local seismicity, both related to the intensity and to the causative sources, [16].

2 OVERVIEW OF NL RHA AND IDA

A key component of modern codes for PBEE design and assessment is the simulation of the structural behavior through realistic nonlinear models, and appropriate analysis protocols. For few cases of very simple and regular structures (1st mode dominated response) the analysis protocol can be of the static type (NL Pushover). In all other cases a dynamic type (NL RHA) is needed to simulate the realistic response due to multi-mode contributions, velocity-dependent effects, randomness of the input, etc.Although many traditional performance-based codes and guidelines describe methods for performing RHA, it must be noted that most of these documents contain rules that were developed in the 80s and were intended for performing analyses of structures with nonlinearseismic isolation and energy dissipation devices [8], with less evidence from application to structures with NL behavior due to plastic hinging, buckling, or structural damage in general.

A crucial point for the selection of the method for NL RHA analysis is to identify the project's goals in terms of analysis, and the key Engineering Demand Parameters (EDP) representative of the structural response/behavior.

This choice is reflected in the two types of approaches that can be found in traditional and more recent PBEE codes/guidelines:
- DESIGN approach: the analysis goal is to compute mean values of response (few GMs are needed, codes prescribe 7 or 3 GMs).
- FRAGILITY/RISK approach: the analysis goal is to compute mean and distribution of response and evaluate collapse probabilities. (Many more GMs are needed, normally 30+, or 11 if conditioning to an IM, less if particular spectra are used).

The Incremental Dynamic Analyses (IDA is a parametric extension of the NL RHA used to estimate performance under seismic loads subjecting a structural model to one (or more) GM records [27]. It consists in a sequence of Monte Carlo analyses, and performs an intensity sweep for each GM by scaling the records to an increasing reference IM until collapse occurs.

IDA has been proposed as 1) a dynamic protocol capable of describing the structural behavior over a number of intensity/response levels and ranges, (to capture the changing in the dynamic structural behavior increasing the seismic intensity, conceptually similar to static pushover), and 2) a probabilistic analysis protocol that incorporates the randomness inherent to the detail of the GM input record, and the randomness in the seismic hazard intensity, through scaling/conditioning the GMs to an appropriate Intensity Measures (IM). Usual choices for IM have been the PGA and the spectral acceleration at the fundamental period $S_a(T_1)$.

IDA can be used for different types of assessment, depending on what kind of information is sought, whether the interest is on structural performance and component checks, or on fragility and decision-oriented information. It may be useful to note that in some cases, the inherent computational burden of performing a large number of Monte Carlo simulation runs, which can be typical of IDA, can be overcome by running parallel parametric probabilistic simulations of a same FEM model, [28]. This approach is feasible with FEM software with capabilities to run relatively simple models on parallel supercomputers [29].

2.1 GMs SELECTION

The first step to perform NL RHA or IDA is the selection of appropriate sets of GMs. The NIST guidelines [8] present a comprehensive overview of codes provisions for NL RHA and provide guidance on methods for selection/modification of input GMs.

2.2 ASCE/SEI 7-05

Rules for selecting and scaling GMs provided by ASCE/SEI 7-05(§16.1.3) [1] can be summarized as follows:

- A GM shall consist of a horizontal acceleration history, selected from an actual recorded event having magnitudes, fault distance, and source mechanisms that are consistent with those that control the maximum considered earthquake.
- The GMs shall be scaled such that the average value of the 5 percent damped response spectra for the suite of motions is not less than the design response spectrum for the site for periods ranging from 0.2T to 1.5T where T is the fundamental period of the structure in the fundamental mode for the direction of response being analyzed
- For 3D analysis GMs shall consist of pairs of appropriate horizontal ground motions components.

- For each pair of horizontal GM components, a square root of the sum of the squares (SRSS) spectrum shall be constructed by taking the SRSS of the 5% damped response spectra for the scaled components (where an identical scale factor is applied to both components of a pair). Each pair of motions shall bescaled such that for a period between 0.2T and 1.5T, the average of the SRSSspectra from all horizontal component pairs does not fall below 1.3 times thecorresponding ordinate of the design response spectrum by more than 10 percent.
- If 3sets (or more) of GMs are selected, the component checking must be done with the maximum values that come from the analysis.
- If 7 sets (or more) of GMs are selected, the component checking must be done using the average values that come from the analysis.

