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Seismic Retrofit of Non-Ductile Reinforced Concrete Dual Frame Building using Fiber Composite Jacketing

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Abstract

As a senior capstone project, students worked on the vulnerability assessment and seismic retrofit of a six-story non-ductile reinforced concrete dual system building comprised of perimeter non-ductile reinforced concrete moment frames and non-ductile core shear walls. Students were given the as-built plans and specification of an existing building in Southern California that is considered to be at risk, from an earthquake resistant standpoint. Students performed structural analysis for both gravity and lateral systems using the SAP 2000 program for the as-built condition. Students then evaluated the demand-capacity ratios for each system. From this study, students were able to identify the main structural deficiencies which are concentrated around the exterior frames. The columns of the frames found lacking the required strength to meet the minimum accepted performance during a major earthquake. Students proposed a retrofit scheme to mitigate the risk of collapse due to seismic loading. The most cost-effective retrofit solution for this building consisted of using fiber composite wrap around beams and columns in all the exterior frames.

Keywords

Seismic Retrofit, Non-Ductile Concrete, Fiber Wrap.

Introduction

California's major metropolitan areas are surrounded by multiple active faults and run the risk of major economical setbacks and loss of lives if its aging infrastructure is not upgraded. It is important to point out that the majority of infrastructure and buildings in California were developed in the post-World War II era where the development of modern model building codes and rigorous construction inspection had not yet evolved. This made the majority of the inventory of its infrastructure in general and buildings in particular vulnerable to damages during a significant earthquake. The State policymakers and building officials are aware of this risk, therefore municipalities in major urban areas such as San Francisco and Los Angeles have passed ordinances to mandate seismic retrofit of buildings that it deems vulnerable. These latest ordinances have generated an increased demand for qualified civil engineers who have the proper knowledge and training in earthquake engineering.

As a Polytechnic University, Cal Poly Pomona and the College of Engineering have been widely known for a hands-on approach to learning. The faculty in the Civil Engineering Department with input from the Industry Advisory Board recognized this needs for qualified structural engineers that are equipped with the proper training to tackle this pressing issue. The faculty developed learning opportunities for undergraduate students to learn the essence of seismic assessment and retrofit of buildings. In this study, we are presenting an example of such learning opportunity that took the form of a senior capstone project. In this project, students learned concepts pertaining to earthquake engineering such as performance-based design, risk assessment, and earthquake risk mitigation. All these principles were embedded into a project-based learning experience where students under the supervision of faculty members, who are experienced in the subject matter, evaluated the seismic vulnerability and risk of damage of an existing building that is considered to be a representative of one of the building categories that possess a high risk of damages during a major earthquake. At the end of the project, students developed design drawings and specifications to retrofit this building to reduce the risk of damage to an acceptable level. Students also performed a feasibility study to select the optimum retrofit strategy for this building considering existing constraints of the building site and current use.

Building Description

The project is an office building in Southern California. The building was designed in the late 1960's where most of the current seismic requirements were not yet developed. Many of the office spaces in this building have an ocean view and the building façade contains architectural features that must be preserved. Students had access to the as-built record drawings of the buildings and conducted a one-time site visit. The review of the as build plans and the site visit reveals the following description: the building is six stories tall with an overall footprint of 123 feet in each orthogonal direction and an overall height of about 100 feet.

Figure 1: Overview of building geometry and architectural features of its facade

The structural system for the gravity loads is comprised of four-inch thick one-way cast-in-place reinforced concrete slabs supported on reinforced concrete T- joists. The T-joists have a typical cross-section of 15 inches wide by 32 inches deep. The enhanced concrete T- joists are supported by reinforced concrete girders at the exterior surfaces of the building envelope. The girder size is 21 inches wide by 54 inches deep. The concrete girders are carried by 28-inch diameter reinforced concrete columns that are supported by isolated pad footings; each with a size of six feet by six feet by 18 inches thick.

