PROPOSAL OF A NEW LOSS RATIO PERFORMANCE MATRIX IN SEISMIC DESIGN FRAMEWORK

Iolanda NUZZO[1], Stefano PAMPANIN[2], Nicola CATERINO[3]

ABSTRACT

The paper proposes a new approach in the Performance Based Earthquake Engineering (PBEE) framework, introducing a loss performance matrix associating the expected Probable Maximum Loss (PML), i.e. the probable repair cost induced by a specific earthquake intensity, to various seismic design performance levels. It allows to better control economic consequences related to damage of structural, non structural elements and contents under different earthquake levels. The proposed loss performance matrix shows the probability of loss as a function of Repair Cost Ratio (RCR), which is the Repair Cost (RC) over the total RePLacement Value (RPLV) of the building/facility, for a given Intensity Measure, IM.
A qualitative shape of the loss performance matrix is illustrated in this paper, discussing the expected trend of the loss probability as a function of RCR for fixed earthquake intensity and for alternative structural systems.
Three different technologies (traditional cast-in-situ, dissipative rocking system, low-damage rocking system) are employed for alternative seismic design of a 5-storey 3-bay ordinary reinforced concrete building under a 500yrs earthquake event. The main aim is investigating how the construction technology may influence probable future repair costs, as well as comparing the analyses results via a newly proposed loss performance matrix.

Keywords: Performance-based; Loss estimation analysis; Repair cost; low-damage technologies

1. INTRODUCTION

The Performance-Based Earthquake Engineering (PBEE) framework, outlined in SEAOC Vision 2000 (1995), provides the seismic design philosophy at the base of modern earthquake engineering. Depending on earthquake intensity and the structure's occupancy or importance level it provides the minimum performance objectives to be achieved. The drawbacks of current design approaches and performance objectives, typically targeting Life Safety under the design-level earthquake (i.e. 500 years return period for an ordinary building) have been highlighted during recent seismic events, such as the Canterbury sequence 2010-2011 in New Zealand (Pampanin 2012, Mayes et al. 2013). A significant number of reinforced concrete buildings designed in accordance to capacity design principles, although preventing human life losses, suffered severe damage to structural and non-structural elements as well as to contents and were deemed to be (economically) irreparable. As a consequence, there were huge economic losses due to demolition and reconstruction activities, including the downtime. From this observation, it is clear the need to involve in the design process considerations about expected damage and economical losses along the service life of the structure. Several research studies have attempted to define damage index parameters, generally being a number between 0 (undamaged condition) and 1 (collapse condition). One of the best-known and commonly adopted damage index was proposed by Park and Ang (1985). It associates damage to ductility and

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energy accumulated during the seismic action through deformation-based and energy-based cumulative relations. Further contributions were provided by Cosenza et al. (1993), Stone and Taylor (1993), who proposed a damage index related to moment and curvature demand. Afterwards, Williams and Sexsmith (1995) introduced a new damage classification based on such indexes. Pampanin et al. (2002) proposed a damage parameter based on residual deformations. The latter resulted to be an effective measure of the actual extent and reparability of damage when interpreted by means of a maximum-residual performance-matrix. Even when assuming that a global structural damage can be actually and reliably quantified, the challenge still remains that of defining an appropriate threshold corresponding to reasonable (i.e. economically convenient) repair costs.
Alternatively, a design approach based on acceptable losses was introduced by Krawinkler et al. (2004). The basic idea was to choose a design alternative able to satisfy target demand values, corresponding to acceptable monetary loss, for a spectral acceleration $S_a(T_1)$ at a given hazard level (Figure 1).

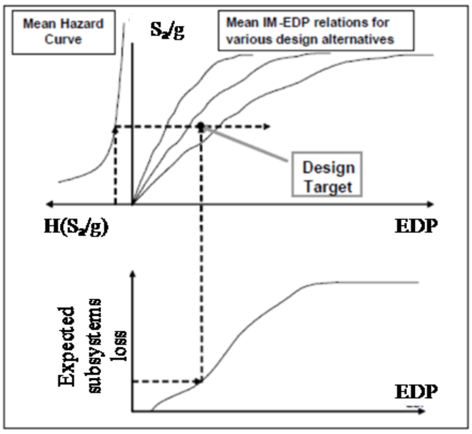

Figure 1 Designing for acceptable monetary loss - after Krawinkler et al. (2004)

