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FRAGILITY CURVE DISAGGREGATION EXAMPLES FOR LOCALIZED MEASURES OF RESPONSE

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Abstract: *In seismic risk assessment, one is often in need of employing fragility curves that are readily available in literature, rather than developing one's own. Unfortunately, such fragilities are essentially summaries of the detailed intensity measure (IM) versus engineering demand parameter (EDP) information. When, as usual, the original data is not available, finding a way to disaggregate the fragilities back into the individual IM-EDP record responses can be useful. For example, it would allow converting them to arbitrary IMs. The authors have previously presented an idea of using equivalent single-degree-of-freedom (ESDOF) models to achieve this, showing acceptable results for global EDPs, such as roof drift. These global response parameters are typically governed by the fundamental eigenmode of the structure, and are thus easier to capture by the proposed ESDOF models. To further build upon this concept, different multiple-degree of freedom (MDOF) structure examples are examined, validating the results of fragility disaggregation and IM conversion for limit-states based on more localized measures of response, such as interstorey drifts or peak floor accelerations. The accuracy of the method is therefore further challenged, going after local EDPs via a proxy that discards the effect of higher modes. The target is to specify the limits of the proposed methodology and quantify the potential error introduced by the method's assumptions, evaluating its usefulness for such cases.*

Introduction

Risk assessment procedures are commonly used by earthquake engineers to quantify the impact of seismic events for buildings and infrastructure. To perform such analyses, high quality fragility curves (Bakalis and Vamvatsikos 2018; Silva et al. 2019) must be available for each individual structure, or at least for each structural typology employed, depending on the size of the study area or portfolio. The derivation of fragilities from scratch comes at a non-negligible cost, both in terms of budget and time invested. Instead, one may employ existing literature fragilities at virtually no cost for many common types of structures. An ultra-short list of examples includes Kappos and Panagopoulos (2010) for Greek buildings, Stefanidou and Kappos (2017) for highway bridges, Rosti *et al.* (2021) for buildings in Italy, the 2020 European Seismic Risk Model (Crowley et al. 2020) for broad classes of European buildings, and PEC (2016) for typical industrial structures.

Still, using literature fragilities can be challenging, given that the specifics of their derivation may not fully align with the needs of the investigation to be performed. Beyond the obvious question of whether a generic structure actually matches the intended typology, design, and overall usage, there are also non-trivial issues of the dependence of fragilities on site characteristics and, for response history aficionados, whether the ground motion records employed actually match the targeted site (Kohrangi et al. 2017). Even discounting such issues for the sake of generality, there is the issue of IM compatibility. Given that the derivation of cross-correlated ground motion fields for different IMs remains a challenge even for the latest versions of probabilistic seismic hazard analysis platforms, using a single intensity measure (IM) site-wide is the simplest approach. In other words, one may have to transform several fragilities from one IM to another, without having access to the original IM versus engineering demand parameter (EDP) information, in case response history analysis was employed, or such data not being available at all when simpler analysis approaches (such as a static pushover analysis) were used.

As a potential remedy, Karaferis and Vamvatsikos (2022) proposed using an equivalent single-degree-of-freedom (ESDOF) proxy to "disaggregate" any fragility into individual IM values, each tied to a given record, whose distribution recreates the fragility curve. This process allows for the direct manipulation of such data via the spectral shape of the corresponding records, to convert

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the original fragilities into any arbitrary IM that is compatible with the needs of the case study. The proposed approach utilizes certain simplifications, such as (i) employing an ESDOF model to replace the original multiple-degree of freedom (MDOF) structure, (ii) using an elastic-perfectly-plastic force-deformation backbone when lacking any better information, and (iii) assuming lognormal fragilities. Therefore, it comes with non-trivial limitations that should be addressed to more clearly identify the range of its applicability. Since the method was previously used to address cases were global EDPs were examined, the applicability of the method will be challenged by trying to use it for localized measures of response that are not typically governed by the fundamental eigenmode of the structure, and are therefore more difficult to handle given the method's assumptions. As testbeds, the following three buildings are employed:

- B1: 4-storey reinforced concrete (RC) building (Chatzidaki and Vamvatsikos 2021),
- B2: 20-storey steel building (Lachanas and Vamvatsikos 2021)
- B3: 4-storey reinforced concrete building (Kazantzi et al. 2022).

The maximum interstorey drift (IDR) is the EDP used to calculate the fragilities in question.

