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DEVELOPMENT OF FEMA P-58 COMPATIBLE STORY LOSS FUNCTIONS: STEEL OFFICE BUILDINGS IN HIGH SEISMICITY REGIONS

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Abstract. *Since their release in 2012, the FEMA P-58 guidelines for seismic performance assessment of buildings have been regarded as the state-of-the-art paradigm for building-specific risk assessment and loss estimation. The latter is carried out through a rigorous component-by-component procedure that requires a complete component inventory, along with fragility and repair cost information. A fully compatible story-based approach is investigated herein as a simplified alternative that can potentially reduce the required input data with only a minor drop in accuracy. As an example, a set of story loss functions relating story repair cost with story-level engineering demand parameters are derived for standard inventory makeups of low/midrise steel office buildings. Preliminary results for a 4-story steel building show a promising balance between accuracy and simplicity.*

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1 INTRODUCTION

Performance-based assessment (PBA) focuses on ensuring the serviceability of a structure over its lifetime, by defining an acceptable level of damage and setting performance objectives. To this end, the latter need to be quantified using metrics that are meaningful for engineers, owners and other stakeholders to make informed risk-management decisions, such as economic losses, downtime or casualties. In addition, the random nature of earthquake events (e.g. in terms of their frequency of occurrence, location, intensity) as well as the epistemic uncertainty involved in predicting the structural response and the associated damage and losses has led many researchers to recognize the need to formalize the PBA procedure within a probabilistic basis. Within this scope, the Pacific Earthquake Engineering Research (PEER) Center has adopted the Cornell & Krawinkler framework [1, 2] for performance assessment; structural risk is evaluated through the calculation of the mean annual frequency (MAF) of a performance metric exceeding a specified threshold [3-8]. Performance assessment within the PEER framework is divided into four separate steps: hazard analysis, structural response analysis, damage analysis and loss analysis. Using the total probability theorem, the MAF can be expanded in terms of different random variables and calculated through Equation 1:

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

where *IM* denotes an intensity measure (e.g., the peak ground acceleration or the spectral acceleration at a specific period), *EDP* denotes an engineering demand parameter (e.g., the interstory drift ratio), *DM* denotes damage measures (e.g., discrete damage states), *DV* denotes the decision variable (e.g., economic losses), $G(x|y)$ is the conditional complementary cumulative distribution function (CCDF) of X exceeding a specified value x given Y=y, and $\lambda(x)$ denotes the mean rate of $\{x < X\}$ events per year.

The continuous advancement of the PEER methodology eventually led to the development of the FEMA P-58 guidelines for seismic performance assessment of buildings [9], which are widely considered the current state-of-the-art framework for building-specific risk assessment. Nevertheless, a few question marks are present over the vast amount of information needed for input, which might arguably impede its application in professional practice. Indeed, the required process of defining complete inventories of building components, and setting fragility and performance groups can prove particularly time-consuming and discouraging for practitioners, leading to attempts for simplification [10]. An alternative to the component-by-component procedure has been introduced by Ramirez and Miranda [11] who proposed an upfront integration of the component fragility functions with repair costs at the story-level, assuming a generic inventory based on the building's structural system and occupancy type. This procedure, termed story-based loss estimation, allows for a tremendous reduction of required input data, relieving the practicing engineer from a tedious duty and enabling quick loss investigations (see also [12]). By employing default component inventories based on the building characteristics, it also paves the way for a conceptual design aiming at loss limitation [13, 14], where story-level *DV-EDP* functions are used as the reference. This study illustrates a simple FEMA P-58 compatible methodology for derivation of story repair cost *DV-EDP* functions, henceforth referred to as story loss functions, that relate story-level repair cost directly to *EDP*s. A case study example for typical steel office buildings is presented and discussed.

2 FEMA P-58 COMPATIBLE STORY LOSS FUNCTIONS

The proposed framework foresees the formulation of story-level component inventories, representative of a considered building typology, their classification to component groups based on a set of criteria, and the FEMA P-58 consistent integration of component fragilities with the repair costs for each group. It can be structured into four steps as shown in Figure 1.

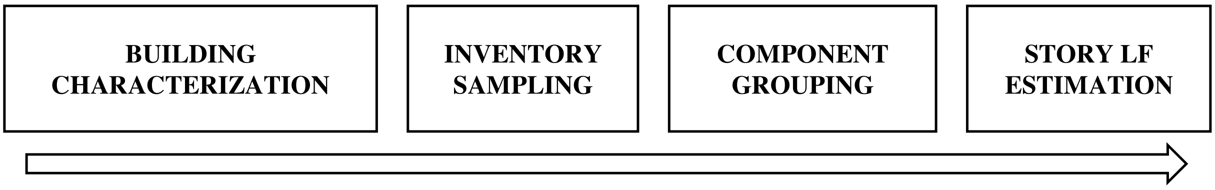


Figure 1. FEMA P-58 compatible story loss function estimation procedure

This initial step refers to defining the considered building typology to a sufficient level that will allow constraining the representative component inventories. Structural system and occupancy type constitute of course the two primary indicators of the component inventory, while height and luxury level could also be meaningful for the structural and content inventories respectively. The floor area size of the building (either in terms of total floor area or story floor area) can also prove to be particularly important; distinguishing inventories based on the size helps mitigate the problem that arises with components whose quantity cannot be approximated as linearly dependent to the story floor area. For example, a per m^2 approach might not be suitable for components such as elevators. Following the definition of the building typology, a compilation of typical inventories can be accomplished through statistics from existing buildings and market surveys, or by employing expert opinion, rules of thumb and judgment when better information is not available.

