



## FRAME V.1.0: A RAPID FRAGILITY-BASED SEISMIC RISK ASSESSMENT TOOL

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### ABSTRACT

This paper describes the software named *FRAME – Fragility-based Rapid seismic Risk AssessMEnt – v.1.0*. Its main objective is the worldwide assessment of structure-specific seismic risk, based on seismic hazard and fragility functions, for a number of structural typologies. To this aim, the software includes worldwide seismic hazard estimates, a literature-based expandable fragility curve inventory and damage-to-loss relationships, allowing to translate the structural damage into an expected loss for both direct damage and business interruption.

### 1. INTRODUCTION

Fragility functions are a key component in the assessment of seismic risk according to the performance-based earthquake engineering (PBEE) framework (Cornell and Krawinkler, 2000). To date, a wide number of fragility curves is available in literature, virtually allowing the assessment of failure probability and loss for several structural typologies. However, fragility functions for the same structural typology may differ due to the differences in structural characteristics and construction practice, as well as for the methods used to obtain them. Moreover, there is a wide variability of these curves in terms of employed ground motion intensity measures and considered damage states.

These issues motivated recent efforts aimed at the collection and comparison of available fragility functions or at their computation for recurrent structural types, mostly at the national or global scale. Examples are the LESSLOSS (2005), SYNER-G (Pitilakis *et al.*, 2014), and GEM projects (D'Ayala and Meslem, 2013). Collections of fragility curves are also provided in loss assessment frameworks and tools, such as in HAZUS (FEMA, 2001). Nevertheless, the selection of a fragility curve for the seismic risk assessment of a specific structure remains a non-trivial task.

In order to support the seismic risk assessment by means of fragility curves and to provide aid in managing a large fragility inventory, the *FRAME - Fragility-based Rapid seismic Risk AssessMEnt - v.1.0* software was developed. FRAME v.1.0 is a collection of MATHWORKS - MATLAB scripts allowing, from one hand, the inventory, the comparison and the harmonization of fragility curves and, on the other hand, their use in conjunction with hazard estimates and expected loss due to failure, for the assessment of the seismic risk of site-specific constructions.

Seismic risk assessment is performed in a PBEE framework, therefore fragility curves describing the conditional probability of reaching or exceeding predefined damage states (DSs) conditional to a ground motion intensity measure (IM) value are employed. The tool may finally provide risk estimated in terms of direct (property-damage-related) and indirect (downtime- and business-interruption-related) losses. Moreover, a specific module is dedicated to the selection of a

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subset of the fragility curve inventory according to a given taxonomy, and to the approximated harmonization of the selected curves with respect to the intensity measures or damage states. Statistics of the selected subset of fragility curves may also be computed.

In the paper, the data included in FRAME v.1.0 are discussed. Then, the implemented procedure and the program’s capabilities are shown. Finally, the FRAME v.1.0 features for the management of a fragility curve inventory are discussed.

## 2. THE FRAME v.1.0 STRUCTURE AND DATA SOURCES

Seismic risk assessment is performed in FRAME v.1.0 through different modules (Fig.1):

- **The FRAME main module** allows the input of the data required for the assessment, that is: (i) information to retrieve site-specific hazard, (ii) information to select fragility curves suitable for the case under consideration, (iii) information to get the expected loss;
- **The FRAME fragility filter module** allows to perform a search within the fragility curves inventory;
- **The FRAME comparison & conversion module** allows to compare fragilities in order to compute statistics, convert intensity measures and manage damage states;
- **The FRAME manager module** allows to manage the fragility curves’ inventory and to modify the taxonomy according to which the fragilities are stored;
- **The FRAME loss module** allows the expected loss assessment, given the probability of failure computed by means of the other modules.