Methodology and challenges

To provide an essential background to the interested reader, a brief overview of the disaggregation and conversion method will be presented. The method relies upon using the existing information provided for a structure and its corresponding fragility, to build an ESDOF model (Figure 1) and use it as a calculation medium to run dynamic analyses, using a set of records to produce the distribution of response, e.g. via incremental dynamic analysis (IDA, Vamvatsikos and Cornell 2002). Some important parameters that should be available to build the model, are the structure's fundamental period, its mass or stiffness, and some information about its global force-deformation behavior. At the very least, if the model is nonlinear, a bilinear representation of its capacity curve is required. Using this information, the ESDOF model is built as a stick model with a rotational spring at its base, having a moment-rotation behavior to match the backbone supplied.

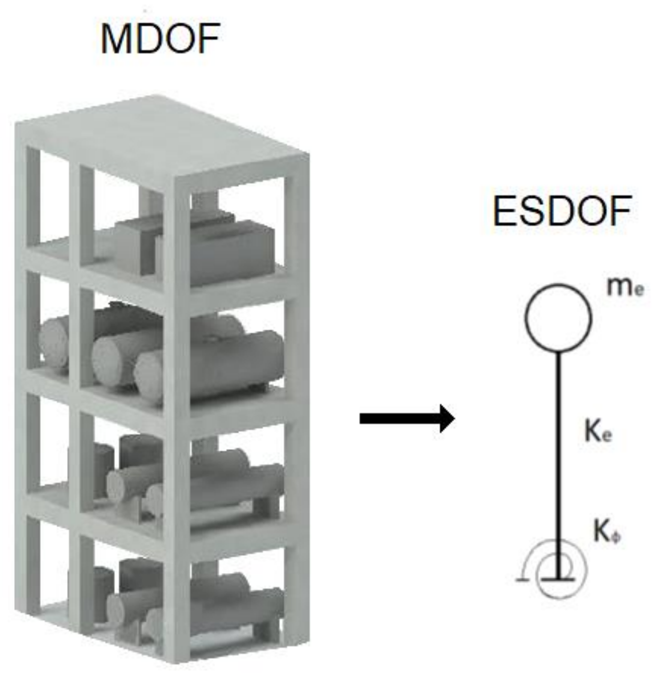

Figure 1. Equivalent single-degree-of-freedom stick model.

To associate the given fragilities with the response characteristics of this proxy model, a suitable EDP threshold, *EDPlim,* must be selected to produce a fragility that matches the original one in terms of the initial IM. Naturally, the ESDOF model's results and its resulting fragilities will not be the same as the ones produced by the more detailed MDOF model, therefore ad hoc correction parameters are employed to match the target fragility:

- α: a correction factor, meant to adjust the *EDPlim* threshold to ensure that the median IM of the ESDOF lognormal fragility matches the median of the MDOF target fragility.
- β_{α}: an additional dispersion, added to the record-to-record variability in a square-root-sum-of-squares fashion to ensure that the total ESDOF fragility dispersion matches the (normally) higher dispersion of the MDOF target fragility.

Their values are established via an iterative calibration process, described in detail in Karaferis and Vamvatsikos (2022). Figure 2 presents a visual example of how this process is applied. Specifically, when first running IDA through the ESDOF, and for an arbitrary *EDPlim*, the initial fragility derived does not match the targeted MDOF one, either in median or dispersion. Adjusting the *EDPlim* threshold by α (found via direct search) allows matching the median, while further adding β_{α} to the dispersion (found analytically) completes the match. Then, the IM-EDP points that correspond to the final α-adjusted *EDPlim* value for the ESDOF, become a faithful representation of the original fragility, effectively disaggregating it into one IM-EDP pair per each ground motion record employed in the IDA. The assumption is that if one employs the corresponding record to transforms each pair into new coordinates, these new IMs would still correspond to the same *EDPlim* and would thus recreate a good representation of the MDOF fragility in this new space. Figure 3 presents an overall conceptual overview of the disaggregation and conversion method.