The compiled inventory is then classified into different performance groups. The components of each group will be assessed together for a mutual demand value at every intensity level, and thus the losses coming from all components within a group need to be tied to the same *EDP*, i.e. the *IDR* (interstory drift ratio) or *PFA* (peak floor acceleration) of a particular story or floor, respectively. As a result, two major distinctions can already be made; firstly into *PFA*-sensitive and *IDR*-sensitive components, and secondly into stories or floors with distinctly different inventories (e.g. ground floor, typical floor, roof). Classifying structural, non-structural, and content components into different groups might also be a useful distinction, as it expands the range of application of each derived story loss function, and helps disaggregate losses into contributions from different component types. Finally, a last distinction may need to be made with respect to the reference area of the component inventory. Indeed, the sampled component group inventories will be scaled to an area unit (e.g. 100 m^2), which might refer to a portion of the story floor area or the total building floor area. The number and capacity of certain components might be better predicted based on the story floor area (e.g. sprinklers), while those of other components might be better predicted based on the total floor area (e.g. HVAC equipment) [9].

The fourth step in Figure 1 refers to the derivation of functions that provide the total repair cost of the group components per area unit for different levels of an *EDP*. Firstly, an area unit is chosen and the number of group components is scaled accordingly. The procedure followed for loss estimation is based on the probabilistic framework adopted in the FEMA P-58. More precisely, the repair cost for the selected unit area at a given *EDP* level is computed through Monte Carlo simulation; in each realization, damage and loss are sampled for each individual component of the group, and all obtained losses are then summed to compute the component group's total loss given *EDP*. The damage and loss sampling can be carried out assuming perfect correlation between similar components within each unit area floor segment, if the latter is sufficiently small. Finally, for the purposes of derivation, we can assume that all components of the given type within the unit area are oriented along the same direction, i.e. as in a 2D building model. Analytical expressions can be obtained through regression analysis via a suitable function form that can fit the derived repair cost *DV-EDP* curves. The following function was found to capture adequately most story loss function shapes, at least for steel office building component groups:

$$\widehat{C}_{repair}(EDP) = MaxCost \cdot \left[e \cdot \frac{(EDP)^a}{b^a + (EDP)^a} + (1\text{-}e) \cdot \frac{(EDP)^c}{d^c + (EDP)^c} \right] \tag{2}$$

The parameters a,b,c,d,e are all obtained from non-linear regression analysis, whereas *MaxCost* is the total replacement cost of the component ensemble.

3 STORY LOSS FUNCTIONS FOR STEEL OFFICE BUILDINGS

3.1 Typology selection and collection of data

The procedure described above is illustrated herein by applying it for the typology of steel office buildings. Three alternative structural systems were examined, namely steel moment resisting frames (SMRF), steel X-braced frames, and steel Chevron-braced frames. With respect to building size, three different story floor area classes were considered for structural component groups, and three different total building floor area classes were considered for *PFA*-sensitive non-structural components at the ground floor/basement. A single occupancy of typical office use was studied, while three luxury levels were assumed for contents, namely high, medium, low.

Typical component inventories were built based on empirical and statistical data, as well as a brief survey conducted in university office buildings, as part of this example. Structural component types and quantities were formulated for typical EU & USA high-seismicity construction practice based on expert opinion (Table 1). In all cases, perimeter framing systems were employed; one brace per four spans was assumed for X-braced and Chevron-braced buildings, while moment resisting framers were placed in the entire perimeter of MRF buildings, apart from the corner bays of buildings with more than 3 bays. For computational reasons X brace components were considered independent in each story, rather than extending to multiple stories to maintain a proper angle. Structural component quantities were formulated for a few realistic combinations of building dimensions, assuming a typical 7 m beam span and simple rectangular plans, while their size and type refer to standard low/mid-rise buildings, which is the norm for most office facilities.

Non-structural components include staircases, exterior walls, interior partitions, but also ceilings, mechanical and electrical equipment and plumbing installations. Quantities were derived from a combination of real office buildings' design drawings, expert opinion from practicing engineers and the FEMA P-58 normative quantities. Based on the collected information and the use of judgment when necessary, an inventory of non-structural components was compiled (Table 2). Exterior wall and interior partition length, and suspended ceiling area quantities were indicatively measured from the design drawings of university office buildings. No sophisticated cladding was considered, but if needed, it can be introduced in addition to the estimated losses. Elevator and staircase types and quantities were assumed based on literature and judgment. Domestic hot and cold water piping and sanitary waste piping quantities were formulated based on the buildings' design drawings and assumptions regarding their configuration, that correspond to Greek construction practice. Hot water was considered to be provided by local water heaters rather than a central heating system. The assumed piping quantities were, however, found considerably smaller than the FEMA P-58 normative quantities, which can potentially be attributed to different construction practices. Hot water piping for heating depends on the HVAC system (all-air, water-air) and the building's layout. Due to lack of information, the FEMA P-58 normative quantity was used. The corresponding FEMA P-58 normative quantities were also used for HVAC ducting, diffusers, fire sprinkler piping and certain HVAC components. Uncertainty in component quantities was not taken into account in the derivation of story loss functions for reasons of simplicity, but should definitely be incorporated in more comprehensive studies; thus, in all cases the expected number of components was employed.