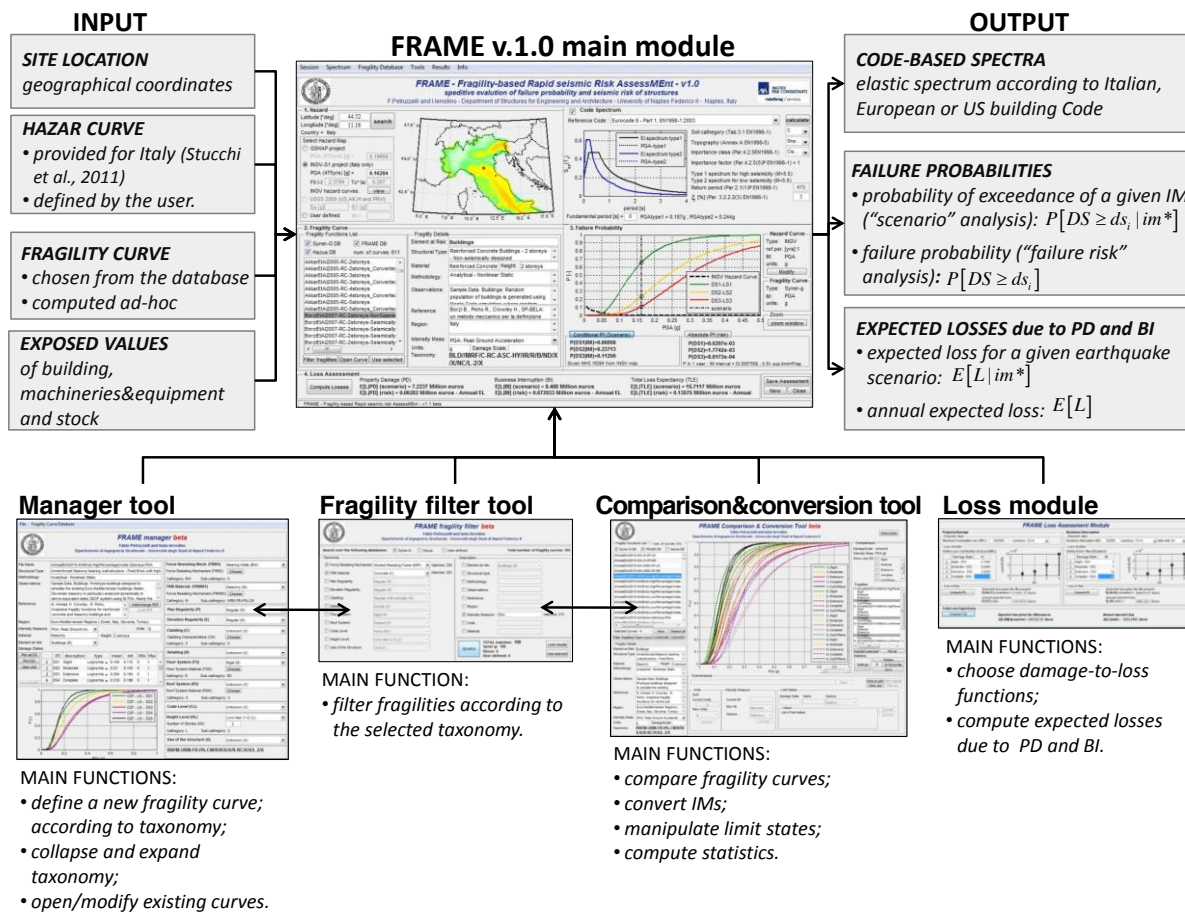


Figure 1. FRAME v.1.0 software modules ensemble.

Therefore, the ensemble of FRAME modules (i) allows performing a rapid (yet rough) and worldwide applicable evaluation of structure-specific seismic losses, (ii) provides an inventory of existing fragility functions that can be managed and expanded, (iii) allows the comparison and manipulation of fragility curves and the identification of the most suitable, among those available, to describe the seismic performance of a structure. To these aims FRAME v.1.0 makes use of literature-based data for what concerns both hazard and fragility.

Regarding the hazard, the software includes:

- the GSHAP worldwide hazard map (Giardini *et al.*, 1999), providing the PGA with a return period of 475 years on rock, in the following referred to as  $PGA_{GSHAP}$ ;
- the hazard curves for Italy (in terms of spectral accelerations) from the INGV-S1 project (Stucchi *et al.*, 2011);
- the USGS 2008 (Petersen *et al.*, 2008) hazard maps providing the 2% in 50 years probability of exceedance of 0.2 s and 1.0 s spectral accelerations, for US 48 conterminous states, Alaska, Hawaii, Puerto Rico or US Virgin Islands.