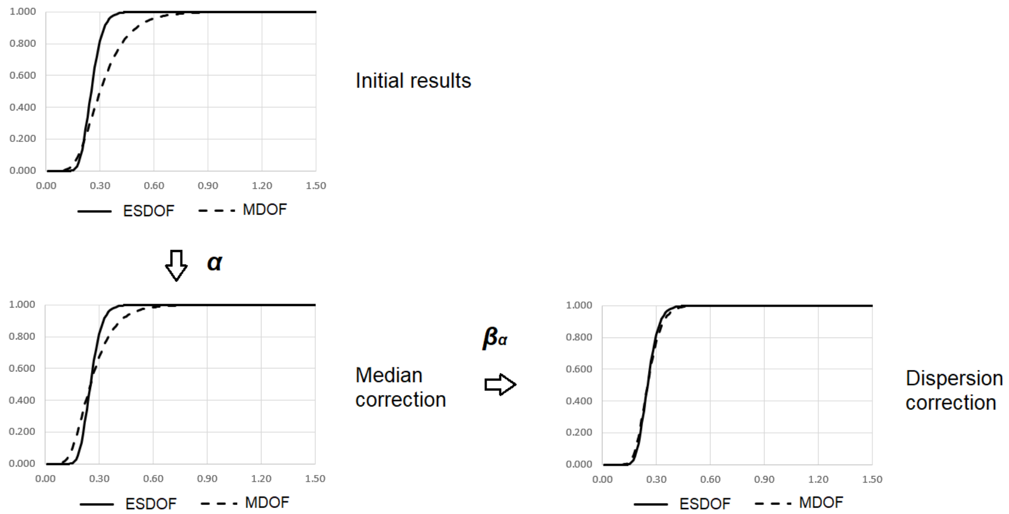

Figure 2. ESDOF fragility calibration process.

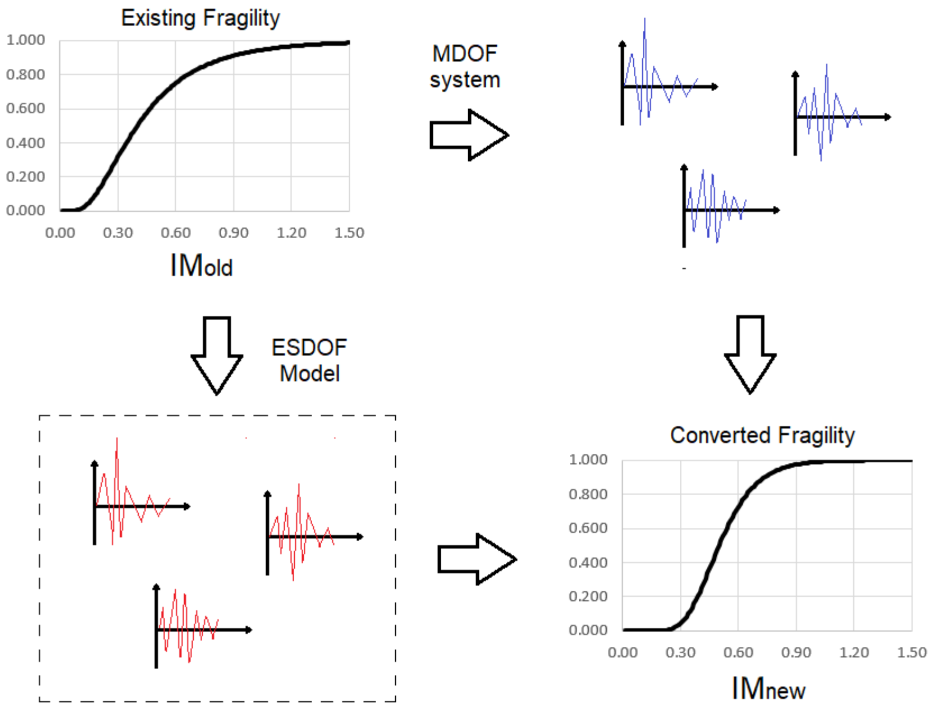

Figure 3. Conceptual overview of the disaggregation/conversion method. It is assumed that the ESDOF path (bottom left) will lead to the same transformed fragility in IMnew terms as the (theoretically correct) MDOF path (top right). As the latter is not available, the former is used to approximate it.

This process is based on the capability of the ESDOF to represent the MDOF, potentially not capturing responses that are affected by higher modes. For nonlinear structures, local failure modes will not be easy to simulate through a simple elastoplastic spring. Moreover, one may not even have (or want to use) the original analysis records, therefore a new record selection may be warranted to match the hazard specifications of the study at hand. The above inconsistencies could potentially be addressed via a more complex equivalent model, or a more elaborate procedure. After all, there is ample literature on reduced-order or surrogate models for complex MDOF structures of any kind. Still, it was a conscious choice to not delve into such endeavours as prescribing a more complex model defeats the purpose of having a simplified method to transform imperfect/generic literature fragilities. Where better accuracy is required, it would be better served by building a better model and redoing the fragility analysis from the start. Thus, it should be clarified that this is not a method to be used for every case at hand, but should be utilized only in a specific range of cases that are compatible to its assumptions.

