A practice-oriented approach to control the effects of epistemic uncertainties on the seismic fragility of reinforced concrete frames

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ABSTRACT
Uncertainties related to material properties and structural details in existing buildings can strongly influence the hierarchy of strength at both member and beam-column joint levels, particularly in the case of reinforced concrete frames. In turn, this can affect the global plastic mechanism, the force/displacement capacity of the structure and its seismic fragility. A rigorous probabilistic approach is arguably the most appropriate method to quantify the effects of such uncertainties on the parameters of the desired fragility curve. However, such an approach is not (yet) feasible in the current engineering practice. In this study, a practice-oriented approach to achieve the above goal is presented. More specifically, the proposed method relies upon a sensitivity analysis based on the Simple Lateral Mechanism Analysis (SLaMA). The latter is an equilibrium-based analytical approach to compute the plastic mechanism and the non-linear force-displacement capacity curve for a given structure. The capacity spectrum method is then adopted to assess the expected performance at different intensity levels and derive fragility curves. Initially, tentative but realistic values of the material properties (e.g., concrete and steel strengths) and structural details are assumed to calculate the above-mentioned quantities. Then, specific variations of those parameters are appraised, and the analyses are repeated to propagate the considered epistemic uncertainties in a simplified way. The effects of such variations are tested in terms of local hierarchy of strength, global capacity curve and fragility curve parameters. Within the seismic performance assessment of existing structures, the results of such sensitivity analysis can be used to drive/define in-situ testing campaigns targeted to the structural members most sensitive to variations of the considered parameters. This can potentially help reducing the overall cost/invasiveness of the testing campaign. The proposed approach is demonstrated for two case study frames, respectively sensitive and non-sensitive to variations of the considered parameters.

1 INTRODUCTION AND MOTIVATIONS

Any seismic performance assessment is inherently affected by uncertainties, both aleatory (i.e. record-to-record variability of the input ground motion) and epistemic (e.g., knowledge of the geometry, the material properties or the detailing in the structural members as well as modelling uncertainties). For existing structures, knowledge of the above information related to the structure characteristics is generally limited due to the often scarce availability of the original structural drawings and design documents. Moreover, deterioration may affect the structural materials (e.g., ageing, corrosion). For reinforced concrete (RC) structures, uncertainties can strongly influence the hierarchy of strength at both member and beam-column joint levels. In turn, this can affect the global plastic mechanism, the force/displacement capacity of the structure and its seismic fragility (i.e., likelihood of damage levels vs earthquake-induced ground-motion intensity measures, IMs).

The level of knowledge can be increased by in-situ inspections of the geometry, a study of any past modification affecting the analysed structure, and simulated design according to the seismic code appropriate to the year of construction. Moreover, according to several international seismic codes it is strongly recommended - if not mandatory – to perform non-destructive and destructive in-situ testing for materials and structural member characterisation. The former may be limited mainly by budget constraints, while the latter is also limited by the level of invasiveness of any testing campaign.

Seismic performance assessment should effectively deal with those uncertainties while minimising the cost and invasiveness of the in-situ testing. Arguably, rigorous probabilistic approaches, e.g., Franchin et al. (2010), could be the most appropriate method to propagate uncertainties on the performance-assessment input variables to the desired output quantities.

However, such approaches are not yet feasible in the engineering practice, mainly due to lack of time and expertise with advanced probabilistic modelling. The complexity of the mathematical model and the inevitable perception of accuracy can also be misleading and lead to inappropriate actions/interventions (or lack of). Simplified approaches are often based on sensitivity analysis. An example related to masonry structures has been proposed by Cattari et al. (2015). Such an approach is considerably more feasible in the engineering practice, when compared to a fully-probabilistic approach. However, it consists of a series of sensitivity analyses structured in a logic-tree framework, which can still pose challenges in terms of their practical implementation. In fact, it requires to run each numerical analysis using a state-of-the-practice software tool for masonry structures. However, for RC structures, state-of-the-practice software tools still do not generally allow to capture all the possible plastic mechanisms (e.g., shear failure in joint panels) and can therefore lead to non-conservative assessments.