Electrical and mechanical equipment quantities, in specific, can be roughly approximated based on the total building floor area but cannot be all assumed to linearly vary with it. Therefore, this led to considering three different building total floor area classes, as mentioned before: $A_{tot} < 2000$ m^2, 2000 m^2 $< A_{tot} <$ 5000 m^2, $A_{tot} >$ 5000 m^2. The non-structural component quantities for the former group were chosen for a 1500 m^2 total floor area building, whereas 3000 m^2 and 6000 m^2 buildings were assumed for the other two respectively. Most HVAC systems nowadays are all-air or water-air systems and heating and cooling is achieved either through heat pumps or boiler-chiller systems. Among them, FEMA P-58 provides fragility information only for chillers, which as a result were the only such component considered in this study. Information regarding the types of electrical and mechanical equipment (chiller, air-handling unit, transformer, low voltage switchgear, generator, etc), their capacity and installation (anchorage, isolation) was obtained from several design offices, rules of thumb, and literature (Table 3). It should be noted that, due to limited information, these data should be taken with caution. Furthermore, most such components were assumed unanchored due to the especially dissenting opinions regarding installation practices, at least in Greece, among practicing engineers.

Component	**FEMA P - 58 Classification Number**	A_{st} **< 750 m^2**	**750 m^2 <** A_{st} **< 1500 m^2**	A_{st} **> 1500 m^2**
Concentric X-Braced Buildings				
X Braces	B1033.013a	1.00	0.56	0.37
Shear Tab Connections	B1031.001	10.92	9.96	9.42
Column Splices	B1031.021a	0.91	0.76	0.68
Concentric Chevron Braced Buildings				
Chevron Braces	B1033.011a	1.00	0.56	0.37
Shear Tab Connections	B1031.001	10.92	9.96	9.42
Column Splices	B1031.021a	0.91	0.76	0.68
MRF Buildings				
RBS connections (1-sided)	B1035.001	0.58	0.63	0.38
RBS connections (2-sided)	B1035.011	2.18	1.10	0.72
Shear Tab Connections	B1031.001	5.99	7.13	7.61
Column Splices	B1031.021a	0.91	0.76	0.68
Column Base Plates (for all structural systems)				
Column Base Plates	B1031.011a		3.09	

Table 1. Mean structural component quantities per 100 m^2 of story floor area

Component	FEMA P-58 Classification Number	Unit	Quantity per 100 m^2	Source
Exterior Walls	B2011.011a	100 SF	8.52	NTUA survey
Wall Partitions	C1011.001a	100 LF	1.00	NTUA survey
Stairs	C2011.001b	1 EA	0.15	Judgement
Suspended Ceiling, Area (A): A < 250	C3032.001a	250 SF	1.62	NTUA survey
Suspended Ceiling, Area (A): 250< A < 1000	C3032.001b	600 SF	0.45	NTUA survey
Suspended Ceiling, Area (A): 1000< A < 2500	C3032.001c	1800 SF	0.04	NTUA survey
Cold Water Piping (dia > 2.5 inches)	D2021.011a	1000 LF	0.013	Judgement
Domestic Hot Water Piping - Small Diameter Threaded Steel	D2022.011a	1000 LF	0.0059	Judgement
Hot Water Piping for Heating - Small Diameter Threaded Steel	D2022.011a	1000 LF	0.0054	FEMA P-58
Hot Water Piping for Heating - Large Diameter Welded Steel	D2022.021a	1000 LF	0.0054	FEMA P-58
Sanitary Waste Piping	D2031.011b	1000 LF	0.028	Judgement
HVAC Fan In Line Fan	D3041.001a	10 EA	0.056	Judgement
HVAC Ducting less than 6 sq. ft	D3041.011a	1000 LF	0.08	FEMA P-58
HVAC Ducting - 6 sq. ft or greater	D3041.012a	1000 LF	0.02	FEMA P-58
HVAC Drops / Diffusers in suspended ceilings	D3041.031a	10 EA	0.97	FEMA P-58
Variable Air Volume (VAV) box	D3041.041a	10 EA	0.76	FEMA P-58
Fire Sprinkler Water Piping	D4011.021a	1000 LF	0.22	FEMA P-58
Fire Sprinkler Drop	D4011.031a	100 EA	0.04	NTUA survey
Distribution Panel	D5012.033b	AP 225	0.17	Expert opinion

Table 2. Statistics of non-structural component quantities per 100 m^2 of story floor area

