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SEISMIC FRAGILITY ANALYSIS OF A FOUR-STORY MASONRY BUILDING WITH RETROFIT TECHNIQUES

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Abstract

Masonry structures can exhibit many different behaviors during a seismic event when compared to other types of structures. Because of this, many older masonry structures are in need of a seismic retrofit. A retrofit can either be forced by a governing authority or completed voluntarily. There are many reasons for a retrofit; a few reasons are the age of the building and the building codes implemented at the time of construction, the purpose of the building, the Risk Category assigned by the International Building Code, IBC, or at the owner's discretion. The purpose of this project is to analyze a case-study building that underwent a seismic retrofit because of all the reasons listed previously. The motivation for this project is to perform the fragility analysis of the building and to determine the economic effect the retrofit had for the owner. A four-story masonry building is selected for this study. The case study building is located in Fullerton, California, which is directly above a portion of the Puente Hills Blind Thrust System. A thrust fault is defined as a fault that is considered to be moving in an almost complete vertical direction with less than a 45-degree dip. The case study structure was deemed in need of a retrofit due to the age of the building, and the building codes that were implemented at the time of construction. The retrofit was completed with the addition of reinforcing materials. The specific material used was Carbon Fiber Reinforced Polymer (CFRP) strips. Seismic fragility of the case-study building prior to the retrofit is estimated to compare to the current retrofitted building. In addition, the study will determine the economic benefit to the owner after the completion of the retrofit based on loss estimation results.

Keywords: fragility analysis; seismic retrofit; Carbon Fiber Reinforced Polymer (CFRP)

1. Introduction

Seismic activity is a usual occurrence in Southern California. Small earthquakes are recorded by the United States Geological Survey (USGS) with great frequency. Often, medium earthquakes occur without public concern. While the feeling of an earthquake can be subjective, large design decisions are made with seismic activity in mind. EQE consulting is a company focused on risk analysis in relation to natural hazards. Seismic hazards are a huge part of their business. Of about 100 earthquakes that EQE Consulting has analyzed, about 30% of them are in California [1].

Because the San Andreas Fault runs throughout California, there is great concern about this specific fault being overdue for a large quake. This causes concern for all along this fault line. The location in question is located less than 50 miles from a portion of the San Andreas Fault. The case study building is located in Fullerton, California and is located directly above a portion of the Puente Hills Blind Thrust System [2]. A thrust fault is when the faults are considered to be moving in an almost complete vertical direction with less than a 45-degree dip [3].

Older buildings are frequently being retrofitted to implement the necessary design requirements in order to withstand seismic activity. While retrofitting may seem absurd due to cost, there has been large amounts of research done into the decision process [4]. Once the research and analysis has been completed, the owners often agree that the benefits greatly outweigh the cost to retrofit their buildings.

Fig. 1 – Present State of the Case-Study Building

2. Research Objectives

The objective of this study is two-fold. The first is to determine fragility analysis of the case study building prior to the seismic retrofit compared to the current retrofitted building. Meaning, this research is looking at one individual case study building, but a before and after snapshot--producing two curves. Also, this research will determine if the building could have been made stronger with a different pattern of CFRP. The building implemented a unidirectional placement.

The ground motion applied during research will not be an exact application of a past earthquake, but rather a synthetic ground motion. Also, the study will determine the economic benefit to the owner after the completion of the retrofit.

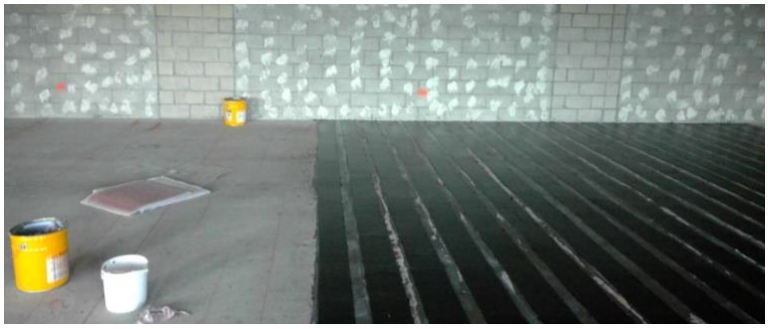

Fig. 2 – Unidirectional CFRP Placement

3. Background & Related Work

The case study building is partnered with an adjacent property in Fullerton, CA. The case study building is a four-story building, which is classified as office buildings meaning they are of Risk Category III per IBC Table 1604.5 [5].