It must be noted that the SRSS method for spectrum matching has no solid technical basis, and the use of Geomean Spectrum is suggested by NIST for spectrum matching [8]. These guidelines point out clearly that the use of a certain number of sets of GMs (in this case 3 or seven are suggested) has no sound technical basis too. As mentioned above, these rules were developed mostly in the 80s in the context of NL RHA of structures with nonlinear base isolation and energy dissipation devices. The correct number of GMs needed depends on many factors such as the goodness of fit of the scaled motion to the target spectral shape, the expecteddispersion in the response, the required degree of confidence, and the required level of accuracy. Some formulations are available which permit to estimate the correct number of GMs needed independentonthe spectral shape [30]. In general more than seven GMs are needed to obtain a reliable and accurate evaluation of the mean response and, as a consequence many tens of GMs are needed to obtain correct evaluations of the dispersions.

2.3 ASCE/SEI 7-10

Rules defined in ASCE/SEI 7-10 [31] are similar to those defined in ASCE/SEI 7-05, the main difference being that the design spectrum definition is done using the maximum rotated component spectrum instead of the geomean spectrum, and so the SRSS method for spectrum matching of 3D components should be preferred to have more reliable results.

2.4 FERC 2007

The US Federal Energy Regulatory Commission drafted the Seismic Design Guidelines andData Submittal Requirements for LNG Facilities (FERC, [32]), whichidentify the performance criteria to be met for this type of structures and refer to ASCE/SEI 7-05 for the procedures for GMs selection.

2.5 Eurocode8 (buildings)

UNI EN 1998-1defines the methods for representing the seismic action through GMs in §3.2.3.1 and prescribes that:

- Recorded GMs may be used, provided that thesamples used are adequately qualified with regard to the seismogenic features of thesources and to the soil conditions appropriate to the site, and their values are scaled tothe value of a_g*S for the zone under consideration.
- A minimum of 3 GMs should be used.
- The mean of the zero period spectral response acceleration values (calculated from singleGMs) should not be smaller than the value of a_g*S for the site inquestion.
- In the range of periods between 0,2T_1 and 2T_1, where T_1 is the fundamental period of

the structure in the direction where the GM will be applied; no value of themean 5% damping elastic spectrum, calculated from all time histories, should be lessthan 90% of the corresponding value of the 5% damping elastic response spectrum.

In §4.3.3.4.3 EC8 defines the required number of GMs:

- If the response is obtained from at least 7 nonlinear time-history analyses with GMs in accordance with 3.2.3.1, the average of the response quantities fromall of these analyses should be used as the design value of the action effect E_d in therelevant verifications of 4.4.2.2. Otherwise, the most unfavorable value of the responsequantity among the analyses should be used as E_d.

2.6 Eurocode8 part 4 (silos, tanks, pipelines)

For the definition of the seismic action UNI EN 1998-4 refers to UNI EN 1998-1.

2.7 Eurocode8 part 6 (towers, pile, chimneys)

For the definition of the seismic action the UNI EN 1998-6 in §3.4 refers to UNI EN 1998-1 in general and allow the use of rotational components of ground motion. These provisions also suggest paying specific attention to the long period components of the time-histories which affect in a critical way the response of this type of structures.

2.8 FEMA P-58 (Next generation PBEE methodology. Buildings)

As noted above the prescriptions of FEMA P-58 could apply to industrial structures in those particular cases where the structural type is similar to buildings. The same hazard and analysis modules would apply in this case, however the exposure and loss modules would have to be made consistent to the particular case studies. We already discussed how exposure and risk/loss are beyond the scopes of PROINDUSTRY. As far as the NL RHA and IDA analysis module is concerned, the FEMA P-58 guidelines are in agreement with the NIST 2011 guidelines.

FEMA P-58 dedicates the entire third chapter to the definition of the seismic hazard, and to themethodsfor selection and scaling of GMs, with the following recommendations:

- Three different kind of spectrum are defined: UHS (Uniform Hazard spectrum), CMS (Conditional Mean Spectrum), and CS (Conditional Spectrum).
- Regardless of the type of selected spectrum, the selected ground motions must match (without specific limitation), on average, the selected spectrum over the period range T_{min} to T_{max}, where $T_{max}$is taken as twice the period of the fundamental translational mode (the larger of T_x, T_y if a 3D analysis is performed) and T_{min} is taken as 0.2 times the fundamental period (the smaller of T_x, T_y if a 3D analysis is performed).
- Selected records should have faulting mechanisms, earthquake magnitudes, site-to source distances, and local geology that are similar to those thatdominate the seismic hazard at the particular intensity level.
- At least 7 pairs of GMs should be used, but when fit with spectral shape is poor eleven or more pairs of motions are needed to correctly capture the median response.