Component	FEMA P-58 Classification Number	Unit	Quantity per 100 m^2		
			A_{tot} < 2000m^2	2000m^2 < A_{tot} < 5000m^2	A_{tot} > 5000m^2
Hydraulic Elevator	D1014.021	1 EA	0.067	0.033	0.033
Battery Rack	D5092.011a	1 EA	0.067	0.033	0.017
Battery Charger	D5092.021a	1 EA	0.067	0.033	0.017
Distribution Panel	D5012.033b	225 AP	0.200	0.133	0.083
Transformer/Primary Service	D5011.011b	250 KVA	0.047	-	-
	D5011.011c	500 KVA	-	0.023	0.023
Low Voltage Switchgear	D5012.021a	225 AP	0.086	-	-
	D5012.021b	400 AP	-	0.049	-
	D5012.021c	800 AP	-	-	0.024
Diesel Generator	D5092.032b	250 KV	0.019	0.019	0.019
Chiller	D3031.012e	250 TN	0.018	0.018	0.018
Air Handling Unit	D3052.011d	30000 CFM	0.026	0.026	0.026

Table 3. Total building floor area dependent non-structural component quantity statistics per 100 m^2

The contents' inventory for office facilities was obtained through a limited survey conducted in four university buildings. Mean values and coefficients of variation for content quantities are presented in Table 4. Bookcase and filing cabinets were considered unanchored and their fragility functions were altered to relate damage probabilities to peak floor acceleration instead of peak floor velocity. To this end, peak velocity to peak acceleration representative ratios [15], originally referring to soils, were used for the conversion, assuming a period of harmonic wave equal to 1.0 sec (roughly indicative of flexible low/mid-rise steel buildings) and using linear interpolation. Contrary to the structural and non-structural component costs, which were taken from the FEMA P-58 database and were therefore assumed equal to the US costs, contents' costs were assigned after a brief market survey in Greece; the prices were considered equivalent to US dollars, not appreciably different from 2016 euros. Three categories were defined based on their value: high, medium and low luxury level; apart from different replacement costs, a different number of components was also assigned to each different luxury level. Without any in-depth investigation, lognormal distributions were chosen for high luxury contents cost, while truncated normal distributions were assigned to low and medium luxury contents. Scale economy effects on replacement and repair costs were chosen to be neglected.

Component	FEMA P-58 Classification Number	Mean Quantity (EA)	CV	low luxury		medium luxury		high luxury	
				Mean Value (€)	CV	Mean Value (€)	CV	Mean Value (€)	CV
Desks	E2022.001	6.05	0.28	80	0.2	200	0.4	500	0.4
Printers/ Fax machines/ Scanners	E2022.023	4.26	0.34	80	0.3	140	0.5	300	0.5
Desktop computers/ Laptops	E2022.023	4.48	0.30	350	0.2	600	0.3	1000	0.3
Monitors	E2022.023	4.37	0.42	80	0.3	120	0.5	200	0.5
Bookcase, 2 shelves	E2022.102a	0.10	2.00	40	0.3	80	0.2	140	0.2
Bookcase, 3 shelves	E2022.103a	0.44	0.74	50	0.3	100	0.2	200	0.2
Bookcase, 4 shelves	E2022.104a	0.64	1.39	70	0.3	140	0.2	250	0.2
Bookcase, 5 shelves	E2022.105a	0.02	2.00	70	0.3	170	0.2	290	0.2
Bookcase, 6 shelves	E2022.106a	9.61	0.66	80	0.3	200	0.2	320	0.2
Vertical Filing Cabinet, 2 drawer	E2022.112a	1.07	0.91	30	0.2	70	0.2	100	0.3
Vertical Filing Cabinet, 4 drawer	E2022.114a	0.49	0.41	40	0.2	80	0.2	110	0.3
Lateral Filing Cabinet, 2 drawer	E2022.124a	0.37	0.37	30	0.2	70	0.2	100	0.3

Table 4. Statistics of content quantities per 100 m^2 of story floor area and values per unit

3.2 Components grouping for steel office buildings

Structural components were distinguished into 10 different groups, for different combinations of structural system and story floor area, along with an additional function for column base plates (Table 5); the latter is to be assigned solely to the ground floor. Non-structural components were firstly distinguished into *IDR*-sensitive and *PFA*-sensitive groups. *PFA*-sensitive non-structural component story loss functions were developed for three different locations, i.e. ground floor or basement, roof floor and typical floor, as the inventories of the first two include mechanical and electrical equipment that is installed only there. In addition, the roof floor inventory includes components normalized to the total building floor area (e.g. chiller) as well as to the roof floor area (e.g. suspended ceilings of the top story); therefore, roof level *PFA*-sensitive components were were further discretized based on their reference area. Finally, as previously noted, three alternate groups for different building sizes were defined for ground floor *PFA*-sensitive components. Content components are all *PFA*-sensitive, scaled to story floor area, with similar inventories defined in all floor levels. Thus, only three content groups were needed, one for each of three luxury levels. All component groups are presented in Table 5, while Figure 2 provides an illustration of their assignment to different stories, which is a choice to be made by the user.