Application examples

To test the methodology presented, the two models used in Karaferis and Vamvatsikos (2022) are revisited alongside a third additional building structure. Building 1 (B1) is a 4-storey RC moment-resisting frame building with a fundamental eigenperiod of T_1 = 1.05sec. It has been modelled in 2D by Chatzidaki and Vamvatsikos (2021). An ESDOF model was developed using the building's fundamental eigenperiod and an elastic-perfectly-plastic backbone fitted to the MDOF capacity curve per Figure 4. Building 2 (B2) is a 20-storey steel moment-resisting frame building, with its fundamental eigenperiod at T_1 = 3.82sec, also modelled in 2D by Lachanas and Vamvatsikos (2021). The ESDOF model built for this structure also employs an elastic-perfectly-plastic backbone fitted to the MDOF pushover curve as presented in Figure 4. Building 3 (B3) is an industrial RC moment-resisting frame structure that has been heavily overdesigned to comply with a high importance rating and stringent fire safety requirements. Essentially it is a high-stiffness high-strength that behaves elastically, at least for any realistic seismic intensity level. It has been originally modelled in 3D, having fundamental eigenperiods of $T_{1,x}$ = 0.57sec and $T_{1,y}$ = 0.54sec for the two principal directions X and Y. For the interested reader, the original model is presented in detail in Kazantzi et al. (2022).

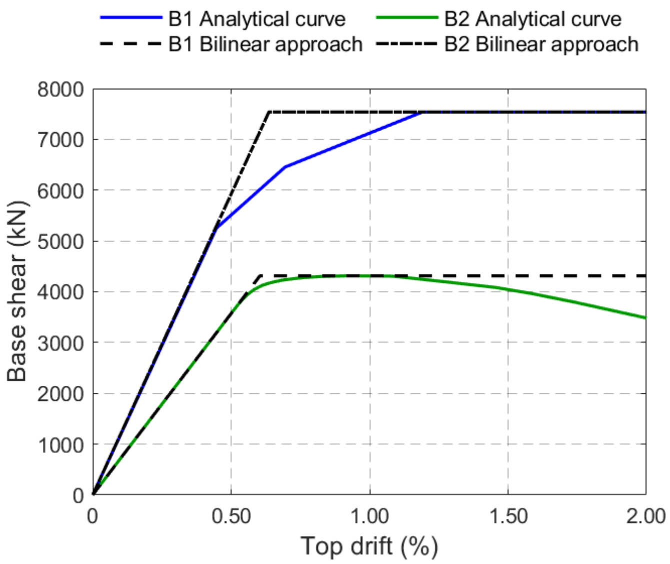

Figure 4. Push over results for structures B1 and B2. The backbone of structure B3 is trivial, by virtue of being elastic, and thus not shown.

Using the detailed MDOF models, IDA analysis was performed using the ground motion sets that were originally employed for analysing the structures in the respective literature. IDR was selected as the EDP to be recorded. To determine the fragilities for each model, two limit state (LS) were defined. For B1 and B2 there are LS1 at IDR = 0.75% and LS2 and IDR = 2.0%, defining two distinct damage states (DS). For the B3 case, LS1 at IDR = 1.00% and LS2 and IDR = 2.0% were adopted, following the original analysis approach. For the aforementioned LS thresholds, the fragility curves for the buildings were calculated using as IMs both the 5%-damped (pseudo)spectral acceleration at the fundamental period, $Sa(T_1)$, and the peak ground acceleration (*PGA*). The objective of this test is to transform the LS1 and LS2 fragilities derived for the MDOFs using $Sa(T_1)$ as the IM, into a *PGA* basis, while only employing the corresponding ESDOFs and record sets in the process.

Subsequently, IDA analysis was performed via the ESDOF built for each model, using the same ground motions employed for the corresponding MDOF. Initial ESDOF fragilities were produced using as EDP the system "roof" (or top node) drift and the same thresholds as for the MDOF. Of course, since the initial ESDOF fragilities cannot fully match the MDOF ones, the aforementioned correction process was applied. Specifically, this resulted to the determination of the optimal correction parameters α and β_α to match the $Sa(T_1)$ results of the ESDOF model to those of the MDOF model. By disaggregating the ESDOF IDA responses on a record-by-record basis, the fragility in terms of $Sa(T_1)$ was converted to a new fragility using *PGA*. This is as simple as estimating the *PGA* value that corresponds to each record's $Sa(T_1)$ and using the resulting set of points to fit a lognormal distribution. Having already calculated the original structure's fragility in terms of *PGA* it was easy to compare the exact results to the results produced through the proposed ESDOF-based approach.

