17th World Conference on Earthquake Engineering, 17WCEE
Sendai, Japan - September 13th to 18th 2020

IMPACT OF SEQUENTIAL EARTHQUAKES ON FUNCTIONALITY OF HOSPITALS

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Abstract

Modeling the recovery process of a community's infrastructure after the occurrence of extreme events is now at the forefront of research. Estimating post-disaster recovery of either single or multiple infrastructure in a community requires proper flow and interaction of information of the physical, economic and social components of the involved sectors. Understanding this recovery process is essential, particularly for critical infrastructure, such as a hospital, which is vital for a community's well-being. In this study, a new socio-technical framework is presented for estimating full functionality and recovery of a hospital in a community following a Mainshock-Aftershock Sequence. The framework includes the estimation of both quantity and quality components of the offered healthcare service over time, changes in patient demand on the investigated healthcare facility while accounting for the hospital interaction with other community infrastructure. In addition, stochastic dynamic optimization is utilized to determine optimal recovery trajectories to account for limited repair resources, repair sequences and change in demand over time, particularly given the presence of an aftershock. The presented approach is applied to highlight the capabilities of the proposed framework and the impact of decision making on the recovery trajectory in the presence of an aftershock. It is observed that existing of functional backup systems is essential to maintain the hospital functionality, especially after the earthquake. It is also shown that proper allocation and distribution of repair resources are key to achieving the desired level of functionality for the hospital.

Keywords: earthquake; aftershock; hospitals; functionality; resilience

1. Introduction

The devastating losses resulting from earthquakes' mainshock-aftershock events have attracted research attention over the years. These sequential hazards can cause serious damage to structures, undermine life safety, and result in substantial economic and social losses [1]. Historical events around the world have highlighted the potential for such losses, which motivated researchers to evalute structural behavior under the combined events, [2-3]. For instnace, the recent 2011 Christchurch mainshock earthquake was also followed by a series of aftershocks, leaving181 dead, 164 seriously injured and causing approximately $15 billion of repair costs [4].

Treatment of injuries resulting from the seismic events is critical for the wellbeing of society. Shortage of the hospitalization service could result in an increase in morbidity and mortality in those who were directly impacted by the event. The long-term effects could include population outmigration and social instability, which could eventually lead to other cascading consequences including significant economic losses. Hospital functionality can be defined as the ratio between quantity (Q_V) and quality (Q_S) of the services offered before and after hazard occurrence [5]. The quantity portion of the offered services is usually estimated based on hospital capacity or number of staffed beds offered for patients based on a daily rate (N_t). According to [6], for these beds to be available for service, three main components are required, which are 1) trained personnel such as physicians, nurses and supporting staff, 2) qualified space to offer an acceptable hospitalization service, and 3) sufficient supplies. The definition of the quality portion of the offered service, on the other hand, is complicated due to its qualitative nature. Previous studies identified several dimensions to describe the quality of the hospitalization service [7,8]. One way to do so is through defining it as a function of losses of different hospital departments while considering the possibility of service redistribution among the departments [6]. The patient waiting time is also commonly used to represent the quality part of the functionality [9].

Different parameters play critical roles in the level of recovery that can be achieved following a major event. These include type of the damaged components, extent of damage, and available funding resources (e.g. insured losses or federal sources). The recovery process of infrastructure or its components is usually represented by plotting functionality over time. Various studies have investigated the use of different approaches for estimating multiple recovery stages for different lifelines such as the statistical curve-fitting model [10–12], recovery functions based on single or multiple parameters [13], and deterministic resource constraint model. However, proper estimations of repair crews and their specific tasks are needed to minimize uncertainties. This approach was introduced and used to estimate losses to the Seattle water system after earthquakes [14,15]. Network models are also used to estimate the restoration process of a series of lifelines where each lifeline is represented using a node connected to another node or lifeline with links. Optimization tools are commonly used with network models to find optimal repair sequences. Markov chain stochastic models have also been employed to estimate restoration curves for lifelines [16–18] and have been modified to account for the interaction between lifelines [19]. A Markov chain stochastic model simulates the functionality of each lifeline by a discrete state in which repair resources can be optimally allocated to each lifeline. In this study, a comprehensive model is utilized to estimate losses, functionality, recovery, and resilience of hospitalization services for a hospital located in Memphis, Tennesse after a mainshock-aftershock scenario.

