Advances in regional seismic risk assessment incorporating spatial and structural correlations

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Abstract

Seismic risk assessment has traditionally concentrated on individual buildings, using metrics such as annual frequency of collapse and annualised losses. However, decision-making for societal planning, asset management, and (re)insurance increasingly requires an understanding of risk across portfolios of structures that may differ significantly in their characteristics. Recent advances in vulnerability modelling, including the development of next-generation intensity measures such as average spectral acceleration and incremental velocity, have shown strong capability in characterising seismic response. Yet standard tools such as ground motion models and correlation models to simulate ground motion fields are not currently equipped to incorporate these newer developments. This paper discusses these challenges associated with regional-scale assessment and introduces some recent remedies. First, novel spatial cross-correlation models are introduced to account for spatially varying ground motions when fragility and vulnerability models are defined using different intensity measures, filling a gap in the limited existing literature. Second, the study examines the correlation of damage between structures within the same region, challenging the common assumption of independence and investigating its relative impacts. A structure-to-structure correlation model is presented, along with a two-step procedure that evaluates exceedance curves for the total number of collapsed buildings and expected losses for surviving structures whilst considering these correlations. These methods integrate efficiently within existing workflows and, in some instances, significantly reduce computation time. Illustrative case studies demonstrate how these developments enable more refined and reliable estimation of seismic losses across regions, providing improved tools for regional seismic risk analysis.

Keywords: Regional risk assessment, spatial correlation, damage correlation, intensity measures, fragility and vulnerability modelling.

1- INTRODUCTION

The seismic risk of individual structures has been studied for several decades, and the body of knowledge accumulated during that period is now well-established. A key enabling component of this work has been the identification of appropriate ground motion intensity measures (IMs) that link seismic hazard to structural response in an efficient and unbiased manner. An IM used in risk assessment should ideally satisfy three properties: it should be *efficient*, in the sense that structural response conditioned on the IM exhibits low dispersion; *sufficient*, meaning that the analysis results are independent of other ground motion characteristics such as magnitude or source distance; and *practically computable*, meaning that a hazard curve for the IM can be obtained using available ground motion models (GMMs) and tools. Much of the research effort over the past decade has been directed at the first two properties, and considerable progress has been made [1–8]. These advances have also found expression in large-scale vulnerability model catalogues, notably the GEM global vulnerability model [9] and the European Seismic Risk Model (ESRM20) [10], which provide openly available fragility and vulnerability functions for analysts working at a regional scale across Europe and beyond.

What this progression has brought to attention, however, is a growing trade-off between what is analytically best for individual structures and what is practically achievable at a regional scale. The IMs that emerged from single-structure studies as superior predictors of response (e.g., composite measures such as average spectral acceleration, $Sa_{\text{avg}}(T)$, and velocity-based measures such as the filtered incremental velocity, *FIV3*) turn out to be difficult to use in practice precisely because the tools needed to compute their seismic hazard were not available. This is not merely a technical inconvenience: it has real implications for the accuracy of regional risk estimates, since the continued reliance on legacy IMs such as peak ground acceleration (PGA) or spectral acceleration at a single period, $Sa(T)$, inflates uncertainty in ways that can distort both loss estimates and the decisions that follow from them.

This short paper recounts how that trade-off has been progressively resolved, and of the new research possibilities that have opened up as a result. It is written with a mixed audience in mind: researchers familiar with the underlying methods, and practitioners in the (re)insurance and risk management sectors who are interested to understand where research is going and why. The developments described are not yet universally adopted in practice, but the case for their adoption is strong, and the barriers to doing so have been substantially reduced by recent work. Several of the contributions described here are presented in detail in companion papers in this session; the aim of this paper is to provide the motivation and context that allows those contributions to be appreciated in full.