According to this approach, statistical state-of-art results and engineering judgement are employed in order to get expected loss directly as a function of the seismic demand. More recently, Dhakal (2011) suggested a multi-objective seismic design procedure, defined as LOSD, "Loss Optimization Seismic Design", that considers the minimization of financial loss in addition to Life-Safety performance criteria.
In the present paper, an evolution of the traditional PBEE framework is proposed through a 3D loss performance matrix that employs the Probable Maximum Loss (PML) as performance measure. The PML is the result of an intensity-based loss assessment analysis and provides the probable repair cost induced by a specific earthquake intensity. The three axes of the new loss performance matrix show the seismic intensity levels, the probability of loss, corresponding to the probability of exceeding a certain level of loss given a seismic intensity, and the Repair Cost Ratio (RCR), that is the repair cost (RC) over the total RePLacement Value (RPLV) of the building/facility, for a given Intensity Measure (IM). Defining RCR and its probability of exceedence practically means defining PML, that is therefore briefly indicated as a new performance measure herein.
The qualitative shape of the loss performance matrix is illustrated in this paper, discussing the expected trend of RCR as a function of the probability of loss, for a given earthquake intensity level. The use of the proposed approach allows to associate building's damage directly to the consequent economic loss. The maximum allowable damage state can be correlated to the maximum amount of repair cost that the stakeholder or the insurance accept to provide. According to the accuracy of the loss analysis performed, both direct and indirect losses can be considered. In this way a direct communication between the stakeholder and the designer is possible, providing higher awareness about the (expected) amount of repair costs (time and money) to face in case of a seismic event. In this paper only direct losses are considered. Through the use of a loss performance matrix it would be possible to implement a cost-based design in which the designer selects the allowable RCR and the maximum (acceptable) probability of loss associated to it. Consequently the PML can become a key

design parameter. The design process would be iterated until the design loss conditions are satisfied, as proposed in Nuzzo et al. (2017). Future research developments should be able to provide the engineers with dedicated charts associating PML to EDP (Engineering Demand Parameters) and IM, thus allowing for a direct control/design of the building system economic performance.

2. LOSS PERFORMANCE MATRIX

A new loss performance matrix is proposed in the attempt to provide higher awareness of economic losses involved in the case of a severe seismic event. Generally, in traditional PBEE framework, performance levels correspond to a qualitative description of structural and non structural damage and are associated to discrete performance measures through Engineering Demand Parameters, EDP, such as interstorey drifts, floor acceleration etc.. Instead, in the herein proposed approach, the PML, Probable Maximum Loss, is assumed as key and overarching performance measure. In order to determine the PML an intensity-based loss analysis should be performed. Loss estimation analysis was first introduced by Cornell and Krawinkler (2000) and then re-defined by Krawinkler (2002) through the following multi-level integral, known as PEER equation:

$$\lambda(DV) = \iiint G(DV|DM)\; dG(DM|EDP)\; dG(EDP|IM)\; |d\lambda(IM)| \tag{1}$$

where

λ(DV) is the annual probability of exceedence of a decision variable;

G(DV|DM) is the conditional probability that the decision variable DV exceeds a specified value given that the damage measures DM equals a certain value;

dG(DM|EDP) is the differential of the conditional probability that DM exceeds a specified value given that the engineering demand parameter EDP equals a certain value;

dG(EDP|IM) is the differential of the conditional probability that EDP exceeds a specified value given that the intensity measure IM equals a certain value;

λ(IM) is the mean annual frequency of the IM

the four variables IM, EDP, DM, DV are continuous, independent, random variables.

If the loss analysis is performed for a given seismic intensity level, i.e. intensity-based analysis, the final DV will be PML. Differently, if the loss analysis is repeated in correspondence of several intensity levels, a multitude of intensity-based analysis is performed, thus realizing a time-based loss analysis. In this case, the final DV would correspond to the Expected Annual Loss (EAL). This latter parameter provides a broad and important set of information, as it describes the annual loss of the facility independently from the specific earthquake that could occur. On the other hand, the parameter PML is strictly correlated to the seismic intensity used to perform the assessment, thus provides knowledge about expected loss during the service life of the facility under the design-level earthquake. Although less complete, PML is also less computationally demanding than EAL. Moreover it provides a very important information, that is the probable maximum loss to face in case of the design earthquake's occurrence, against which the structure has been specifically designed. This data can be very useful for government's institutions in preparing urban emergency plans. For these reasons, PML is assumed in this paper as key performance measure in the loss matrix. An integrated version of the same matrix, out of the scope of this paper, would combine both PML and EAL as loss indicators.

The 3D loss performance matrix (Figure 2 - left-hand side) proposed in this paper associates different PML values, that is pairs of RCR-Probability of loss-exceedance, to different loss performance design levels, according to the seismic intensity IM. In particular, the lower are both RCR and corresponding probability of loss, the better is the facility's performance in terms of losses under the design earthquake level, yielding towards an ideal design. Conversely, when a system provides low probability of loss in correspondence of high values of RCR, it means that it is susceptible of significant damage, as well as a system characterized by high probability of loss associated to small repair cost values. When PML values are not satisfactory because RCR and/or its probability of exceedance are too high, the building's design is defined unacceptable, since economically

unrepairable. The gradual passage from ideal to unacceptable design is progressively less severe as the design seismic intensity (IM_d) level increases.
Given a fixed level of seismic intensity, the 3D loss performance matrix is reduced to a 2D version, as shown in Figure 2 - right-hand side. Actually, a PML curve, i.e. the curve associating the probability of loss to RCR, corresponds to a specific level of Intensity Measure. Considering the 2D loss matrix, the probability of exceeding a certain loss given a fixed intensity level is reported on the vertical axis. Conversely, on the horizontal axis RCR, defined as the ratio between the repair cost RC and the total replacement value RPLV, is presented within a range between 0% (no loss) and 50%, considered as the maximum loss threshold for which it is economically feasible to repair the facility (FEMA P-58-1 2012).