In Figures 5 and 6, the results for the two nonlinear buildings B1 and B2 are presented. Even though the calibration of the ESDOF successfully captured the target fragilities in terms of $Sa(T_1)$, the fragility conversion to *PGA* was not as accurate. While the medians were near-perfectly captured, the dispersion was overestimated, especially LS2 where the nonlinearities are more prevalent. The results are very different for building B3, shown in Figure 7, since both the $Sa(T_1)$ fragility matching and the conversion to *PGA* resulted to highly accurate results. This is due to the model's elastic properties and first-mode-governed behavior that make it easier for the method to capture the building's IDR fragilities. Table 1 presents a summary of all fragility parameters for the MDOF models, alongside their ESDOF-based results.

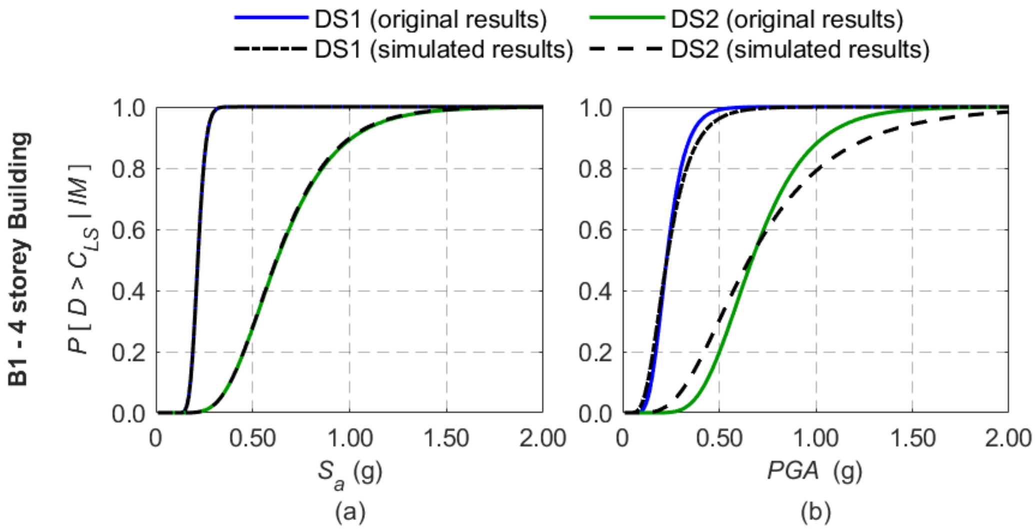

Figure 5. Fragility results for B1 (4 storey RC building)

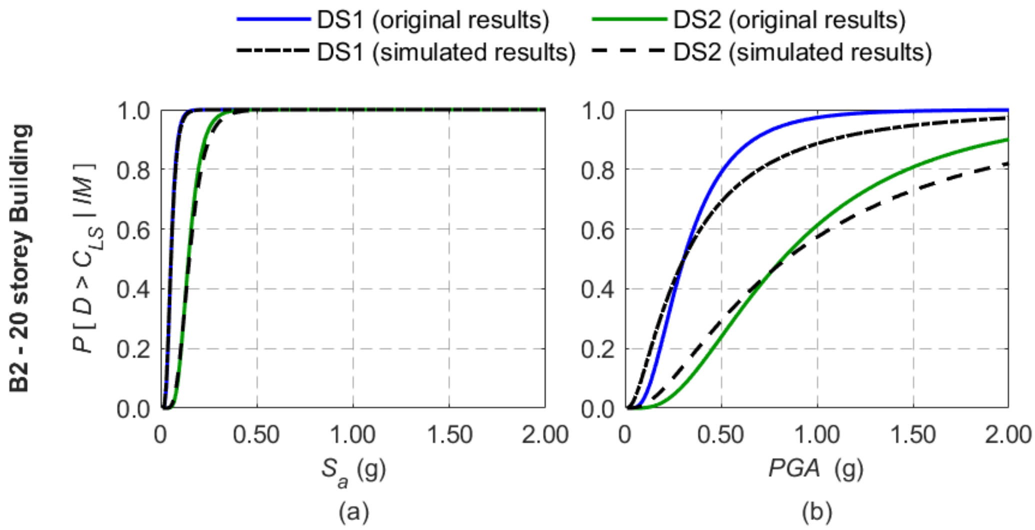

Figure 6. Fragility results for B2 (20 storey steel building)

