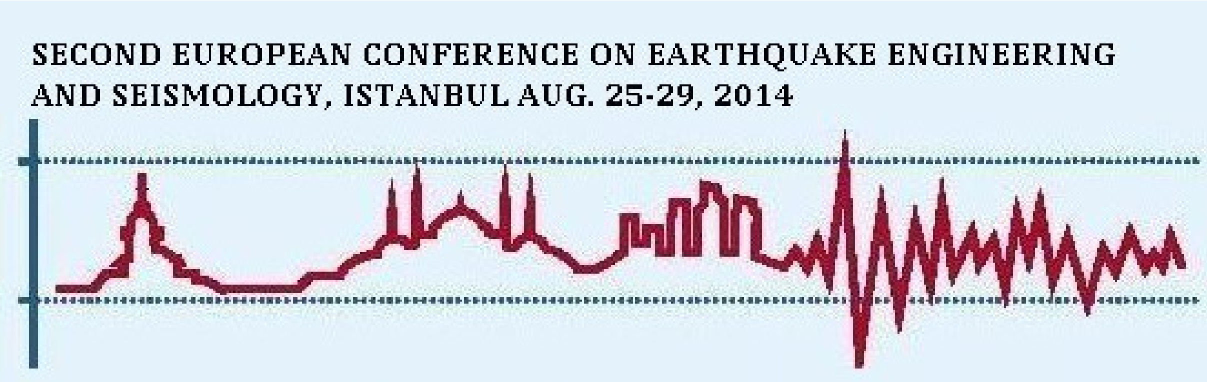

A COMPREHENSIVE METHODOLOGY FOR EVALUATING THE SEISMIC RESILIENCE OF HEALTH CARE FACILITIES CONSIDERING NONSTRUCTURAL COMPONENTS AND ORGANIZATIONAL MODELS

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ABSTRACT

The main objective of this paper is to present through a case study a comprehensive methodology for evaluating the seismic resilience of health care facilities considering all the aspects that are usually considered individually, such as: ground motions selection for probabilistic seismic hazard analysis, structural and non-structural performance and organizational models for functionality evaluation. The different research groups of the project analyzed each aspect, with innovative and original implemented approaches. However, the main contribution of the study is the combination of all these aspects in a unique methodology that takes into account all the parameters necessary to evaluate the seismic resilience of health care facilities. In order to show the implementation of the proposed methodology, an Italian hospital located in Tuscany (Italy) is considered as a case study.

INTRODUCTION

Hospitals constitute an important component of a health-care system during a disaster (e.g. earthquake, hurricane, etc.), playing a critical role in providing timely treatment to injured patients so as to minimize fatalities. In particular, the lack of operability of a single hospital can cause cascading effects capable of incapacitating the healthcare system of an entire region and of impeding rapid response and recovery. Therefore, hospital facilities need to be resilient (Cimellaro et al., 2010a) and functional within a short time after an extreme event.

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Recent extreme events have shown how healthcare systems are vulnerable to natural disasters, including man-made human events, reducing or nullifying the entire functionality of the systems. The response of a system during an extreme event depends on its structural and technical performances (including non-structural performances), but also on the organizational capabilities during the first hours after the event. The organizational aspect depends on the structural and non-structural aspects, thus, it is necessary to find out which are the weak elements of the response chain in order to plan wisely any future investments. Strategies must be elaborated in order to maintain full functionality of the system even in case of emergency. Being able to foresee the consequences of extreme emergency scenarios minimizes the probability of functionality interruption of a facility, which can be critical for the population.

In this study, a hospital in Italy was considered for a case study (Figure 1); it consists of 17 different buildings with different shapes and dimensions, which were built during different time periods. One particular building (building 15 in Figure 1), which accommodates the most important function of the hospital in case of emergency, i.e. the Emergency Department, was chosen for the case study described in this paper.