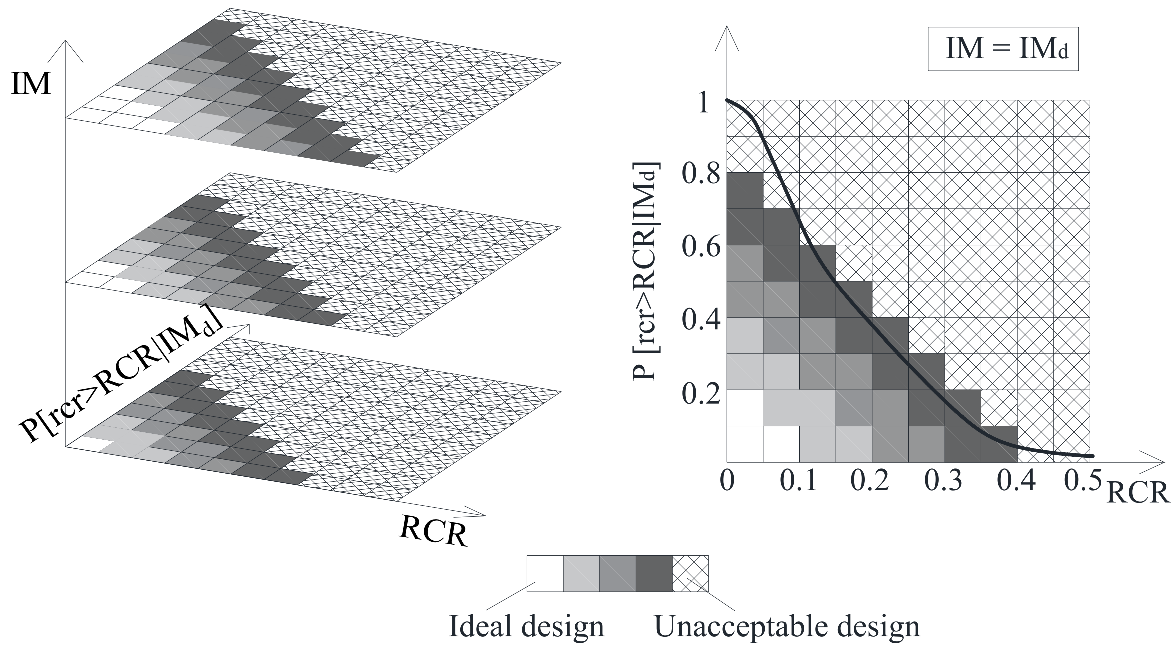

Figure 2. Loss performance matrix in 3D (left side) and 2D (right side) views

Superimposing the losses curve to the 2D loss performance matrix is the way suggested herein to check the achievement of a performance objective. This approach could be usefully involved within a cost-based design framework. According to such methodology, a building would be designed for a certain seismic hazard such that the maximum acceptable repair cost is associated to a minimum defined level of probability of loss (Nuzzo et al. 2017). As a matter of fact, through a calibrated loss performance matrix, the stakeholder can immediately appreciate the (expected) probability of loss associated to the design RCR value and decide if it is deemed acceptable. The lower the RCR the higher the probability of exceeding it under the given level of earthquake intensity. An ideal design corresponds to a system able to provide low probability of loss (e.g. lower than 20%) associated to low design repair cost (e.g. RCR ≤ 10%). As the IM increases, the PML curve increases as well (left-hand side of Figure 3).
In some cases it could happen that there is no correspondence between the allowable RCR value and the acceptable probability of loss, given IM. Then it can be necessary to implement low-damage technologies to reduce the probability of loss. For example consider the right-hand side of Figure 3, where alternative technology-based performance-objective are represented within a loss performance matrix for two different technologies, e.g. a traditional (TR) monolithic solution and a low-damage (LD) systems respectively. In correspondence to a certain RCR=rcr the probability of loss of the LD system is significantly lower than the TR one, given the design seismic intensity (IM_d):