2- INTENSITY MEASURES: FROM SINGLE STRUCTURES TO THE REGIONAL SCALE

2-1- DEVELOPMENT OF NEXT-GENERATION INTENSITY MEASURES

The spectral acceleration at the fundamental period of vibration, $Sa(T_1)$, has long served as the default IM in seismic assessment, and its prevalence is well-founded: for structures whose response is dominated by first-mode behaviour in the elastic range, it is an efficient and computationally practical choice. Its limitations, however, become apparent when structures respond well into the non-linear range, when period elongation is significant, or when the structural typology has dynamic characteristics that are not well captured by a single spectral ordinate. A substantial body of research across different structural systems has documented these limitations and identified more capable alternatives [1–8]. The most widely studied of these is $Sa_{\text{avg}}(T)$, defined as the geometric mean of spectral acceleration values over a range of periods. By averaging over a period range rather than anchoring to a single period, $Sa_{\text{avg}}(T)$ implicitly accounts for period elongation and spectral shape effects, and has been consistently shown to reduce dispersion in structural response predictions whilst also being less sensitive to ground motion scaling. More recently, *FIV3*, the filtered incremental velocity proposed by Dávalos and Miranda [11], has demonstrated strong capability for structures sensitive to velocity pulse characteristics of the ground motion. These measures, which we have termed next-generation intensity measures (NGIMs) [12–14], represent a meaningful step forward in the accuracy of structural response characterisation.

The difficulty that arose with NGIMs was with the third desirable property: practical computability. For many years, no GMMs existed for $Sa_{\text{avg}}(T)$, meaning that their seismic hazard could not be quantified through probabilistic seismic hazard analysis (PSHA). Without a hazard curve, seismic risk, which combines hazard, exposure, and vulnerability, cannot be computed. This left practitioners in an uncomfortable position: the research community had identified clearly superior IMs for characterising structural response, but without the hazard infrastructure to support them, they could not be used in practice. As Vamvatsikos [15] noted with some irony in his keynote lecture at the 2024 World Conference on Earthquake Engineering in Milan, the criteria most used to select IMs in practice had become decoupled from those advocated in research.

One of the first significant steps toward resolving this impasse was taken by Kohrangi et al. [16], who proposed an indirect method for constructing a GMM for $Sa_{\text{avg}}(T)$. The approach exploits the mathematical definition of $Sa_{\text{avg}}(T)$ as a geometric mean of individual spectral ordinates: since GMMs for $Sa(T)$ at individual periods are widely available, and since the statistical properties of $Sa_{\text{avg}}(T)$ can be derived from those of its constituent ordinates, a $Sa_{\text{avg}}(T)$-based GMM can be assembled indirectly without requiring a dedicated empirical dataset. This indirect approach was verified against a directly fitted model [17] and found to be sufficiently accurate for practical use. Around 2018, this indirect approach was implemented in the OpenQuake hazard engine [18], which made $Sa_{\text{avg}}(T)$-based hazard computation accessible to a wide user community for the first time. The effect was catalytic: once the practicality barrier was lifted for $Sa_{\text{avg}}(T)$, research on its use in fragility and vulnerability modelling accelerated considerably.

It is important to acknowledge that the indirect approach, whilst effective, carries its own limitations. As a piecewise aggregation of models developed independently for individual spectral periods, its accuracy depends on the mutual consistency of those constituent GMMs. Small incompatibilities in the underlying models can propagate into the aggregate, and the approach is not straightforwardly extendable to IMs whose definition does not decompose naturally into a sum of single-period quantities. *FIV3* is a case in point: its definition involves a filtering operation on the velocity time history, and no indirect formulation analogous to the $Sa_{\text{avg}}(T)$ approach is available. This motivated the development of direct GMMs and within-site cross-IM correlation models for NGIMs [12,17,19–21], which provide self-consistent solutions applicable to both $Sa_{\text{avg}}(T)$ and *FIV3*. These direct models represent the current state of the art for single-site NGIM-based risk assessment.