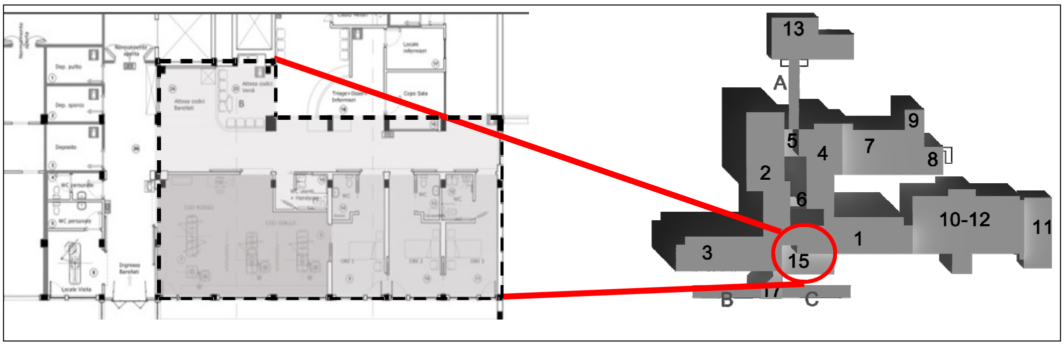

Figure 1 Architectural plan of Building No. 15 and position into the hospital complex.

This work focuses on all aspects of the system, starting from the selection of reference ground motions, which plays an important role on the evaluation of seismic resilience. A collapse fragility analysis was performed on building 15, based on two different approaches. A simplified, post-processing procedure was also developed to construct collapse fragility curves for the infill masonry walls of the structure. At the end, an organizational model has been constructed taking into account the real data about patients and personnel, as well as the data coming from reference ground motions and collapse fragility curves.

The main goal of this paper is to evaluate the seismic resilience, in terms of a single index (the patient waiting time), considering all the aspects that are usually considered individually.

GROUND MOTION SELECTION

Two different procedures were adopted for performing nonlinear dynamic analyses in order to evaluate the collapse fragility curves of the structure considered in this study. The first approach was the Incremental Dynamic Analysis (IDA) using the far-field record set defined within the FEMA P695 methodology (FEMA, 2009). The second approach was the Multi Stripe Analysis (MSA) using different sets of earthquake records for four seismic intensity levels associated with the specific site of interest. The latter procedure is briefly described in this section.

The first step was to obtain seismic intensity and deaggregation data for the specific site for stiff soil from the INGV website (Spallarossa and Barani, 2007; Barani et al., 2009). Four different seismic intensity levels were considered associated with a probability of exceedance (POE) of 2%, 5%, 10% and 22% in 50 years. For each seismic level, the Uniform Hazard Spectrum (UHS) was obtained as well as the mean values of magnitude M, distance R and ε of the causal earthquake for a period of 1.0 sec, which was the period closest to the fundamental period of the structure that this type of data was available for. Figure 2 illustrates the related UHS and Table 1 lists the related deaggregation data for the mean causal earthquake for each level of seismic intensity.

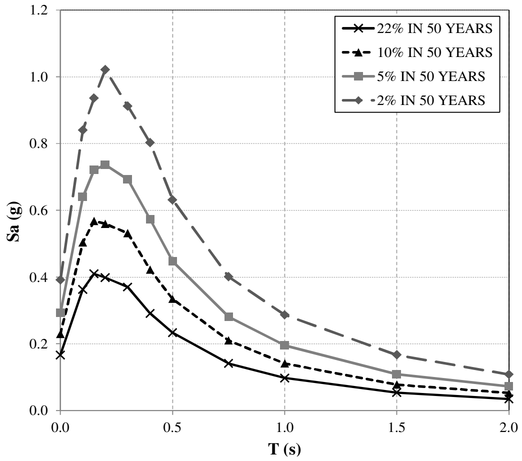

Figure 2 Uniform Hazard Spectra for Sansepolcro for different probabilities of exceedance

Table 1 Deaggregation data for Sansepolcro for T = 1 sec.

POE in 50 years	M	R (km)	ε
2%	5.90	8.50	1.48
5%	5.83	11.90	1.29
10%	5.75	15.60	1.15
22%	5.66	20.70	1.02

The second step was to define the Conditional Mean Spectrum (CMS) for each seismic level, which provides the expected response spectrum, conditioned on occurrence of a target spectral acceleration value at the period of interest (Baker, 2011). The CMS was preferred to the UHS because using the latter as a target spectrum for selecting ground motions can be too conservative as it implies that large-amplitude spectral values will occur at all periods within a single ground motion. The CMS, instead, is based on the prevailing (or mean) EQ scenario at a given period and has a spectral shape that is more realistic since it is based on the spectra of ground motions from a similar EQ scenario. The CMS and the associated variance at each period were defined using the Ground Motion Prediction Equations (GMPE) provided by Ambraseys et al. (1996) and the correlation coefficient for horizontal spectral accelerations provided by Cimellaro (2013). Both these studies were specifically developed for European earthquakes. Figure 3 presents, among others, the CMS and UHS as well as the 97.5/2.5% percentiles of the conditional spectra for each level of seismic intensity.