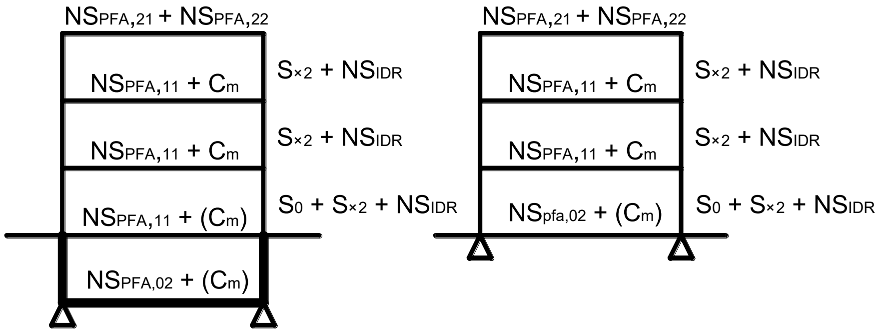


Figure 2. Examples of component group assignment: story loss functions NS_{IDR} and S_{X2}, assuming an X-braced system and a medium story floor area, are assigned to all stories above ground; $NS_{PFA,11}$ is assigned to all typical story floor levels; $NS_{PFA,21}$ and $NS_{PFA,22}$ are assigned to roof level; $NS_{PFA,02}$ is assigned to basement (on the left) or ground floor (on the right) level, assuming a medium total building floor area; S_0 is assigned on the ground floor; and C_m functions, for medium value contents, are assigned on the levels where content components may be located.

Group Description	Total or Story Area	Name
X-braced building structural components	$A_{st} < 750$ m^2	S_{X1}
	750 m$^2 < A_{st} < 1500$ m^2	S_{X2}
	$A_{st} > 1500$ m^2	S_{X3}
Chevron-braced building structural components	$A_{st} < 750$ m^2	S_{C1}
	750 m$^2 < A_{st} < 1500$ m^2	S_{C2}
	$A_{st} > 1500$ m^2	S_{C3}
MRF building structural components	$A_{st} < 750$ m^2	S_{M1}
	750 m$^2 < A_{st} < 1500$ m^2	S_{M2}
	$A_{st} > 1500$ m^2	S_{M3}
Column base plates	-	S_0
IDR-sensitive typical floor NS components	-	NS_{IDR}
PFA-sensitive ground floor NS components	$A_{tot} < 2000$ m^2	$NS_{PFA,01}$
	2000 m$^2 < A_{tot} < 5000$ m^2	$NS_{PFA,02}$
	$A_{tot} > 5000$ m^2	$NS_{PFA,03}$
PFA-sensitive typical floor NS components	-	$NS_{PFA,11}$
PFA-sensitive roof floor NS components scaled on story floor area	-	$NS_{PFA,21}$
PFA-sensitive roof floor NS components scaled on total building floor area	-	$NS_{PFA,22}$
Low luxury contents	-	C_L
Medium luxury contents	-	C_M
High luxury contents	-	C_H

Table 5. List of story loss function component groups

3.3 Estimation of story loss functions for steel office buildings

Story loss functions per 100 m^2 of floor area were computed for all component groups. As already mentioned, dispersion in structural and non-structural component quantities was neglected, as they are assumed to vary little from building to building on the basis of the area. The dispersion of the more variable contents' quantities was indirectly taken into account by altering the quantities of high and low luxury level contents by one standard deviation σ vis-à-vis the medium luxury estimates. Component fragility functions and most consequence information (repair and replacement costs) were taken from the FEMA P-58 database.

Some of the obtained story loss functions are presented in Figure 3, starting with the one for structural components of X-braced buildings (S_{X2}) in Figure 3a. The repair cost starts rising for particularly small values of *IDR*, since the first damage state for the assumed X-braces is identified for a median *IDR* of 0.0035 according to the FEMA P-58 fragility data. After all braces have reached their final damage state, the increase of *IDR* does not translate to any further increase in repair cost; therefore, the loss curve maintains a relatively constant value between *IDR* values of 0.02 and 0.03. Gravity connections and column splices enter their first respective damage states for a median *IDR* of 0.04; this explains the second sharp surge of the repair cost before it stabilizes again, when all structural components are fully damaged. Figure 3b shows the loss curve for structural components of MRF buildings (S_{M2}). This time economic losses start to appear for larger values of *IDR* due to the increased lateral flexibility of MRFs in comparison with braced frames. Thus, the loss curve exhibits only one clear plateau in terms of repair cost for different values of *IDR*, when all components are damaged. The loss curve of *IDR*-sensitive non-structural components (NS_{IDR}) in Figure 3c resembles in shape the one of the S_{X2} component group: in fashion similar to X-braces, interior wall partitions and staircases fail much earlier than the exterior cold formed steel walls with flat strap X-bracing. Figures 3d, 3e and 3f present the loss functions of the *PFA*-sensitive component groups $NS_{PFA,11}$, $NS_{PFA,02}$ and C_M.