In this paper, a simplified semi-probabilistic approach is proposed consisting of simple sensitivity analyses based on $2N+1$ non-linear structural analyses, conducted perturbating N parameters, with N rarely exceeding five. Either (non-linear) static or dynamic analysis methods can be adopted, provided that all the plastic mechanisms are modelled and could be properly captured. To this aim, it is herein proposed to use the Simple Lateral Mechanism Analysis, SLaMA (NZSEE, 2017; Pampanin, 2017; Gentile et al., 2019, 2019a, 2019b, 2019c), an entirely-analytical, simple-yet-accurate, non-linear static method. Based on the available time and expertise of the user, simplified, mechanics-based fragility curves can be derived by using the Capacity Spectrum Method, CSM (Freeman, 1998) using a suite of unscaled ground motion records.

The proposed approach is described in details in the next section and then demonstrated for two case study frames, respectively sensitive and non-sensitive to variations of the considered parameters.

2 PROPOSED SENSITIVITY ANALYSIS

2.1 Overview of the procedure

For a given structure, the proposed procedure to quantify the effects of the epistemic uncertainties consists of four main steps:

1. **Analysis of the base-case structure.** Before any in-situ testing is performed, it is required to set up a preliminary structural model. In the common practice, this is based on the best knowledge of geometry, structural details and material properties. This information may be acquired by means of the original structural drawings (if available), in-situ inspections (including using a rebar detector/scan and/or local sampling), and/or simulated design according to the appropriate seismic code for the year of construction/retrofit. The non-linear structural capacity (force-vs.-displacement curve and plastic mechanism) of this base-case structure is calculated. According to the availability of time and resources by the practitioner, it is also suggested to quantify the structural response for a suite of ground motions, possibly adopting simplified methods, and perform fragility analysis.
2. **Definition of the sensitivity-analysis input parameters.** Generally, a number of assumptions are needed to perform the preliminary analysis of the base case. Therefore, engineering judgement is herein required to define a set of N *sensitivity-analysis input parameters* x_i (geometry, structural details, material properties) that might affect the analysis results, if perturbated. The effects of such perturbations are measured according to a set of M *objective functions* y_j , which should also be structure-specific. For RC frame structures, example of sensitivity parameters might be: concrete and steel properties (e.g., strength and/or strain capacity), amount, location and spacing of reinforcement in members inaccessible with a rebar detector, structural details in the beam-column joints panel zone,

stiffness/strength of the floor slabs/diaphragm, foundation typology and/or connection, etc. Typical objective functions might be: displacement and/or base shear capacity for a given Damage (or limit) State (DS), hierarchy of strength in selected beam-column joints, plastic mechanism, seismic response in terms of Engineering Demand Parameters (EDP), seismic fragility, etc.

3. **Variations of the sensitivity-analysis parameters.** Reasonable variation ranges should be identified for each sensitivity parameter x_i. The lower (x_i^-) and upper bounds (x_i^+) of such ranges will be used for the sensitivity analysis. If possible, such bounds can be defined according to available statistical data (e.g., one standard deviation confidence interval). Alternatively, reasonable percentage variations of the base-case values should be based on engineering judgement and/or knowledge of the construction practise at the year of construction of the analysed structure. Variations for typological parameters (e.g., structural details in the joints) should be defined to produce non-conservative and conservative variations of the base-case structure, respectively for the lower and upper bounds.
4. **Analysis of the structural perturbations.** For *N* selected sensitivity parameters, the procedure requires *2N* perturbations of the base-case structure. Each perturbation is defined using one perturbated sensitivity-analysis parameter ($x_k = x_k^+$ or $x_k = x_k^-$) and the base-case values for the remaining x_i. Each perturbation is analysed with the same method adopted for the base case. The sub-set of perturbations in which a sensitivity-analysis parameter is increased (or decreased) is named *upside* (or *downside*).
5. **Quantify sensitivity.** It is proposed to quantify the effect of the epistemic uncertainties using one tornado plot for each objective function y_j. The horizontal axis represents the objective function. Firstly, a vertical line is drawn representing the base-case value of the objective function. The sensitivity-analysis parameters x_i are listed in the vertical axis. For each perturbation, an horizontal line represents the change in the objective function with respect to the base case. By combining the upside and downside bars, the sensitivity (variation range) of the objective function is appraised. The sensitivity-analysis parameters are ordered top-to-bottom for decreasing values of the sensitivity. The outcome of this procedure visually resembles a tornado (Project Management Institute, 2013), provided that the objective function is monotonic with respect to the parameters of the sensitivity analysis. The final results allow to identify the parameter(s) that most influence the objective function, and that likely need in-situ further investigations if the epistemic uncertainties are to be reduced.