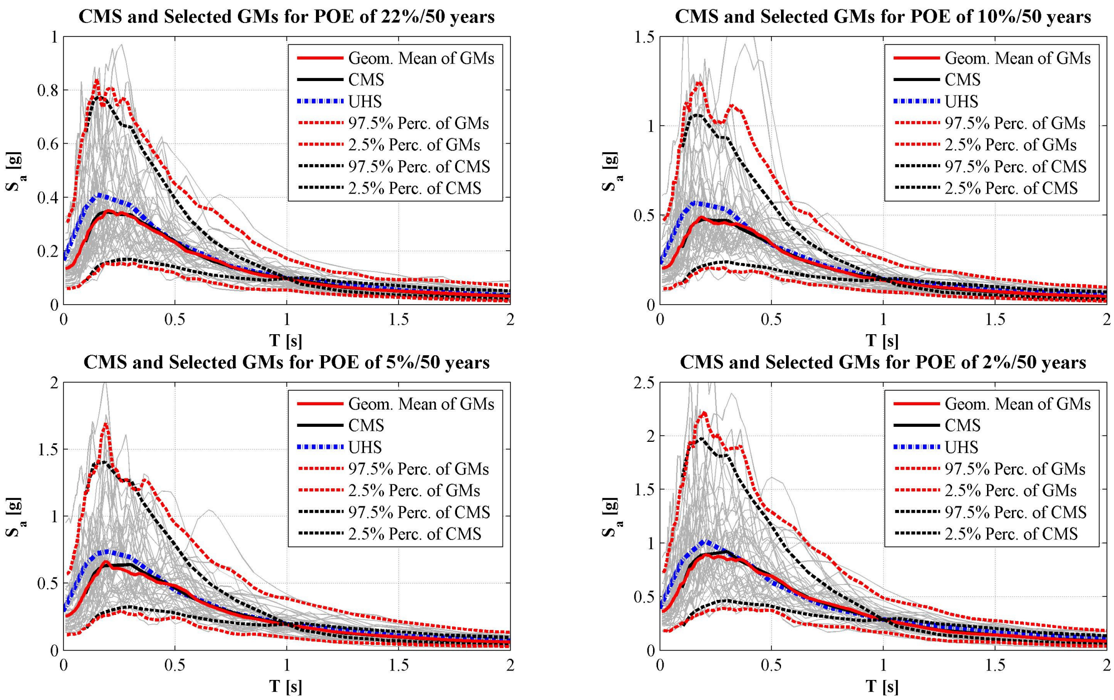

Figure 3 Comparison between target and achieved mean and standard deviation of spectral ordinates of selected ground motions for POE of 22%, 10%. 5% and 2% in 50 years

The third step entailed the selection of a set of 22 pairs of ground motions for each seismic intensity. The ground motion selection was based on the work of Jayaram et al. (2011). Only unscaled motions were considered in the selection process in order to minimize the scaling magnitude in the last step, which is described below. Figure 3 illustrates the response spectra of the 22 pairs (in terms of the geometric mean spectrum of the two horizontal components) and the mean and 2.5%/97.5% percentiles of the set of 22 pairs for each seismic intensity. It can be observed that although the ground motions are unscaled, the procedure of Jayaram et al. (2011) achieves a very good matching of the mean and variance spectral values at all periods. Obviously, the achieved variance in the region of the fundamental period is nonzero, as opposed to the zero target variance, which is a direct effect of the use of unscaled recordings.

The last step was to define appropriate scaling factors for each set of ground motions in order to extend the concept of IDA in the MSA procedure, providing more data points in the formation of the collapse fragility curve that would facilitate the determination of the optimal parameters. Table 2 lists the scale factors proposed for each set of seismic intensity and Figure 4 illustrates the resulting response spectra.

