2018 ASEE Mid-Atlantic Section Spring Conference: Washington, District of Columbia Apr 6

# Seismic Vulnerability Assessment of a Non-Ductile Reinforced Concrete Shear Wall Building

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# Seismic Vulnerability Assessment of a Non-Ductile Reinforced Concrete Shear Wall Building

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## Abstract

This paper presents results of a capstone senior project at California State Polytechnic University, Pomona. Students conducted a vulnerability assessment of a five-story building constructed in Southern California. The structure has non-ductile concrete shear walls at the core and gravity frames at the perimeter. Partial infilled walls exist within the perimeter frames, creating captive columns. Students studied as-built plans for the structure and conducted an assessment of the building based on FEMA-310. They modeled the structure in ETABS and performed an analysis under combined gravity and lateral loads. The students identified the most vulnerable structural elements in the building. They proposed a retrofit scheme to mitigate the risk of collapse due to seismic loading, which includes adding supplemental reinforced concrete shear walls to reduce torsion, shotcreting to increase wall shear capacities, saw-cutting infill walls, and fiber wrapping to increase the shear capacity of vulnerable perimeter columns.

## Keywords

Seismic, Assessment, Concrete, Walls, Columns

## Introduction

Standard undergraduate civil engineering curricula generally focus on the analysis and design of classical problems. Structural engineering design courses usually focus on component design and typically do not address upgrading the condition of existing structures. However, an aging infrastructure demands that practicing engineers have the skills to design economical and effective retrofits. This is evidenced by the American Society of Civil Engineers, ASCE 2017 Infrastructure Report Card[1], which reports America's cumulative infrastructure grade point average at a D+. With this in mind, a capstone senior project was created for a team of six undergraduate students at California State Polytechnic University, Pomona. Students worked on the seismic vulnerability assessment of a five-story non-ductile reinforced concrete building constructed in Southern California. This paper summarizes the assessment strategies considered and reports on their findings and proposed seismic mitigation strategies.

## Building Description

The structure investigated by the students is a five-story school building, built in 1965, that houses several faculty offices, classrooms and laboratories. The rectangular building has plan dimensions of 114 ft. along the east-west direction by 171 ft. along the north-south direction and resides on a sloping ground. The entrance on the south side is at the ground/first floor level, while the entrance on the north side is on the second floor level (see Figure 1). The elevator core is located at the south entrance and houses three elevators. At the south end, the second floor slab creates a breezeway at the ground level between this five-story building and an adjacent two-story building. The height of the first story, which is partially underground, is 12.5 ft., while the height of each of the upper four stories is 13.5 ft. Thus, the total height of the building from the ground level to the main roof is 66.5 ft. In addition, a two-story penthouse with dimensions of approximately 27 ft. by 70 ft. and 26 ft. tall is located above the main roof. The penthouse, which is fabricated of structural steel wide-flange sections and a corrugated metal deck roof, contains an electric supply area, a cooling tower, a fan room and an elevator machine room.

*Figure 1: North elevation of five-story building*

The first floor provides laboratory space and rooms dedicated for examinations. The second through fifth floors combined, provide over 52,000 ft.$^2$ of classroom and office space. The classrooms and offices are situated around the perimeter of the rectangular building. Egress corridors separate the outer rim of classrooms and offices from the inner core, which houses the elevator shaft, stairways, restroom facilities, and miscellaneous offices and conference rooms.

The primary structural system for this building can be described in terms of the gravity-load resisting system and the lateral-load resisting system. The gravity-load resisting system consists of a 5 in. thick concrete slab supported by joists or beams arranged to create one-way action throughout the building, except at the breezeway, where two-way action is prevalent. Floor joists are typically 7.5 in. wide by 24 in. deep. Beams vary in size from 9.5 in. wide by 22 in. deep to 20 in. wide by 30 in. deep, and are supported by columns or load-bearing walls. Columns are square or rectangular and vary in size throughout the building. Typical column dimensions are 12 in. by 16 in. and 20 in. by 20 in. At certain locations in the bottom story, columns are as large as 25 in. by 25 in. Columns and load-bearing walls are supported by pile caps and circular piles at the foundation. The piles have a diameter of 10.75 in. and are approximately 33 ft. deep, penetrating through mostly clayey and medium- to coarse silty sand layers. Approximately 350 piles are used throughout the structure.

The lateral-load resisting system consists of non-ductile reinforced concrete shear walls. In the bottom story, which is partially underground, 12-in.-thick concrete walls are located around the perimeter of the building as well as at the interior. The perimeter walls along the north edge of the building, and partially along the northeast and northwest corners serve as soil-retaining structures.

