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COMPARISON OF RESILIENCE RATING SYSTEMS: ASSESSING POST-EARTHQUAKE HOSPITAL FUNCTIONALITY

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ABSTRACT

A community's ability to recover from an earthquake is heavily tied to the overall resilience of that community. Damage to critical infrastructure can dictate how the community as a whole recovers. Efforts have been made to quantify the resilience of important infrastructure components of a community, i.e., individual buildings. These resilience frameworks aim to predict damage, life safety concerns, and recovery times and cost. Several rating systems have been developed to help stakeholders assess vulnerabilities in their buildings and address specific areas for improvement. Each rating system has a different way of quantifying resilience, however, they have a common goal of reducing the adverse effects of a disaster and keep critical facilities running. Hospitals are critical to a community's well being, and contribute to their resilience and ability to recover following an earthquake. Physical damage to structural and nonstructural components in a hospital can severely limit the ability of the hospital to provide critical life saving services to the community. Predicting post-earthquake hospital functionality is critical for planning and preparing for future earthquakes. Rating systems provide valuable information on the predicted performance of these critical facilities. The results of three different rating systems are compared for a single hospital building.

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Comparison of Resilience Rating Systems: Assessing Post-Earthquake Hospital Functionality

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ABSTRACT

A community's ability to recover from an earthquake is heavily tied to the overall resilience of that community. Damage to critical infrastructure can dictate how the community as a whole recovers. Efforts have been made to quantify the resilience of important infrastructure components of a community, i.e., individual buildings. These resilience frameworks aim to predict damage, life safety concerns, and recovery times and cost. Several rating systems have been developed to help stakeholders assess vulnerabilities in their buildings and address specific areas for improvement. Each rating system has a different way of quantifying resilience, however, they have a common goal of reducing the adverse effects of a disaster and keep critical facilities running. Hospitals are critical to a community's well being, and contribute to their resilience and ability to recover following an earthquake. Physical damage to structural and nonstructural components in a hospital can severely limit the ability of the hospital to provide critical life saving services to the community. Predicting post-earthquake hospital functionality is critical for planning and preparing for future earthquakes. Rating systems provide valuable information on the predicted performance of these critical facilities. The results of three different rating systems are compared for a single hospital building.

Introduction

Earthquakes and other disasters can cause significant damage to a community's built environment, which in turn can lead to injuries and fatalities. Hospitals have a critical role in the post-disaster recovery providing needed treatment and medical care to those injured and continued care to existing patients. During emergencies, hospitals are expected to be functional, but damage to the structural, non-structural, or connecting utilities, can cause closures to these essential facilities. Hospitals are not immune to damage, and despite the advances in building designs and building code improvements, hospitals have still performed poorly in past disasters [1-2]. Code conforming hospitals may be at risk for service disruptions.

To help ensure hospitals remain functional after a disaster, governments and

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organizations have taken steps to provide policies and guidelines for estimating damage and functionality [3-6]. In addition to these policies, there is a need to measure and evaluate a hospital's potential performance during a disaster. Resilience rating systems provide one way to quantify resilience in a way that can be compared across buildings. Several rating systems have been developed to help educate the public on potential building performance and to encourage building owners to go beyond code level design to have buildings that are more likely to survive disasters and remain operational.

Rating systems have been used extensively in many contexts to convey a message to the public concerning safety, sustainability, or quality. Quantification of performance varies between the agencies that develop the rating systems. Common methods used to best convey information to the general public include: letter grades similar to a school report card (e.g. ASCE Infrastructure Report Cards [7]); certification levels comparable to awards for athletic achievements (e.g USGBC LEED certified buildings [8]); or stars as commonly seen in product reviews (e.g. Star Community rating system for sustainability [9]).

Each of the above rating systems provides an important contribution to understanding safety or sustainability. However, none of the systems address the safety of buildings, particularly buildings faced with physical disasters. Due to the need to understand and quantify not only the safety of building occupants in a disaster, but also the time and resources to repair a building following a disaster, several resilient specific rating systems have been and are currently underdevelopment. As each rating system varies in their assessments of post disaster functionality, it is important to understand how the results of each system compare and what they mean for hospital functionality.