The study of seismic analysis is a heavily documented field. Because of high seismic activity in California, many engineers are working on methods to reinforce current structures in order to increase the performance levels.

3.1 Four-Story Building

The four-story property was deemed in need of a retrofit due to the age of the building, and the building codes that were implemented at the time of construction. This retrofit was completed voluntarily by the owners and the decision was motivated by providing a safer structure. The retrofit was completed by the addition of reinforcing materials. The specific material used was carbon fiber reinforced polymer strips. The original configuration of this building was a reinforced concrete framed building with masonry infill. This is significant, because concrete has low tensile strength. Earthquakes can potentially subject the building to greater forces than originally designed for. With the addition of the CFRP, the building was engineered to withstand higher tensile forces. In a specific experiment, Önal [6] proved that CFRP increased the strength of beams by 38%. This is a significant increase and is a simple justification as to why CFRP is an optimal option for the seismic retrofit of structures.

While many other engineers have completed research using many case study buildings, the purpose of this research is to analyze a single case-study building. While a single case-study building is being considered, the building will be analyzed both pre- and post-retrofit. Hueste and Bai [7,8] have also conducted their research using a solitary case-study building. Those who have analyzed numerous buildings have used buildings of varying sizes as well [4,7]. Others have completed research not on full buildings, but on portions of walls [11,12,13,15]. Whether the research used full buildings, walls, or partial walls, each result determined--with various degrees of confidence--that the reinforcing materials were indeed beneficial. While this may seem self-explanatory, this research proves further that the money spent on the retrofit did increase the safety of the building--thus lowering the overall risk.

Fig. 3 – Case-Study Building during construction

3.2 Applied Ground Motion

The ground motions applied during research can differ depending on the research methods. For instance, some engineers have used past earthquakes and, they have applied those to their research [7]. Other engineers have used synthetic ground motions. The synthetic ground motions will incorporate an average of past earthquakes. By using a synthetic ground motion, a more accurate analysis can be performed--assuming an exact past ground motion cannot happen again [8,9]. The case study building will be subjected to the spectral acceleration—similar to the research completed by [7]—in order to accurately compare the pre- and post-retrofitted structures. The spectral acceleration will provide an estimation of how the building will react during time of the earthquake.

A suite of 20 synthetic ground motions from the SAC project is used [16]. It includes 10 pairs of horizontal ground motions for Los Angeles with probabilities of exceedance of 2% and 10% in 50 years for the nonlinear time history analyses.

3.3 Reinforcement Materials

FEMA 547 determined that one of the best ways to retrofit against seismic events is through the use of additional materials such as shear walls or braced and moment frames [10]. These are the most common techniques used by engineers through the retrofitting analysis procedures. During their research, Hueste and Bai [8,9] analyzed the addition of shear walls, reinforced concrete column jackets, and the restriction of the column plastic hinge. This team focused on one case-study building that was classified as an office building. Another group of engineers have completed research using steel bracing or shear walls in to retrofit reinforced concrete frames. Pincheira and Jirsa [7] furthered their research by using buildings of three different heights.

In the field of masonry structures, Darbhanzi et al. [11] completed research using steel ties to reinforce the structure. In addition, Can [12] investigated methods to reinforce masonry structures. The material analyzed was Carbon Fiber Reinforced Polymer (CFRP). This engineer applied this material in three different patterns, and in conclusion he determined that the CFRP was an effective means to reinforce masonry. Further research was completed in analyzing the effects of reinforcement polymers. Iacobucci et al.

[13] used both CFRP and glass fiber-reinforced polymers (GFRP) in their retrofitting research. The research proved that CFRP is an economical way to increase the ductility of the structure--in this case, near-full size concrete columns. Gattesco and Boem [14] further investigated the effectiveness of GFRP mesh. In all test results, the GFRP significantly increased the effectiveness of the masonry walls.