2. Investigated hospital

The considered hospital is a buckling restrained braced building, assumed to be located in Memphis, Tennessee, USA, and is designed professionally for the National Earthquake Hazard Reduction Program (NEHRP) and [20,21]. The building comprises of six bays in the N-S direction and five bays in the E-W direction. It is a six-story building with an additional basement floor as shown in Fig. 1. The typical span of a given bay is 9.14 m and the typical floor height is 4.27 m, except the first floor where the height is 6.10 m as it serves as a hospital lobby floor. Therefore, the total area of each floor is 2506.18 m^2 and the total building height is 31.70 m. Buckling restrained braces are utilized to resist the lateral loads in both the N-S and E-W directions. The braced bays were selected to be close to the building's center to reduce the torsional deformations of the structure. A reinforced concrete wall with 0.30 m thickness is used at the basement floor to support earth pressure since the basement floor is located underneath the street level. The 2-D frame in the E-W direction is selected to estimate the building fragilities for mainshock-aftershock sequences. More detailed descriptions of the structure can be found in Hassan and Mahmoud [22].

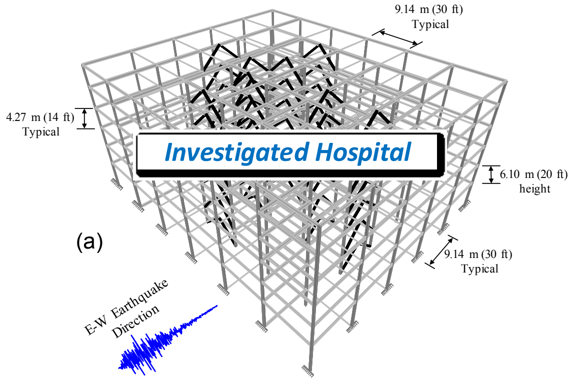

Fig. 1 – hospital building general configuration

The hospital building is assumed to have been built in 2012 and struck by the earthquake in 2017. The values for the structural repair cost are obtained from Hazus-MH 2.1 [12]. The total construction cost is $408.14 per square feet with a total cost of $77,138,000 [20]. Therefore, the replacement cost can be computed as $14,777,000 for the superstructure, R_S, $30,955,000 for the equipment, stairs and elevators including the mechanical and electrical components, R_{NS}, and $14,971,000 for the interior partitions and finishes, R_C. In addition, design and general site work cost of $16,435,000 are considered and is uniformly distributed to each building's component. The annual depreciation and discount rates are assumed as 1% and 4%, respectively. Because of the significance of non-structural components in a typical hospital building, the estimated losses from damage to non-structural components have a higher weighting factor in the loss calculations.

3. Hospital losses, functionality, recovery, and resilience models

In this section, the approaches utilized to estimate hospital losses, functionality, recovery, and resilience after the mainshock-aftershock scenario are illustrated.

3.1. Direct losses

The direct loss estimations due to hazards are commonly subdivided into two main categories: economic losses (L_{DE}) and social losses (L_{DS}) [13]. The economic losses are categorized into losses to the Structural and non-structural components as well as the contents. The structural losses are associated with damage to structural elements such as beams, columns, and bracing. The non-structural losses pertain to equipment, mechanical components, stairs, and alike. The content losses include elements such as furniture, partitions, and doors. The direct social losses are presented as a ratio between the instantaneous number of injured or dead to the total number of building occupants before earthquake occurrence. These direct losses are calculated using Hazus-MH 2.1 [12] as a function of the structural, non-structural drift-sensitive and non-structural acceleration-sensitive fragilities. The total direct losses, L_D, of the hospital building can be presented as a combination of the direct economic losses and the direct social losses as per Cimellaro [13] as shown in Eq. (1). Where α_{DE} and α_{DS} are weighting factors. More detailed descriptions of the losses estimation framework can be found in Hassan and Mahmoud [23]. These losses are utilized to estimate the drop-in functionality of the investigated hospital after both the mainshock and aftershock occurrence.

