Available online at www.eccomasproceedia.org
Eccomas Proceedia COMPDYN (2017) 4184-4193

ECCOMAS
Proceedia

COMPDYN 2017
6th ECCOMAS Thematic Conference on
Computational Methods in Structural Dynamics and Earthquake Engineering
M. Papadrakakis, M. Fragiadakis (eds.)
Rhodes Island, Greece, 15–17 June 2017

PERFORMANCE BASED EARTHQUAKE ASSESSMENT OF AN INDUSTRIAL GAS FILTER STRUCTURE

Raffaele Laguardia[1], Andrea Piscini[2], Marco Faggella[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
{andrea.piscini@ing, francesco.morelli@dic, walter@ing}.unipi.it

Keywords: Nonlinear Response History Analysis (NL RHA), Performance Based Earthquake Engineering (PBEE), Incremental Dynamic Analysis (IDA), Ground Motions (GM), Uniform Hazard Spectrum (UHS), Conditional Mean Spectrum (CMS).

Abstract.

Industrial facilities often store a large amount of hazardous material and, in case of seismic event, there is a high probability that accidental scenarios as fire, explosion, toxic or radioactive dispersion may occur. Moreover, the structural configuration of industrial facilities are often the fruit of plants and functionality requirements, that lead to strong irregularities and different load resisting systems within the same structure. This paper presents a performance-based earthquake assessment of an industrial gas filter structure, characterized by the presence of important masses placed at significant height and of different horizontal resisting systems, such as moment resisting frames, inverted V bracings and diagonal bracings. Within the framework of the PROINDUSTRY research project critical failure mechanisms of industrial structures and relevant limit states are analyzed and discussed. The structural response is computed via nonlinear finite elements analyses of the static pushover (PO) and dynamic response history type (RHA). The seismic input is defined through Probabilistic Seismic Hazard Analysis (PSHA) and a set of natural Ground Motions (GM) which are selected and scaled with different criteria with respect to the Uniform Hazard Spectrum (UHS) and the Conditional Mean Spectrum (CMS). An overview of significant aspects of the structural performance assessment is presented with respect to input definition and choice of Intensity Measures (IM), irregular structural behaviour and probabilistic treatment of key Engineering Demand Parameters (EDP) for this type of industrial structure.

doi: 10.7712/120117.5715.18439

1 INTRODUCTION

Recent earthquakes have pointed out the high vulnerability of industrial facilities[1][2][3][4][5][6]. The risk associated to the failure of the plant, or a part of it, is very high since the consequences may be disastrous, in terms of human lives, environmental contamination and economic losses. These aspects make the risk assessment of industrial buildings particularly complex requiring different approach with respect to risk assessment of residential and commercial buildings [7][8]. Such buildings are characterized by structures often designed according to old codes, which were not performance oriented or did not consider anti-seismic design. Some efforts were carried out in the past to address evaluation and upgrading of seismic performances of non-structural elements [9][10][11][12].

Seismic design provisions for industrial plants can be found in ASCE/SEI 7-10 [13], ASCE-SEI 43-05 [14], FERC 2007 (Liquified Natural Gas facilities) [15], API Standard 620 and 650 (Storage Tanks) [16][17], UNI EN 1998-4 (Silos, tanks and pipelines)[18], UNI EN 1998-6 (Towers, piles and chimneys) [19]. Such international codes define rules for performance assessment at the component level, checking/comparing member demand with capacity through a traditional Performance Based Earthquake Engineering (PBEE) approach. These codes prescribe also methods of nonlinear analysis, both static and dynamic, and rules for Response History Analysis (RHA) and Ground Motions (GMs) selection. A comprehensive review of Non-Linear Response History Analysis (NL RHA) code procedures for different types of structures is carried out in the NIST GCR 11-917-15 document [20]. Despite the high number of references in literature and international codes, to date, there is not a unique and recognized method for selecting and scaling GMs.

In this paper, an industrial structure from the PROINDUSTRY project is selected as case study, and NL RHA are performed adopting two different GMs sets, respectively coherent with UHS and CMS. The results obtained in terms of different EDPs are investigated and discussed, focusing on the influence of the different GMs selection and scaling techniques.