2-2- EXTENDING NGIMS TO REGIONAL ANALYSIS: THE SPATIAL CORRELATION GAP

Regional seismic risk assessment involves simulating spatially distributed ground motion fields (GMFs) across a region for a given earthquake scenario, and subsequently evaluating the consequences for the building stock at each location. The simulation of GMFs requires, in addition to a GMM, a spatial correlation model: a description of how the within-event residuals of the ground motion IM are correlated between pairs of sites, primarily as a function of their separation distance. This correlation structure determines how concentrated or dispersed the ground shaking pattern is across the region, which in turn has a direct bearing on the spatial distribution of damage and loss. For classical IMs such as $Sa(T)$, the literature on spatial correlation models is extensive, with a recent review by Monteiro and O'Reilly [22] documenting over 45 available models. For NGIMs, by contrast, essentially no spatial correlation models existed, meaning that the advantages of $Sa_{avg}(T)$ and *FIV3* at the single-site level could not be carried through to regional applications.

An indirect spatial correlation model for $Sa_{avg}(T)$ was proposed by Heresi and Miranda [23], following the same aggregation logic used for the indirect GMM. Since the spatial correlation of $Sa_{avg}(T)$ can be expressed in terms of the correlations of its constituent $Sa(T)$ ordinates, and since models for those are well established with the widely used model of Jayaram and Baker [24] being a prominent example, the required spatial correlation structure can be assembled without a direct empirical fit. This model enabled a new generation of regional studies using Sa_{avg}(T) as the conditioning IM [8,25], and represented an important enabling contribution. A recent study by Monteiro and O'Reilly [26] examined the performance of this indirect model in detail, benchmarking it against a newly developed direct model. The conclusion was that the indirect model performs reasonably well under typical conditions, but introduces non-negligible errors in specific configurations, particularly at longer separation distances and for certain period ranges. More practically, the direct model was found to be considerably more computationally efficient to use in GMF simulation, since it avoids the repeated evaluation of multiple underlying $Sa(T)$ correlation functions. For *FIV3*, no indirect formulation is available, making the direct model the only viable option.

3- DIRECT SPATIAL CROSS-CORRELATION MODELS FOR NEXT-GENERATION INTENSITY MEASURES

The direct spatial correlation model developed by Monteiro et al. [27] is constructed using principal component analysis (PCA) applied to empirical within-event residuals from a dense strong-motion network. PCA identifies the dominant modes of spatial variability in the residual field, and the resulting model characterises the spatial correlation structure of $Sa_{avg}(T)$ and *FIV3* directly, without recourse to aggregation of single-period models. The PCA formulation brings two practical advantages. First, it is computationally efficient: the dimensionality reduction achieved by retaining only the leading principal components means that GMF simulation is substantially faster than an indirect approach that requires the evaluation of multiple correlated $Sa(T)$ fields. Second, it is much more accurate: by fitting directly to observed residuals of the target IM, it avoids the approximation errors introduced by the indirect aggregation.

A notable additional capability of this model is its treatment of cross-IM spatial correlation. Conventional spatial correlation models address a single IM: they describe how the within-event residual of, say, $Sa_{avg}(T)$ at one site is correlated with the residual of $Sa_{avg}(T)$ at another site. The model of Monteiro et al. [27] extends this to allow the joint simulation of GMFs for multiple IMs simultaneously, producing sets of ground motion fields that are mutually consistent across IM types. Figure 1 shows an example set of cross-IM coherent GMFs for a rupture scenario with four IMs generated in OpenQuake using the Monteiro et al. [27] spatial correlation model. This capability matters for two distinct reasons. The first is that it enables the collective assessment of building portfolios in which different structural typologies are characterised by different IMs: rather than treating each typology independently and aggregating the results, which ignores the statistical dependence between co-located assets, the analyst can simulate all required IM fields jointly and assess the portfolio in a single coherent framework. In practice, many applications will continue to treat buildings as independent, and this remains a defensible default; but where portfolio correlation matters, as will be discussed in Section 5, the tool now exists to handle it correctly. The second benefit of cross-IM spatial correlation is that it opens the door to vector-based fragility and vulnerability functions. The use of vector IMs, where structural response is conditioned on more than one ground motion parameter simultaneously, has a substantial research history and has been shown to offer improved response characterisation compared to scalar IMs [1,28–31]. However, vector-IM approaches have remained largely impractical, because neither vector-IM PSHA nor the simulation of cross-IM GMFs was readily achievable in standard software environments. The second of these barriers has now been addressed: the cross-IM spatial correlation model of Monteiro et al. [27] is being implemented in OpenQuake, which previously included spatial correlation models only for $Sa(T)$, specifically those of Jayaram and Baker [24] and

Heresi and Miranda [32], and the engine is being updated to include the simulation of cross-IM GMFs. This implementation makes NGIM-based GMF simulation, including cross-IM scenarios, practically accessible to a wide user community for the first time.