Resilience Rating Systems

Three rating systems: the Resilience-based Earthquake Design Initiative (REDi) rating system, the United States Resiliency Council (USRC) Rating System, and the World Health Organization (WHO) Hospital Safety Index are used to assess the predicted performance of a hospital building. The hospital building is located in San Francisco California and is designed and built to California building code.

Resilience-based Earthquake Design Initiative Rating System

The REDi rating system, developed by the engineering firm Arup, is an extensive planning and design resource for engineers designing buildings expected to perform beyond code requirements. REDi is a holistic approach to building design that requires input from multiple disciplines and requires involvement from building owners, occupants, and other stakeholders to lessen physical damages to the building and to eliminate organizational and business losses [10]. REDi can be applied to all building occupancies but is currently limited to earthquake analysis. REDi encourages focus beyond the physical building and recognizes the important role external factors such as site access, mobilization time, and municipal infrastructure can have on a building and the encompassed organizations. A REDi evaluation provides building stakeholders a comprehensive building classification of either platinum, gold, or silver, based on the building's combined predicted performance in occupant safety, financial losses, and recovery time and in meeting a required set of prescriptive requirements. The breakdown for assigning a certification based on is given in Fig. 1. In order to qualify for a certification level, the building must meet all of the requirements for that level.

	Downtime Re-occupancy	Downtime Functional	Direct Financial Loss	Occupant Safety
Platinum	Immediate (Green Tag)	< 72 hours	< 2.5%	Injury is unlikely
Gold	Immediate (Green Tag)	< 1 month	< 5%	Injury is unlikely
Silver	< 6 months (Yellow Tag)	< 6 months	< 10%	Injury is possible but structural collapse is unlikely

Figure 1. The loss assessment requirements for recieving a REDi certification. Adapted from REDi User Manual [10].

United States Resilience Council Rating System

The United States Resiliency Council (USRC) has created a rating system to standardized methodologies for describing the performance of a building to natural hazards such as earthquakes [11]. Like REDi, the USRC rating system is applicable to all building occupancies, but currently limited to earthquakes. The USRC rating system for earthquakes allows the use of two standardized methodologies. One methodology is adapted from the Structural Engineers Association of Northern California [12] that uses ASCE 31 analysis procedures [13]. The other follows the performance-based earthquake engineering methodology as outlined in FEMA P-58 [14]. In this study, the FEMA P-58 methodology is used.

The rating evaluates the estimated building performance in three dimensions: safety, damage, and recovery. The building is given one to five stars in each of the three categories based on meeting threshold values. The USRC rating system requires a structural analysis of the building subjected to the potential hazard and a loss assessment to predict damages, repair costs, and recovery times. The ratings are based on the performance of the physical building and not the human infrastructure or businesses within the building (USCR, 2015). The requirements for receiving a given number of stars in each category are illustrated in Fig. 2. The building is not given an overall rating but rather three individual ratings, one for each dimension.

Stars	Safety	Damage	Recovery
★★★★★	**Injuries and blocking of exits unlikely** Fatality < $3x10^{-5}$	**Minimal Damage** Repair Cost < 5%	**Days** Recovery < 5 days
★★★★	**Serious injuries unlikely** Fatality < $1x10^{-4}$	**Moderate Damage** Repair Cost < 10%	**Weeks** Recovery < 4 weeks
★★★	**Loss of life unlikely** Fatality < $4x10^{-4}$	**Significant Damage** Repair Cost < 20%	**Months** Recovery < 6 months
★★	**Loss of life possible in isolated locations** Fatality < $4x10^{-3}$	**Substantial Damage** Repair Cost < 40%	**1 Year** Recovery < 1 year
★	**Loss of life likely** Fatality > $4x10^{-3}$	**Severe Damage** Repair Cost > 40%	**Years** Recovery > 1 year

Figure 2. The requirements for achieving each level in USRC Rating System [11].

Hospital Safety Index

The Hospital Safety Index [5-6] is a hospital evaluation tool created by the World Health Organization (WHO) and the Pan American Health Organization (PAHO) to give a rapid and inexpensive evaluation of hospital safety during an emergency or disaster. The goal of the Hospital Safety Index is to have hospitals worldwide that remain safe, assessable, and functioning during and immediately after any emergency or disaster. The Hospital Safety Index considers all hazards in the vicinity of the hospital including natural, manmade, mass casualty events, and biological emergencies.