2.2 *Structural capacity*

The adopted procedure requires the determination of the non-linear structural capacity for each analysed structural configuration. For practical applications, any analysis method (and/or any software tool) can be used for the sensitivity analysis, as long as all the possible failure modes of the structural components are effectively considered; and compliance with the seismic code is ensured. In this paper it is proposed to adopt the SLaMA approach, which provides a valuable trade-off between simplicity of the analysis and accuracy of the results.

SLaMA is an analytical procedure allowing one to assess the non-linear capacity (force vs deformation) and the plastic mechanism of a structural system starting from the capacity of the primary structural members/systems (NZSEE, 2017; Pampanin, 2017; Gentile et al., 2019, 2019a, 2019b, 2019c). Since it relies on basic principles (i.e. equilibrium and compatibility), SLaMA is referred to as a “by hand analytical pushover analysis” since all the calculations can be easily implemented in a spreadsheet. Given the numerous and typical “deficiencies” of existing buildings (e.g., lack of capacity design, inadequate joint panel reinforcement), there is a need for practical implementation tools to test the reliability of numerical models in predicting the plastic mechanism. SLaMA aims to address this need, together with supporting the selection of retrofit strategies/techniques at earlier stages of the assessment process.

By referring to RC frames, the first step of SLaMA is the characterisation of the lateral response of the main structural members (i.e., beams, columns, beam-column joints) composing the frame. The flexural capacity of the RC members can be derived using reliable numerical or analytical procedures and including the effect of the axial load. Then, flange effect (Quintana Gallo, 2014; NZSEE, 2017), lap splice failure (Priestley et al., 1996), shear failure (Kowalsky and Priestley, 2000; Elwood and Moehle, 2005), bar buckling (Berry and Eberhard, 2005) should be considered, as they can significantly modify the lateral response of the members

The interaction between the members in the beam-column joint sub-assemblies is studied using the hierarchy of strength and sequence of events evaluation within a M-N interaction diagram (Pampanin et al., 2007). To compare different member-level mechanisms (e.g., yielding, ultimate), the equivalent column moment is used as a reference parameter. This is the moment in the column, calculated at the joint interface, corresponding to a given member mechanism in the sub-assembly. By means of equilibrium conditions at sub-assembly level (Figure 1), this is calculated for each member-level mechanism and plotted in an equivalent column moment-axial load M-N performance domain (Figure 3.c, related to an exterior sub-assembly). For instance, the equivalent column moment corresponding to the yield moment of the beam (which does not vary with the column axial load) corresponds to a horizontal (constant) line in the performance domain.

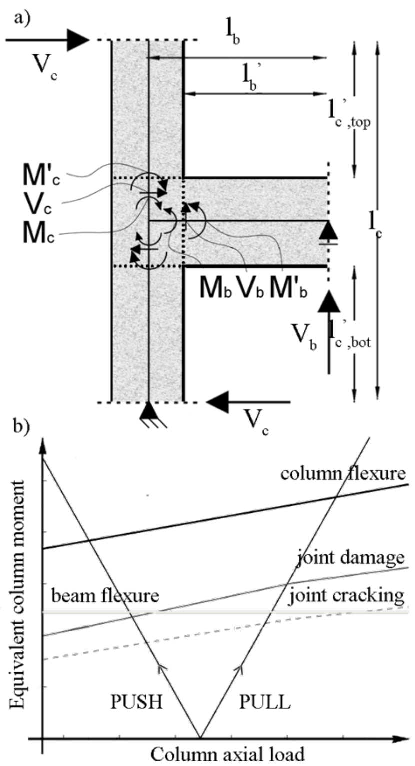

Figure 1. Hierarchy of strength: a) exterior beam-column joint; b) performance domain. Modified after Gentile et al. (2019).