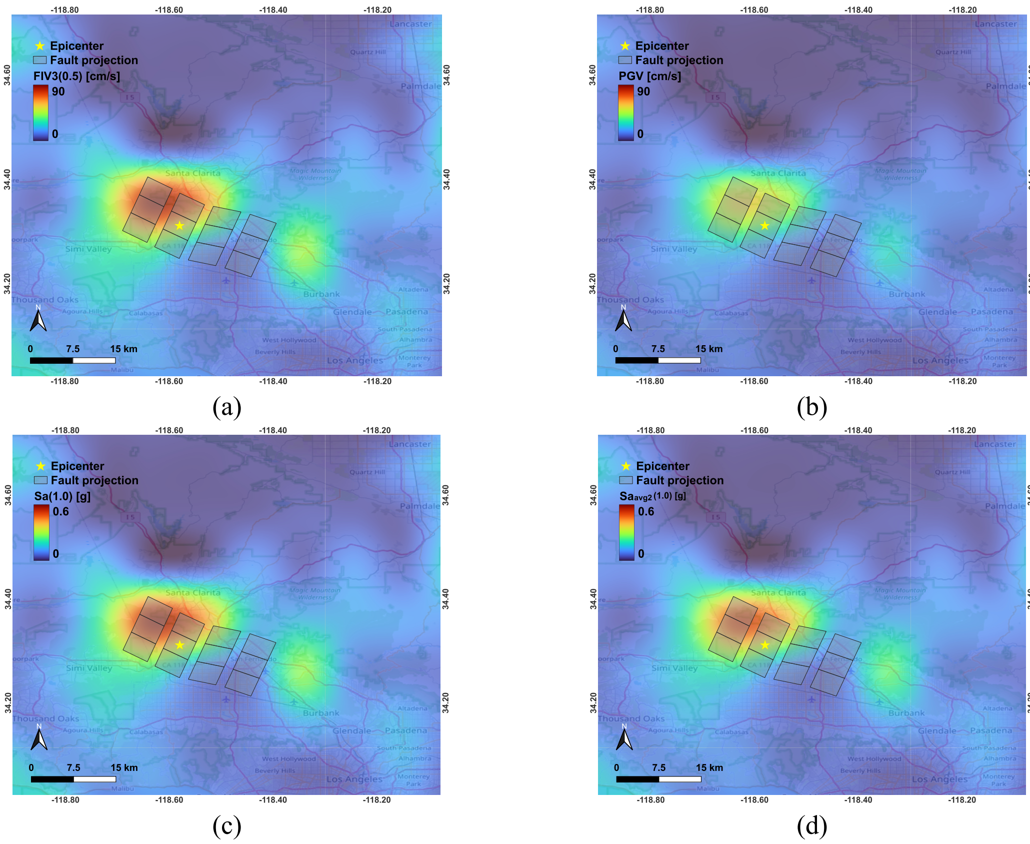

Figure 1- Illustration of cross-IM GMF set generated in OpenQuake using the Monteiro et al. [27] spatial correlation model for *FIV3*(*T*=0.5s) , *PGV*, *Sa*(*T*=1s), Sa_{avg}(*T*=1s)

4- THE INTENSITY MEASURE CHOICE IN REGIONAL SETTINGS

A practical question that arises in regional risk assessment is what to do about the large existing libraries of fragility and vulnerability functions developed using legacy IMs such as PGA, PGV or *Sa*(*T*). These functions are embedded in current practice and underpin the major regional risk models currently in operational use. Abandoning them in favour of NGIM-based alternatives is neither necessary nor realistic in the short term. The more pragmatic position, and one of the central arguments of this short paper, is that future risk models should be developed in terms of NGIMs, now that the hazard and spatial correlation infrastructure exists to support them, whilst legacy models continue to serve the applications for which they were designed.