Regarding the fragilities, the curves obtained from the following studies are considered:

- SYNER-G (Crowley *et al.*, 2014; Lagomarsino and Cattari, 2014), providing fragilities for reinforced concrete (RC) and masonry European structures;
- HAZUS@MH MR4 (FEMA, 2003), providing fragility curves for structures in the US;
- Other curves for specific structural typologies, for example, those from Bolognini *et al.* (2009) and Senel and Kayan (2010), regarding RC precast industrial buildings, and those from Fabbrocino *et al.* (2005); i.e, fragility curves for atmospheric steel tanks.

Currently FRAME includes 585 fragility curve sets, 320 of which for RC structures, 153 for masonry, 37 for precast concrete, 58 for steel and 17 for other materials or structural types (wood, mixed systems and tanks). However, the possibility of considering user-defined hazard and/or fragility curves is also provided by the software.

### 3. LOSS ASSESSMENT IN FRAME v.1.0

The approach performed by default in FRAME is a *conditional failure probability* (or *scenario*) analysis, providing the conditional probability of failure  $P[DS \geq ds_i | im^*]$ , that is the fragility, or the probability of reaching or exceeding the  $i$ -th damage state (out of  $n+1$ ), given a scenario earthquake intensity  $im^*$ . Since FRAME includes the GSHAP hazard map, this kind of approach is always feasible, if a fragility curve is available for the structure of interest, and may provide the probability of the construction being in the  $i$ -th damage state given  $PGA_{GSHAP}$ , as reported in Eq.(1) and sketched in Fig. 2. It is to note that  $ds_0$  is defined as the no-damage condition.

$$P[DS = ds_i | PGA_{GSHAP}] = \begin{cases} 1 - P[DS \geq ds_{i+1} | PGA_{GSHAP}] & i = 0 \\ P[DS \geq ds_i | PGA_{GSHAP}] - P[DS \geq ds_{i+1} | PGA_{GSHAP}] & 0 < i \leq n - 1 \\ P[DS \geq ds_i | PGA_{GSHAP}] & i = n \end{cases} \quad (1)$$

The loss measure computed in this analysis is  $E[L | PGA_{GSHAP}]$ , that is the expected loss, given the scenario IM. It can be computed as in Eq.(2), in the hypothesis that the expected loss, given that the structure is in the  $i$ -th damage state, is independent of  $PGA_{GSHAP}$ .

$$E[L | PGA_{GSHAP}] = \sum_i E[L | ds_i] \cdot P[DS = ds_i | PGA_{GSHAP}] \quad (2)$$

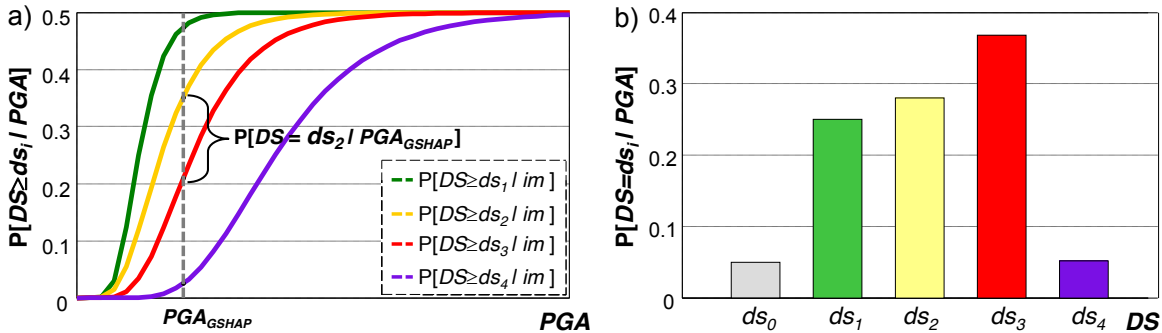


Figure 2. Scenario approach for a given  $PGA_{GSHAP}$  value in FRAME.