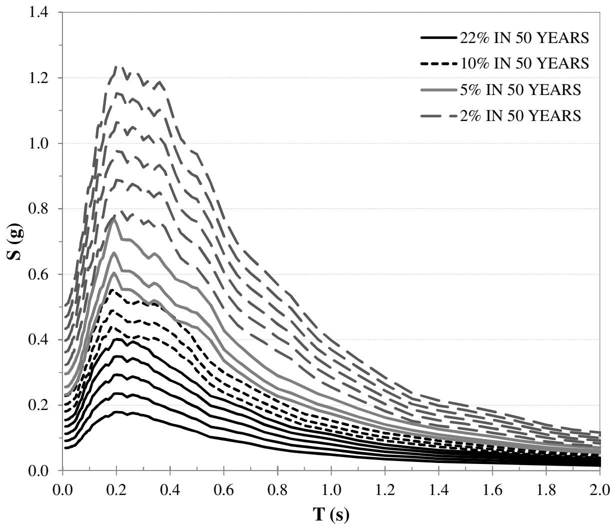

Figure 4 Acceleration response spectra of the ground motion sets as scaled according to Table 2

Table 2. Scale factors used for the IDAs of the MSA procedure

GM Intensity Level	SCALE FACTOR	SA (T=1SEC) [G]
22% in 50 years	0.513	0.050
	0.676	0.066
	0.838	0.082
	1.000	0.097
	1.149	0.112
10% in 50 years	0.897	0.126
	1.000	0.141
	1.129	0.159
5% in 50 years	0.907	0.177
	1.000	0.195
	1.156	0.226
2% in 50 years	0.894	0.256
	1.000	0.286
	1.099	0.315
	1.198	0.343
	1.297	0.372
	1.397	0.400

STRUCTURAL PERFORMANCE

A collapse fragility assessment was performed on building 15 of the Sansepolcro hospital complex. For this purpose, a three dimensional model was developed in the RUAUMOKO 3D computer software (Carr, 2007). The structure was modelled to capture the response at high deformation demands up to collapse.

The beam and column members were modelled using line type elements with concentrated plastic hinges at their ends. The flexural behaviour of the members was defined with a bi-linear moment-curvature profile. The elastic portion of the profile was defined using the nominal moment capacity of the section and the effective secant stiffness taken at the first yield of the section. Lack of proper concrete confinement was a concern during modelling so ultimate moment and curvature capacities of the members was limited by an ultimate concrete cover strain of 0.005, which is taken as an effective strain limit for unconfined sections (Priestley et al., 1996). Once a member reached its ultimate curvature, it was assumed that the member would fail. As a result the capacity of the member was reduced to a small residual value after the ultimate curvature is exceeded. Figure 5 shows an example of the moment-curvature profile of the beam and column members.

Bi-axial moment interaction was accounted for in the column members. The moment capacities of the sections were dependent on the current axial load on the section. In addition, the section moment capacity was reduced when moment demands in both directions were applied simultaneously. Hysteretic behaviour of the column and beams members was modelled using a peak-orientated Takeda model (Otani, 1981) to account for the stiffness deterioration under cyclical loading.

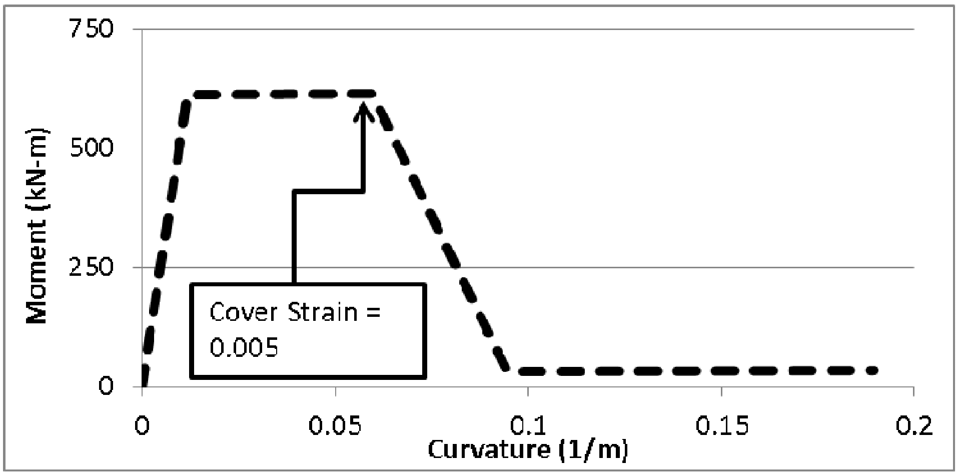

Figure 5 Example of Beam and Column Moment Curvature Profile

The shear capacity of the members was calculated using the modified UCSD shear model (Kowalsky and Priestley, 2000). Member shear failure was not incorporated directly into the modelling and instead it was checked in a post-processing manner as a non-simulated form of collapse; once shear failure occurred in any member then collapse was also assumed.