This position does, however, raise a question about consistency. If a regional portfolio contains buildings characterised by different IMs, some using NGIMs and others using legacy measures, how can they be assessed collectively? When buildings are treated as statistically independent, this is not a fundamental problem: each building can be assessed using its own IM, and the results aggregated afterwards. The cross-IM GMF simulation capability described in the previous section provides a consistent framework for doing this even when buildings are not independent. A complementary approach is to convert all fragility and vulnerability functions to a common reference IM, so that the portfolio can be assessed using a single IM field. Past work by Suzuki and Iervolino [33] proposed a total-probability-based methodology for converting *Sa*(*T*)-based fragility functions from one period to another. This approach has been substantially extended by O'Reilly et al. [34,35], who tested several conversion methods applied not only to *Sa*(*T*)-based models but also to NGIMs. A key finding of that work is that fragility and vulnerability models developed in terms of NGIMs offer a particularly flexible starting point: they can be converted to other IMs, including legacy measures, with good accuracy. The reverse (e.g., converting a PGA-based model to a NGIM-based one) is considerably more difficult, because the legacy IM captures less of the relevant information. Borrowing terminology from blood transfusions: legacy IMs like PGA can be thought of as universal receivers, whilst NGIMs like *FIV3* and $Sa_{avg}(T)$ are universal donors.

An important additional benefit of IM conversion is that it enables direct comparison between vulnerability models developed by different groups or using different methodologies. For industry practitioners managing large portfolios, the ability to benchmark competing vulnerability models against a common IM is of considerable practical value. It reduces the opacity of model selection and provides a more rigorous basis for the choices that feed into catastrophe models and underwriting decisions.

5- CORRELATION OF DAMAGE BETWEEN STRUCTURES

5-1- WHY INTER-BUILDING CORRELATION MATTERS

Even when the spatial variability of ground motion is correctly accounted for, a distinct source of correlation in regional loss estimates is routinely neglected: the correlation of damage states (or structural response state) between buildings. In current practice, the damage outcomes of buildings within a portfolio are treated as statistically independent, conditional on the ground motion IM at their respective locations. That is, once the GMF has been simulated and each building's fragility function evaluated, the damage states are sampled independently, as illustrated in Figure 2. This assumption is computationally convenient and is embedded in most existing regional risk frameworks, but it may not be physically well-founded.

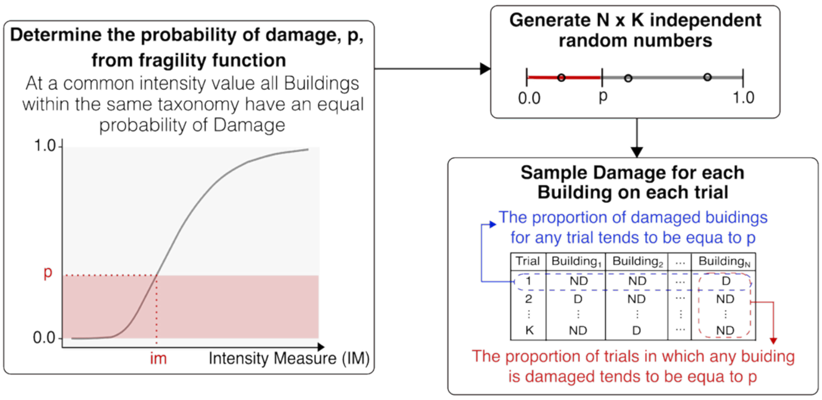

Figure 2- Monte Carlo sampling and assignment of damage states to buildings within a portfolio

Buildings of the same structural typology and construction era within a given region will share features that are not fully captured by the conditioning IM: similarities in material quality, construction practice, workmanship, detailing, and the systematic biases or construction deficiencies (both in terms of their initial design and their execution and maintenance) that characterise a given building stock at a given point in time. These shared characteristics will tend to make their responses more correlated than independent sampling implies. The consequence is not a bias in the expected loss, as the mean is unaffected by correlation, but a change in the full loss distribution. Ignoring inter-building correlation tends to underestimate the probability of simultaneous widespread damage, compressing the tails of the loss exceedance curve. For applications such as (re)insurance pricing, catastrophe reserve estimation, and resilience planning, it is precisely these tails that matter most.