The seismic retrofit for the building in question was completed in 2017. The use of Carbon Fiber Reinforced Polymer (CFRP) was included in the seismic retrofit. The increased strength was proven in Can [12] by placing CFRP in three different directions. Can's research proved that the full wrapping of the structure was the best approach. Because the building underwent a voluntary seismic retrofit, the restrictions were not high as to how the building had to be reinforced. The seismic retrofit on the case study building has implemented the process of CFRP strips being placed running the width of the building and vertically on the shear walls. This unidirectional placement is specific to the building and was deemed to have enough stability for the retrofit.

Fig. 4 – CFRP placement in the Case-Study Building

4. Methodology

The research on the case-study building will provide actual results on the post-retrofitted building. Past research was completed by others during the design phase but was kept in-house and nothing has been presented. By completing this research, the case-study building will have legitimate data to be associated with it in regard to the fragility analysis and economic value.

4.1 Structural Analysis Software

There are many different types of software that can provide two-dimensional and three-dimensional analyses. The software being discussed in this paper is developed by Computers and Science, Inc. or CSi. SAP2000 has been in use for over thirty years and has been used in many different applications [17]. This specific software allows the user to use models such as: “large deformation analysis, Eigen and Ritz analyses based on stiffness of nonlinear cases, catenary cable analysis, material nonlinear analysis with fiber hinges,”

and many more [17]. With the power of this software, the case study building will undergo great testing to determine the limits of the seismic retrofit.

4.2 Analytical Model Designs

While many different design models are available in SAP2000, the focus of this paper is to apply a nonlinear static analysis (NSA) and a nonlinear dynamic analysis (NDA). Each of these follow their own applications and assumptions resulting in different results. The NDA method requires a more detailed model as well as more time to complete the actual processing of the results.

The NSA is commonly referred to as a pushover analysis. When looking at the NSA, the case-study building will be subjected to the ultimate loads. Because the building is faced with the strongest loads it can handle, the building is expected to fail—this failure is the end result in the modeling procedures. By understanding how and where the building failed, the retrofit techniques can be applied, and the building's functionality and safety can be improved.

The NDA is quoted to "lead to better designs" [18]. The NDA method is more complex, because it requires the user to define a more detailed model. Instances where the NDA method prevails is for buildings that subjected to extremely high lateral loads such as wind and seismic loads. By nature, these buildings will have a far greater number of shear walls than an ordinary building might have. Shear walls are designed to help the overall structure resist the lateral loads. While this is extremely important in high-rise buildings. The case-study building in a four-story building, so this effect is minimal.

For the model used in this paper, the authors took advantage of some assumptions. The first assumption is that the geotechnical aspects of the location are all perfect. The soil characterizes are deemed best case scenario. This assumption allows the authors to ignore the foundational components and simply analyze the structural components of the case-study building. Another assumption made in this modeling process was to ignore the structural integrity of the elevator pit and shaft. This assumption is simple to apply, because the elevator components do not add a large amount of structural integrity for low-rise buildings. The model was generated by creating a 3D model of the case-study building. This model took into account the reinforced concrete beams and columns along with the masonry infill. A second model was made; this model was built from the original model, but then was updated to reflect the CFRP that was added during the retrofit.