$$L_D = L_{DE}^{\alpha_{DE}}(1 + L_{DS}^{\alpha_{DS}}) \quad (1)$$

3.2. Functionality

The hospital functionality comprises a quantity portion (Q_v) and a quality portion (Q_S). The quantity aspect of the functionality is assessed using the fault tree analysis as per [23,24], where three main components (staff, space, and supplies) required to operate the hospital are considered. In this study, the quantity portion of hospital functionality is represented in terms of the total number of staffed beds, and the quality in terms of patient waiting time before receiving the hospitalization service. Eq. (2) shows the hospital total functionality as a combination of the quantity and quality portions.

$$Q = Q_V^{\alpha_V} * Q_S^{\alpha_S} \quad (2)$$

Where α_V and α_S are weighting factors. As mentioned in Hassan and Mahmoud [23,24], the hospital functionality level depends mainly on five other infrastructure (water, power, transportation, telecommunication, wastewater, and drinking water). Therefore, in this study, the recovery of these five lifelines in addition to the hospital itself are considered. In addition, the availability of alternative staff, backup systems, and backup space are considered. The travel time, the basic waiting time, and the time added due to loss of staffed beds and an increase in hospital demand are considered in the patient waiting time calculation.

3.3. Recovery

A discrete Markov chain process is utilized in this study to estimate the recovery of all infrastructure considered including the hospital building. Eq. (3) shows the Markov chain process as introduced by Zhang [19].

$$Q_n(k \vartriangle t) = Q_n(0) * \prod_{j=0}^{k-1} A_n P_n(x_n, j \vartriangle t) \quad (3)$$

Where, Q_n $(k\Delta t)$ is the functionality of lifeline n at time $k\Delta t$, which represents the time after the earthquake; A_n is an adjustment factor that is used to adjust the transition probability matrix (P_n). This adjustment factor, which is shown in Eq. (3) is calculated as a function of the interaction matrix (E) as a multiplication of the α_j factor for each lifeline from lifeline 1 to lifeline N. Whereas, the factor α_j can be set equal to 1.0 if the interaction factor (e_{nj}) equals 0.0 or Q_j/α_{nj} if e_{nj} is more than 0.0. Each interdependency factor is an element of the interaction matrix as shown in Eq. (4). The factors (e_{ij}) represent the effect of lifeline j on lifeline i, which is assumed based on Cimellaro [13].

$$A_n = \prod_{j=1}^{N} \alpha_j \quad (4)$$

$$E = \begin{pmatrix} e_{11} & \cdots & e_{1n} \\ \vdots & \ddots & \vdots \\ e_{n1} & \cdots & e_{nn} \end{pmatrix} = e_{ij} \quad (5)$$

The transition probability matrix is assumed based on Kozin and Zhou [16] as mentioned in Eq. (5).

$$P_{n,j}(x_n) = a_n * \{1 - \exp[-b_n * x_n * (0.1 * j)^{0.5}]\} \quad (6)$$

Where a_n and b_n are the transition matrix factors that depend on geographical and structural data and j is the functionality state ranging from 0% to 100%. The assumed values of the transition matrix factors are shown in Table 1.

Table 1 – Transition matrix factors.

	Electricity	**Trans.**	**Telecom.**	**water supply**	**wastewater treatment**	**Hospital**
a_n	0.95	0.85	0.930	0.72	0.75	0.610
b_n	0.145	0.12	0.092	0.166	0.185	0.196

The change of the available repair crews (X) is modeled based on Porter [25] as shown in **Error! Reference source not found.**. In this study, the repair crews are distributed among the various lifelines based on the importance of each lifeline. The lifeline's importance, expressed in terms of the expected economic return (R_n)

for each lifeline (n), can be summed for all lifelines to obtain the economic return of the whole community (R). The economic return can be assumed based on the leadership indices presented by Cimellaro [13]. To achieve the maximum economic return for the community, a dynamic optimization method is applied as shown in Eq. (6). The optimization problem is subjected to the constraint of the maximum available repair crews and the maximum workers or repair crews per lifeline, which is based on Almufti and Willford [26] as shown in Eq. (7).