5-2- DAMAGE-STATE-BASED CORRELATION MODEL AND ITS LIMITATIONS

The conceptual framework for inter-building damage correlation was developed by Heresi and Miranda [36], who proposed a probabilistic formulation for correlating the damage states of structurally similar buildings in a scenario earthquake. Building on this foundation, Mejia and O'Reilly [37] developed and tested an explicit structure-to-structure correlation model within scenario-based regional risk assessments in Italy. The study examined a portfolio of reinforced concrete buildings and found that, relative to an independent-buildings assumption, accounting for damage correlation produced a non-trivial widening of the loss exceedance curve and a shift in the estimated total damage counts. A case study application by Mejia and O'Reilly [37] showed that including both damage and spatial correlation resulted in a 21% increase in estimated buildings to repair. Spatial IM correlation was found to be the dominant contributor to aggregate loss variability, as one would expect, but damage correlation between buildings was a secondary effect of practical significance - one that becomes more pronounced for homogeneous portfolios in which many buildings share the same taxonomy and construction characteristics.

The damage-state (DS)-based correlation model is, however, not without its own limitations when extended to heterogeneous portfolios. A separate correlation model is in principle required for each damage state of each structural taxonomy, since the correlation between buildings in damage state DS_i of taxonomy A and buildings in damage state DS_j of taxonomy B is not the same quantity as the correlation within a single taxonomy. For a realistic regional portfolio containing many different building types (i.e., ranging from pre-code unreinforced masonry to modern reinforced concrete frames) this combinatorial proliferation quickly becomes unmanageable. It is this limitation that has motivated the development of an alternative formulation based on engineering demand parameters (EDPs) rather than discrete damage states.

5-3- An EDP-based approach and the two-step hybrid procedure

An EDP-based correlation framework operates at a more fundamental level: rather than correlating damage state outcomes, it correlates the structural responses (e.g., peak storey drifts or floor accelerations) from which damage states are subsequently inferred. Several studies have adopted versions of this approach [38–40], and it carries a natural advantage for heterogeneous portfolios: the EDP is a continuous quantity that does not require a separate model for each combination of damage state and taxonomy. The correlation structure of the EDP across a portfolio can be characterised more parsimoniously and extended to new building types without the need to develop new damage-state-specific models.

The EDP-based approach is not, however, straightforwardly applicable to all cases. The primary difficulty is with collapse: when a building collapses, its structural response is not described by a finite EDP value, and it cannot therefore be handled within the same continuous framework as non-collapsed buildings. Forcing the collapse cases into an EDP-based model requires either an arbitrary threshold to represent collapse or an approximation that may introduce bias. To address this, a two-step hybrid procedure is being developed within the current research programme discussed in Mejia and O’Reilly [41]. In the first step, collapse is treated as a binary outcome and its correlation between buildings is characterised using the DS-based approach, drawing on the framework of Heresi and Miranda [36] and the procedure followed in Mejia and O'Reilly [37], for example. This step identifies which buildings in the portfolio have collapsed and handles their inter-building collapse correlations accordingly. In the second step, the surviving non-collapsed buildings are assessed using the EDP-based framework, capturing the continuous variation in response across this subset. The two-step approach thus preserves the strengths of both formulations while avoiding the need to apply either of them universally.

The correlation models required for the EDP-based approach are being developed using a Bayesian inference approach, following the general methodology of Bodenmann et al. [42]. A key aspect of the modelling challenge is to distinguish between two distinct sources of inter-building correlation: correlation that arises from similarities in dynamic properties and structural response between buildings of the same typology, and correlation that arises from systematic deficiencies or construction-quality issues shared across a building class. These two sources have different spatial and typological dependencies, and separating them is important for ensuring that the resulting models are both physically interpretable and transferable to new contexts. Preliminary results from this work are encouraging, and are discussed in Mejia and O’Reilly [41].

6- Future directions

The developments described in this paper open several further research directions that are worth noting, both for their scientific interest and for their potential practical impact.