If a hazard curve, that is the exceedance rate (for example annual) of any IM value,  $\lambda(im)$ , is available for the site (defined by the user, or embedded in FRAME as it happens, for instance, for Italy), the *absolute failure probability*, or *failure risk*,  $P_f$ , is computed (Eq.3). In this case, the unconditional annual expected loss is provided according to Eq.(4). To get these results, FRAME v.1.0 operates via the steps summarized in Fig.3 and described in the following.

$$P_f = P[DS \geq ds_i] \approx \int_{im} P[DS \geq ds_i | im] \cdot d\lambda(im) \quad (3)$$

$$E[L] = \sum_i E[L | ds_i] \cdot P[DS = ds_i] \quad (4)$$

**STEP 1 – HAZARD DEFINITION**  
**Required input:**  
 site location (Lat, Lon).  
**Output:**  
 • GSHAP  $PGA_{475yrs}$  (worldwide);  
 • INGV  $PGA_{Tr}$  (Italy);  
 • INGV Haz. Maps (Italy);  
 • USGS 0.2 and 1.0 s accelerations (US, Puertorico, Virgin Islands, Alaska);  
 • user-defined IM;  
 • user-defined hazard curve;

**STEP 2 (optional) – ELASTIC SPECTRUM**  
 defined according to:  
 • International Building Code (ICC, 2012);  
 • Eurocode 8 (CEN, 2004);  
 • Italian Building Code (C.S.LL.PP., 2008).

**STEP 3 – FRAGILITY SELECTION**  
**Required Input:**  
 fragility curve set from the inventory or user-entry.

**STEP 4 – FAILURE PROBABILITIES**  
 computed for damage states defined according to the fragility curve set.  
 Two possible approaches:  
 • “conditional failure probability” (“scenario”) analysis;  
 • “absolute failure probability” (“failure risk”) analysis.

**STEP 5 – LOSS ASSESSMENT**  
 Expected loss in terms of Property Damage (PD) e Business Interruption (BI).  
**Required Input:**  
 • exposed values given by user-entry for building, machineries&equipment and stock;  
 • user-defined damage-to-loss functions or (for industrial occupancies) on the basis of the activity sector.

Figure 3. Graphical user interface (GUI) of FRAME’s main module and steps of the loss assessment.

### Step 1 – Hazard definition

The top left panel of the GUI (Fig.3) refers to the hazard: the user inputs the geographical coordinates of the site and the software retrieves the  $PGA_{GSHAP}$  value. If the facility is located in the US, Alaska, Hawaii, Puerto Rico or US Virgin Islands, besides the  $PGA_{GSHAP}$  value, the 0.2 s and the 1.0 s spectral accelerations according to the 2008 USGS map are retrieved. If the facility is located in Italy, in addition to the  $PGA_{GSHAP}$  value, the PGA with 475 years on rock according to Stucchi *et al.* (2011) is shown. These values can be directly employed in the conditional failure probability approach.

If the hazard in terms of more than one IM is available at the site (e.g., in Italy), the user can choose among them. The corresponding hazard map is plotted in the top-left panel. In any case, the input of a specific  $im^*$  value, or of a user-defined hazard curve, is possible. In the case of Italian sites the retrieval at the site under investigation of hazard curves and uniform hazard spectra from INGV data is also possible.

### Step 2 (optional) – Computation of elastic spectrum

The top right panel of the GUI (Fig. 3) allows the computation of elastic spectra according to: the Italian Building Code (C.S.LL.PP., 2008); the Eurocode 8 (CEN, 2004) and the 2012 International Building Code (ICC, 2012). This function can be employed also in order to roughly account for, in a code-based approach, the local site conditions at the construction location, if known.

### Step 3 – Selection of the fragility curve set

The bottom left panel of Fig. 3 presents the list of the fragility curves available in the database. Selecting one record of the list, the main characteristics of the curve, such as structural type, construction material, geographical region, units, damage scale, and the taxonomy parameters, are shown. The taxonomy allows to summarize the main characteristics of the buildings to which the fragility applies, and its definition is a key issue for the inventory of fragility curves (see Section 4.1).

To aid the selection of a fragility curve, it is possible to filter the database by means of the *FRAME fragility filter* module (Fig. 1). This tool allows the user to define search queries and to select the portion of the database matching a specific taxonomy. As it will be discussed in Section 4.2, the adopted taxonomy is derived from that employed in the SYNER-G project.

