Fragility Curves of Restoration Processes for Resilience Analysis

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ABSTRACT: In literature the fragility curves are usually adopted to evaluate the probability of exceedance of a given damage state, while in this paper is presented for the first time a procedure for building fragility curves of restoration processes which can be adopted for resilience analysis. The restoration process describes the capacity to recover of a system after a failure. In order to have a resilience system, it is necessary to reduce the consequences from failures by shortening the recovery time and reducing the probability of damage. The *restoration process* is one of the most uncertain variables in the resilience analysis therefore, it is necessary to consider it in probabilistic terms. The method has been applied to the performance of a hospital during an emergency. A discrete event simulation model has been built to simulate different restoration processes. The set of restoration processes obtained through Monte Carlo simulations has been analyzed statistically to determine the probability of exceedance of a given restoration state. Restoration Fragility Functions (RFF) are obtained using the maximum likelihood estimation (MLE) approach. The probability of restoration for a given earthquake intensity (e.g. MMI) level, x, can then be estimated as the fraction of records for which restoration occurs at a level lower than x. A lognormal cumulative distribution function is used to fit the data, to provide a continuous estimate of the probability of restoration as a function of MMI. Two different case scenarios are compared: the Emergency Department (ED) with and without emergency plan applied. Finally, different methods to build fragility curves are compared in order to evaluate the RFF.

1. INTRODUCTION

Hospitals are critical facilities which affect the emergency response after a catastrophic event such as a strong earthquake. The non-functionality of an emergency department (ED) during an emergency might significantly impact the health care services and affect the recovery process. The hospital's capability to remain accessible and able to function at maximum capacity, providing its services to the community when they are most needed can be evaluated using the resilience indicators. A possible resilience indicator for health care facilities is the waiting time, which is the time the patient waits from the moment he walks in the ED until he receives the first service from medical personnel (Cimellaro et al., 2010, 2011). A key role in the evaluation of the resilience indicator is played by the *recovery time* and the shape of the *restoration curve*, because they are both uncertain quantities.

Therefore, in this paper a procedure for building fragility curves of restoration processes called *Restoration Fragility Functions* (RFF) which can be adopted for resilience analysis, is presented.

RFFs are introduced to take into account the uncertainties of the restoration process. In detail, RFFs are defined as *the probability of exceedance of a given restoration process when a certain damage state occurs*. To calculate the RFF it is necessary to define the functionality (*Q*) of the system considered and the recovery time. The Emergency Department (ED) of the Umberto I Mauriziano Hospital in Italy is considered as case study. After building and calibrating a Discrete Event Simulation (DES) model of the emergency department (ED) using real data collected on site, different scenarios has been tested by modifying the patient arrival rate and changing the number of available emergency rooms. In this research two configurations have been considered: the ED with emergency plan applied and the ED in normal operating condition. RFFs of both cases are compared.

1.1. State of art on fragility functions

In the current state-of-art, fragility functions describe the conditional probability that a structure, a nonstructural element or in general a system, will exceed a certain damage state, assuming a certain demand parameter (e.g. story drift, floor acceleration etc.) or earthquake intensity level (e.g. peak ground acceleration (PGA), peak ground velocity (PGV) or spectral acceleration (SA)) is reached. Usually, fragility functions take the form of lognormal cumulative distribution functions, having a median value θ and logarithmic standard deviation, β (Porter et al. 2006). The first attempts to introduce uncertainties in the restoration processes of infrastructures such as bridges is present in the work of Zhou and Frangopol (2014) where they defined the probability of a bridge experiencing different performance and functionality levels (e.g., one lane closed, all lanes closed). They got inspired by the Federal Highway Administration (FHWA, 2010), which following ATC-13 (1999), modeled the restoration process of bridge functionality by a normal cumulative distribution function corresponding to each bridge damage state considered. In fact, the recovery functions are highly dependent on their associated damage states. For example, a bridge categorized in a severe damage state may need more time to be restored to its full functionality compared to a bridge slightly damaged.

On the other hand, in this paper, the recovery functions are computed for three different damage states (DS), *no damage*, *moderate damage* and *complete damage*. For each DS a characteristic restoration curve is defined.