2 CASE STUDY DESCRIPTION

The building analyzed in this paper is characterized by a mass placed at a significant height and different typologies of horizontal forces resisting systems, as it is shown in Figure 1. The same building was already adopted in [21] for the evaluation of the seismic behavior of steel structures equipped with self-centering devices [21].

The building has a regular plan with dimensions 37.80 m x 16.94 m and total height 29.64 m. The supporting structure, with a total height of about 10.80 m, has six bays in the longitudinal direction and three in the transversal one. The horizontal loads resisting systems comprises moment resisting frames (X direction - ground floor), inverted V bracings (Y direction - ground floor) and diagonal bracings (X and Y directions - first floors). The total mass of the silo (23700 kN), considering the structural elements and the infill material, represents the 86% of the total mass (27650 kN).

A 3D model was created in OpenSEES [22] adopting the simplified geometry shown in Figure 1. The nonlinear analyses carried out through a more geometrically accurate model in [21] and the linear modal analysis, showed that the building behavior is governed by the deformation of the supporting structure and the silo and roof behave as a rigid body. Steel elements are modeled through Fiber sections, each fiber is assigned the “Steel02” material property, second order effects are modeled through a “corotational transformation” for braces and through a “P-Delta transformation” for columns.

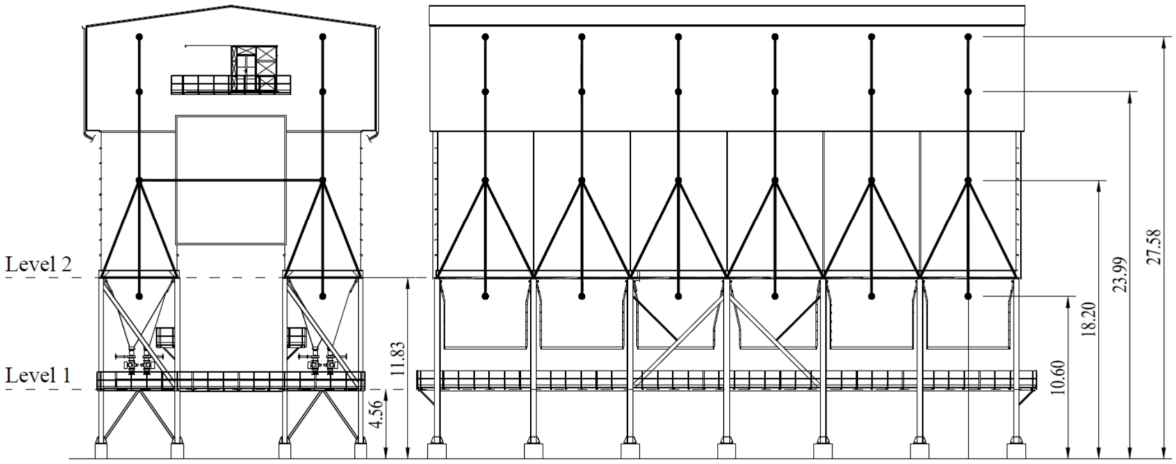


Figure 1. Case study nonlinear model geometry [21].

3 SEISMIC INPUT DEFINITION

Two sets of GMs are selected for an Italian high seismicity zone corresponding to the site of Reggio Calabria (Italy). One set is coherent with the spectral shape of UHS and the other is coherent with CMS. The spectrum coherence rules used is consistent with the requirements of Eurocode 8 (§3.2.3.1) [32][32]. The target spectrum is matched with the Geomean spectrum of the two orthogonal GM components. Coherence is sought in the period range between 0 sec and 2 sec. The reference spectrum chosen is the Italian code NTC08 [31] Design Spectrum computed for Reggio Calabria (Lat 38.1, Long 15.65), with Soil C, reference period V_R =100 years and a probability of exceedance PoE=10%, which corresponds to a return period of 949 years. GMs have been selected in accordance with Magnitude-distance (M-R) hazard deaggregation in the range of $6<M_w<8$ and $0<R[km]<40$. The selected UHS coherent GMs, are those used also in [21] [29] [33] [34] [35] [36] and [37], for the seismic evaluation of different industrial structures. The seismic action associated to the Damage Limitation Limit State (DLS), characterized by a probability of exceedance PoE=50% in the reference period (100 years), is evaluated scaling the reference spectrum by a factor of 0.433. The CMS refers to a scenario event for a given Hazard Level (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 lower than those on the UHS. The conditioning period T* has been chosen as the average period of the two first vibration modes T_{1x}=1.08sec and T_{1y}=0.57sec.