$$P[rcr > RCR \mid IM_d]_{LD} < P[rcr > RCR \mid IM_d]_{TR} \tag{2}$$

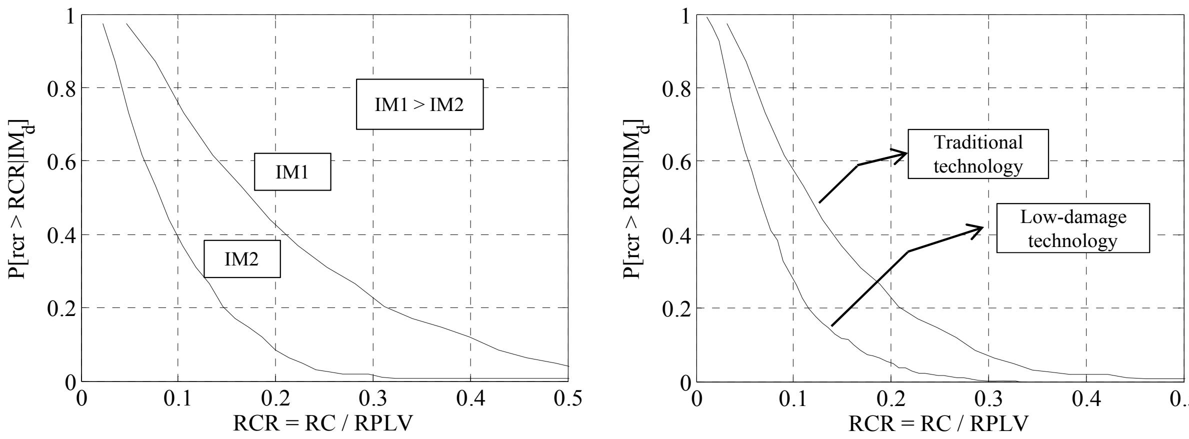

Figure 3 PML curve within a loss-performance matrix for different IM values (left). Alternative technology-based performance objectives, within a loss-performance matrix (right).

Vice versa, a certain confidence on the design in terms of probability of achieving that loss for a given earthquake intensity would result to higher RCR in the traditional TR solution when compared to the low-damage solution LD.

The use of this new loss performance matrix could imply that seismic design might not necessarily be carried out in order to limit a specific EDP, as it is in the traditional PBEE, rather it will pursue pre-defined level of economic losses associated to a certain level of confidence. In more practical terms, a combination of an EDP-based design approach (i.e. Displacement-Based Design) and loss-based charts/spectra would allow to integrate the two approaches and enhance the current mechanical-based approach with some more explicit economical considerations.

3. CASE STUDY APPLICATION

In this section, an intensity-based loss analysis is carried out for a case-study structure in order to provide a practical example of the use of proposed loss performance matrix. In particular, a new reinforced concrete structure, consisting in a 5-storey-3-bay building, characterized by seismic frames along the perimeter, with 7.5 m bay length and 3.2 m intestorey height, is considered. Beams and columns transversal sections are respectively 400x600 mm and 600x600 mm. The building's occupancy is assumed to be commercial office. Plan and elevation views of the structural system are given in Figure 4.

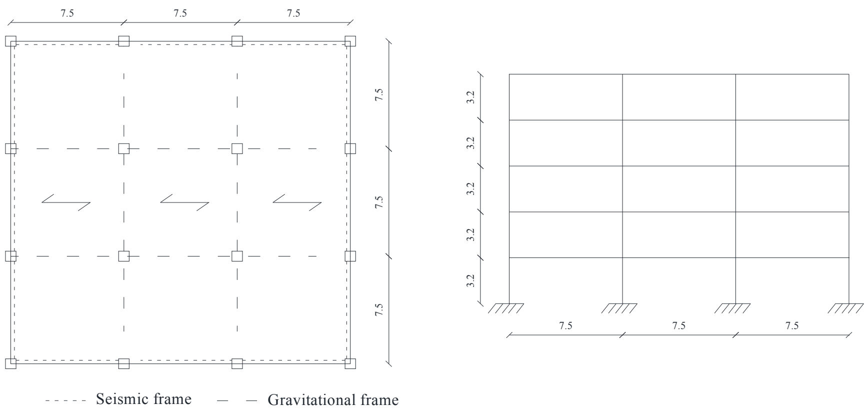

Figure 4 Geometry of the case study building (dimensions in m)

The structure has been designed first as a conventional cast-in-situ Moment Resisting Frame (MRF) system, for a design drift of 2%, adopting the Displacement Based Design (DBD) approach (Priestley 1997, Priestley et al., 2007), for a 500yrs return period event, in the respect of the Italian (NTC 2008) seismic code. The structure is assumed to be located in Norcia, where the Central Italy Earthquake stroke in 2016 (Mw 6.5), on a site class B, topography class T2. Concrete is C25/30 (f_{ck}=25MPa), steel reinforcement is B450C (f_{yk}=450MPa). Mechanical characteristics of beam-column connections in terms of moment M and rotation θ have been estimated in correspondence of yielding (θ_y, M_y) and ultimate capacity (θ_C, M_C) according to Italian and European code prescriptions. Results are summarized in Table 1.

Table 1 Mechanical characteristics of MRF connections

Element type	Section	# Rebars	Axial load [kN]	θ_y [rad]	M_y [kNm]	θ_C [rad]	M_C [kNm]
Beam at level 1-2-3	40x60	12Φ22	0	0.0067	436	0.0671	453
Beam at level 4-5	40x60	10Φ22	0	0.0065	364	0.0669	379
External column	60x60	12Φ22	323	0.0047	445	0.0505	524
Internal column	60x60	12Φ22	1163	0.0042	556	0.0308	642

A lumped plasticity finite element model has been constructed adopting "elasticBeamColumn" element for beams and columns. As far as plastic hinges modelling is concerned, element of zero length with "uniaxialMaterial Hysteretic" has been defined within beam-column connections and at the base of columns, assuming values of Table 1 and a degrading unloading stiffness factor of 0.3 and 0.5 respectively. Actually, since the elastic chord rotation at yielding is already accounted within the deformability of the "elasticBeamColumn" elements, a rigid-plastic moment-rotation behavior has been defined.