2. DEFINITION OF RESTORATION FRAGILITY FUNCTION (RFF)

In this paper is presented for the first time a procedure for building fragility curves of restoration processes which can be adopted for resilience analysis. RFF is the probability of exceedance of a given restoration curve (rf) when a certain damage state (DS) occurs for a given earthquake intensity measure *I*. The general definition of RFF based on earthquake intensity *I* is given by

$$RFF(i) = P\left(RF_j \geq rf_{DS1} \middle| DS = DS1, I = i\right) \quad (1)$$

Where the RF_j=jth restoration function; rf_j=restoration function associated to a given damage state DS (1,2,…n); *I*=earthquake intensity measure which can be represented by pga=peak ground acceleration; pgv=peak ground velocity; PVS =pseudovelocity spectrum; MMI=modified Mercalli intensity scale, etc.; and i=given earthquake intensity value.

The main difference between RFF and standard fragility functions is that the RFF is correlated to a given damage state (DS). In other words, RFF is conditional on DS and *I*, while standard fragility curves are only conditional on the intensity measure *I*.

2. METHODOLOGY

The RFF are evaluated using the experimental data of the restoration curves collected by the numerical analyses of the model considered. Different output can be considered, but in this specific case, the waiting time (WT) spent by patients in the emergency room (ER) before receiving care. (Cimellaro et al. 2010), is considered as an indicator of functionality. In particular, the following relationship has been used to define its functionality Q:

$$Q = \frac{WT_0}{WT} \tag{2}$$

where WT_0 is the acceptable waiting time in regular condition, when the hospital is not affected by a catastrophic event, and WT is the waiting time collected during the simulation process. When the WT is less or equal to WT_0, the value of Q is equal to 1, meaning that the hospital's functionality is at its maximum.

Different restoration functions (*rf*) associated at different damage states have been chosen. Then, for each simulation, the probability of exceedance of a given restoration curve (rf) has been calculated. The frequency of exceedance at a given instant is defined as

$$f = \frac{N}{N_{tot}} \tag{3}$$

where N is the number of times when the restoration curves exceed the restoration curve associated at a given damage state; N_{tot} is the number of simulations.

Finally the probability of exceedance of a given restoration state has been calculated by

$$P_{ex} = \frac{\sum f_i}{T} \tag{4}$$

Where $\sum f_i$ is the sum of the frequencies at each time instant, while T is the length of the simulation (e.g. $T=12$ *days* in the case study).

Finally, different methods to fit fragility curves are compared such as:

-*MLE method: maximum likelihood method ;*

-*SSE method: sum of squared errors;*

3. CASE STUDY: THE MAURIZIANO HOSPITAL IN TURIN

The Umberto I Mauriziano Hospital located in Turin, Italy has been considered as case study to show the applicability of the methodology. The hospital is located in the southeast part of the city, at almost 3 km from downtown. It was built in 1881 but it was bombed several times during World War II. This explains why several buildings have been rebuilt or added. Presently the hospital includes 17 units, which correspond to different Departments and it covers an overall surface of 52827 m^2. Only the Emergency Department (building 17) has been modeled (Figure 1).

A discrete event simulation model (DES) of the emergency department has been developed (Figure 2) using ProModel version 7.0, downloaded on February 15, 2014. Discrete *event simulation models* represent useful tools to test Emergency Plans response under a rapid increase in the volume of incoming patients. Using discrete-event Monte Carlo computer simulation, hospital administrators can model different scenarios of the hospital to see how they compare to the desired performance (Morales, 2011). Moreover, DES model allows investigating and planning the use of hospital resources (Šteins, 2010).

The data input of the model is the patients' arrival rate in normal operating conditions, which has been extracted by the hospital's register statistics. These data have been used to calibrate the model. During the emergency, the increments of patients entering in the ED has been obtained using the data collected in a Californian hospital during 1994 Northridge earthquake. The pattern of the Northridge patient arrival rate is given in the paper of Cimellaro et al. (2011). Then the patients' arrival rate has been scaled to the seismic hazard in Turin using a procedure based on the Modified Mercalli Intensity (MMI) scale. An earthquake with a return period of 2500 years has been considered, assuming a nominal life for a building of strategic importance of 100 years according to the Italian seismic standards (NTC-08, 2008).

RFFs both with and without emergency plan are compared. The emergency plan is considered effective if the waiting time obtained when the emergency plan is applied is significantly lower than the waiting time obtained under emergency conditions when the emergency plan is not active.