Starting from the deaggregation analysis of the chosen site, the scenario event which mainly influences the hazard is computed based on the hazard data of INGV [23] and through the Ground Motion Prediction Equations (GMPE) proposed by Ambraseys et al. [24]. Through this procedure the average values of M,R and ε are respectively 6.9, 12.62Km and 0.61.

The CMS is then computed as described by Baker [25] and is shown in Figure 2.

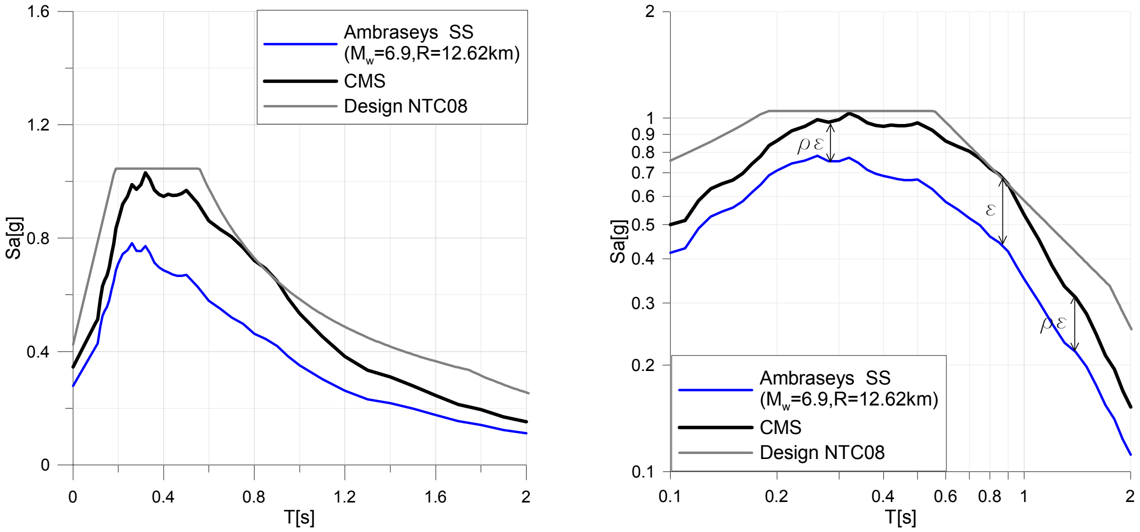


Figure 2. CMS for the Reggio Calabria site. Decimal scale (left). Logarithmic scale (right).

Once the CMS is defined a corresponding set of GMs is selected based on coherence rules and deaggregation data. The selected records are shown in Figure 3 (right).

In order to investigate the effects of the dispersion of some IMs that most influence the response, the UHS coherent set has been scaled to the spectral acceleration of the first mode of vibration in the X direction ($S_a(T_{1X})$) and in the y direction ($S_a(T_{1Y})$), as it is shown in Figure 4 and Figure 5.

4 NONLINEAR ANALYSIS

The seismic performance is evaluated through both non linear static (pushover) and Non linear Response History Analysis (NL RHA). Table 1 summarizes the total number of NL RHA performed using the different GMs sets described above at hazard levels with PoE =10% and PoE=50%. The NL RHAs were performed applying to the building the three concurrent components, two horizontals and one vertical, of each GM.