The total replacement cost is estimated to be 2177 \$/m^2, for a total RPLV=6.631.488 \$ (the total area is 506 m^2 per floor). Nonlinear time-history analyses have been performed using an Opensees (McKenna 1997)-Matlab code with the aim of evaluating the maximum inter-storey drift and acceleration at each floor, the residual drift and the collapse structural fragility curves, which are all input data required for the implementation of a loss estimation study according to FEMA P-58 methodology (FEMA P-58-1 2012), through the Performance Assessment Calculation Tool - PACT (FEMA P-58-2 2012). In particular a set of 7 couples of spectro-compatible records (Iervolino et al. 2009), listed in Table 2, have been selected from SIMBAD database (Smerzini and Paolucci 2013) for the evaluation of EDP quantities, such as interstorey drift and floor acceleration. Target design spectrum and corresponding records' response spectra are shown in Figure 5.

Table 2 Set of 7 spectro-compatible records

#	Waveform ID	EQ ID	Earthquake Name	Mw	PGA_x [g]	PGA_y [g]	Scaling Factor_x	Scaling Factor_y
1	242	111	Eastern Fukushima pref	6.6	0.19	0.18	1.84	1.95
2	139	51	Southern Iwate prefecture	6.9	0.30	0.22	1.18	1.59
3	243	111	Eastern Fukushima pref	6.6	0.13	0.10	2.73	3.55
4	432	83	Parkfield	6	0.36	0.23	0.98	1.54
5	438	83	Parkfield	6	0.14	0.23	2.50	1.54
6	146	54	S Suruga Bay	6.2	0.42	0.26	0.85	1.38
7	421	46	Irpinia	6.9	0.18	0.16	2.02	2.24

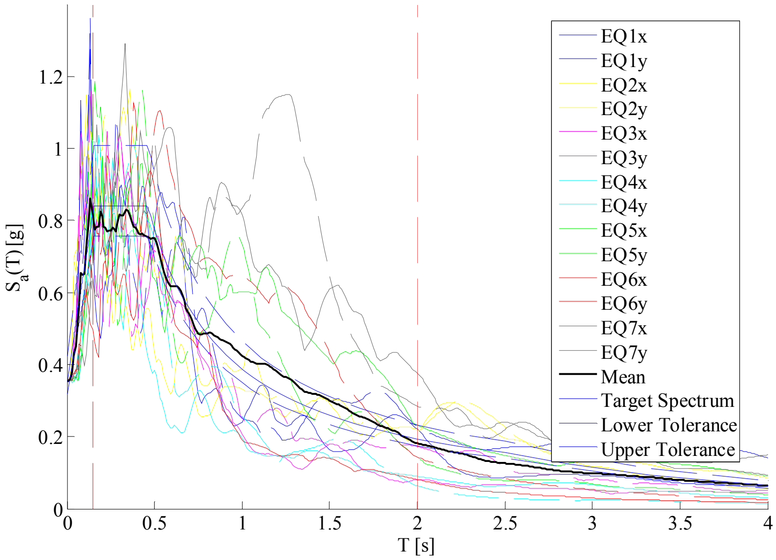

Figure 5 Selected record spectra

As far as the assessment of collapse probability is concerned, Incremental Dynamic Analysis (IDA) are performed (Vamvatsikos and Cornell 2002), selecting the 5% damped spectral acceleration at the fundamental period of vibration $S_a(T_1)$ as IM and investigating the interstorey drift as EDP. A wide number of ground motions is considered in the attempt of reducing uncertainties of the collapse fragility curve. In particular, a total of 42 records is selected on soil type B, covering a range of magnitude between 5 and 7 and distance between 15km and 40km (so including mid-to-far field events). Ground motion records are scaled considering an IM step of 0.1 g. Consistently with recent IDA applications (Miano et al. 2016), for each record only one of the two horizontal components is selected, i.e. the one giving the higher spectral acceleration at the fundamental period of vibration. The structural fragility curve is derived from IDA curves in correspondence to the 5% maximum drift value, commonly considered to generate collapse in MRF systems (Welch et al. 2014). In order to perform a loss estimation analysis through PACT, the user has to identify all the structural and non-structural (including furniture) elements which may contribute to determine losses and define for each of them possible damage states and corresponding fragility curves. More than 700 fragility components are already integrated in PACT software. Among them structural (beam-column joints), non-structural (curtain walls, internal partitions, prefabricated steel stairs, suspended ceiling, pendant lighting, elevator, sprinkler drops and piping, water distribution and sanitary piping, HVAC ducting, VAV box, packaged air handing unit, motor control center, low voltage switchgear) and contents (modular office workstation, electronic equipment) fragility components have been selected for the present case-study. A total of 500 realizations have been considered in the Montecarlo simulation. The final output of the analysis is the cumulative distribution function (CDF) of Repair Cost, RC (Figure 6 - left-hand side), then adimensionalized by RPLV obtaining the Repair Cost Ratio, RCR (Figure 6 - right-hand side), that is the probability of non-exceedance of a certain RCR value, given the seismic intensity.