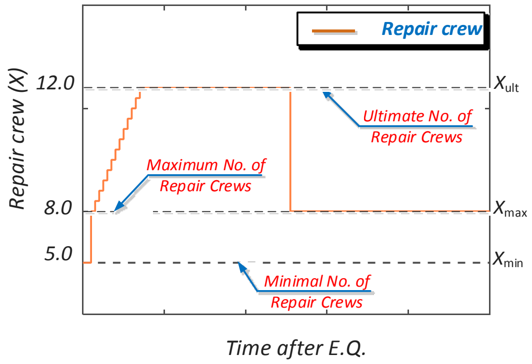

Fig. 2 – Change in the total number of repair crews per time after the earthquake hazard

$$Maximize\ \ R(t) = \sum_{n}^{N} R_n(t)$$
$$Subject\ to\ \ X(t) = \sum_{n}^{N} x_n\ (t) \qquad (7)$$
$$x_n \le x_{n,max}$$

$$Where \quad x_{n,max} = 2.5 \times 10^{-5} A_t + 1.0, and\ 2.0 \le x_{n,max} \le 26.0 \qquad (8)$$

Where; A_t is the total area of the investigated lifeline in units of sq. ft. More detailed descriptions of the recovery framework used in this research can be found in Hassan and Mahmoud [24].

3.4. Resilience

Bruneau et al. [27] introduced four dimensions of resilience including Rapidity, Robustness, Redundancy, and Resourcefulness. Based on this approach, Cemellaro [28] presented a framework to measure community resilience using seven dimensions to describe the whole community. On another hand, resilience can be defined graphically as the area underneath the functionality curve through a certain time frame as shown in Fig. 3 (a). The resilience framework in Fig. 3 (b) is used in this study and focuses on estimating the functionality of the hospital building and calculate resilience as the integration of this functionality from the mainshock earthquake occurrence time to the total recovery time.

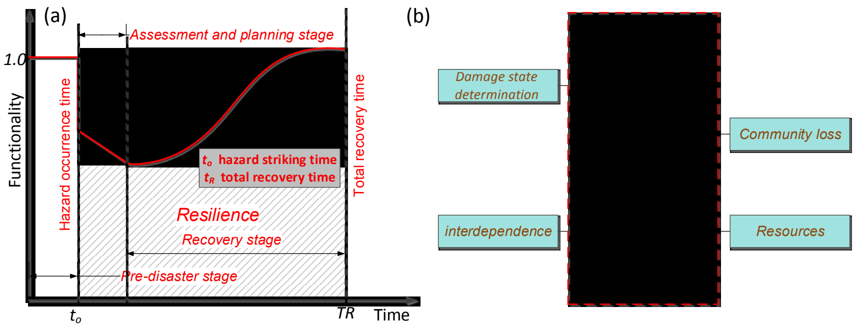

Fig. 3 – (a) Resilience definition and (b) resilience framework

4. Mainshock-aftershock record selection and scaling

In this study, the FEMA-P695 far-field records [29] are utilized for both the mainshock and aftershock. The FEMA-P695 far-field records composed of 22 earthquake records and are commonly used to develop seismic fragilities for buildings. The magnitudes of the aftershocks are commonly less than their corresponding mainshocks; therefore, a scaling approach is needed to simulate the real mainshock-aftershock earthquake events. Different models can be found in the literature that investigated the relationship between mainshocks and aftershocks such as The empirical Bath's law [30]. However, this empirical equation was devised using limited observations. Therefore, to scale the aftershocks in this study, the work by Zakharova et al. [31] is used, in which the seismic moment of the aftershock events were analyzed in comparison to the seismic moment of the respective mainshock events and a relationship between the magnitude of the mainshock and the mean value of the difference between the mainshock magnitude and the magnitude of the respective largest aftershock was provided as shown in Fig. 4. The earthquake events considered in Zakharova et al. [31] occurred between 1973 and 2011 with a cutoff magnitude of 5.0 and are only shallow earthquake events with depth less than 50 km, which is similar to the FEMA-P695 far-field records. A gap between the mainshock and aftershock is also considered as shown in Fig. 4. These mainshock-aftershock sequences are used to develop seismic fragilities for the investigated building.