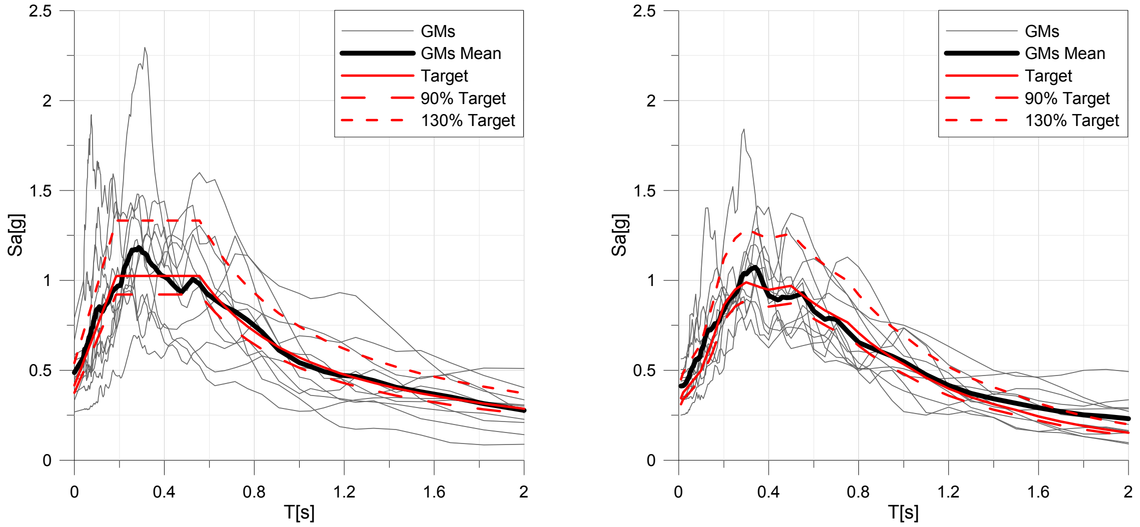


Figure 3. Set UHS coherent (left), set CMS coherent (Right).Unscaled GeoMean components

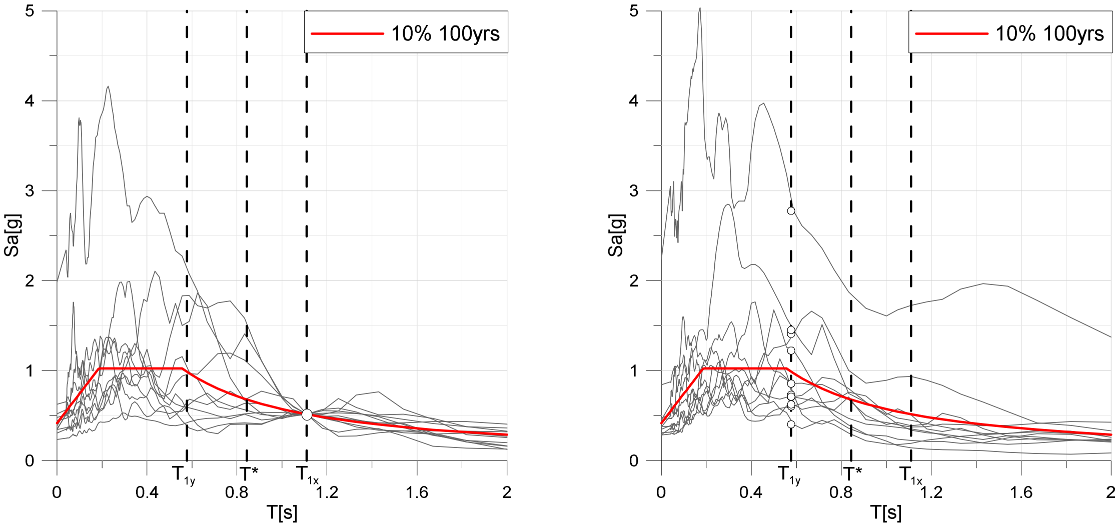


Figure 4. Set UHS scaled to Sa(T1x). Long.-component (left). 2Trasv.-component (right)