3 POSSIBLE APPROACHES

Inthe scientific literature and in building codes it is difficult to identify a general ruleNL RHA and IDA method, and the protocols are strictly dependent upon what is the goal of the analysis, in terms of what is the type of assessment sought, and in terms ofwhat are the critical mechanisms and the relevant Engineering Demand Parameters (EDPs) and response indicators (drift-governed structural damage, force-controlled mechanisms, floor accelerationgoverned component vibrations, anticipated relevance of higher modes, etc.), and what is the level of confidence requested.

Based on the building codes and guidelinesalready described, three different approaches for selecting and scaling GMs are analyzed. For each approach advantages and disadvantage are discussed, with respect tothe specific goals and challenges of the PROINDUSTRY project, and of the specific case-study structures.

In general, the possible methods comprise the following steps:

1) Definition of facilities and locations;
2) Identification of the analysis needs;
3) Identification of the Ground Motions Intensity Measure (PGA or IM=$S_a(T^*)$, etc.) for a specific Hazard Level (HL);
4) Development of the Probabilistic Seismic Hazard Analysis (PSHA) in terms of IM, (Attention to how the local PSHA is derived, one horizontal component, maximum, or geomean, etc.);
5) Definition of the Target Spectrum (UHS, CMS, or CS);
6) *Selecting horizontal GMs for coherence/scaling to the target spectrum*;

The three approaches suggested herein differ in how point 6) is developed, based on which of different kinds of target spectra and on the use of scaled vs. unscaled GMs.

The criteria to perform the spectrum matching are similar in most guidelines/codes, and require that the average spectrum of the set does not differ from the reference spectrum with a tolerance of +30% / -10%. The period range where it is necessary to ensure this tolerance is between 0.2T^*(to account for higher modes) and 2T^*(to consider inelastic response with relative loss in stiffness and shift of period, as per UNI EN 1998-1). If the structurehas identifiablemodes associated with translational response along two orthogonal axes, X and Y, the corresponding fundamental translational periods associated witheach axis are denoted with T^*_X andT^*_Y, respectively. The reference period T^* to use for spectrum matching/anchoring can be the mean of the two periods T^*_X andT^*_Y. For the particular case of this project, and due to the difficulty of defining a reference period, it would be desirable to enlarge the period range used for coherence as much as possible.

Table 1. NL RHA and IDA GM selection/scaling approaches as per ASCE-7, NIST 2011, FEMA P-58.

APPROACH	Reference Spectrum	Scaling	Goal(s)	Coherence	GMs
1. UHS, Un-scaled	Uniform Hazard Spectrum (UHS) Design Spectrum (DS)	Unscaled	Median	Y	**7+**
			Median and STD	Y	30+
2. UHS, Scaled	Uniform Hazard Spectrum (UHS) Design Spectrum (DS)	Scaled to IM=$S_a(T^*)$	Median and STD	Y	7+
				N	11+
3. CMS, Scaled	Conditional Mean Spectrum (CMS)	Scaled to IM=$S_a(T^*)$	Median	Y	7+
			Confidence on median	Y	<11

With reference to spectral matching and scaling, specific attention deserves the choice of the directional GM components. A common method suggested by several guidelines (FEMA P-58) performs the spectrum matching or in general the coherence assessment based on the geomean of the X and Y components. Other reference codes, in particular building codes provisions, may consider the two components separately, their maximum or a different combination, such as the SRSS. The consistency of the methods is strictly related to the hazard definition, whether the reference spectra and the underlying PSHA are derived based on the geomean, or on a single GM component. The consistency should be checked on a case-by-case basis, particularly for those case study structures where the directional effect can be significant due to different behavior in two orthogonal directions.The three candidate approaches for the WP2 of the PROINDUSTRY project are summarized in Table 1, in terms of number of GMs needed, of scaling/unscaling criterion, of spectral coherence, and goal in statistic confidence.

3.1 APPROACH 1 (UHS-coherent Unscaled GMs, Design).

IDA with unscaled GMs, consistent with a design spectrum (UHS), referred to PGA of HL.

The first approach is a 'design' approach, in line with 1st generation PBEE codes/guidelines. It is based on unscaled recorded GMs coherent with the UHS or with the Design Spectrum. In this method the PGA is used as reference IM, therefore the definition of the input is independent on the structure.