The second technology adopted is a low-damage unbonded post-tensioned rocking re-centering system (synthetically indicated as hybrid - HYB). It was first studied in the late 1990s in the U.S. PRESSS (PREcast Seismic Structural System) program at the University of California, San Diego (Priestley 1991, Priestley 1996, Priestley et al. 1999). It consists of precast concrete elements jointed through dry ductile connections given by unbonded post-tensioning tendons/bars and longitudinal mild steel or additional external dissipation devices (Figure 7 - left-hand side). In this way both energy dissipation and self-centering are provided, leading to negligible residual deformation. In the present case-study the rocking mechanism is supposed at the base of ground columns and in the beam-column connections, although post-tensioning is inserted only in beams (axial load in columns is provided by gravity loads alone).

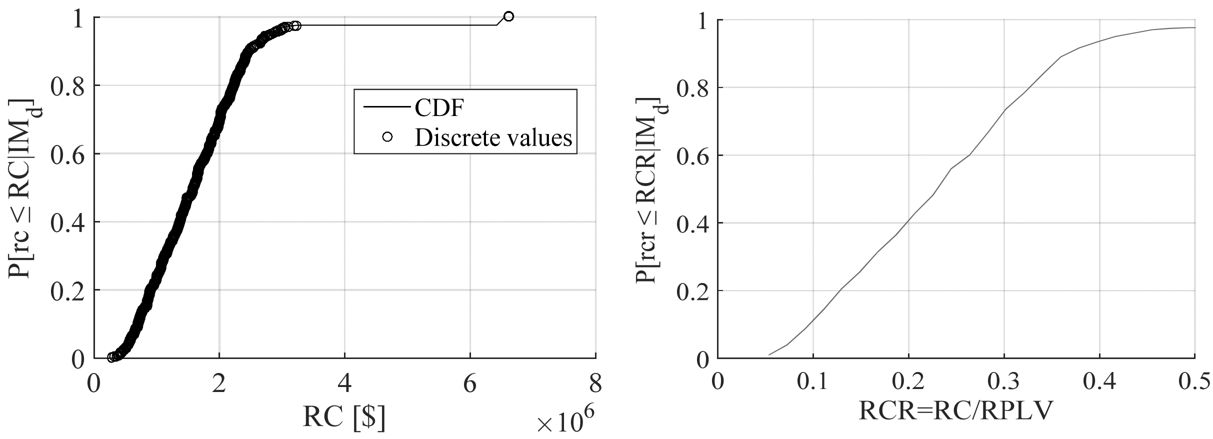

Figure 6 MRF case-study loss curves

The system is designed again through DBD (Pampanin et al. 2010) for a 500yrs return period event, resulting in connections details summarized in Table 3. Design drift is 2% and concrete class is assumed to be C28/35. HYB connections have been modeled in Opensees as two springs in parallel. The first corresponds to mild steel and is described by "uniaxialMaterial Hysteretic", as already employed for MRF system. The other represents the elastic nonlinear post-tensioning behavior, modeled by "uniaxialMaterial ElasticMultiLinear".

The total replacement cost is 2272 $/m^2$, corresponding to a total of 6.902.063 $. The increase of the cost, with respect to the MRF system, is due to post-tensioning. The fragility curve is get through IDA analysis and collapse is assumed at 6.9% of drift (Fitzgerald et al. 2016).

The loss estimation analysis is repeated for the hybrid case-study, assuming the same fragility components adopted for the MRF system with the exception of the structural beam-column joint, that is clearly different. The fragility component adopted for the hybrid beam-column connection has been developed by Fitzgerald et al. (2016) processing experimental results of 12 specimens reported in previous studies. The comparison between MRF and HYB beam-column connections' fragility curves at different Damages States (DS) is represented in Figure 7 - right-hand side. The probability of non-exceedance of loss in terms of RC and RCR are given in Figure 8.