### Step 4 – Assessment of failure probability

In this step, the failure probability related to each damage state (defined by the fragility curve set employed) is evaluated according to the type of analysis performed. Therefore, Eqs. (1) and (3) are computed, in the case of conditional and absolute failure probability analyses, respectively. Results are shown in the bottom right panel of the GUI (Fig.3).

### Step 5 – Loss assessment

As it concerns the loss assessment, it is possible to use the previous probabilities to evaluate Eq.(2) and Eq.(4). To perform the assessment in terms of property damage (PD), the exposed (*at risk*) value (EV) of the structure under investigation is required. Besides the EV, FRAME also requires to define the loss-to-damage fractions,  $k_i$ , each of which representing the fraction of EV that is expected to be lost, for each damage state  $ds_i$ . Therefore, the expected property loss associated to the  $i$ -th damage state, is:

$$E[L_{PD} | ds_i] = EV \cdot k_i \quad (5)$$

Regarding the expected loss related to the business interruption (BI), a similar approach to the one discussed for PD is pursued. The main difference is that the EV is replaced by the loss due to business interruption per unit time (i.e., unitary business interruption, UBI) and the  $k_i$  coefficients are replaced by  $n_i$ , representing the length of downtime (in time units) for each damage state (Eq. 6).

$$E[L_{BI} | ds_i] = UBI \cdot n_i \quad (6)$$



Such calculations are performed through the *FRAME loss* module (Fig. 3, box 5), which allows to entry the EV and UBI values, and to define  $k_i$  and  $n_i$  coefficients, or to select them among some suggested values based on expert judgement.

#### 4. FRAGILITY INVENTORY MANAGEMENT

Assigning a fragility curve to a structure is the key step of the previously outlined procedure. This task must be carried out taking into account the characteristics of the building under investigation.

The wide variability of existing structural typologies (Brzev *et al.*, 2013) is such that in some cases (e.g., cast in place RC structures, Crowley *et al.*, 2014) a large number of fragility functions exists, while a lack of functions can be observed for others (e.g., industrial steel structures, Petruzzelli *et al.*, 2012). Therefore, it was chosen to develop specific modules in FRAME v.1.0 dedicated to the storage, harmonization, and manipulation of a fragility curve inventory.

##### 4.1 Fragility database

The *FRAME manager* module (Fig.4) was developed with the specific aim of collecting and storing fragility curves in a coherent manner, with also the possibility of editing them.

A relevant issue in managing fragility curves is the adoption of an appropriate taxonomy, which is the definition of the main features useful to associate a fragility curve to a structure. Several taxonomies have been developed for classifying buildings and/or defining homogeneous classes of structures (e.g., ATC, 1985; FEMA, 2003).

In FRAME, a taxonomy adapted from that of the SYNER-G project was adopted. The considered taxonomy consists of seventeen non-hierarchical categories (such as material, lateral load resisting system, detailing, design code level, etc.), and some descriptive fields for the fragility curve (such as geographical context, method of analysis, paper reference, etc.). This information is collected in FRAME as a relational database.

Finally, it is to mention that the FRAME manager module also allows the entry of user-defined, fragility curves, in terms of parametric and non-parametric functions.