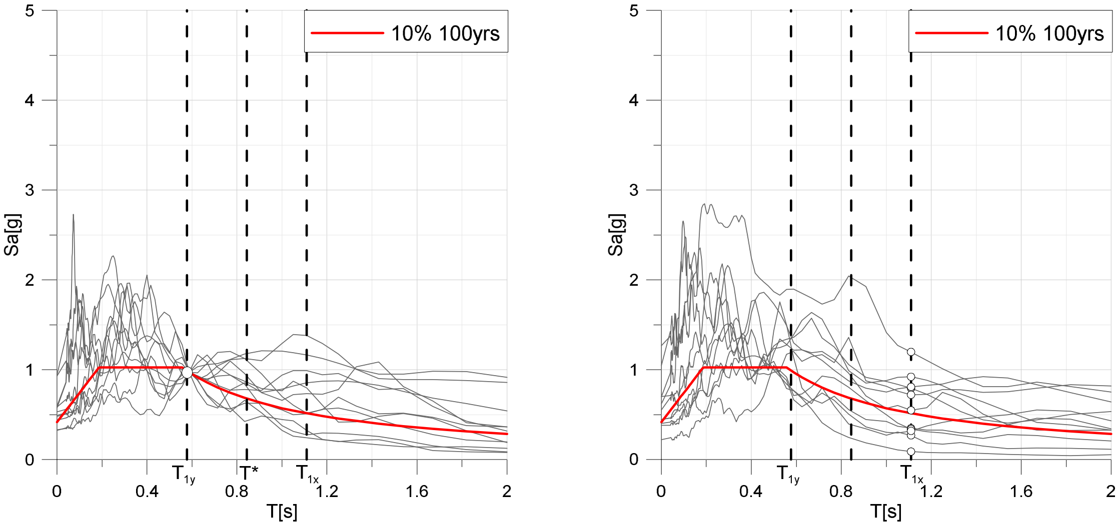


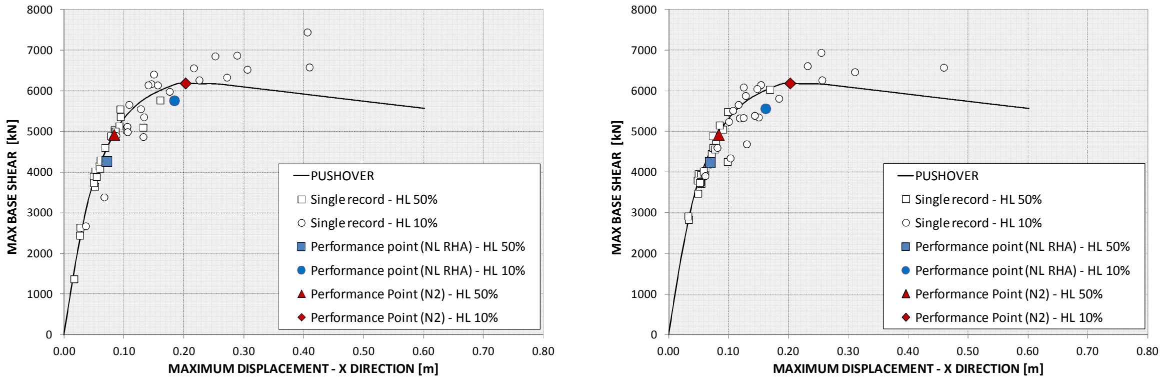
Figure 5. Set UHS scaled to Sa(T1y). Long.-component (left). Trasv.-component (right)

Table 1. NL RHA executed for HL 10%.

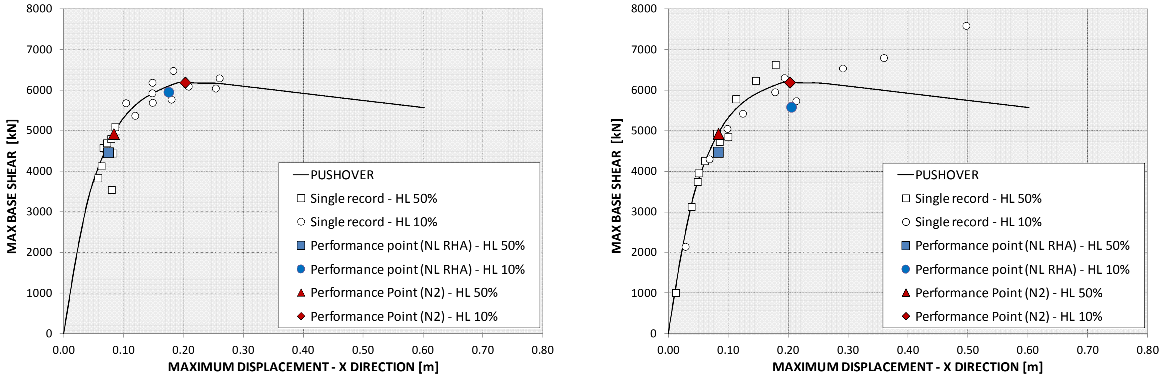
GM selection	Scaling technique	Total number of analyses	Directional combination
UHS	Unscaled	22	11 analyses. GM long. comp. - building X dir. GM trans. comp. - building Y dir.
	Scaled on $S_a(T_{1X})$	11	11 analyses. GM long. comp. - building X dir. GM trans. comp. - building Y dir.
	Scaled on $S_a(T_{1Y})$	11	11 analyses. GM long. comp. - building Y dir. GM trans. comp. - building X dir.
CMS	Unscaled	22	11 analyses. GM long. comp. - building X dir. GM trans. comp. - building Y dir. 11 analyses. GM long. comp. - building Y dir. GM trans. comp. - building X dir.