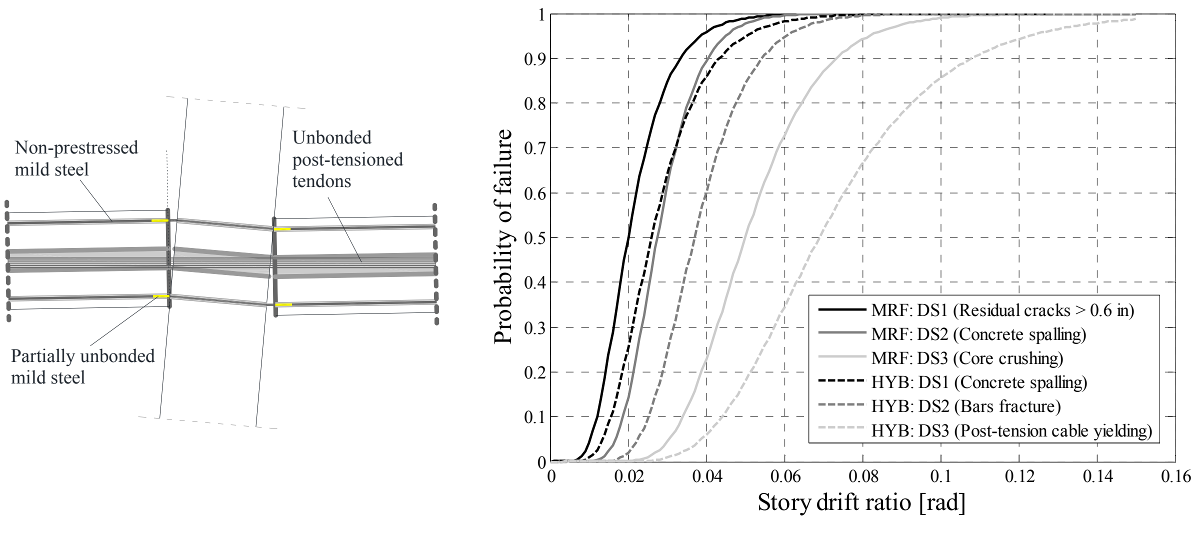

Figure 7 Hybrid system connection

Table 3 Mechanical characteristics of hybrid connections

Element type	Section [cm²]	Rebars	Axial load [kN]	M_{DEC} [kNm]	θ_y [rad]	M_y [kNm]	θ_C [rad]	M_c [kNm]
Beam at level 1-2-3	40x60	6Φ20; 7-15.2 Super Strands ($A=139mm^2$ - $T_{PT,initial}$=900kN)	0	90	0.0015	391	0.0447	468
Beam at level 4-5	40x60	6Φ18; 5-15.2 Super Strands ($A=139mm^2$ - $T_{PT,initial}$=400kN)	0	40	0.0012	258	0.0616	376
External column	60x60	12Φ20	265	27	0.0012	403	0.0635	518
Internal column	60x60	12Φ20	1163	116	0.0015	574	0.0332	652

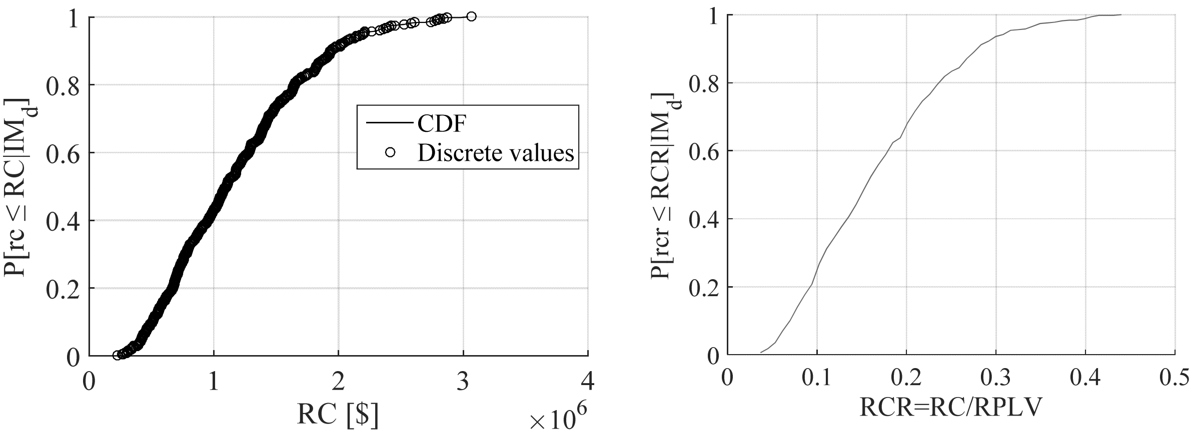

Figure 8 HYB case-study loss curves

Finally, in order to avoid excessive damage to non-structural components in a system, such as the HYB one, which is in principle (less damping) slightly more flexible than the corresponding MRF, it is advisable to use low-damage non structural components as well, at least for exterior curtain walls and internal partitions. More details can be found in Nuzzo et al. (2017) about fragility curves of low-damage components. Repeating the loss analysis in correspondence of the low-damage hybrid case study (LD-HYB), the CDF curves in Figure 9 are obtained.