Once the failure mode of the sub-assembly is detected, its strength and deformation capacity are assessed using equilibrium considerations. It is proposed to use the results of the hierarchy of strength for all the sub-assemblies to identify the probable plastic mechanism of the frame. Extending the principles of direct displacement-based design (Priestley et al., 2007) and in particular the concept of equilibrium approach to derive the internal actions within a frame system, sets of equations are given to calculate the capacity curve for three recurrent plastic mechanisms (Figure 2). A "Column-Sway" (soft-storey), with plastic hinges at the top and the bottom of all the columns of a given storey, a "Beam-Sway", global mechanism characterised by plastic hinges at the end of all the beams, and a "Mixed-Sway" (or actual mechanism), in which a combination of beam, column and/or joint failures can be triggered.

2.3 *Structural response and seismic fragility*

A cloud of points in the EDP vs IM space is defined for each structural configuration. The maximum inter-storey drift is the selected EDP as it is a convenient proxy highly correlated with (non)structural damage and repair costs. The selected IM is defined as the geometric mean (*AvgSA*) of the pseudo-spectral acceleration in a period interval (T_1-$1.5T_1$), where T_1 is the first fundamental period of the analysed structure. This ensures increased efficiency and sufficiency in estimating a given EDP by means of a scalar IM (Kohrangi et al., 2017; Minas and Galasso, 2019). A suite of 150 unscaled natural ground motions are selected from the SIMBAD database, "selected input motions for displacement-based assessment and design" (Smerzini et al., 2014). As in Rossetto et al. (2016), the 467 records in the database are ranked according to their PGA values (by using the geometric mean of the two horizontal components) and then keeping the component with the largest PGA value. The first 150 records are adopted.

The CSM (Freeman, 1998) is applied for each ground-motion record to calculate the maximum inter-storey drift for each natural ground motion and derive EDP vs IM pairs. It is worth mentioning that the CSM is carried out adopting the equivalent viscous damping formulation provided in Priestley et al. (2007).

Fragility functions are calculated for four DSs: slight (DS1), moderate (DS2), extensive (DS3) and complete damage (DS4). Those can be defined according to (Hill and Rossetto, 2008) among others, and quantified using the non-linear analyses

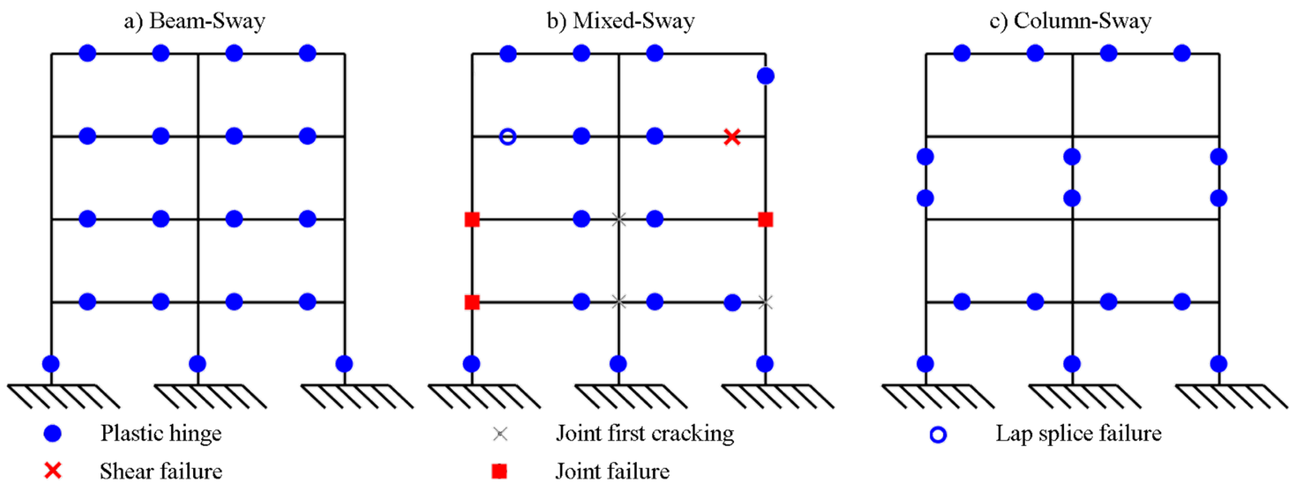

Figure 2. Assumptions for the plastic mechanism in SLaMA (modified after Gentile et al., 2019).