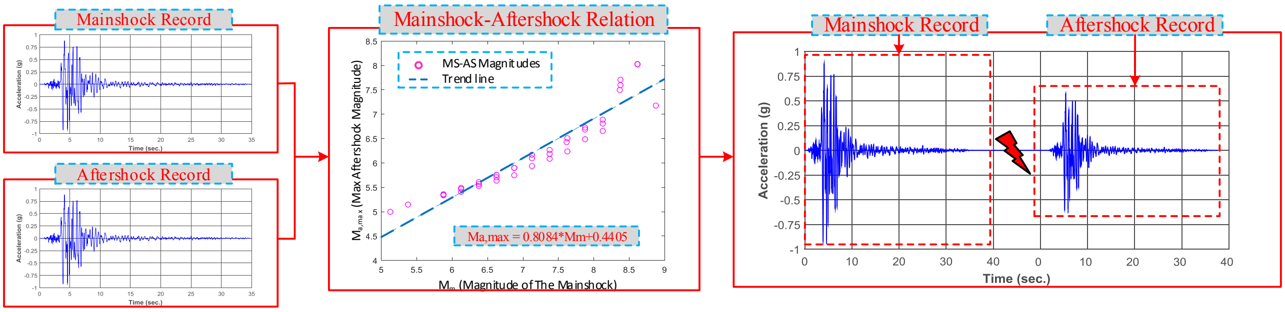

Fig. 4 – development approach for the mainshock-aftershock sequences

5. Results and discussions

The results presented in this section are focused on direct losses, functionality, recovery, and resilience of the investigated hospital building for two different earthquake scenarios. The first scenario only considers the occurrence of the mainshock earthquake with a spectral acceleration of 1.0 g. The second scenario considers the same mainshock followed by an aftershock with magnitude calculated using the relationship in Fig. 4. The time span between the mainshock and the aftershock occurrence is assumed to be18 days.

Fig. 5 (a) shows a comparison between different expected losses of the investigated hospital for the two previously mentioned scenarios (mainshock only and mainshock aftershock). Different components of economic losses including structural, non-structural and contents are shown in the figure below as well as the social losses. These losses are then combined to estimate the total losses according to Eq. (1). From the analysis, it can be seen that the social losses are expected to be minimal for both scenarios. The building losses are higher for the mainshock-aftershock sequence resulting in 8.5% increase in total losses caused by the mainshock-aftershock sequence in comparison to the mainshock alone. Fig. 5 (b) displays the change of functionality for the hospital's supporting infrastructure with time for the mainshock-aftershock scenario as well as the recovery of the hospital building components (structural, non-structural, and contents).

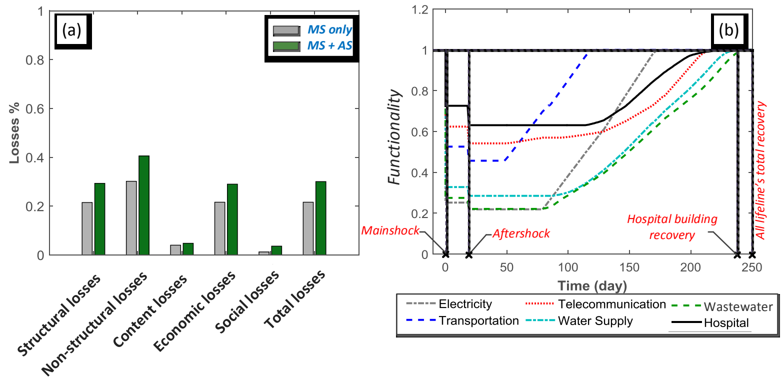

Fig. 5 – a) Comparison between the expected hospital losses for mainshock only and mainshock-aftershock sequence and b) functionality of the supporting infrastructure and the hospital building functionality for mainshock-aftershock scenario

Generally, the restoration process after earthquake events can be categorized into the assessment and planning stage and recovery stage. Shortage of the supporting infrastructure functionality, especially after the occurrence of the aftershock, reduced the hospital quantity and quality functionality as shown in Fig. 6. The assessment and planning stage is elongated as a consequence of the aftershock that occurred during this restoration stage following the main event. It can be observed from the figure that the expected total recovery time of the hospital is delayed.