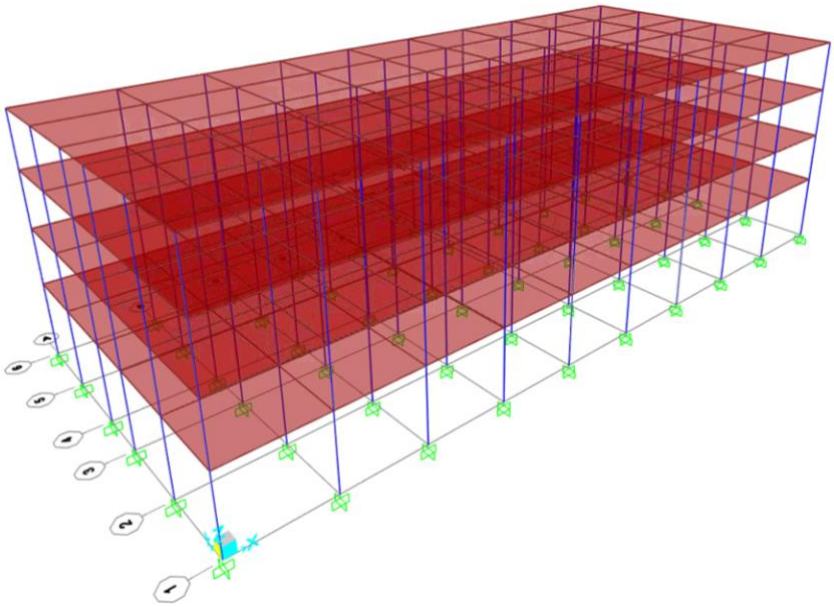

Fig. 5 – SAP2000 model used during the research

4.3 Seismic Fragility Estimates

The fragility of the case study building will be determined according to the performance levels defined by ASCE-41 [19]. The study will determine the Immediate Occupancy (IO), Life Safety (LS) and Collapse Prevention (CP) for the case study building both pre- and post- retrofit. The Immediate Occupancy is described as remaining in tack as pre-seismic activity; Life Safety is defined as having structural damage, but with enough stability to avoid collapse [20]. The evaluation of the case-study building will be in accordance with FEMA 356's Structural Performance Levels and Damage [20]. These performance levels will be used to determine the efficiency of the retrofit. Once the efficiency is obtained, then the economic analysis can begin.

A fragility curve is produced after the analysis has been completed. These results provide a graphical representation of the statistical analysis of the performance. The graph can be described in terms of the ASCE-41 performance levels. The fragility curves for the model will be produced in order to provide a basis of findings for the effectiveness of the retrofit.

5. Results

SAP2000 proved to be a great modeling tool once the model was defined in an accurate manner. After the original case-study building model was created in SAP2000, the synthetic ground motion was applied. Once the motion was applied, the deformed building was analyzed. The SAP2000 results were then imported into Excel in order to generate the fragility curve. The curve for the pre-retrofitted structure can be seen below.

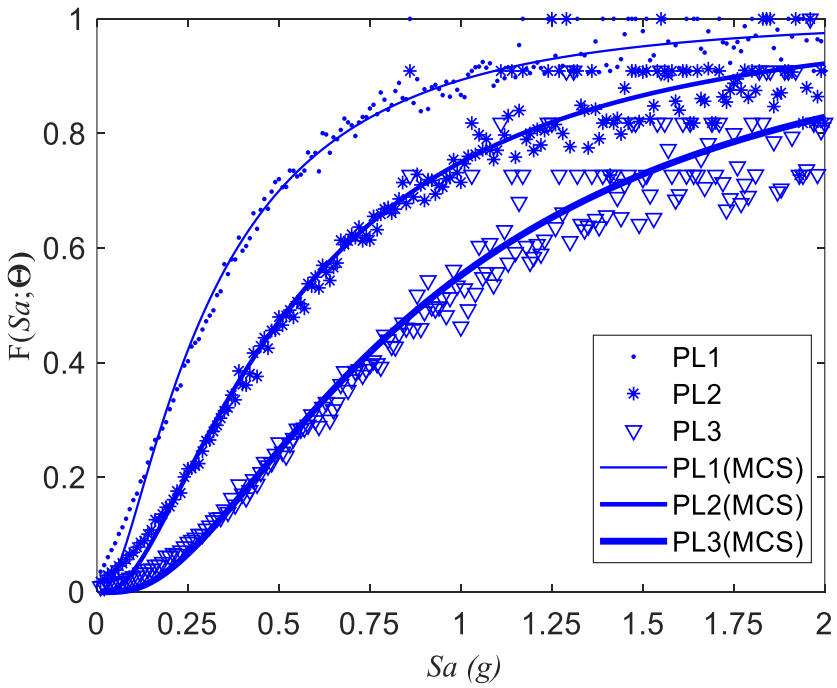

Fig. 6 – Fragility Curve for the Pre-retrofitted Building

Figure 6 provides a graphical representation of how the original building performed once the ground motion was applied. The X axis is the spectral acceleration in g-force. The Y axis is the probability of exceeding the performance levels or in other words—the probability of failure. PL1 is Performance Level 1, which is known as Immediate Occupancy according to ASCE 41. PL2 is equivalent to Life Safety, and PL3 is likened to Collapse Prevention.

