

Resilience by Design: Improving Hospital Functionality Following Earthquake

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Introduction

Hospitals are a critical component to community resilience following disasters. Hospitals need to be able to provide needed medical assistance to people injured during the earthquake and continued care to those already in the hospital. Recent policies and guidelines have emphasized the need for hospitals to remain operational following a major disaster. To remain functional, it is critical to understand what types of physical damage contribute to losses of specific hospital services and the loss of the hospital as a whole. In addition to structural damage, damage to nonstructural components such as suspended ceilings, partition walls, and piping, can severely hinder the hospital's ability to continue providing life saving treatment.

The necessity of hospitals to continue to operate and function following an earthquake highlight the need to move beyond code design and beyond performance-based design. Performance-based design moves beyond code-based design by considering the potential damage and downtime of the building. However, it does not provide needed information on the ability of critical facilities, such as hospitals, to continue to operate in the presence of minor to moderate nonstructural damage. Thus, a further level of understanding and analysis is required to accurately predict realistic functionality of a hospital immediately after an earthquake and during the recovery period. Resilience-based design add an additional level of analysis that maps physical damage to actual hospital services and operations to provide a depiction of what real time functionality of a hospital will actually be.

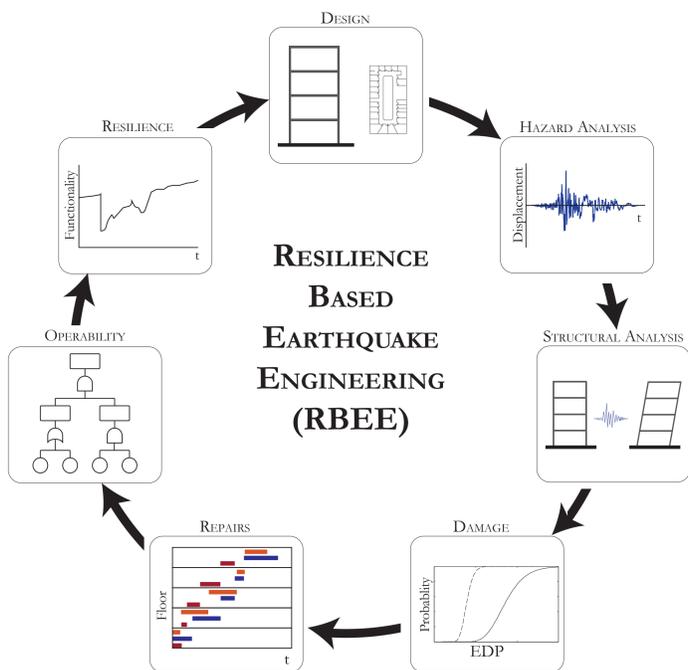


Figure 1. Diagram showing the iterative process for resilience-based earthquake engineering. It is a seven-step process that changes the structural and non-structural design of the hospital to meet performance, operability, and resilience objectives. 1. Design the structural and nonstructural components, also consider the building layout, placement of hospital services, and traffic flow through the building. 2. Perform a hazard analysis for the site location. 3. Perform a structural analysis of the building. 4. Estimate damage to structural and non-structural components. 5. Create a repair schedule based on estimated downtimes, mobilization needs, and ambient factors. 6. Use the damage and downtime estimates to determine the operability of individual hospital services. 7. Combine the operability of all hospital services to estimate the functionality of the hospital at any time during the recovery timeframe. Plot the change in functionality over time. Make adjustments to the design until all requirements are met.

Fault Tree Analysis

For this method of resilience-based design, fault trees are used to map estimated physical damage and downtime (determined following a P-58 PACT assessment) to clinical and non-clinical hospital service. A fault tree is created for each service considered in the hospital. Fault tree consider the physical damage to the service area as well as nonlocalized damage that could also impact the operability of the hospital service.

Damaged components feed into the basic events of the fault tree. By following the binary logic up through the tree, it is possible to determine whether a service will be operable or not. Using the downtime estimations for repairs, the fault tree analysis is rerun at each point in time to provide a resilience curve that shows the change in functionality over time. Changes to the design of the hospital will change the damage and downtime, which will also change the functionality of the hospital. Resilience-based design should be an iterative process where changes to the hospital design are made until the build reaches a desired performance and resilience objective.

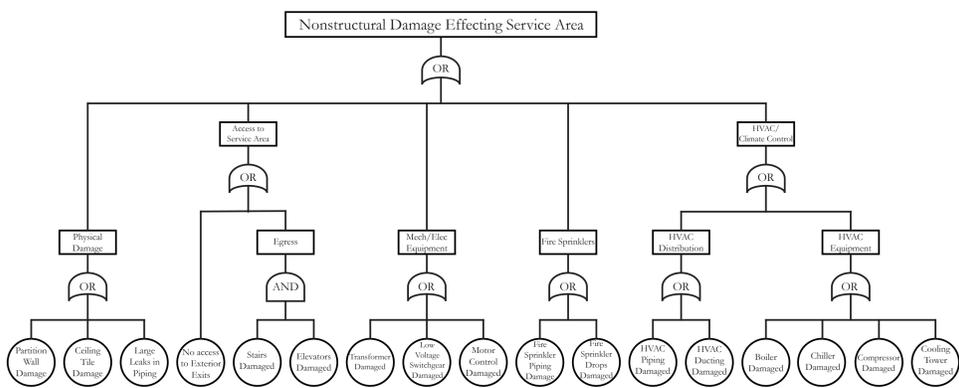


Figure 2. Sample fault tree for checking for nonstructural damage that will effect a service area.