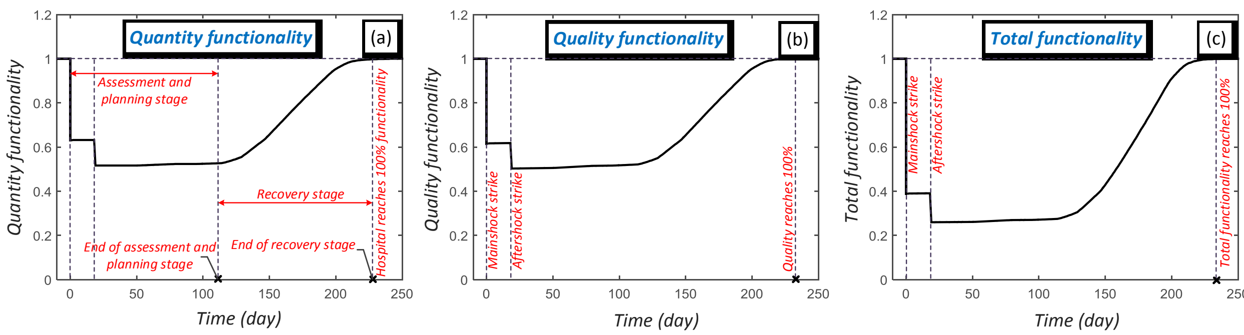

Fig. 6 – Hospital functionalities: a) quantity functionality, b) quality functionality and c) total functionality

Fig. 7 shows the resilience of the investigated hospital for the two earthquake scenarios. The hospital resilience reduced from 63.41% to 60.72% in the case of the mainshock and aftershock. The recovery time of the hospital functionality increased by 39-day in case of the mainshock-aftershock scenario.

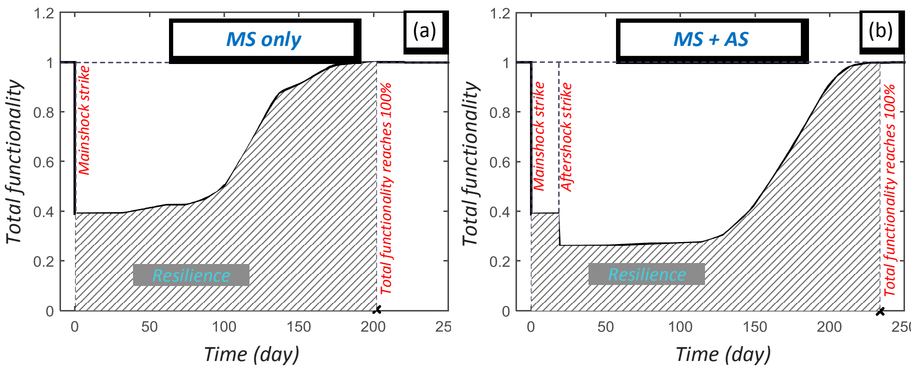

Fig. 7 – Hospital resilience: a) for mainshock only and b) for mainshock-aftershock sequence

6. Conclusion

This study pertains to investigating the impact of the multiple earthquake hazard (mainshock-aftershock) on the functionality of a steel hospital building located in Memphis, Tennesse. A comprehensive approach is used to estimate the losses, functionality, recovery, and resilience of the investigated hospital. A comparison between the mainshock only scenario and the mainshock-aftershock is presented. The following conclusions can be drawn from this study:

- Occurrence of aftershock can disturb the functionality of the hospital and impact the ability of the hospital to treat the increased patient demand.
- Aftershocks are impacting the hospital supporting infrastructure, which can significantly delay the restoration process of the hospital and decelerate the assessment and planning stage.
- Aftershocks can severely impact the resilience of the hospitals and decrease the total number of staffed beds, increase the patient travel and waiting time.

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