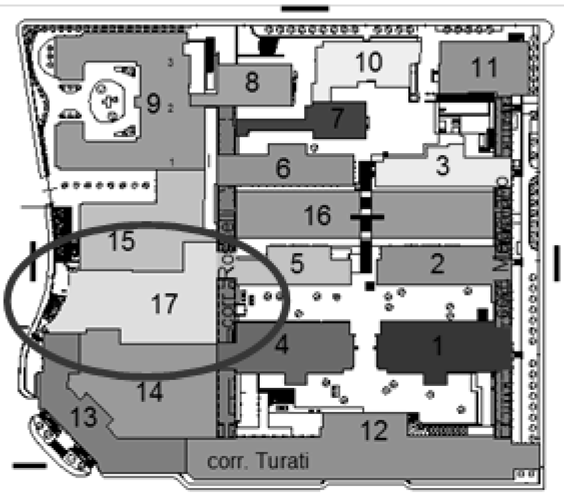

Figure 1: Hospital's units – Emergency Department building.

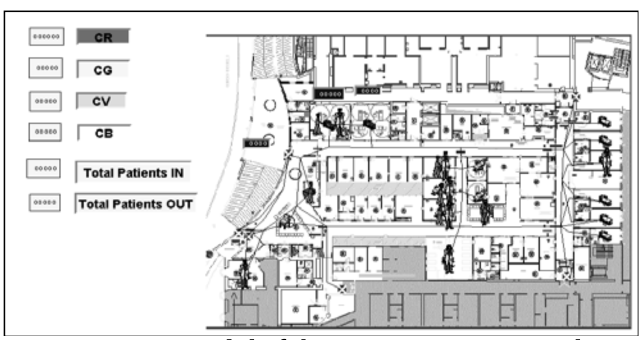

Figure 2: DES model of the Mauriziano Hospital in Promodel.

3.1. Hospital performance and restoration functions (rf)

Generally, the performance of a hospital under seismic hazard is quantified considering all its possible damage states. The performance of the Emergency Department (ED) is quantified within this paper by mapping the current damage state to a value between 0 and 1.0. Assuming a certain damage state occurs in the hospital, then different restoration functions (*rf*) can be applied to the damaged structure to restore its functionality. However, the restoration functions (*rf*) of the ED are highly dependent on their associated damage states. For example, an ED categorized in a severe damage state may need more time to be restored to its full functionality compared to an ED slightly damaged, so some *rf*s have more probability to happen with respect to others.

3.2. Numerical results

As outputs of the model, the waiting times of the ED when the emergency plan is active have been collected for different scenarios. Three different damage states (DS) have been considered:

1. DS=*Fully operational/No Damage* (n=0);
2. DS=*Moderate Damage* (n=1);
3. DS=*Severe Damage* (n=2);

where n is the number of emergency room not functional because damaged by the earthquake.

For each DS, several simulations have been conducted by changing the intensity of the seismic event using the methodology described above. The intensity has been increased by means of scale factors that multiplied the patient arrival rate.

Three different Restoration Functions (RFs) have been chosen as comparison. The results are shown in the following paragraphs.

The functionality Q of the ED has been evaluated for increasing seismic intensities based on the Modified Mercalli Intensity (MMI) scale (Figure 3, Figure 4, Figure 5). Each graph shows different damage states (DS):

-Emergency plan fully operational with n=0, where n is the number of emergency room not available because damaged by the earthquake (Figure 3);

-Emergency plan affected by moderate damage (n=1) (Figure 4);

-Emergency plan affected by severe damage (n=2) (Figure 5);

As shown in the graphs, the functionality is reduced and the recovery time increases when two emergency rooms are not operative. The functionality is also dependent on the seismic intensity. As the seismic intensity increases, the restoration curves take longer recovery time to get back at their initial functionality. In Figure 6 for higher seismic intensities, the functionality at the end of the simulation doesn't reach the ideal value, showing that the emergency department is not yet back to its original operating condition.