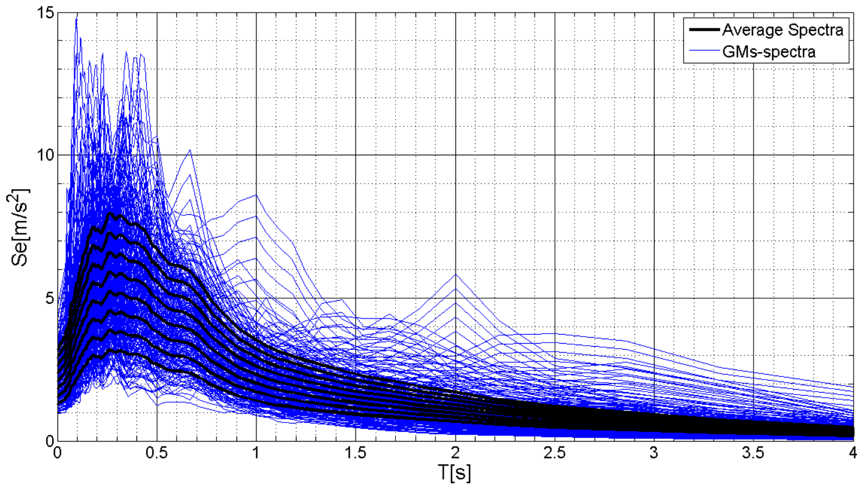

Figure 2.Example of relatively unscaledGMs sets, uniformintensity-scalingto different HLs based on PGA.

Unscaled natural GMs will have a fairly uniform dispersion of spectral ordinates over the range of periods of interest. This type of input is not specific to a particular structure or behavior and is intended to give the same importance to first mode, higher modes, and period-elongated/damaged fundamental modes. This will be reflected in the estimates of the different response parameters (drifts, accelerations, etc.). As a consequence of this dispersion, a greater number of GMs will be required to capture the median response and dispersion, normally 7+ GMs to capture the median, and 30+ GMs to capture a distribution. Given the design/check-oriented objectives of PROINDUSTRY, the suggested number of GMs is 11.

3.2 APPROACH 2 (UHS-coherent GMs scaled to $S_a(T_1)$).

IDA with scaled GMs conditioning/anchoring to $Sa(T_1)$ of HL on the UHS.

This approach uses as reference IM the spectral acceleration at a defined conditioning period IM=$S_a(T^*)$. Usually, for structures that are 1st mode dominated $S_a(T_1)$ is a good predictor of the response, and is well correlated with nonlinear response at increasing intensity levels. However, in general T^* could differ from the 1st mode period and should be selected on a case-by-case basis as the period whose spectral ordinate more influences the EDP that governs the seismic behavior and the design/assessment process.

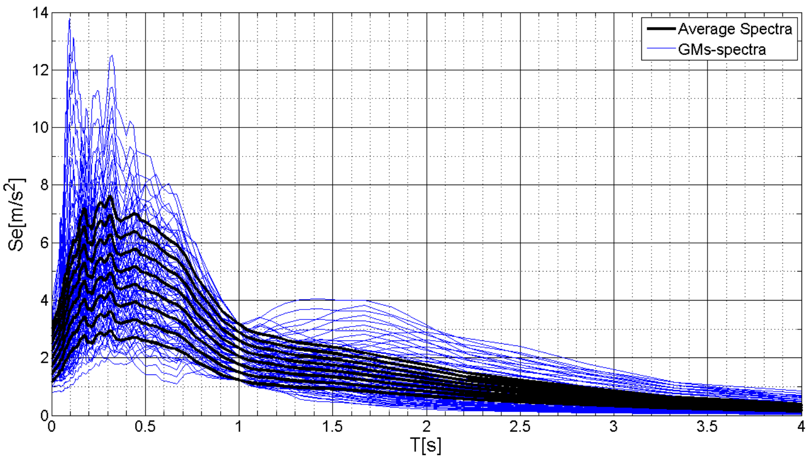

Figure 3. Example of GMs sets with different intensity, scaled to $S_a(T^*)$ values.

Scaling/anchoring the GMs to a given IM allows obtaining sets with less variability around the selected spectral ordinate, resulting in a reduced number of GMs needed to capture the distribution of the response. On the other hand, scaling to a specific IM can result in overly inflated ordinates and increased dispersion at other frequencies (Figure 3). For this reason this method could introduce inconsistencies if the analyzed structures and the selected response parameters are not well correlated to $S_a(T^*)$, since this IM can be not sufficient nor efficient [34] for many structures. For the PROINDUSTRY case studies, and in particular for those sensitive to acceleration spectra [35], [36], this method could result in too conservative and not realistic IDA estimates of forces as well as of displacements/damage.