4.1 Results of NL RHA

The pushover curve and NL RHA for all the GMs sets adopted in terms of V_{max} - d_{max} for the X direction and V_{max} – $V(d_{max})$ for the Y-direction are shown in Figure 6 and **Figure 7**, respectively. Each plot reports also the performance points evaluated based on the N2 method for NL static analysis and the performance points evaluated as mean values of the maximum base shear and maximum displacement obtained through the NL RHA. It should be noted that in the X direction the structure is more flexible than the Y direction and post-yielding behavior is governed mainly by the flexural deformations of the moment resisting frames at ground and first floor. In the Y direction, the behavior is completely different and the displacement ductility is limited due to the buckling of the inverted V diagonal bracings causing a fast drop of the global resistance. The structure is stiffer due to the presence of several bracings. The collapse mechanism is thus characterized by the formation of a soft-storey mechanism at the ground level, while the first floor remains substantially elastic.



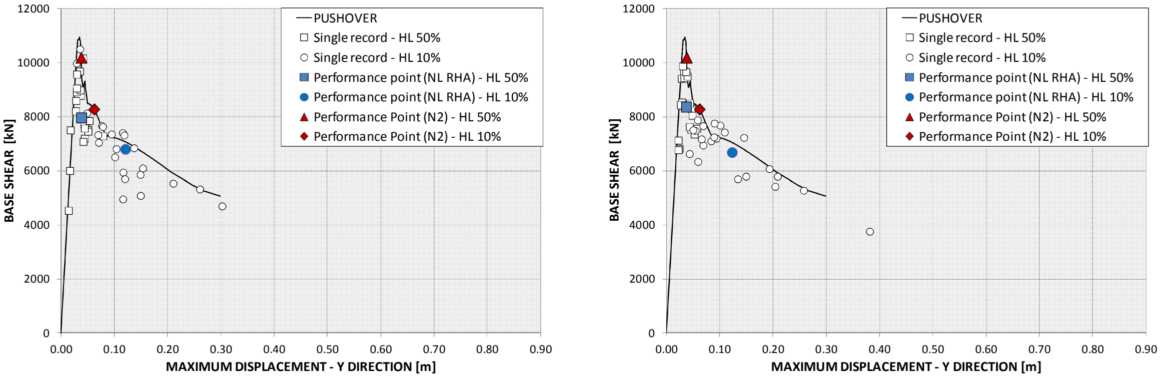
a) GM set: UHS unscaled e) GM set: CMS unscaled



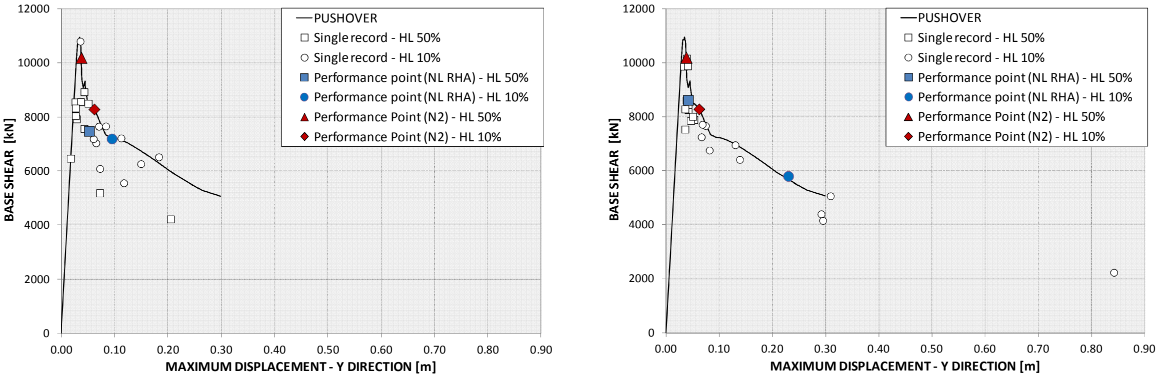
c) GM set: UHS scaled on $S_a(T_{1X})$ d) GM set: UHS scaled on $S_a(T_{1Y})$