The joint panel zones of the structure were modelled using rigid ends with rotational springs in between the rigid end and frame member. The rotational springs were used to account for joint deformability. Their rotational stiffness was established based off the geometry of the joint and frame members. Due to typical construction practices in the region at time of construction, it is expected that the building does not possess joint shear reinforcement and so the development of joint shear hinge mechanisms was a concern. The joint shear hinge mechanism can result in a large deformation increase for minimal demand increase in the joints once a critical demand level is reached. According to experimental results from Pampanin, et al. (2002), this mechanism can occur once a principal stress limit of $0.2\sqrt{f_c'}$ and $0.42\sqrt{f_c'}$ is reached for exterior and interior joints, respectively. To account for this, the columns of critical joints had their yield moments reduced to match the moments corresponding to these principal stress limits. In addition, the column post-yield stiffness was reduced to zero to replicate the hinge type behaviour.

From a static pushover analysis, it was determined that the development of a column sway mechanism was likely. This was also confirmed through the calculations of the sway potential indices of the structure, which are the ratio of the column capacities to the beam capacities for a given joint [Priestley, et al. 2007]. The sway indices showed that a majority of the joints in the structure have strong beams and weak columns. Table 3 shows the average sway indices over both floors of the structure. Note that a sway index over 1 indicates the likelihood of a column sway mechanism, although Priestley et al. (2007) recommend a conservative limit of 0.85 to indicate column sway.

Table 3 Average Storey Sway Indices

STOREY	TRANSVERSE DIRECTION	LONGITUDINAL DIRECTION
FIRST	2.44	4.25
GROUND	0.99	9.45

A series of incremental dynamic analyses (IDAs) were performed using two different ground motion record sets; the record set used in the FEMA P695 methodology (FEMA P695, 2009) and the record set selected specifically for this site, as described above. All of the records were scaled based off the median spectral acceleration of the record set at the fundamental period of the structure. The records were scaled up until collapse was observed in the model. Collapse for the structure model was set as the point where the model becomes numerically unstable and the drifts in the model become excessive. The collapse spectral acceleration for that time history record was taken to be at this point. Afterwards the analysis results were post-processed to check for member shear failure. If member shear failure occurred before the collapse point, then the collapse spectral acceleration was set to the point of shear failure; however it was found that the shear capacities of the members were not exceeded before collapse was observed. Another observation from the IDA results is that the structural model exhibits a brittle type of failure. The model would show little softening behaviour before collapse would be observed.

The collapse fragility assessment was performed for both of the ground motion record sets according to the FEMA P695 methodology (FEMA P695, 2009). The resulting collapse fragility curves can be seen in Figure 6. The vertical line on the figure represents the spectral acceleration at the fundamental period for a probability of exceedance of 2% in 50 years. At this maximum considered earthquake (MCE) intensity the fragility curves predict a 56.1% and 77.3% probability of collapse for the FEMA and site specific fragility curves, respectively. Although the two curves show some difference, from an assessment standpoint the difference isn't significant as both fragility curves reveal that the structure model has a poor collapse performance.