The walls in this building are considered to be non-ductile because the detailing requirements do not satisfy current ACI 318-14 Code[2] requirements for ductile shear walls. For example, the spacing of the ties is specified as 12 in. in the structural drawings, which is too large for today's standards.

At the east and west elevations, between the perimeter gravity frames, partial infill walls rise three-quarters of the story height to accommodate continuous rows of windows in stories 2 through 5 (See Figure 2). The infill walls reduce the effective height of each column in these stories, resulting in a condition referred to as a captive column. This effect has been seen to promote an undesirable shear-dominated failure in the columns[3-6]. This is attributed to the increased column lateral stiffness, which results in the attraction of higher shear loads. As Guevara and Garcia[3] point out, any captive column designed and built prior to the mid 1970's may be vulnerable in shear, due to the fact that captive column considerations did not appear in the governing design codes until the 1973 Uniform Building Code[7]. Because this building was constructed in 1965, it is concluded that captive column effects will need to be mitigated.

*Figure 2: East elevation of five-story building*

## Methodology

The seismic vulnerability assessment was performed based on FEMA-310[8]. Initially, students conducted a Tier 1 evaluation, also known as the screening phase. Multiple checklists exist in FEMA-310[8] to guide the evaluators through a Tier 1 evaluation. The required checklists for a particular structure depend on the region of seismicity (low, moderate, or high) and on the expected performance level (life-safety or immediate occupancy). For this project, the building is located in a region of high seismicity and the target performance level of life-safety was established. The corresponding checklists for this building are summarized in Table 1. Each checklist has multiple evaluation statements that must be addressed, as shown in Table 1. Thus, a total of 66 evaluation statements had to be considered by the students as part of the Tier 1 evaluation. As part of this evaluation, students conducted a walk-through of the building that included the roof and penthouse.

The evaluation statements under the Basic Structural- and the Supplemental Structural Checklists depend on the building type. The building in this study falls under Type C2, which is reserved for a concrete shear wall building with stiff diaphragms. Accordingly, the evaluation statements treated under the Basic Structural- and the Supplemental Structural Checklists are related to the building system, the lateral force resisting system, the diaphragms and connections. Each evaluation statement in the checklists needs to be marked as compliant, non-compliant, or not applicable. Compliant statements correspond to issues that are acceptable in accordance with FEMA-310[8]. Non-compliant statements identify issues that require further investigation; Tier 2 evaluation procedures are available in FEMA-310[8] for this purpose. Certain statements may not apply to a particular building being evaluated.

*Table 1: Checklists required for a Tier 1 evaluation of the structure treated in the present study*

| Region of Seismicity | Performance Level | Required Checklists | | | |
|---|---|---|---|---|---|
| High | Life-Safety (LS) | Basic Structural (17)[1] | Supplemental Structural (12)[1] | Geologic Site Hazard and Foundation (10)[1] | Basic Nonstructural (27)[1] |

[1]Values shown in parentheses represent the number of evaluation statements addressed within each checklist.

After completing a Tier 1 evaluation, students performed a Tier 2 evaluation to address non-compliant statements. Under a Tier 2 evaluation procedure, students performed detailed hand calculations and created a three-dimensional model of the five-story structure in ETABS, a structural analysis software. They utilized the Linear Static Procedure to analyze the structure under combined gravity- and seismic lateral loads. Hand calculations included estimations of the building's seismic weight, center of mass and center of rigidity for each floor, seismic base shear, and maximum shear stress in walls.

Students relied on as-built structural engineering drawings of the building to create their analysis model in ETABS. Figure 3 shows the analytical model created by the students. Each concrete column was modeled using frame elements that included the correct dimensions, material properties and column reinforcement. Walls were modeled using shell elements with the appropriate thicknesses. Slabs were modeled using shell elements that were assigned rigid diaphragm constraints. The meshing of the slabs allowed the application of heavier live loads (75 psf) at corridors and at stairwells, and lighter loads (50 psf) in other areas, such as classrooms and offices. For simplicity, joists and beams were not explicitly modeled, but their self-weight was incorporated in the model. Elevators were not modeled, but the elevator shaft was accounted for with an opening in the slabs. The captive columns were modeled by shortening the wall elements and allowing for the window openings to be included. The frame elements modeling the captive columns were discretized between floors such that each captive column and the adjacent infill walls shared a common node. The penthouse above the main roof was not modeled, but the weight was accounted for. Lastly, piles were not explicitly modeled, but their restraining effects on columns and walls were modeled by assuming fixed boundary conditions. The model included dead loads, live loads, and seismic loads. A modal analysis was also performed to obtain the fundamental periods of vibration and corresponding mode shapes.