It can be identified that the original building performed poorly when the ground motion was applied. The curve demonstrated how the increase in spectral acceleration caused a drastic increase in failure probability. The production of this curve could provide an additional justification that a retrofit was needed and had the potential to greatly eliminate risk of failure.

The retrofitted structure was also modeled in SAP2000 and the same suite of ground motion was applied to the retrofitted model. The research required the users to understand how the CFRP application created a stronger case-study building and then apply these concepts into the model in SAP2000. The intent of this retrofitted model is to also generate the fragility curve and accurately analysis if and how the retrofit increased the integrity of the building. Below is the resulting fragility curve for the retrofitted structure.

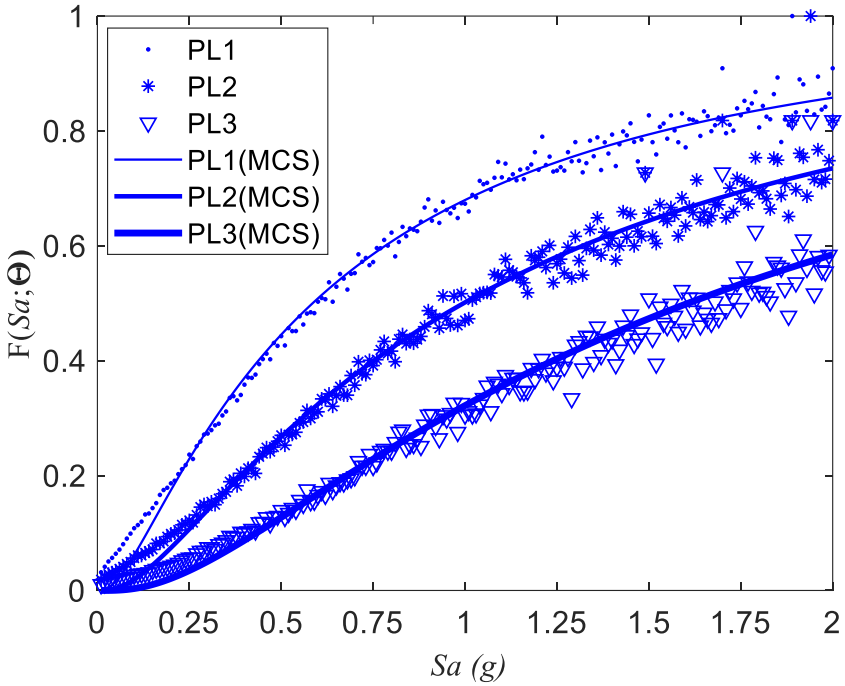

Fig. 7 – Fragility Curve for the Retrofitted Building

Figure 6 and Figure 7 are set up in the identical manner in order to a meaningful comparison to be made. After looking at both the original and retrofitted curves, it becomes apparent that the CFRP did in fact decrease the probability of failure. When looking at a spectral acceleration of 1g, the original building had over an 80% chance of failing at PL1. At the same acceleration, the retrofitted building decreased its failure probability by over 20%. This decrease did come at a cost to the owner, but the cost provided the potential to save more lives in the case of a building collapse due to seismic activity.

6. Conclusion

After completing the modeling and the fragility estimations, the results provided lead the reader to determine that the retrofit was successful. One might say that is only a logical conclusion, and in a way that is correct. When elements of a structure are upgraded, once could only hope that there was a benefit associated with that upgrade. While the CFRP did in fact provide an increase in safety, it did come at a cost. CFRP retrofitting, and retrofitting in general, is often a cost the owner will incur without a real or complete budget. While the cost cannot be ignored, the benefits greatly outweigh the cost, because lives are being saved. Because this building was Risk Category III, the number of human lives within the walls of the building is

high. The owner is faced with an easier decision to spend the money to retrofit when there can be an accurate, statistical depiction of lives being saved as a result of the retrofit. This research was deemed effective and will be continuing. Further, the authors will continually define the model and update the results accordingly. The case-study building will be expanded upon, and similar buildings will be included in the additional research.

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