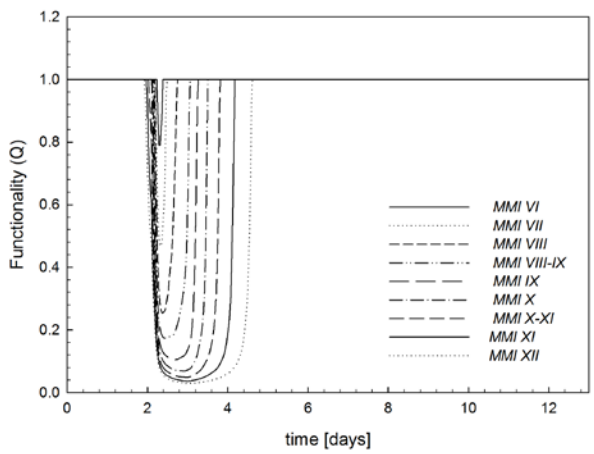

Figure 3: Functionality curves as a function of seismic intensity, no damage (n=0)

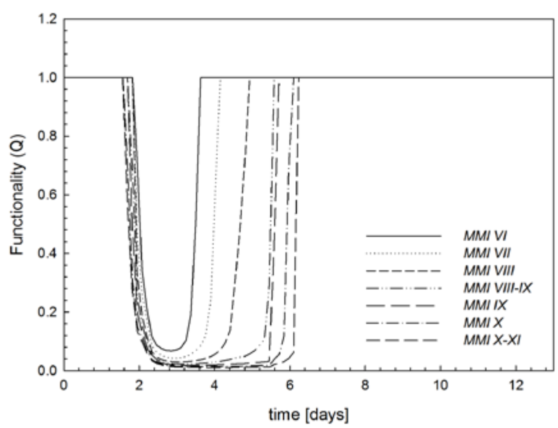

Figure 4: Functionality curves as a function of seismic intensity, moderate damage (n=1)

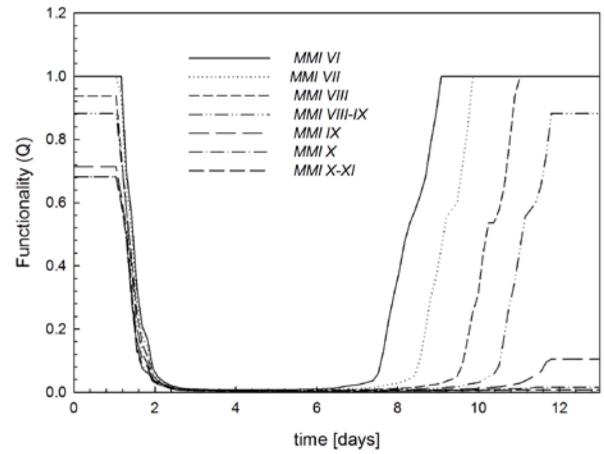

Figure 5: Functionality curves as a function of seismic intensity, severe damage (n=2)

In this case study, the Modified Mercalli Intensity (MMI) scale has been adopted, but other parameters such as peak ground acceleration (PGA), peak ground velocity or spectral acceleration (SA) can also be used.
Three restoration functions (*rf*) associated to specific damage states have been chosen to calculate the fragility restoration curve. The *rf*s chosen in this study refer to the functionality curve assuming no damage (RF0), moderate damage (RF1) and complete damage (RF2).
As shown in Figure 6, RF0 has a restoration time of 1 day, while RF1 and RF2 have restoration times of 2 days and 6 days respectively. The restoration time t_r specifies how long the ED takes to recover from a disaster.

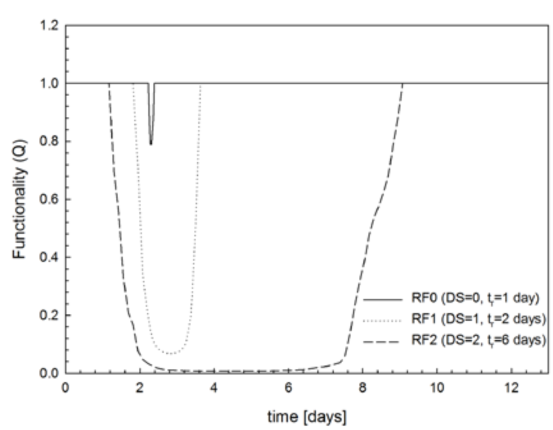

Figure 6: Restoration functions assuming earthquake of magnitude VI

The restoration fragility functions for each damage state scenario have been calculated. RFF is the probability that a given restoration function *rf* (Figure 6) is reached when a certain damage state (DS) occurs for a given earthquake intensity measure *I*.

In Figure 7-Figure 9 the probability of restoration are plotted.

The lognormal cumulative distribution function is used to fit the data, to provide a continuous estimate of the probability of restoration as a function of MMI. Two different methods to fit fragility curves are compared:

-MLE method: maximum likelihood method ;

-SSE method: sum of squared errors;

Both methods are described by Baker (2013).