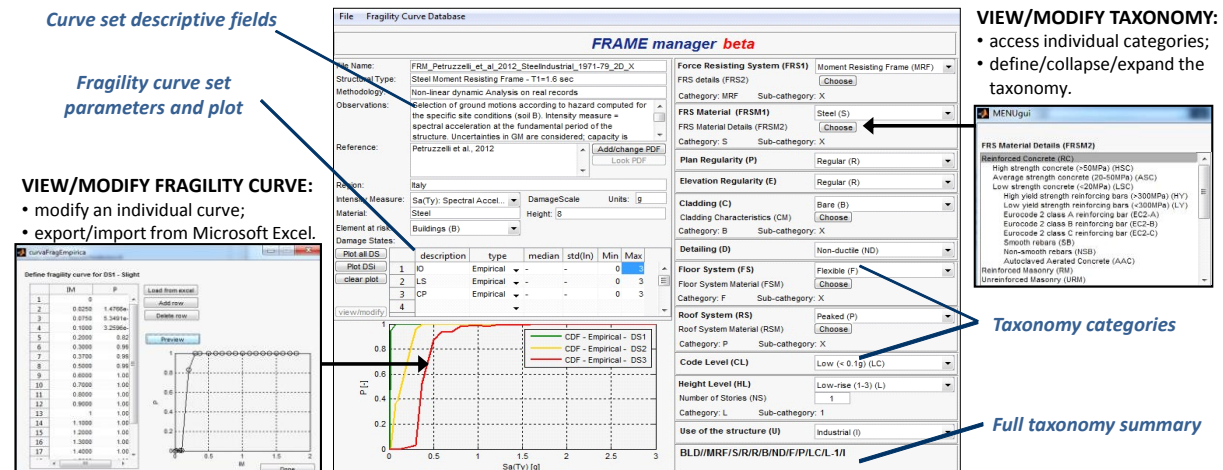


Figure 4. FRAME manager tool GUI (centre) and windows allowing the input of fragility curves (bottom-left) and the definition of the taxonomy (top-right).

##### 4.2 Comparison and conversion of fragility curves

The *FRAME comparison & conversion* module (Fig.5) was developed with purposes and functions similar to the SYNER-G Fragility Manager (Silva *et al.*, 2014), that can be summarized as follows: (i) modifying the set of curves relevant to a single building, converting the intensity measures or modifying the considered damage states; (ii) comparing fragility curves and computing statistics.

Regarding the first point of the list, fragility curves available in literature are characterized by a large variability of the employed intensity measures of the earthquake. Among the formulas available in literature for the conversion of IMs (for a review the reader could refer to Musson and Grünthal, 2010, and Cua *et al.*, 2010) some were implemented in FRAME.

The conversions of PGA into macroseismic intensity and vice-versa are performed according to the following studies: Faenza and Michelini (2010); Margottini *et al.* (1992); Wald *et al.* (1999b); Murphy and O'Brien (1977); Sorensen *et al.* (2008); Tselentis and Danciu (2008). Faenza and Michelini (2010) and Wald *et al.* (1999b) also provide for the conversion from PGV to macroseismic intensity (see Petruzzelli, 2013, for details).

Fragility curves developed for similar structures can also be different for the number and type of damage states (see Rossetto and Elnashai, 2003, and D'Ayala *et al.*, 2013, for discussions). To deal with this issue, in FRAME it is possible to homogenize the fragility curve inventory (or a subset of it) in terms of number of damage states, via the arbitrary definition of a new set of damage states to which are converted those of all the considered curves (see Petruzzelli, 2013, for details).

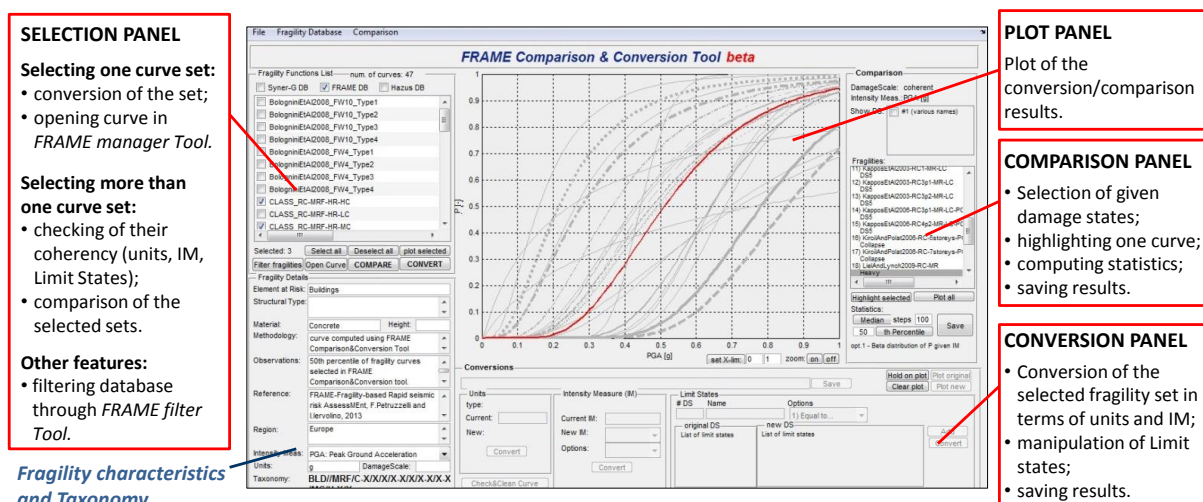


Figure 5. FRAME comparison & conversion module GUI.