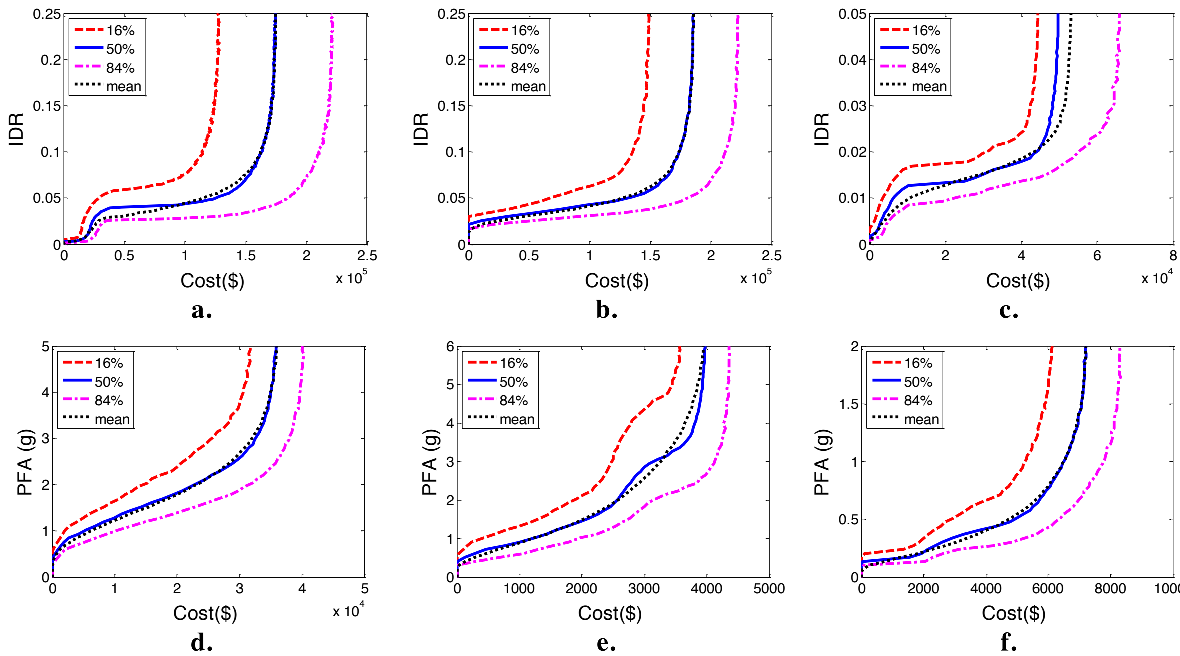
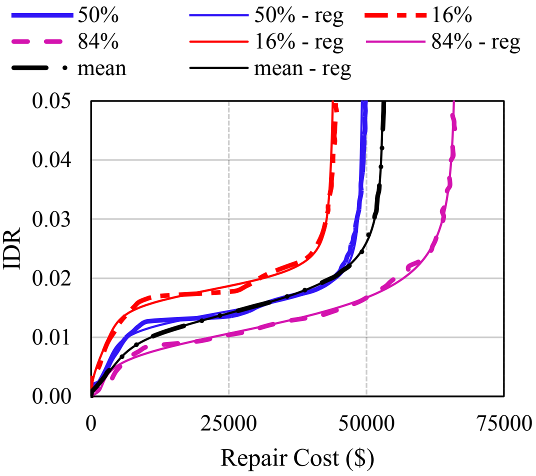


Figure 3. Story loss functions for a) X-braced building structural components for 750 m^2 < A_{st} < 1500 m^2 (S_{X2}), b) MRF building structural components for 750 m^2 < A_{st} < 1500 m^2 (S_{M2}), c) *IDR*-sensitive typical floor NS components (NS_{IDR}), d) *PFA*-sensitive typical floor NS components ($NS_{PFA,11}$), e) *PFA*-sensitive ground floor NS components for 2000 m^2 < A_{tot} < 5000 m^2 ($NS_{PFA,02}$), f) medium luxury level content components (C_M)

In order to derive analytical formulas, a non-linear least-squares regression was carried out using the Generalized Reduced Gradient algorithm [16]. All curves were fitted via Equation 2 (Figure 4). Maximum relative regression errors were occasionally found seemingly large, but that was the result of a local mismatch at the onset of losses (i.e. at very small values of actual repair cost).



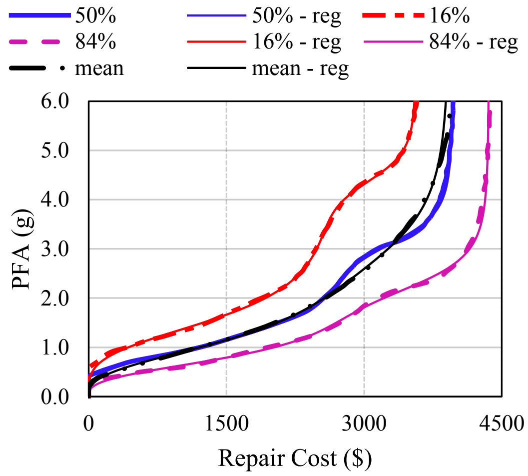


Figure 4. Examples of loss function regression fitting: (a) *IDR*-sensitive typical floor NS components NS_{IDR}, (b) *PFA*-sensitive ground floor NS components $NS_{PFA,02}$