Results

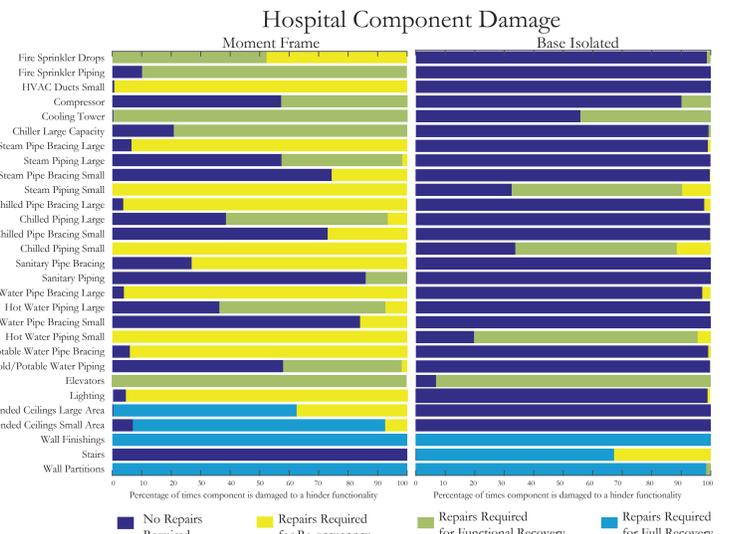


Figure 3. Example of damage distribution for two designs of a hospital building. The one on the left is a steel moment frame design with a long period. The one on the right is the same hospital with added base-isolation. The results show the percentage of times a component is damaged to a certain level. Each hospital design was analyzed for 2000 realizations. The colors indicate the level of damage in terms of functionality: no repairs require, repairs required before the building can be re-occupied, repairs required before the building can be used for its intended function (functional Recovery), and repairs required to restore building to the pre-earthquake state (full recovery). Changing the design from a moment frame to a base isolated frame decreases the amount and severity of damage in the hospital.

Hospital Service Operability

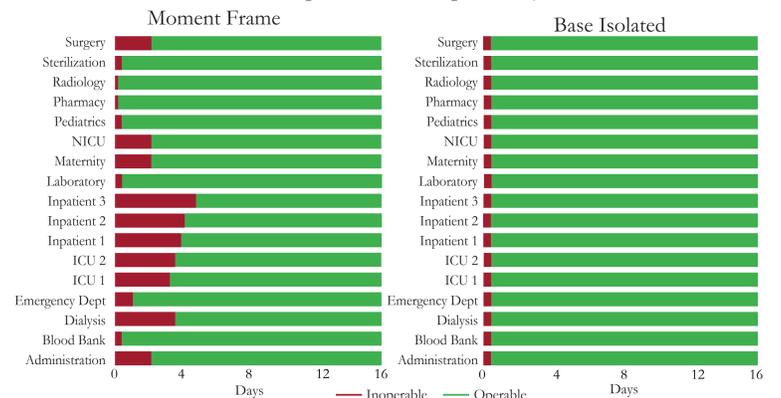


Figure 4. For each realization of the damage and downtime analysis, the results can be fed into the fault trees to determine what hospital services are inoperable or operable immediately after the earthquake and during the recovery. The results above are for the realization that had the median amount of downtime for all the results. Hospital components that were damaged and required repairs to meet re-occupancy and functional recovery were used as inputs to the fault tree analysis. Based on the layout of the hospital, the location of physical damage, and the fault tree logic, each hospital service is analyzed to determine if it is operable. Due to the decrease of damaged components in the base isolated building, there is a lower loss of operability in the hospital as a whole compared to the regular moment frame hospital.

Resilience Curves

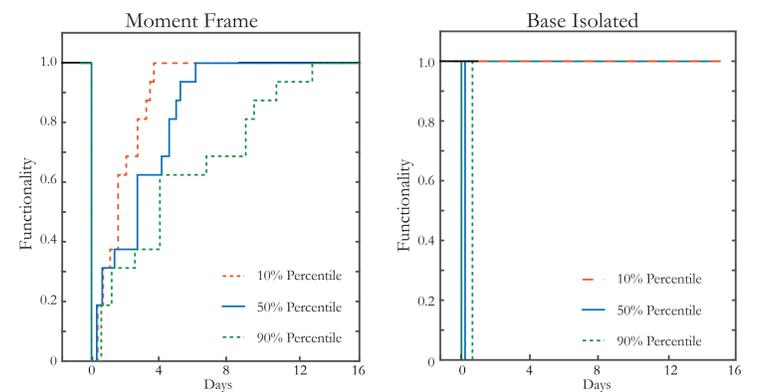


Figure 5. The operability of each service can be combined to estimate the overall functionality of the hospital over time. The graphs above show the resilience curve for the two hospital models. Resilience is shown as the functionality of the hospital over time. Due to more severe and distributed damage in the moment frame model, this model experiences a longer period of reduced services and restoration of functionality. It has lower resilience to the earthquake than the base isolated model which has a rapid recovery and functionality restoration after an earthquake.

Conclusions

Resilience-based design with fault tree analysis can be used:

- in scenarios to predict loss-of-service to one or more hospital services given a set of damage
- in probabilistic assessments of building performance following a performance-based design analysis
- for rapid real time analysis of a hospital's current state of operability following an event
- for developing emergency planning scenarios
- to inform decisions on placement of critical equipment, hospital services, and general hospital layout to improve services the hospital can render following an earthquake

Future Work

This resilience-based design framework can be expand to:

- different building occupancy types
- multi-hazard analysis
- city wide resilience analysis