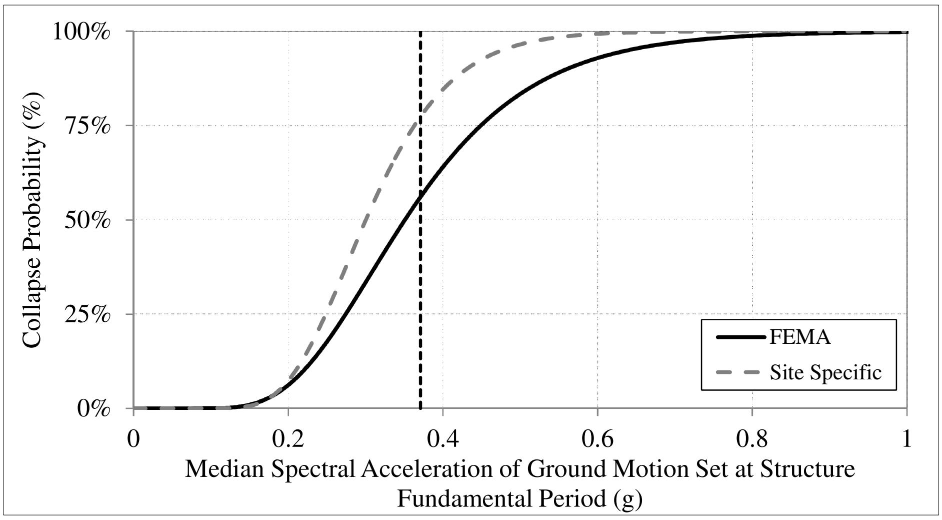

Figure 6 Collapse Fragility Curves

EMERGENCY DEPARTMENT

The Emergency Department (ED), an operating unit of the hospital, is dedicated to emergency cases and uses the space reserved to Intensive Brief Observation (OBI). The ED gives the initial treatment for all cases of urgency and emergency, from the most severe to the less important ones. The access to the Emergency Room is not based on order of arrival, but on the severity of the patient's conditions. At the reception, a degree of urgency is assigned represented by a "colour code": the higher colour-code is red, which corresponds to emergencies with immediate access to a room, and the lower one is white, which designates a "non-urgent" patient. The colour codes can be grouped in two categories; the White, Blue and Green codes belong to the *Minor Codes*, while the Yellow and the Red codes are part of the *Major Codes*. During normal scenario, the operating rooms (ORs) of the hospital are used only for scheduled surgeries, therefore they don't affect the patients who come to the ED.

The data for the calibration of the simulation model is associated with a period of three months, from January to March, 2012. This data has been obtained from the hospital database or collected through interviews with key personnel of the hospital. Examples of database records are the arrival of the patients, the daily volume of patients and the different types of treatments for the various colour code categories. Information collected during the interviews included the work time-schedule of the staff and the usual procedures for different tasks with the time needed for their execution. To estimate the time required for patient transportation from one place to another, a matrix of the distance was prepared. It is worth to specify the difference between the usual distances during a normal scenario and an emergency scenario.

For the simulation of the hospital, a discrete event simulation (DES) model was used (Figure 7) and implemented using a commercial software called ProModel (ProModel, 1999). This model contains the parameters needed such as the patients' arrivals, the paths through the ED, the different waiting rooms for the patients, the processing times and the procedures that take place in each location, as well as all the resources such as nurses or doctors.

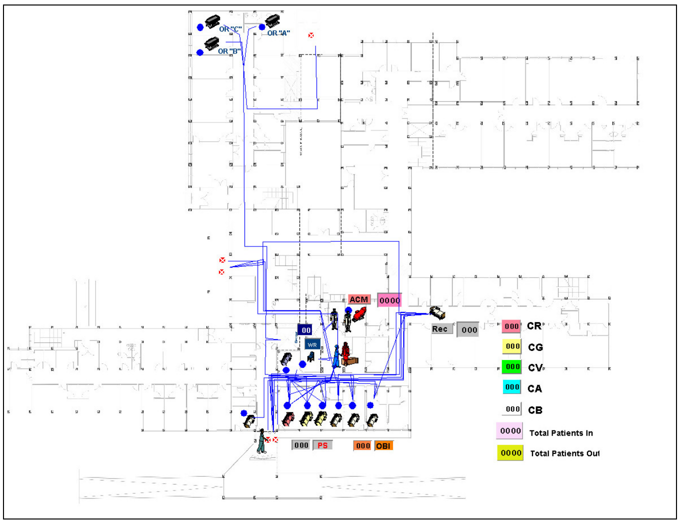

Figure 7 Discrete event organizational model of Sansepolcro hospital

The output data have been compared with the data provided to verify the model and its calibration. Some discrepancies may appear during the comparison, due to the probability distribution used by the program, especially with regards to the arrivals acceptance rate. The output data to compare is the waiting time (WT) of each patient. The waiting time is defined as the time that a patient waits from the moment of arrival until receiving the first service from medical personnel.

SEISMIC ARRIVAL RATE

The functionality conditions of a normal scenario are drastically changed in case of emergency, when more resources, such as operating rooms (ORs), are activated. The ORs, according to the emergency procedures, must suspend all the programmed surgeries in order to accommodate the emergency cases. At the same time, all of the patients who are in conditions to leave the hospital are to be discharged thus increasing the number of beds available for admissions.

In order to evaluate the performance of the organizational system of the Sansepolcro hospital in case of emergency, the following modifications were made to the basic model:

1. the staff volume is increased following the emergency plan
2. operating rooms (ORs) activation
3. variation of the patient flow chart following the emergency plan
4. activation of seismic arrival rate.