Hospitals are evaluated by using a checklist that considers 145 items in three different categories: structural, nonstructural, and functional [6]. Each item has three levels: low, average, and high. The items are evaluated based on the current conditions, adequate design, preparation, or amount of supplies on hand as appropriate for each item and as defined by the Hospital Safety Index guidelines. Index values for the individual categories are calculated based on the condition of the items and their corresponding weight, the total hospital index is found by weighting each of the main categories, structural (50%), nonstructural (30%), and functional (20%). The final index value (a numerical value between 0 and 1) gives the probability of the hospital surviving an emergency or disaster and maintaining functionality [5]. The index can be translated to a classification level, see Fig 3., which indicates predicted outcomes. The index can be useful in helping hospital owners and managers strategically plan repairs to help improve building performance. The sub-scores for structural, nonstructural, and functional capacity are also useful for knowing where to target the repairs to improve overall hospital performance. Unlike other rating systems, it considers the vulnerability of hospitals to all potential hazards and puts emphasis on the staffing, emergency preparedness, and the organization of the hospital in emergencies. A major weakness in the index is the financial losses and recovery are not included. These are important indicators to the hospitals long-term viability after a disaster and give an understanding of the hospital availability during the critical recovery time.

Safety Index	Classification	Predicted Outcomes	Recommendations
0.66 - 1.0	A	Hospital is likely to function	Continue to improve emergency and disaster management capacity
0.36 - 0.65	B	Ability to funciton is at risk	Short term intervention needed
0.0 - 0.35	C	Unlikely to function	Urgent intervention is needed

Figure 3. Hospital Safety Index values and correlations to predicted performance and recommendations

Case Study Hospital

A sample hospital, located in San Francisco, California, is used to compare the three rating systems. The hospital model was designed with two different code compliant lateral-force resisting systems. The first model is a steel moment frame with a fixed base; the second model uses a friction bearing base isolation system in addition to secondary steel moment frames. The two systems were chosen to show the difference in expected performance between a basic code compliant building and a seismically updated structure that goes beyond code requirements. The building houses acute care services such as emergency, surgical, inpatient, and critical care. The hospital is a recent construction and is assumed to have emergency policies and procedures in place to deal with earthquakes and other hazards. Additionally, it is assumed that the facility has sufficient backup supplies of food, water, power, and medical equipment to continue operating for 7 days as required by a REDi prescriptive requirement for platinum certification.

Two of the rating systems require a detailed nonlinear structural analysis of the hospital building as input for their loss assessments. A nonlinear structural analysis was completed using the computer software ETABS [15]. The hospital models were analyzed with a suite of seven earthquakes representing that represent the design base earthquake for the San Francisco Bay Area, defined in US code as 10 % in 50 year. The maximum drift and acceleration demands from the analysis were used in a loss assessment to determine damage to structural and nonstructural components.

Results

The results of both hospital models analyzed with the three rating systems are shown in Fig. 4. For each rating system, there is slight difference between the moment frame and the base isolated model, with the base isolated model performing slightly better in all three of the rating systems. There are also differences in the final rating and the interpretation of the rating between the three rating systems in both structural models.