results. The cloud of points resulting from the analyses is divided in two parts: the "collapsed (C)" cases, which correspond to dynamic instability of the analysis or to analyses exceeding 10% drift; and the "non-collapsed (NoC)" cases, corresponding to the other cases. Eq. (1) describes the derivation of the fragility functions. $P(EDP \geq EDP_{DS}|IM, NoC)$ is the conditional probability that the EDP threshold is exceeded given that collapse does not occur, and $P(C|IM)$is the probability of collapse. It is implicitly assumed that the EDP threshold (EDP_{DS}) is exceeded for collapse cases, i.e. $P(EDP \geq EDP_{DS}|IM, C) = 1$.

$$P(EDP \geq EDP_{DS}|IM) = P(EDP \geq EDP_{DS}|IM, NoC)(1 - P(C|IM)) + P(C|IM) \quad (1)$$

The linear least square method is applied on the "NoC" pairs in order to estimate the conditional mean and standard deviation of EDP given IM and derive the commonly-used power-law model $EDP = aIM^b$, where a and b are the parameters of the regression. This allows to define a lognormal cumulative distribution function (CDF) representing $P(EDP \geq EDP_{DS}|IM, NoC)$ for a given DS. The probability of collapse $P(C|IM)$ is fitted with a logistic regression, which is appropriate for cases in which the response variable is binary ("collapsed" or "non-collapsed"). The final result is converted into a lognormal CDF, defined by a median and a logarithmic standard deviation.

3 ILLUSTRATIVE APPLICATIONS

3.1 *Description of the case studies*

The proposed sensitivity-analysis approach is demonstrated for two case-study RC Italian frames (Figure 3). The first one (*non-sensitive*) is selected such that it shows a negligible sensitivity to the considered sensitivity-analysis input parameters. This is a three-bays, four-storeys Italian RC frame with details typical of the 1970-80s. The bay length is 5m while the inter-storey height is 3m. This is simulated designed according the 1976 Italian seismic code (Consiglio dei ministri, 1976), including some basic capacity design principles.

Typical beams (end sections) have 300x500mm rectangular cross sections with 30mm cover. The longitudinal reinforcement is made by 3ϕ16+2ϕ12 on the top layer and 2ϕ16+2ϕ12 on the bottom one. Perimetric ϕ6 stirrups are placed at 150mm spacing.

Typical columns have 300x350mm rectangular cross sections with 30mm cover. 4 corner ϕ16 longitudinal bars are adopted, together with ϕ6 stirrups are placed at 100mm spacing.

The second case study (*sensitive,* Section *3.4*), is a three-bays, seven-storeys frame that shows a much higher sensitivity to the selected input parameters, allowing one to identify the most important parameters to be further investigated with in-situ testing. The bay length is 5m while the inter-storey height is 3m. This is simulated designed according to the pre-1970s Italian structural code (Consiglio dei ministri, 1939).

Typical beams have 300x500mm rectangular cross sections with 20mm cover. The longitudinal reinforcement is made by 4ϕ18 on the top layer and 2ϕ18 on the bottom one. Perimetric ϕ6 stirrups are placed at 300mm spacing. Exterior columns have 250x250mm rectangular cross sections with 20mm cover. 4 corner ϕ14 longitudinal bars are adopted, together with ϕ6 stirrups are placed at 200mm spacing. On the other hand, interior columns have 300x300mm cross-sections, 4ϕ14 longitudinal bars and ϕ6 stirrups (300mm spaced).

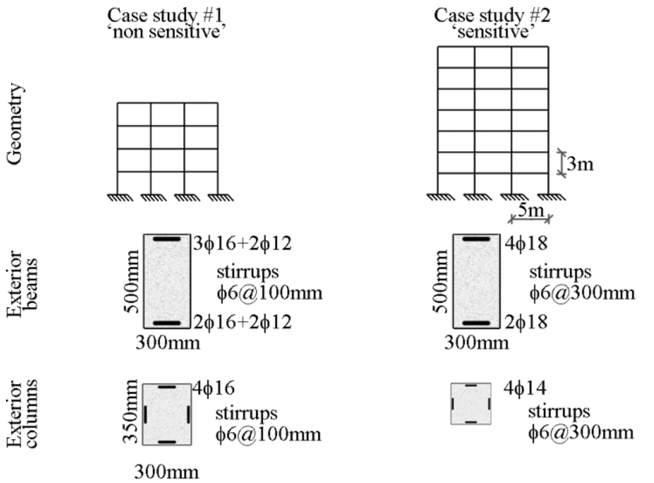

Figure 3. Characteristics of the case studies.