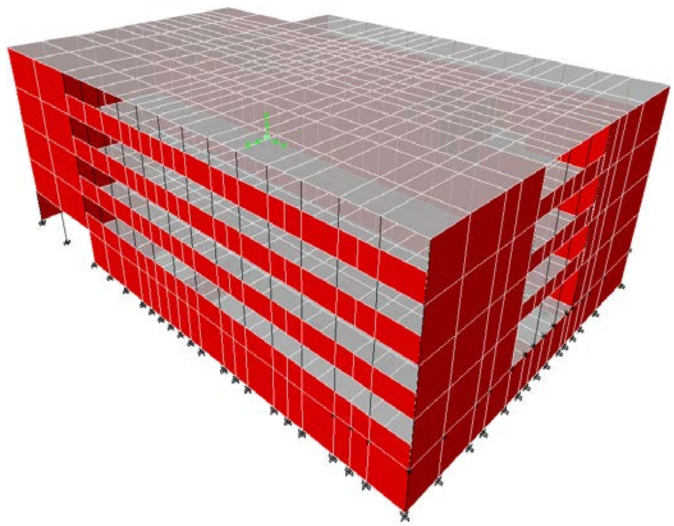

*Figure 3: ETABS structural analysis model of five-story building*

The material properties were either obtained from the construction drawings or estimated based on the date of construction. A concrete compressive strength of 4,000 psi was used, while the reinforcing steel yield strength was assumed to be 40 ksi, based on the year of construction.

**Results and Recommendations**

Of the 66 evaluation statements addressed under the Tier 1 evaluation, 55 evaluation statements were identified as compliant, five were flagged as non-compliant, and six statements were not applicable to this structure. The most significant conditions are discussed here. An issue related to the load path was discovered by the north entrance, where a discontinuous shear wall exists. It is recommended to retrofit the beam supporting this wall by installing a new steel beam, as long as the height clearances are not affected. An alternative consists of utilizing fiber reinforced polymer wrap (i.e., fiber wrap) to strengthen the beam.

It was found that several concrete shear walls in the building exceed allowable stress limits under seismic loads. FEMA-310[8] limits the shear stress to less than 100 psi or $\mathbf{2}\sqrt{\boldsymbol{f'_c}}$. For a concrete strength of 4,000 psi, the second terms yields 126.5 psi. Thus, the 100 psi limit controls. Figure 4 show contours of maximum stress in the east walls under combined gravity- and earthquake loading. It is clear that stresses in several walls exceed the allowable limit. A mitigation strategy would consist of reducing the eccentricity (i.e., the distance between the center of mass and the center of rigidity of the building) and increasing the shear strength of the walls by using shotcrete to thicken them or by utilizing fiber wrap.

Lastly, a significant effect that requires mitigation is the captive column condition which occurs primarily along the east and west faces of the structure. The ETABS model showed that the majority of the captive columns are overstressed, but the most severe columns are located in the north-east and north-west corners of the building. A mitigation strategy involves saw-cutting the infill walls to create a separation between the infill walls and the columns. Furthermore, the columns can be strengthened using fiber wrap.

A modal analysis of the building showed that the fundamental period of vibration is 0.17 seconds, and the fundamental mode of vibration acts in the east-west direction.

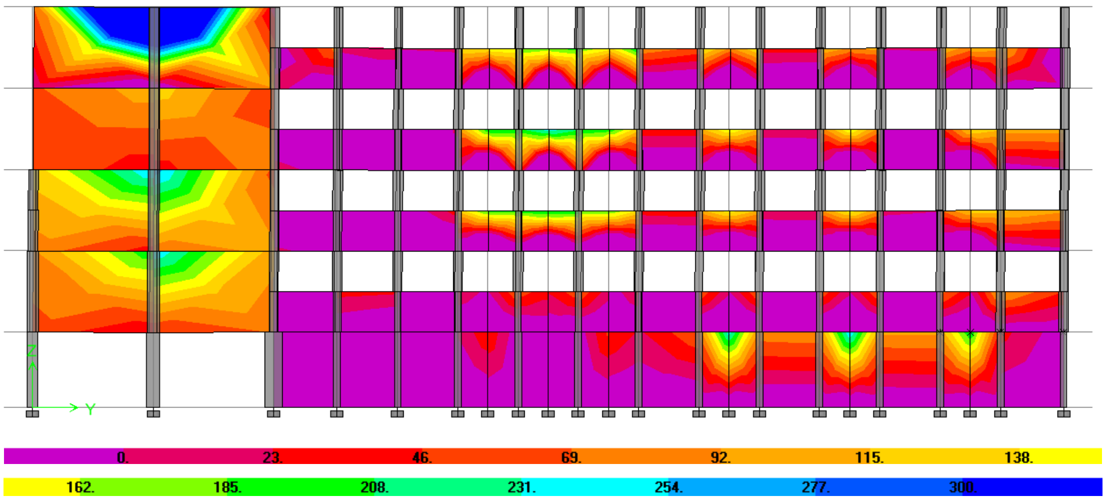


*Figure 4: Stress contours of shear walls along east elevation, obtained from ETABS (psi)*