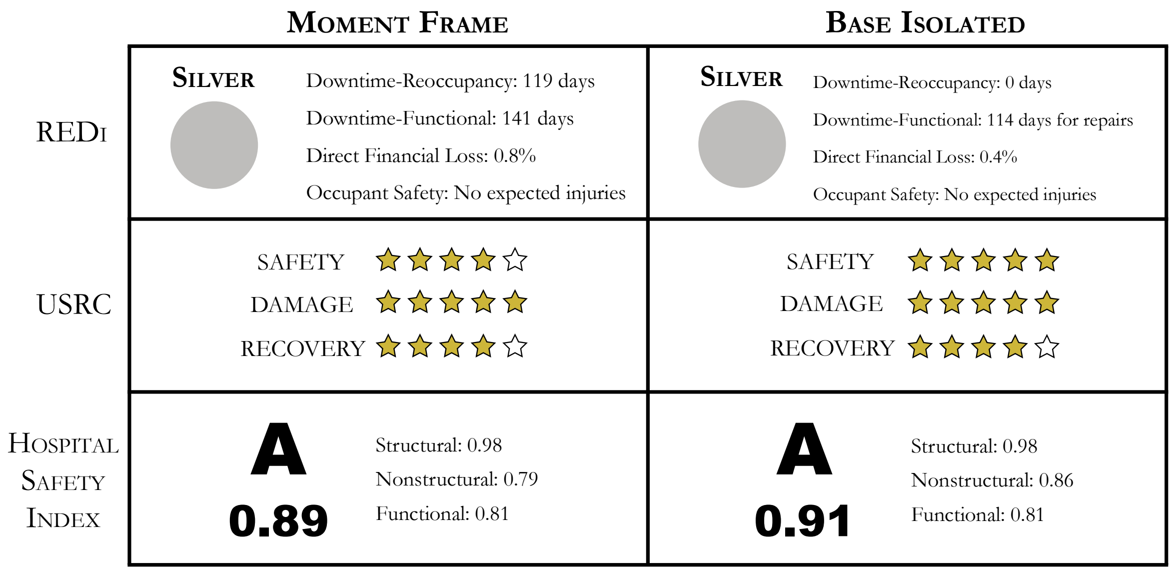

Figure 4. The results of the predicted hospital performance and rating for both hospital building models for the three different rating systems.

Discussion

The hospital receives the lowest ratings using the REDi certification system. A breakdown of the loss assessment results for both models is shown in Fig. 4. Both models receive a silver REDi certification. For re-occupancy (time until it is safe to use as a shelter), the moment frame model has a repair time of 6 days and an additional 113 days of downtime for impeding factors. The functional recovery time (time until it can be used as a hospital) is 22 days for repairs plus an additional 119 days for impeding factors resulting in a total of 141 days for functional recovery. Base isolating the structure dramatically decreases the re-occupancy time to zero days including downtime for impeding factors, but only slightly decreases the function downtime 14 days for repairs and 100 days for impeding factors. The primary cause of the functional delay is contractor mobilization. While the base isolated model shows improved recovery time and performance over the moment frame model both receive a Silver REDi certification. According to this rating system, the base isolated hospital is not expected to be operational immediately after a major earthquake.

Both building models perform acceptably for financial loss. The direct financial loss considers only the cost to repair the hospital to the pre-earthquake condition and is calculated as the repair cost divided by the building value. The build cost is approximately $900 million US dollars. The mean value from all the realizations in the loss assessment is used to calculate the repair cost value. The mean repair cost is about $6.85 million for the moment frame model and $3.6 million for the base isolated model, which is 0.8% and 0.4% respectively of the building replacement cost, both under the platinum certification levels of less than 2.5%.

For occupant safety, both models again do well. The loss assessment indicates that the building is unlikely to have collapse of the suspended ceiling tiles or other structural or nonstructural members that would cause injury to the building occupants. The building is unlikely to collapse and fatalities are unlikely, this alone would allow for gold or platinum certification.

Accounting for all dimensions in the REDi analysis, both models only earn Silver REDi certification. The building is expected to keep occupants safe and will have a low recovery cost, but the hospital will not remain functional after a major earthquake. The results indicate that repairing either building model is achievable, but the hospital will not be able to continue providing necessary medical care during and immediately after a major earthquake. To best improve performance, impeding factors such as contractor mobilization and utility disruption need to be lessened or eliminated.

The final USRC results are shown in the second row of Fig. 4. The results from the loss assessment used in REDi where also used to determine the USRC rating. The moment frame building received four stars in safety, five stars in damage, and four stars in recovery. The base isolated building receives five stars in safety, five stars in damage, and four stars in recovery. USRC only considers functional re-occupancy and does not consider additional delays due to impeding factors. There is not a significant difference between the ratings for the moment frame model and the base isolated model, both perform relatively well in all categories. The base isolated model out performs the moment frame model in safety only. Even though the base isolated model has a shorter recovery time and half the repair cost, the difference is not enough to improve the ratings. While both hospital models perform well under the USRC rating system, neither model is expected to be immediately operational after an earthquake.