Figure 6. Pushover curve and NL RHA results, in terms of maximum base shear - maximum displacement, in the X direction.

Analyzing the structural response in the X-direction, in all the cases, dynamic analyses yield lower values of EDPs with respect to static analysis. Considering first the "Unscaled set", it should be noted that for PoE=50% the results obtained based on the CMS and on the UHS sets are very similar, while for PoE=10% the CMS set produces lower values of EDPs (about 12% for displacements and IDR) due to the elongation of the period and lower spectral accelerations for $T>T_{1x}$ of the CMS compared to UHS. The coefficients of variation are very similar between the two Unscaled sets and there is only a slight increase of this parameter for seismic action with PoE=10%, as it was expected. The set scaled on $S_a(T_{1x})$ provides less scattered response for both the hazard levels considered, however, when the set is scaled on the spectral ordinates of the spectrum of the orthogonal direction (i.e. $S_a(T_{1y})$ when X-direction is investigated) the dispersion of results due to input uncertainty increase significantly, consistent with observations made by [26] [27] and [28].



a) GM set: UHS unscaled e) GM set: CMS unscaled



c) GM set: UHS scaled on Sa(T_{1X}) d) GM set: UHS scaled on Sa(T_{1Y})

Figure 7. Pushover curve and NL RHA results, in terms of base shear associated to the maximum displacement - maximum displacement, in the Y direction.

For the Y-direction, when the hazard level with PoE=50% is investigated, the results of static and dynamic analysis are comparable in terms of mean values and the set "Scaled on $S_a(T_{1y})$" gives the lower dispersion, as expected. Results for the hazard level with PoE=10% show how the static analysis underestimates significantly drift and displacements but, more significantly, the dispersion of results is very high for all the investigated cases. Furthermore, scaling on $S_a(T_{1y})$ does not give the expected advantages in terms of coefficients of variation and mean values. These values are considerably higher compared to the other case, also due to a few analyses with very high displacement demand which affect the final estimate.

5 CONCLUSIONS

The industrial structure investigated herein exhibits very different behavior in the two principal directions, and this behavior leads to very different observations regarding the effectiveness of the different GMs sets and scaling techniques.

In the X direction, the CMS provides less conservative results when the structure exhibits an inelastic behavior, due to the reduced values of spectral accelerations for periods longer than the first elastic mode period T_{1x}. Scaling GMs to Sa(T_{1x}) and Sa(T_{1y}) we observed that, for all the action levels investigated, the dispersion is highly reduced in the principal direction but, on the contrary, it becomes significant in the perpendicular direction. In the Y-direction, none of the GMs sets investigated herein led to significant advantages in the prediction of the response, due to the soft story mechanism and buckling of V bracings.

For this particular industrial structure, it is complex to define an IM that governs entirely the response, especially when the structure exhibits inelastic behavior and when 3D response is investigated. The use of CMS and the proposed scaling techniques may be not conservative or unsuitable for 3D analysis of industrial facilities and, in general, for structures which exhibit very different behavior in the two principal directions.

ACKNOWLEDGEMENTS

The authors acknowledge the support of the European Union's Research Fund for Coal and Steel (RFCS) research programme through the project PROINDUSTRY, "Seismic PROtection of INDUSTRial plants by enhanced steel based sYstems", grant agreement n° [RFSR-CT-2013-00019]. The content of this paper reflects the opinions of the authors and do not necessarily represent the opinions of the funding agency.

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