The arrival rate was determined by scaling the patient inflow of the Northridge hospital in Los Angeles, California, calculated during the earthquake which occurred in 1994 (Cimellaro et al., 2011). First, the peak ground acceleration (PGA) at the site of the Sansepolcro hospital was determined using the Italian seismic standard (for a Probabilty of Exceedance -P_{VR}- of 10% in 50 years), and the arrival rate at the Northridge hospital following the 1994 earthquake was scaled to the PGA value measured in Sansepolcro. However, this scaling procedure presents some limitations; for example, it does not take into account the real level of damage related to the area in which the earthquake happens. The

Modified Mercalli Intensity (MMI) scale, which takes in account all the above features, has been used as a second scaling procedure. The MMI scale was determined using the relationships available in the literature between the MMI values and the horizontal average and maximum PGA values at the site. Figure 8 shows the trend of the seismic patient inflow of the Northridge hospital and the patient seismic inflow modified according to the PGA (small dotted line) and to the MMI (dotted line) for the Sansepolcro hospital; Table 4 shows the percentage of patients during normal and emergency conditions, along with the number of entries.

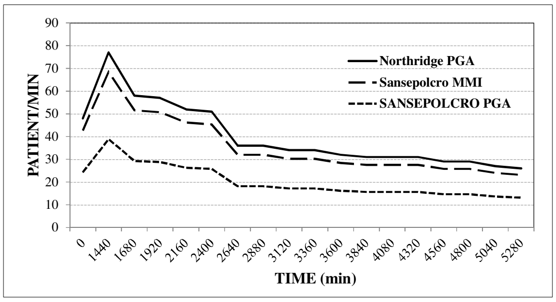

Figure 8 Arrival rate in case of Emergency, following the Northridge data trend.

Table 4 Entries at the Emergency Department in normal condition and emergency condition

PATIENT TYPE	NORMAL SCENARIO	EMERGENCY SCENARIO	
	%	%	Number of people
RED COLOR	0.5	3.7	37
YELLOW COLOR	10.6	40	396
GREEN COLOR	45.11	48.4	476
BLUE COLOR	1.72	7.8	77
WHITE COLOR	41.88	0	5

From the obtained trend of patient inflow at the hospital, it was necessary to divide the entries by colour codes. According to Pengfei (2005), the patients who have similar medical needs and go through the same treatment procedure are grouped in the same category, and then they are associated to the colour codes, in order to distribute the patient/treatment during an earthquake. During the emergency scenario, the ED treats only the major codes, while the minor codes are directed towards other parts of the hospital in order to facilitate the entrance to the ED. Since waiting times differ significantly between surgical and non-surgical patients, these categories are further classified in OR and non-OR patients.

RESULTS

The unique parameter considered in this study for evaluating resilience is the patient waiting time, taken as the time that a patient waits from the moment of arrival until receiving the first service from medical personnel. The waiting time has been determined by a scenario-based organizational model. The total running duration of the model is 17280 minutes (12 days) with an initial normal scenario. After two days (or 2880 minutes) of normal scenario an earthquake strikes (Figure 9, on the right), and the emergency scenario is introduced for three days; seven more days are then simulated in order to reinstate normal conditions. The preliminary investigation presented in this paper assumed that the intensity of the ground motion did not cause any structural or non-structural damage in the building analysed. Therefore, the organizational models and procedures during emergency scenarios are not expected to be modified as a result of the earthquake. Further case of studies will be conducted in the future using the collapse of fragility curves for the various campus buildings similar to that shown in Figure 6.

One hundred analyses were conducted for 12 days under normal scenario conditions, as well as one hundred analyses for the following 12 days comprised of (i) 2 days under normal scenario conditions, (ii) 3 days of emergency scenario and (iii) 7 days to reinstate normal conditions. In the latter model a seismic arrival rate was introduced together with more resources only for the three days of emergency. Taking into account only the ED, as Figure 9 (on the right) shows, the minor codes are suspended for the three day emergency scenario, and activated again after 7200 minutes (5 days from the beginning of the simulation).

The results from the analysis are in terms of waiting time, for each patient: the normal scenario model (Figure 9, on the left) was used to calibrate the model and add three days of emergency situation (Figure 9, on the right). As shown in the graph, during the emergency scenario the minor codes have been suspended from the ED activities, and only red and yellow codes are treated.

It is worth focusing on one unexpected trend for the red codes, for which the WT decreases during the emergency situation. This is due to the adding of resources and beds. The yellow codes' waiting time grows drastically, reaching a peak of 287.03 minutes. This value is unacceptable for the Italian standards, but it is necessary to underline the amount of patients arriving during the earthquake.