4 LOSS ESTIMATION OF A 4-STORY STEEL BUILDING USING STORY LOSS FUNCTIONS

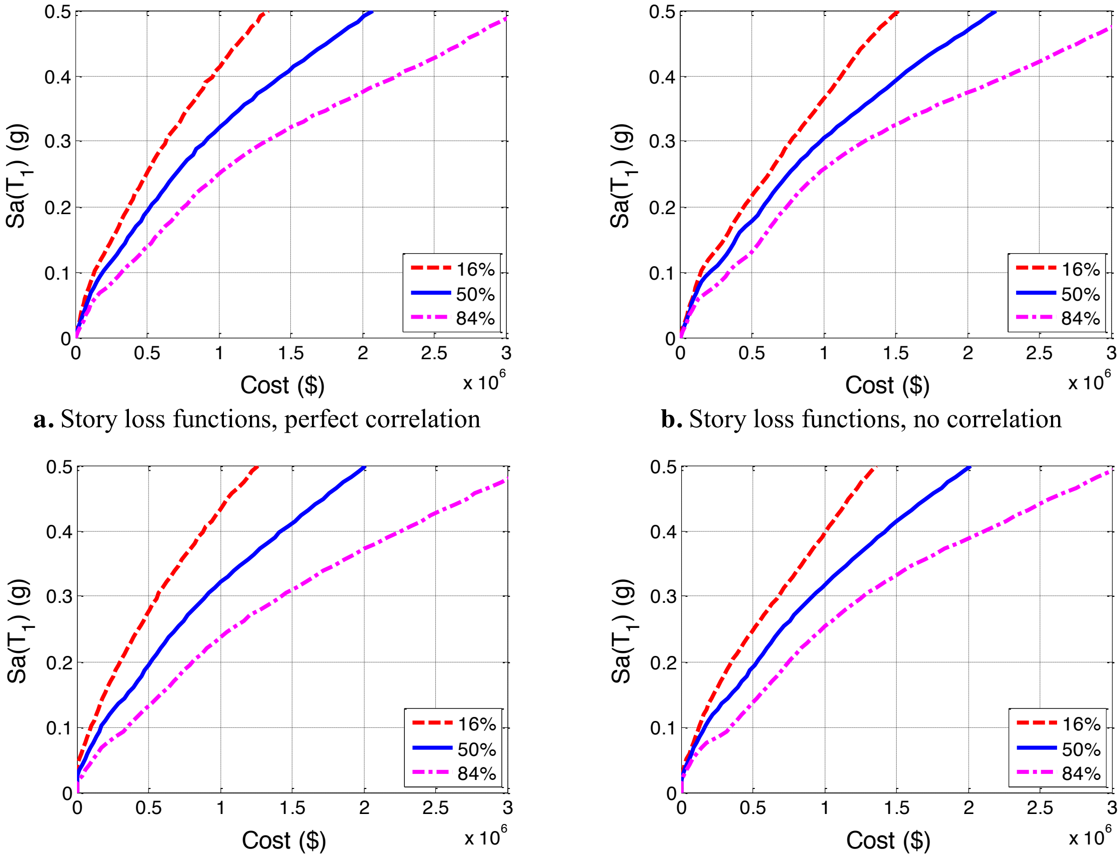
Having this type of story loss functions in one's disposal can immensely facilitate loss estimation. By defining the conditional CCDF function of *DV* exceeding a specified value given the *EDP* value, *G(DV|EDP)*, Equation 1 can be rewritten as:

$$\lambda(DV) = \iint G(DV|EDP)\cdot|\mathrm{d}G(EDP|IM)|\cdot|\mathrm{d}\lambda(IM)| \tag{3}$$

where $G(DV|EDP)$ can be directly calculated with the use of story loss functions, merging the steps of damage and loss analysis at the expense of some accuracy and flexibility. Other than that, the loss estimation procedure is similar to its FEMA P-58 component-by-component counterpart, except that component groups are now assigned to each story level instead of individual components. For each level of response, repair costs can now be sampled by performing a series of Monte Carlo simulations for each component group rather than for each component. The distribution of repair cost given the *EDP* value can be inferred based on the 16th and 84th quantile values that are provided for each function. Correlation between the individual area unit floor segments can be assigned or not, according to the user's preference. Repair and replacement costs, if obtained from the FEMA P-58 report, correspond to the US market. Nonetheless, by adopting a few additional assumptions one can, for instance, extend cost conversion procedures proposed for the component-by-component methodology [10] for application within the story loss function approach.