3.2 *General sensitivity parameters*

Table 1 shows the assumed values for the selected sensitivity-analysis input parameters, which are valid for both case studies. The parameters are:

1. Concrete cylindrical compressive strength f'_c. This affects the concrete modulus of elasticity according to the relationship $E_c = 5000\sqrt{f'_c}$ (Mander et al., 1988). As also suggested in NZSEE, 2017, 20% variation with respect to the mean is adopted, which reflects approximately one standard deviation for older RC structures (Nowak et al., 2003). Such parameter strongly affects the shear strength of the joints, while having negligible effects on the moment capacity of beams and columns;
2. Steel yield stress f_y. Together with f'_c, this directly affects the flexural, shear, lap-splice and bar buckling capacity of all the structural members. A 5% variation with respect to the mean is adopted, which reflects approximately one standard deviation for older Italian steel (Galasso et al., 2014). Such parameter strongly affects the moment capacity of beams and columns, while having a minor influence on the shear strength of beams, columns and joints;
3. Number of horizontal stirrup legs in the beam-column joints: two for the base case (one stirrup), zero for the downside, four for the upside;
4. External joint detailing. The considered alternatives for the longitudinal bars of the beams are: 1) hooks; 2) bent out of the joint; 3) bent inside the joint. Similarly to the previous one, it is quite challenging to know this parameter in advance (i.e., without performing any in-situ testing), especially if the original structural drawings/design reports are not available. Therefore, it is always suggested to consider joint-related parameters in the sensitivity analysis.

The main objective function selected for the sensitivity analysis is the predicted plastic mechanisms. Along with this, the hierarchy of strength in selected beam-column joints, the base shear and displacement capacity at the life safety limit state (DS3), and the median of the DS3 fragility are considered.

Table 1. Input sensitivity parameters.

	Down	Base	Up
Concrete strength [MPa]	20	25	30
Steel yield stress [MPa]	285	300	315
Joint stirrup legs	0	2	4
Ext. joint detail	hook	bent-out	bent-in

3.3 *Case study #1: 'non-sensitive' frame*

Figure 4 shows that the calculated plastic mechanism for case study #1 base case is a Mixed Sway, and the ultimate displacement (DS3) is equal to 75mm and governed by the external joints failing in shear (surrounded by red circles). This behaviour reflects that, in the adopted seismic code, higher provisions for columns were required, if compared to pre-1970s standards, while no requirements were provided for the joints.

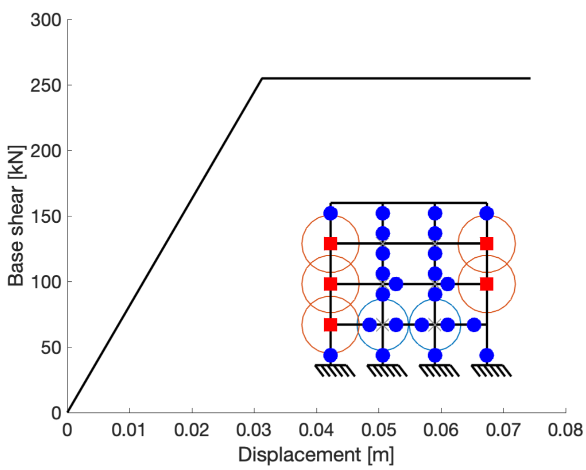

Figure 4. Case study #1: base-case results. Blue circles represent members causing global yielding; Red circles represent member causing global ultimate limit state.

The analysis of the eight structural perturbations defined according to Table 1 show a very low sensitivity of the objective functions.

Firstly, the predicted plastic mechanism is always a Mixed Sway. For the upside perturbation related to the joint detailing (bent-in bars), some external beam-column joints are subjected to minor changes in the hierarchy of strength: the column is able to protect the joint panel, given the increased capacity of the latter.