3.3 APPROACH 3 (CMS-coherent GMs scaled to Sa(T1)).

IDA with scaled GMs conditioning/anchoring to $S_a(T_1)$ of HL on the CMS.

Recent studies proposed the so-called Conditional Mean Spectrum (CMS), [16], to overcome the limitationsof UHS.In a single event it is very unlikely that the spectral ordinates of the UHS are observed at all periods, especially for rare events and so coherence of GMs with UHS is not realistic. The CMS refers to a scenario event for a given HL and conditioning period T^* based on disaggregation data (M, R); the spectral ordinate at this period is maximized (through the parameter ε) and should reach the value given by the UHS for the HL selected. The spectral ordinates at other periods are then related to the $S_a(T^*)$ through conditional probability and correlation factors, and their values are less than those of the UHS. In this way it is possible to reduce the seismic demand for periods away from the conditioning period (reducing overestimates of high-mode response for example) while retaining consistency with the seismic hazard derivation in terms of a primary IM at a given HL.

The CMS provides the expected (mean) response spectrum, conditioned on occurrence of a target spectral acceleration value at the period of interest. This is a better tool for GMs selection because it is very unlikelyfor a single event to containall the spectral ordinates with the same probability of exceedance. It is more realistic to correlate the different spectral ordinates through conditional probability. The limitations of this method are similar to those of for the approach n.2, and are due to the definition of a specific spectral ordinate for scaling. In addition, computing the CMS could be difficult due to limited disaggregation data for Europe [37], and due to the multi-modal hazard scenarios in most cases, [16], particularly for the sites where the case-study facilities are located.

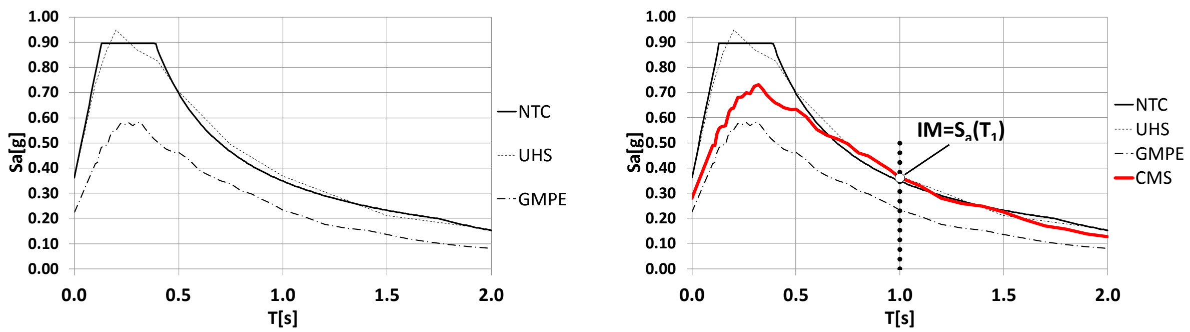

Figure 4.Reggio Calabria site, (a) determination of the median Spectrumusing M, R values, (b)determination of the CMS.

4 CONCLUSIONS AND RECOMMENDATIONS

The three methods illustrated herein can produce different results. It is therefore necessary to identify a reference method that would lead to consistent results for the different project case studies. It is also desirable to compare analysis results among partners working on different case studies. As requested by the project, in order to achieve the worst damage scenarios with a robust and reliable procedure, the first method suggested should be preferred.

The approach n.1 is based on unscaled GMs and is consistent with 1st gen. PBEE design/assessment. This would decouple the definition of the action from the evaluation of the response, and render the seismic input not strictly structure-specific. A major drawback of using unscaled GMs is that a higher number of records need to be used.The project focus is on the assessment of the structural behavior [38] and on proposing retrofit solutions [39], and the interest is on capturing the mean response. To achieve this goal at least 7 GMs are needed but, considered the high variation of the selected GMs (Approach n.1) a higher number of GMs is to be preferred, at least 11 GMs. The results will be processed in terms of best estimates and where necessary also in terms of distribution. This would allow, in a subsequent phase, to compare results and performance assessment based on 2nd gen. risk-based PBEE approaches, by introducing scaling criteria to key IMs, and perform more accurate probabilistic analyses, as well as loss-based comparisons of retrofit solutions [40], [41], 0.

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