As shown in Figure 7-Figure 9 , the two fitting methods have similar results.

In Figure 7 the probability of exceedance the restoration function RF0 increases with the increment of the MMI. For higher MMI, the probability of exceedance of RF1 reaches the probability of exceedance of RF0. In Figure 7 the same behavior can be observed.

In Figure 7 the probabilities of exceedance of RF0 and RF1 overlap. The RRF related to RF2 increases considerably respect to the previous DSs.

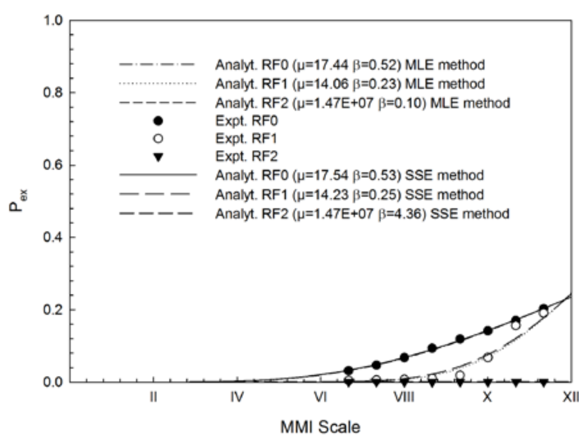

Figure 7:RFF given DS=0(no damage) using MLE and SSE methods, ED with emergency plan applied

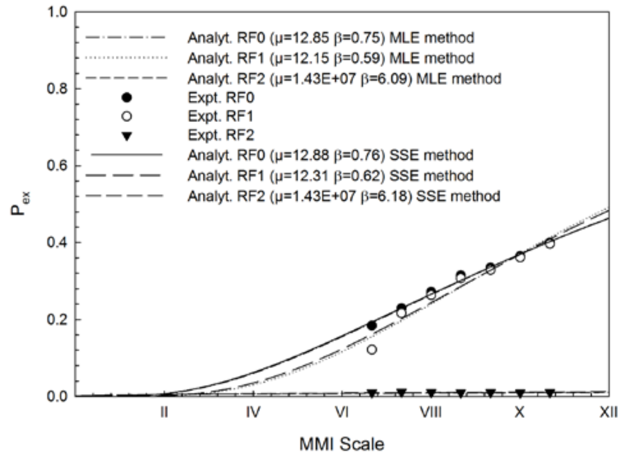

Figure 8: RFF given a DS=1(moderate damage) using MLE and SSE methods, ED with emergency plan applied

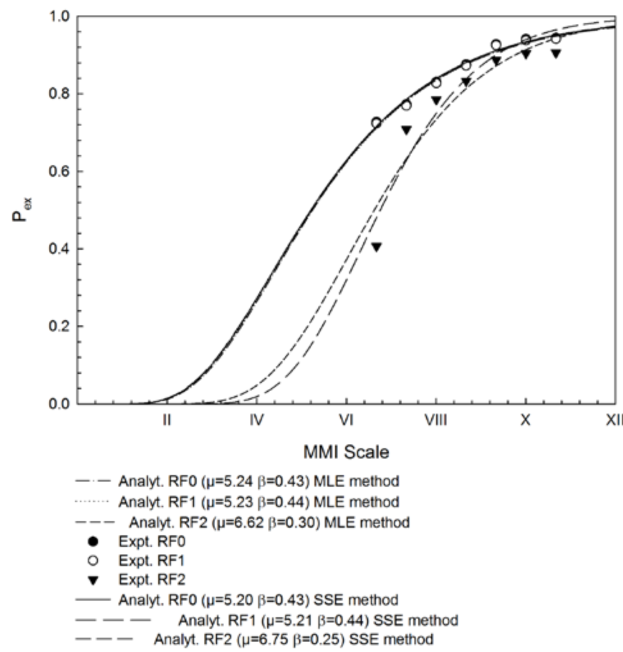

Figure 9: RFF given a DS=2 (severe damage) using MLE and SSE methods, ED with emergency plan applied

Figure 10-Figure 12 show the RFFs related to the ED without emergency plan.

Results and comparison between RFFs of both cases are presented in the following paragraph.