These results also lead to a negligible sensitivity of the life-safety displacement to the considered input parameters, given that it is always caused by the ultimate drift in a joint panel. As shown in Figure 5, concrete strength is the parameter that mostly affects the life safety (DS3) base shear capacity. However, the maximum sensitivity is equal to [-4%, +3%], and therefore it can be neglected.

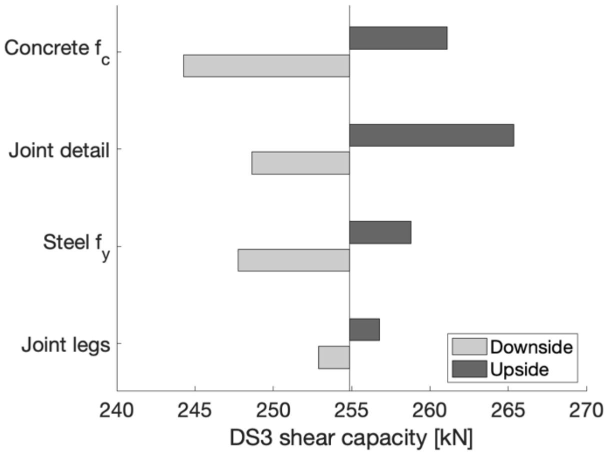

Figure 5. Case study #1: sensitivity of the life safety (DS3) base shear capacity.

A similar trend is shown in Figure 6 for the median of the DS3 fragility curve. Again, concrete strength is the most influencing parameter. However, the maximum sensitivity for the fragility median is equal to -2%.

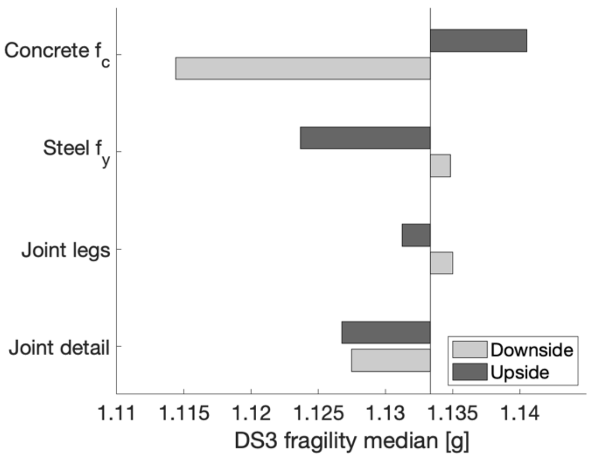

Figure 6. Case study #1: sensitivity of the median of the DS3 fragility.

3.4 *Case study #2: 'sensitive' frame*

As expected for pre 1970 frames, a Column-Sway mechanism is predicted (Figure 7) for case study #2, with a soft-storey mechanism located at the first storey. The life-safety displacement is caused by the attainment of the ultimate curvature at the base of the interior columns.

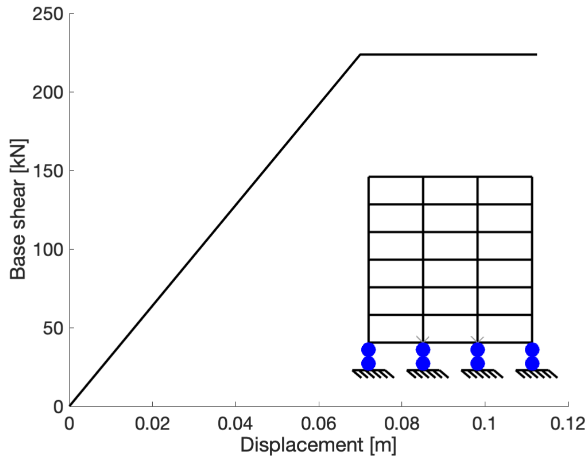

Figure 7. Case study #2: base-case results.

Figure 8 clearly shows that exterior joint panels play a major role in determining the plastic mechanism. Indeed, either a decrease in the number of stirrups or the adoption of a poorer joint detailing can shift the mechanism from a Column-Sway (CS) to a Mixed-Sway (MS). With such poor details, the external joint panels become weaker and "protect" column hinging, while "preventing" the soft-storey mechanism.