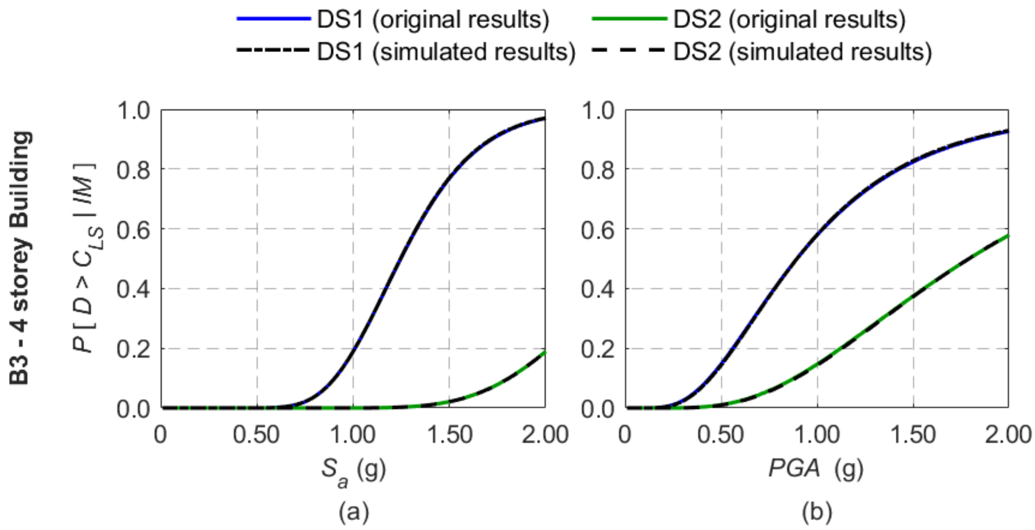

Figure 7. Fragility results for B3 (4 storey RC elastic building)

Fragility Results			**DS1**		**DS2**	
			Median (g)	**dispersion**	**Median (g)**	**dispersion**
B1 - 4 storey RC building	MDOF	$S_a(T_1)$	0.217	0.151	0.625	0.379
		PGA	0.228	0.336	0.670	0.343
	ESDOF	$S_a(T_1)$	0.217	0.150	0.622	0.375
		PGA	0.229	0.441	0.656	0.523
B2 - 20 storey Steel building	MDOF	$S_a(T_1)$	0.054	0.402	0.145	0.361
		PGA	0.306	0.613	0.821	0.694
	ESDOF	$S_a(T_1)$	0.054	0.427	0.149	0.411
		PGA	0.307	0.981	0.841	0.947
B3 - 4 storey RC elastic building	MDOF	$S_a(T_1)$	1.247	0.251	2.494	0.251
		PGA	0.896	0.554	1.792	0.554
	ESDOF	$S_a(T_1)$	1.246	0.250	2.492	0.250
		PGA	0.896	0.547	1.792	0.547

Table 1. Fragility parameters estimated via the MDOF (baseline) and the ESDOF (approximate) for B1, B2 and B3.

Conclusions

The methodology presented for fragility curve disaggregation and IM transformation, was challenged by addressing its weaknesses in terms of effectively handling fragilities based on localized measures of response, such as the maximum interstory drift, and the presence of nonlinearities. The simplicity of the approach and the constraints of the ESDOF model prevent us from accurately capturing all MDOF modes of response. The inconsistencies of the method when used under these conditions were highlighted by using two nonlinear buildings, where even though the fragility matching was easy to perform for an initial IM, a potential IM transformation would lose quality in terms of an overestimated dispersion. On the other hand, the elastic building studied, even thought its original model was more complex, was accurately represented by this adjusted ESDOF model, while the IM conversion was successful as well. To conclude, the method has a clear range of application, being suitable for addressing global responses e.g. roof drift, but struggles with more localized effects. High strength, effectively-elastic structures could be an exception though (e.g. industrial buildings that usually are overdesigned on purpose), while in general, the closer the structure's behavior seems to be to an inverse pendulum type model, the more effective the approximation.

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