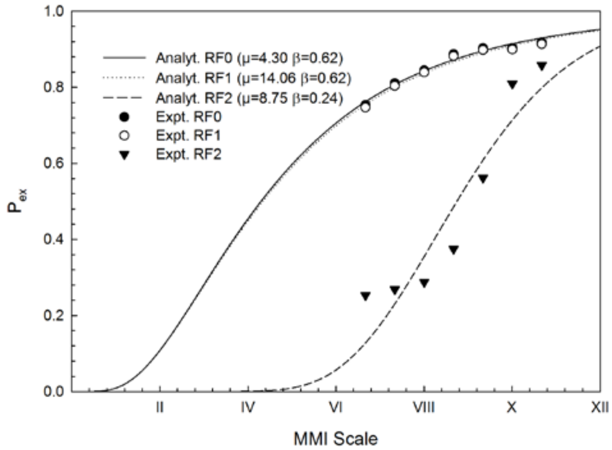

Figure 10: RFF given a DS=0 (no damage) using MLE method, ED without emergency plan

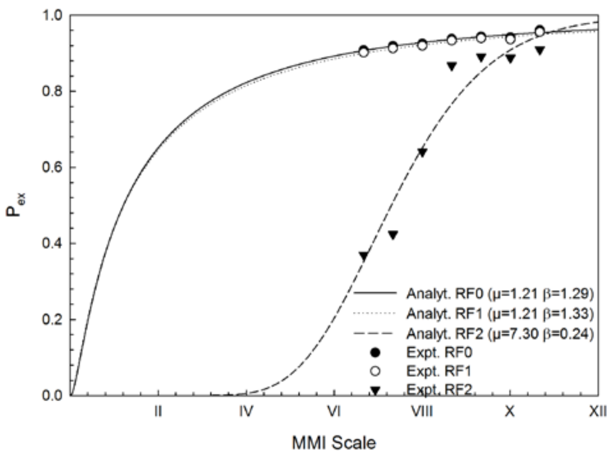

Figure 11: RFF given a DS=1 (moderate damage) using MLE method, ED without emergency plan

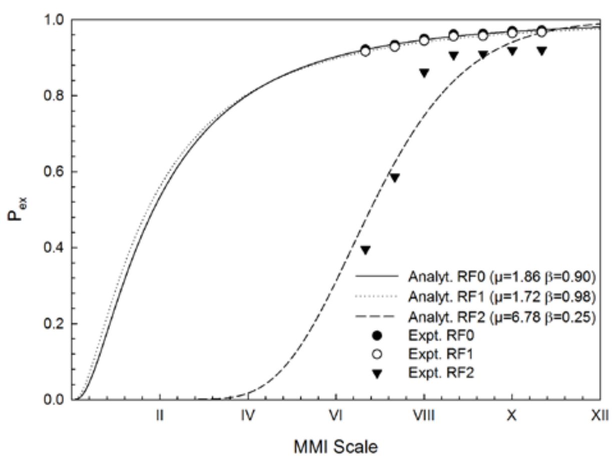

Figure 12: RFF given a DS=2 (severe damage) using MLE method, ED without emergency plan

3.3. RFF Comparison between ED with and without Emergency Plan applied

As can be seen in Figure 7-Figure 12 , the probability of exceedance of a given restoration curve is higher without emergency plan than when the emergency plan is applied. Therefore, the emergency plan can be considered effective, since the waiting time when the emergency plan is applied is significantly lower than the waiting time without emergency plan. However, the only exception is in Figure 9 and Figure 12, when the damage state is severe (DS=2), because in that case the RRFs of both case scenarios mainly overlap.

4. CONCLUDING REMARKS

In the paper is presented a methodology for building Restoration Fragility Functions (RFF), which describe the probability of exceedance a given restoration curve associated to a given damage state. The reasons for introducing RFFs is because the *restoration process* is one of the most uncertain variables in the resilience analysis therefore, it is necessary to consider it in probabilistic terms.

Restoration fragility functions can be a useful tool to define resilience of a hospital network. They can be used to estimate the restoration process of the emergency department as a function of the seismic intensity.

The main difference between RFF and standard fragility functions is that the RFF is correlated to a given damage state (DS). In other words, RFF is conditional on DS and *I*, while standard fragility curves are only conditional on the intensity measure *I*. The method has been applied to the model of the Emergency Department of an existing hospital during a crisis when the emergency plan is applied and in regular condition. The data used for building the fragility curves are related only to the yellow code, while the restoration functions (RF) refer to three damage states (DS).

5. ACKNOWLEDGMENTS

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