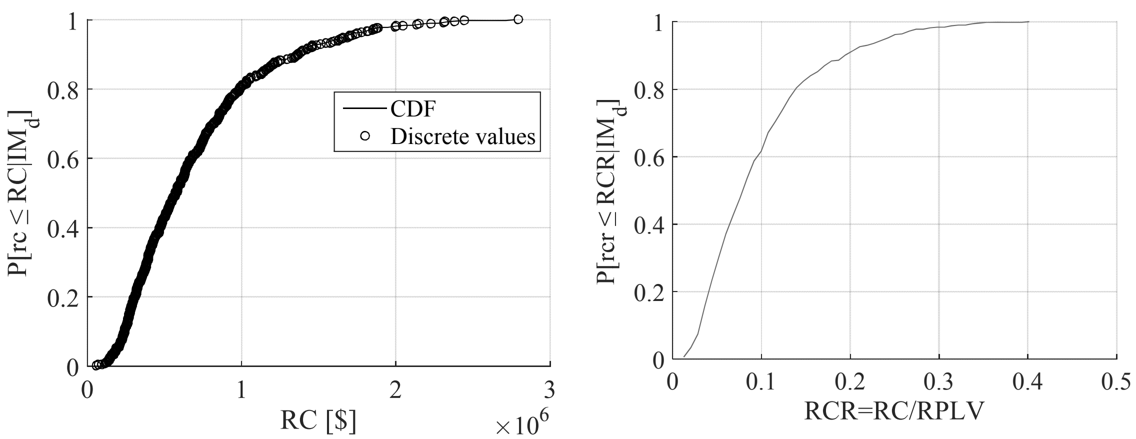

Figure 9 LD-HYB case-study loss curves

The three above construction techniques are compared in Figure 10 within the loss performance matrix. The benefits achieved employing low-damage technologies are evident, given that the performance of the MRF system fall within the undesired zone of the chart, i.e. where economic losses are unacceptably high. When low-damage techniques are adopted for both structural and non structural elements (see the case of LD-HYB configuration), the performance enhancement is much more significant compared to the MRF as well as to the HYB cases. Actually, low-damage non structural components could be assumed also for MRF system, but this would not prevent losses. Indeed, at the occurrence of a seismic event damaging only the skeleton (plastic hinges), the intervention to repair it would anyway require temporary removing of non-structural parts, thus generating a significant repairing cost. Moreover, it is to mention that in this application the first version of the PRESSS technology, with longitudinal mild steel as energy dissipation source, is considered since closer to the MRF system. Although an interesting advancement of the PRESSS technology consists in the use of external dampers, known as “plug & play", which provide higher dissipation and can be easily substitute after the occurrence of a severe seismic event, implying a lower economic repair impact (Pampanin 2005).

It is interesting to observe that the probability of loss approaches the zero for RCR values respectively of 0.40, 0.45 and 0.50 for HYB-LD, HYB and MRF respectively. This means that 40%, 45% and 50% of loss is the maximum (probable) expected, under the design-level earthquake, for the three technologies. Also it is worth noting that the LD-HYB system provides a RCR value of 10% associated to a probability of (exceeding) loss of almost 0.40, which may still be retained acceptable. Differently, in HYB and MRF structures the same level of loss would correspond to a probability of exceedance quite higher (0.8 and 0.9, respectively).

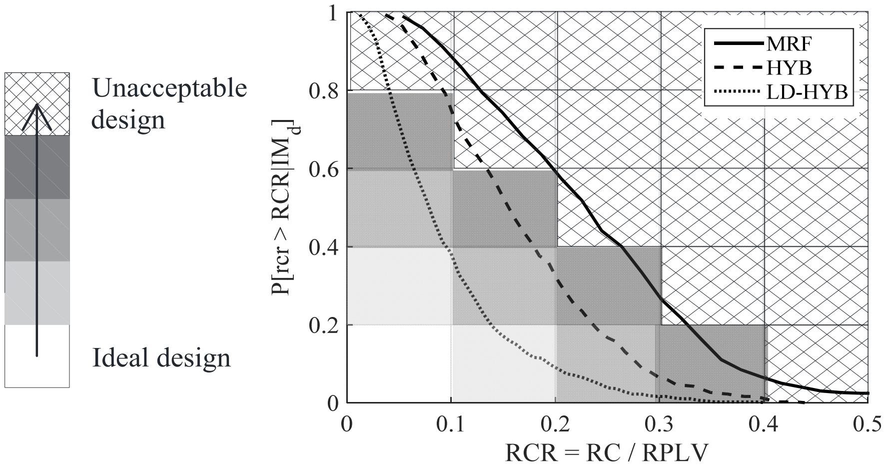

Figure 10 Comparison of traditional and low-damage technologies in the loss performance matrix

4. CONCLUSIONS

In the present study, a loss performance matrix has been introduced with the main aim of creating a tool able to assess and control the repair costs caused by seismic events. In particular, it considers the Probable Maximum Loss (PML) as new performance measure, instead of, or in addition to, typical discrete engineering demand parameters suggested by traditional PBEE framework. The probability of loss, corresponding to the probability of exceeding a certain loss once the seismic intensity is fixed, is expressed as a function of repair costs (RC) adimensionalized with respect to the total RePLacement Value (RPLV). The introduction of the loss performance matrix allows the implementation of a cost-based design approach, according to which seismic design is satisfactory when the maximum allowable Repair Cost Ratio (RCR), corresponding for example to the risk insurance coverage, is associated to a probability of loss sufficiently low, given the seismic design intensity. PML is chosen as performance measure in this paper due to its less computationally demanding evaluation with respect to EAL and the more clear meaning to the designer/stakeholder.

In this work, traditional and low-damage technologies are adopted as case-study to perform intensity-based loss estimation analysis and compare results in the loss performance matrix. It is interesting to observe the great improvement in terms of reduction of losses and corresponding probability of exceedance, achieved by the use of low-damage hybrid system with low-damage non-structural components, with a small increase of initial cost.

In on-going developments, the authors aim to perform significant high number of parametric analysis in order to give range of values in the new loss performance matrix for different structural typologies.

In particular, it would be very useful to know which are the possible PML values associated to a specific seismic-resistant system, depending on initial design considerations, technology and earthquake design intensity, so that a more direct cost-based design approach could be performed.

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