The hospital receives the highest scores using the Hospital Safety Index rating system. There is only a slight difference between the scores for the standard moment frame building and the base isolated building due to a slight change in the predicted nonstructural performance, see row three of Fig. 4. Even though the structural system changes, the structural index value remains the same (0.98). The structural section in Hospital Safety Index focuses on the current condition of the building (i.e. prior damage, deterioration, construction quality), irregularities in the structures plan or height, and structural system design in terms of code requirements. Since both the regular moment frame building and the base isolated building meet code requirements, and the overall design is the same, the structural index value is the same. The functional components are independent of the structural system and nonstructural components used in the hospital design, changing the structural design does not change the estimated functional performance of the hospital. The functional section of the evaluation receives a score of 0.81. This value is obtained by following the same assumptions that are required for platinum certification in the REDi prescriptive requirements. When the functional performance criteria is unknown, it is assumed that plans and training are in place, but supplies may be insufficient to fully carry out recovery requirements.

There is a slight difference in the nonstructural capacity between the two models. Buildings with moment resisting frames can have higher accelerations, leading to damage of suspended ceilings, pipes, and equipment. Even though a loss assessment is not required for the Hospital Safety Index rating, the loss assessment results from the other two rating systems predict damage to these components. The same level of damage does not occur in the base isolated building model. As such, the index items relating to acceleration sensitive nonstructural elements are adjusted to reflect the possibility of damage that would disrupt hospital functionality and are given lower assessment values in the moment frame model. The moment frame building received a nonstructural index of 0.79 while the base isolated model has a value of 0.86. The lower value indicates that there is a definite increase in the probability that building will not remain functional due to nonstructural damage.

According the Hospital Safety Index, both building models will have a high probability of continued operations following an earthquake or other disaster. The moment frame building has a score of 0.89 while the base isolated has a score of 0.91. Both will receive an A for expected performance. The weighting factors minimize the impacts that the nonstructural component damage can have on the total hospital index value. Thus, both buildings have high scores due to the good structural score and the high weighting for the structural portion of the survey.

While the rating systems have different results and capture different dimensions of the overall hospital performance, none capture post-earthquake performance perfectly. The same hospital model receives different results based on the rating system. The hospital receives the least favorable rating with the REDi rating system. However, this system includes several factors that are critical to accurately estimating recovery time that are not captured in the other systems. Both hospital models receive good ratings from USRC and the Hospital Safety Index.

Each rating system has advantages and disadvantages. Each attempts to capture the probability of functioning after a disaster. A common disadvantage is the inability of any of the systems to capture emergent human behavior in solving and working around problems immediately after an earthquake. For REDi and USRC, the maximum damage level of any component in the building drives the recovery state. Therefore, a building that has a few severely damaged components in an otherwise sound building might be falsely closed, when in reality just that section or area of the building would need to be closed. This also leads to a lower recovery rating for the building. Further, none of the rating systems directly address resilience in terms of functionality. Instead, each tend to focus on building performance and not on operability of building services and overall functionality.

Conclusions

Each of the rating systems captures a different part of the building's overall performance. However, none of the rating systems specifically address the continued functionality of the hospital after an earthquake. The Hospital Safety Index comes the closest to addressing functionality, as the index is an estimate of the probability of continued functionality. Neither REDi nor USRC provide a way to assess the ability of the building to service the needs of the organization housed within, rather they focus on building performance requirements. None of the rating systems provide a measurement of the level of functionality after the earthquake or an idea of the restoration of services over time.

Considering all three rating systems gives an idea of the strengths and weaknesses that need to be addressed to insure better performance and post disaster recovery. However, further work must be done on combining the performance of the building with the functionality of the organizations within to the building to truly measure and quantify resilience. This is particularly important for complex critical facilities such as hospitals that have unique needs that can be directly affected by physical damage. As each of the rating systems provide critical information on the resilience, future iterations of these rating systems should seek to combine the strengths of the other systems and incorporate functionality in addition to performance.

While none of the current rating systems directly measures all aspects of resilience, they are a step in the right direction for assisting building owners and stakeholders to consider resilience and building performance. Support from practicing engineers and insurance or tax incentives can provide further momentum for future resilience research and guidelines to best measure and rate buildings for resilience.

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