A simple case study was carried out for a seismically designed four-story steel moment-resisting frame (SMRF) building studied in NIST GCR 10-917-8 [17]. It has a rectangular 42.67m x 30.48m layout with a story floor area equal to 1301 m^2; the bay length is 6.1 m; story height is 14.57 m for the first story and 13.96 m for the rest. Further details regarding the structural properties and loads applied can be found on the aforementioned report. Structural response quantities were obtained through an incremental dynamic analysis [18]. Additional information on the modelling and analysis of the building are provided in [19]. Component groups S_{M2}, NS_{IDR}, $NS_{PFA,11}$, C_M were assigned on typical floors, $NS_{PFA,03}$ and S_0 were assigned only on the ground floor, while $NS_{PFA,21}$, $NS_{PFA,22}$ were assigned on the roof. Within this study, the repair cost at each *EDP* level was modeled with a normal distribution for all story loss functions; the lower tail was truncated at zero, so as to prevent negative cost values. With respect to component correlation, two different cases were examined; in the first one, perfect correlation was assumed between the 100 m^2 segments of each component group at each story, while in the second case no correlation was considered between the segments.

The total losses for the two cases are presented in Figures 5a and 5b for spectral accelerations up to 0.5g. More precisely, for a 0.5g acceleration, the no correlation assumption yields a median total repair cost of $2.19 \cdot 10^6$ €, while the perfect correlation assumptions leads to drop of 5% in median total repair cost ($2.07 \cdot 10^6$ €), but as anticipated, with a considerable increase in dispersion. Losses were also calculated with a very crude approach, using solely the median *EDP* and repair cost values, ignoring any dispersion; for a 0.5g acceleration they were estimated as equal to $1.4 \cdot 10^6$ €. This discrepancy is certainly not minor, and therefore such a simplification should be deemed inappropriate.



a. Story loss functions, perfect correlation

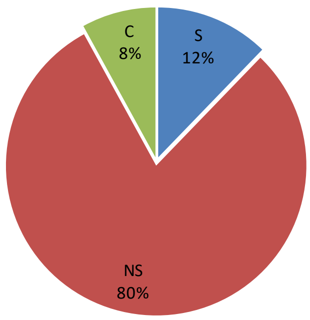
b. Story loss functions, no correlation

c. FEMA P-58, perfect correlation

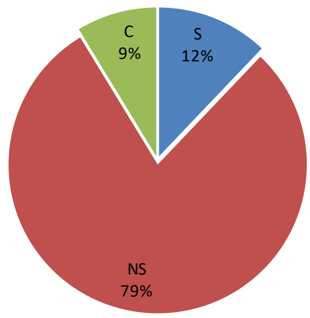
d. FEMA P-58, no correlation

Figure 5. Total repair cost for different levels of spectral acceleration *Sa* calculated a) through story loss functions assuming perfectly correlated 100 m^2 segments of each component group, b) through story loss functions assuming uncorrelated 100 m^2 segments of each component group, c) according to FEMA P-58 and assuming similar components to be perfectly correlated, d) according to FEMA P-58 and assuming similar components to be uncorrelated.

These results are compared to those obtained following the component-by-component method of the FEMA P-58 guidelines (Figures 5c and 5d). The purpose of this comparison was not to investigate the impact of using a “standardized” inventory instead of an actual building-specific one, but to quantify the error introduced due to the assumptions on the distribution of repair cost for a given *EDP* value, the assumed correlation of similar components within the 100 m^2 segments, and the regression fitting. Hence, the same inventory that was used for the calculation of the story loss functions was kept and assigned to the building. The results show a median total repair cost of $2.01 \cdot 10^6$ € for a spectral acceleration equal to 0.5g when perfect correlation is assigned between similar components, and $2.02 \cdot 10^6$ € for the case of no correlation. These values are deemed close to the ones obtained using the story loss functions. Likewise, the disaggregation of loss into different component groups (Figure 6) appears very similar for the component-by-component and story loss function based approaches.



a.



b.

Figure 6. Contributions to losses from structural (S), non-structural (NS) and content (C) components for a spectral acceleration of 0.5g from a) story loss functions, b) FEMA P-58

5 CONCLUSIONS

A FEMA P-58 compatible methodology for derivation of story-level repair cost *DV–EDP* functions was offered and illustrated. Such story loss functions were built for steel office buildings based on estimations of common structural layouts and component inventories; they are expected to provide a satisfactory approximation of seismic losses in regular buildings without major peculiarities in terms of structural and non-structural inventories. Their quality can be notably improved with more extensive statistical studies of building typologies, component inventories and associated costs, as well as with the development of a wider range of component fragility functions. Variability in component quantities should also be considered, instead of just using mean or expected - based on expert opinion - values.

The case study, performed for a four-story steel moment resisting frame building, revealed minor but acceptable differences between the full FEMA P-58 methodology and the proposed one, justifying the assumptions on the distribution of repair cost and the partitioning of the floor area into 100 m^2 segments. A better fit than the assumed normal distribution of repair cost might be required in certain cases, however most component story loss functions do not seem to maintain the same distribution shape over the range of their associated *EDP*. Keeping in mind that the use of story loss functions over the refined FEMA P-58 procedure constitutes a trade-off between accuracy and simplicity, the proposed methodology can prove to be a valuable tool for common building typologies with regular geometry, either as a means to achieve quick preliminary loss investigations, or as a reference in a conceptual design procedure that aims to limit potential losses.

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