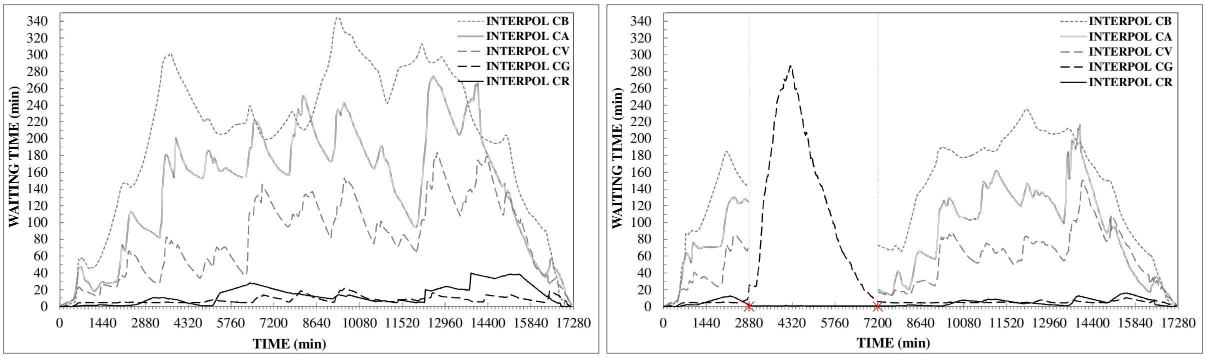

Figure 9 Waiting time for all the patients in Normal Scenario (left) and Emergency Scenario (right).

Considerations can be made taking into account the peaks of waiting times for the Major Codes and the increase of arrival rate during the two scenarios. For the same increase in the number of patients, the response of the system in terms of waiting time is considerably different.

Table 5 Peaks and percentage of arrival rate for the two scenarios

PATIENT TYPE	NORMAL SCENARIO		EMERGENCY SCENARIO		RATIO	
	Peak (min)	Arrival rate %	Peak (min)	Arrival rate %	Peak	Arrival rate
RED COLOR	21.59	10.6	287.03	40	13.29	3.77
YELLOW COLOR	39.79	0.5	16.08	3.7	0.40	7.4

Regarding the yellow codes, the maximum waiting time during the emergency phase is more than ten times the maximum peak calculated in the days of a normal scenario. Table 5 shows that the percentage of entries is increased during the emergency phase by about 4 times. The red codes, in contrast have a decrease of waiting time during the emergency phase; nevertheless the entries percentage is increased by about 7 times.

SUMMARY AND CONCLUSIONS

The response of a local hospital is one of the most fundamental aspects of the emergency response of a community to an earthquake.

This paper presents discusses a holistic model for evaluating the performance and seismic resilience of a case study hospital located in Italy. Starting from the ground motion selection trough two different procedures, IDA with far-field ground motion record sets, collapse fragility curves for one of the building of the hospital campus have been estimated. A discrete event simulation (DES) model was used to assess the functionality of the hospital for 12 days of simulation including three days of emergency scenario. The data resulted from structural and non-structural evaluation becomes important descriptors of the physical system, as well as the base for the organizational aspects.

Preliminary waiting times for patients in the hospital affected by a seismic shock causing no structural or non-structural damage have been calculated and are used as the indicator for the hospital functionaly.

The waiting time for the yellow codes during the emergency phases increases drastically, while the waiting time for the red codes decreases during the emergency time. This phenomenon is due to the high priority reserved for red codes during the increased inflow, along with a substantial increase of resources (personnel and beds) dedicated to them.

This work highlights how the organizational aspect closely depends on all of the others aspects, which are indispensable to guarantee an efficient and safe response by hospital; for example, the influence of the performance of structural and non-structural components compromises the effectiveness of the organizational plan. An adequate planning is essential for an efficient medical response to any future earthquake disaster. The behaviour of the hospital, and consequently the treatment capacity can be predict taking into account every aspect of the system, in order to minimize the probability of functionality interruption as only the hospital is able efficiently to satisfy local requests for medical services and facilities.

The results of this study suggest that is it necessary to consider jointly the elements of the building to plan appropriate provisions and applications, such as the retrofit initiative of the building and its contents, in order to increase the resilience and thus decrease the waiting time of the patients in the hospital even during an earthquake. While this study starts to address the coupling between physical damages, structural and non-structural performances, organizational response and their effect on loss function, more research is needed to fully understand relationship adaptable for predictive purposes in other systems and hazard scenarios.

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