Such results is consistent with the work by Gentile et al. (2017), which showed the importance of structural detailing for pre-1970s Italian RC frame buildings.

For this particular case, the high sensitivity of the plastic mechanism to the input parameters does not lead to a major sensitivity of the life-safety displacement capacity (Figure 9).

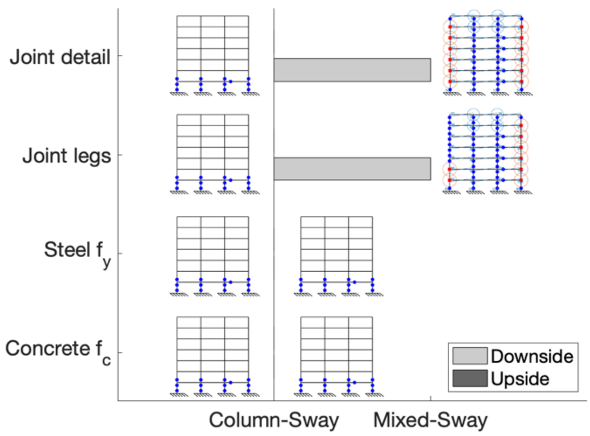

Figure 8. Case study #2: sensitivity of the plastic mechanism.

Nonetheless, it is clear that a precise knowledge of the joint details is paramount for the structural assessment and, clearly, for any possible structural retrofit planning. Results of the analysis clearly indicate that part of the budget for in-situ inspections should be prioritised/allocated to the exposure of at least one exterior joint panel (reasonably assuming that equal details are provided for the entire frame).

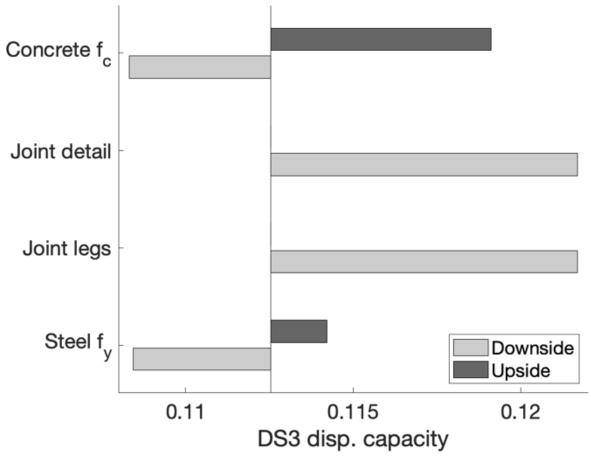

Figure 9. Case study #2: sensitivity of the life safety (DS3) displacement capacity.

4 CONCLUSION AND OUTLOOK

In this paper, a practice-oriented sensitivity analysis is proposed to quantify the effects of epistemic uncertainties in seismic performance assessment. Although the approach is general, this paper has focused on RC frames. After the non-linear analysis of the base-case structure is carried out, the sensitivity analysis is based on selecting a small number of input parameters (generally less than five), and analysing perturbations of the base case by increasing or decreasing one input parameter at the time.

Such procedure is clearly less rigorous than a fully-probabilistic approach, but it could arguably be more feasible in the engineering practice. The procedure can be carried out adopting commercial software tools, provided that the selected modelling strategy allows to capture all the possible plastic mechanisms. For a simple-yet-accurate alternative it is proposed to use SLaMA, together with the derivation of simplified fragility curves based on the CSM using unscaled ground motions.

The procedure is demonstrated for two case-study RC frames, with mid-1970s and pre-1970s details, which show rather different results. In the first case, consisting of more modern details and basic capacity design principles, the output quantities (plastic mechanism, hierarchy of strength, displacement/base shear capacity, median of the fragility) are rather insensitive to the perturbation of the input parameters. On the other hand, the second case study, where the critical structural weakness are more likely given the lack of capacity design principles, shows a strong sensitivity to the joint detailing, which causes the predicted plastic mechanism to change from soft storey to global Mixed Sway.

Overall, the proposed simplified sensitivity analysis allows to identify the input parameters mostly affecting the desired output quantities. In turn, this allows taking informed decisions for the prioritisation and budget allocation for in-situ inspections.

Although the obtained results are promising, a thorough validation of the proposed procedure against fully-probabilistic approaches is still needed and under preparation.

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