The EDP-based correlation framework described above is not limited to scenario-based post-earthquake loss estimation. EDP observations from real earthquake events (i.e., gathered through structural health monitoring (SHM) networks like that presented in [43,44]) provide a natural data source for updating and refining correlation models empirically. A monitoring network distributed across a building portfolio generates time histories of structural response at each instrumented location, and the spatial correlation of those responses is directly observable. These data can be used to continuously update the prior correlation models as new earthquake data become available, in a manner directly analogous to how SHM data are used to update fragility functions or structural identification models. Some initial work on integrating this concept with digital twin frameworks has been carried out by Taherian et al. [40], who showed that even a small number of instrumented buildings can provide significant information about the response of uninstrumented neighbours. The potential to extend this to regional correlation models is a promising avenue for future investigation.

A further extension of the inter-building correlation work concerns economic losses rather than structural response. The current focus is on correlating EDP and damage state outcomes, but the loss assessment step, which maps damage to monetary consequences, introduces its own sources of variability and correlation. The Oasis Loss Modelling Framework (https://oasislmf.org/) used widely in the (re)insurance sector includes a coefficient that analysts can assign to represent the correlation of losses between assets, but the values currently used in practice are not well-grounded in empirical evidence. The models being developed within this research programme are expected to lead to improved guidance on appropriate correlation values for different structural typologies and regional contexts, which would represent a direct and practical contribution to industry applications.

Finally, it is worth noting that the developments described here (i.e., direct spatial correlation models for NGIMs, cross-IM GMF simulation, and inter-building damage correlation) are individually useful, but their combined value is greater than the sum of the parts. A regional risk assessment that correctly accounts for all three, such as that proposed in Heresi and Miranda [45], for example, will produce loss exceedance curves that are both more accurate in their central estimates and more reliable in their tails. For an audience working in (re)insurance or catastrophe risk management, this translates directly into better-calibrated models for pricing, reserving, and risk transfer decisions.

7- Conclusions

This paper has traced the development of next-generation intensity measures from their origins in single-structure analysis through the successive technical barriers that limited their adoption at the regional scale, and has described the contributions that have progressively resolved those barriers. The account is one of incremental but purposeful progress, in which each advance has built on what came before whilst opening new avenues for both research and application. The following conclusions are drawn:

- Direct spatial cross-correlation models for NGIMs, based on principal component analysis, have been developed and implemented in OpenQuake. These provide the first direct spatial correlation models available for *FIV3* and enable the joint simulation of consistent GMFs for multiple IMs simultaneously. Their computational efficiency and accuracy make them a practical tool for regional risk assessment, and their inclusion in OpenQuake substantially lowers the barrier to adoption. The ability to simulate cross-IM GMFs also enables the practical use of vector-based fragility and vulnerability functions in scenario assessments.
- The choice of IM in regional assessment is not an inconsequential decision, but nor does it require discarding existing vulnerability libraries. Fragility and vulnerability models developed in terms of NGIMs offer the most flexible starting point, since they can be converted to other IMs with good accuracy; the reverse is considerably more difficult. Future vulnerability model development should therefore be encouraged to adopt NGIMs from the outset, whilst existing legacy models can continue to serve the applications for which they were developed. Conversion methodologies provide a practical bridge between the two.
- Inter-building damage correlation is a non-trivial contributor to the variability of aggregate regional losses, particularly in the tails of the loss distribution where (re)insurance decisions are most sensitive. A damage-state-based correlation model has been demonstrated, and a two-step hybrid procedure combining damage-state- and EDP-based correlation is under development to extend this to heterogeneous portfolios. The EDP-based approach also provides a natural pathway for incorporating SHM data to update correlation models empirically, and for extending the framework to provide quantitative guidance on loss correlation values currently assigned on largely ad hoc grounds in industry applications.

Taken together, these developments move regional seismic risk assessment toward a more complete and internally consistent treatment of uncertainty, one that is grounded in the physical behaviour of ground motion and structural response rather than in historical conventions of convenience. The case for their adoption in practice is strong, and the tools to support that adoption are increasingly available.

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