In FRAME, the comparison of an ensemble of fragility curves can be performed only if their coherency in terms of units, intensity measures and number of considered damage states is ensured. The comparison and conversion module enables the selection of a set of curves from the inventory and the automatic check of their coherency. Then, the ensemble of fragility curves is returned and it is possible to select those damage states to be shown, to highlight one curve among the others, and to compute statistics with respect the considered set.

To this regard, the first option is based on the evaluation of the distribution of the probability of reaching or exceeding a damage state, conditional to a given IM level, as shown in the top panel of Fig.6. The choice of a statistical model, to fit such a distribution, may be formally performed with respect to the following models: normal, lognormal, Weibull, exponential, beta, gamma. Then the resulting probability density function (PDF) or cumulative distribution function (CDF) may be displayed.

The second option is similar to the one proposed by Bradley (2010): under the assumption the curves follow a lognormal model, the mean of the logarithms  $\mu_{\ln(IM)}$  (related to the median) and the standard deviation of the logarithms  $\sigma_{\ln(IM)}$  of each curve are used to fit a bivariate distribution for these parameters.

The third option is to fit separate models (univariate) for  $\mu_{\ln(IM)}$  and  $\sigma_{\ln(IM)}$ , based on the parameters of the ensemble of fragility curves under consideration (see Petruzzelli, 2013, for further details).

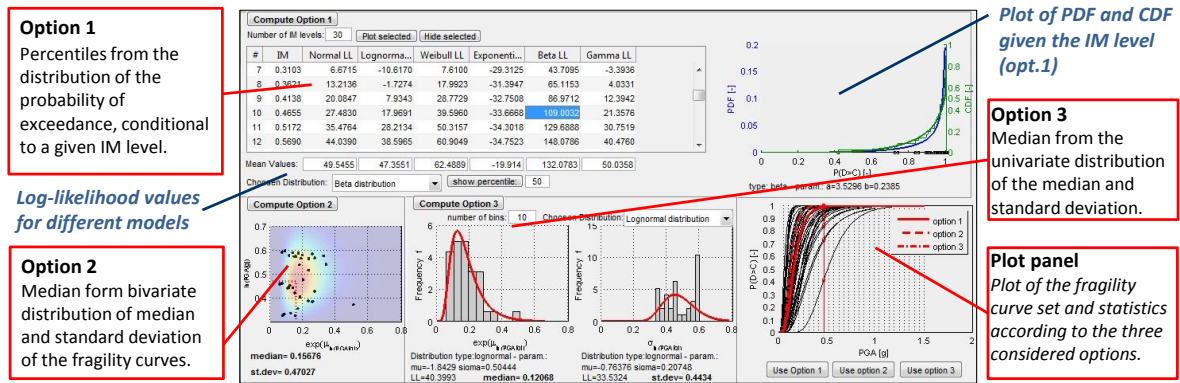


Figure 6. Options for computing statistics of a fragility curve inventory in FRAME v.1.0.

## 5. SUMMARY

In this paper the FRAME v.1.0 prototype software for the assessment of earthquake losses was briefly presented. FRAME was developed as a collection of modules, each of which performing a different task related to the seismic risk assessment. In fact, FRAME allows the use of hazard studies for different geographical regions, the storage in a relational database of a large number of fragility curves available in literature, and the definition of damage-to-loss functions based on the occupancy of the building under consideration.

The software is also able to perform conversions of fragility curve units, IMs, and to manipulate damage states, in order to homogenize a set of functions. This could be useful to account for model uncertainty with respect to structural vulnerability.

The tool was developed to be user-friendly and expandable. In fact, it is possible to employ user-defined hazard curves, fragility functions, and damage-to-loss relationships.

FRAME allows the estimate of conditional and absolute expected losses for specific constructions worldwide on the basis of a structural taxonomy. However, the success of the risk assessment is related to the knowledge level that is possible to achieve about the structures under investigation and to the availability of fragility curves suitable to probabilistically describe their vulnerability with respect to the available hazard measures.

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