## Conclusions

A senior project was created for six undergraduate students studying civil engineering at California State Polytechnic University, Pomona. Students conducted a seismic vulnerability assessment of a five-story non-ductile reinforced concrete shear wall building constructed in 1965. The vulnerability assessment was performed in accordance with guidelines set forth in FEMA-310. The guidelines present several checklists identifying numerous structural items that need to be considered. Students conducted a visual inspection of the building as well as detailed Tier 1 and Tier 2 assessments per FEMA-310. As part of the vulnerability assessments, students performed hand calculations and created a three-dimensional model of the structure to perform linear static analysis under combined gravity- and lateral loads. Results showed that the structure has conditions that are not in compliance with FEMA-310 requirements. Issues related to a discontinuous shear wall, excessive shear stresses in shear walls, and captive columns are identified. Strategies are presented to retrofit the structure and mitigate the risk of collapse due to seismic loading. These include introducing supplemental reinforced concrete shear walls to reduce torsion, shotcreting to increase wall shear capacities, saw-cutting infill walls, and fiber wrapping to increase the shear capacity of vulnerable perimeter columns.

## References

1 American Society of Civil Engineers Committee on America's Infrastructure, "2017 Infrastructure Report Card, A Comprehensive Assessment of America's Infrastructure," American Society of Civil Engineers, ASCE, 2017, 110 pp.

2 American Concrete Institute, "Building Code Requirements for Structural Concrete," ACI 318-14, Sept. 2014, 520 pp.

3 Guevara, T.L. and Garcia, L.E., "The Captive- and Short-Column Effects," Earthquake Spectra, Vol. 21, No. 1, Feb. 2005, pp. 141-160.

4 Pradhan, P.M., Maskey, R.K. and Pradhan, P.L., "Stiffness Behavior and Shear Effect in Partially Infilled Reinforced Concrete Frames," Journal of Earthquake Engineering, 2014, Vol. 18(4), pp. 580-588.

5 Thinley, K., “Effect of Partially Infill Wall on the Seismic Behavior of RC Frame Buildings,” Mechanics of Structures and materials: Advancements and Challenges – Proceedings of the 24th Australasian Conference on the Mechanics of Structures and materials, ACMSM24 2016, 2017, pp. 619-626.
6 Jayaguru, C. and Subramanian, K., “Retrofit of RC Frames with Captive-Column Defects,” KSCE Journal of Civil Engineering, Vol. 16, No. 7, Nov. 2012, pp. 1202-1208.
7 International Conference of Building Officials (ICBO), 1973. *Uniform Building Code*, Whittier, CA, 704 pp.
8 FEMA-310, “Handbook for the Seismic Evaluation of Buildings: A Prestandard,” American Society of Civil Engineers (ASCE) and the Federal Emergency Management Agency (FEMA), Department of Homeland Security. 1998, 288 pp. www.fema.gov/media-library/assets/documents/2007.

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Garrett Jones is a senior undergraduate civil engineering student at California State Polytechnic University, Pomona. He works for a land development company called TAIT & Associates, but still has an interest in structural engineering. Mr. Jones wishes to further his education in the areas of land development and/or structural engineering by pursuing an M.S. degree. He also wishes to become professionally licensed as a civil engineer. He intends to pursue LSIT and LS licenses as well. He has aspirations of someday returning to Cal Poly Pomona as an instructor.

**Daniella Ginocchio**

Daniella Ginocchio is a senior undergraduate civil engineering student at California State Polytechnic University, Pomona. She is a member of the American Society of Civil Engineers Student Chapter and has been a member of the Steel Bridge Club for two years. This year she serves as the secretary of the club. Ms. Ginocchio is currently an intern in the land development at KWC Engineers.

**Edwin Medina**

Edwin Medina is a senior undergraduate civil engineering student at California State Polytechnic University, Pomona. He has served as the Technical and Construction Captain for the Steel Bridge Team and has been a member of the American Society of Civil Engineers Student Chapter. Mr. Medina is in the process of completing a 9-month term for the Metropolitan Water District of Southern California under a student co-op program.

**Kevin Chin**

Kevin Chin is a senior undergraduate civil engineering student at California State Polytechnic University, Pomona. He plans to specialize in structural engineering after obtaining the necessary experience and qualifications. Mr. Chin's goal is to be E.I.T certified by the end of the year.