The lateral resisting system is comprised of cast-in-place reinforced concrete shear walls forming a core that surrounds the staircase and the elevator shaft. The shear wall thickness varies from floor to floor, with an average thickness of 14 inches. The connection details between columns and exterior girders indicate that the exterior circular columns and the perimeters girders are considered to form a moment frame action. The students were able to identify the design parameters from the as-built drawings' general notes sheet and used these values for their analysis. The design concrete strength is 4000 psi, and the yield strength of the reinforcement is 50 ksi.

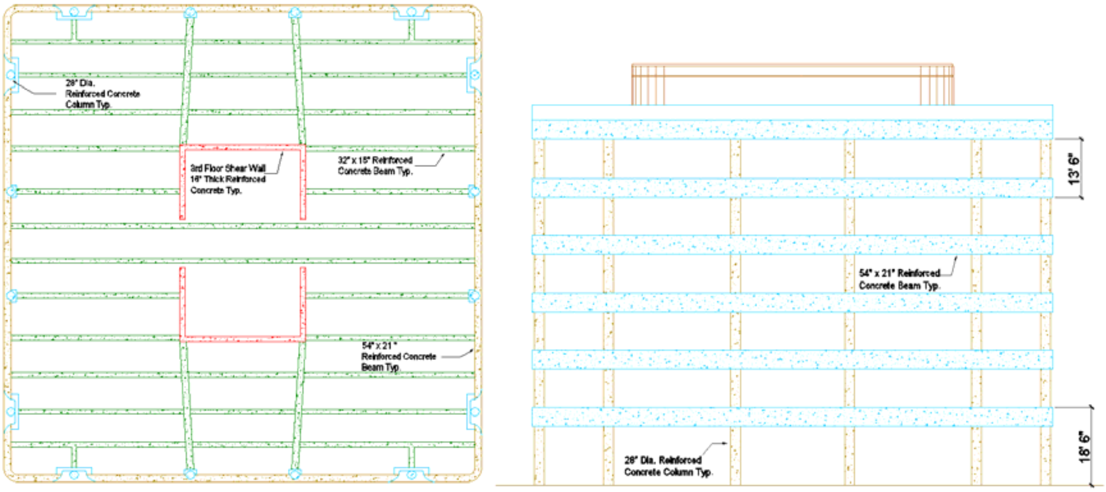

Figure 2: Typical floor framing plan and exterior framing elevation illustrating the main structural systems

Methodology

In this project, FEMA 356 Prestandard and Commentary for Seismic Rehabilitation of Buildings was found to be the appropriate set of guidelines used to assess the condition of this building. The Linear Elastic Procedure was used to calculate the seismic demands on the structures. The students developed a structural model that depicts the primary structural systems using the SAP 2000 program. The base shear was calculated using the acceleration parameters published on the USGS website. The students performed material take-offs to come up with reasonable estimates of the dead loads that will be applied to each floor and the roof. The live load was calculated using the procedure in the ASCE 7-10. The students were able to extract the internal forces acting on each structural element using load combinations provided by FEMA 356. The load combinations represent the effect of gravity load and seismic loads for the most credible earthquake. Demands on the core shear walls, exterior columns and exterior beams of the moment frames were calculated and compared with acceptance criteria set for Life Safety performance level, which is a typical performance objective for an office building. Moment frames are considered deformation-controlled elements because flexural and shear demands in the moment frame sections were governed by deformations; shear walls are considered force-controlled elements because shear demands in the walls were governed by loads. The demand-capacity ratio was evaluated for each column, beam and shear wall segment of the building. If the numerical value of the demand-capacity ratio for any particular member exceeded unity, it indicated that this particular member will not meet the objective performance and will require strengthening or retrofitting. After strengthening the members, the analysis was carried out again using a new structural model and the demand capacity ratios were once again evaluated. When all member demands capacity ratios were less than unity, that indicated the retrofit strategy succeeded in achieving the desired performance of this building.

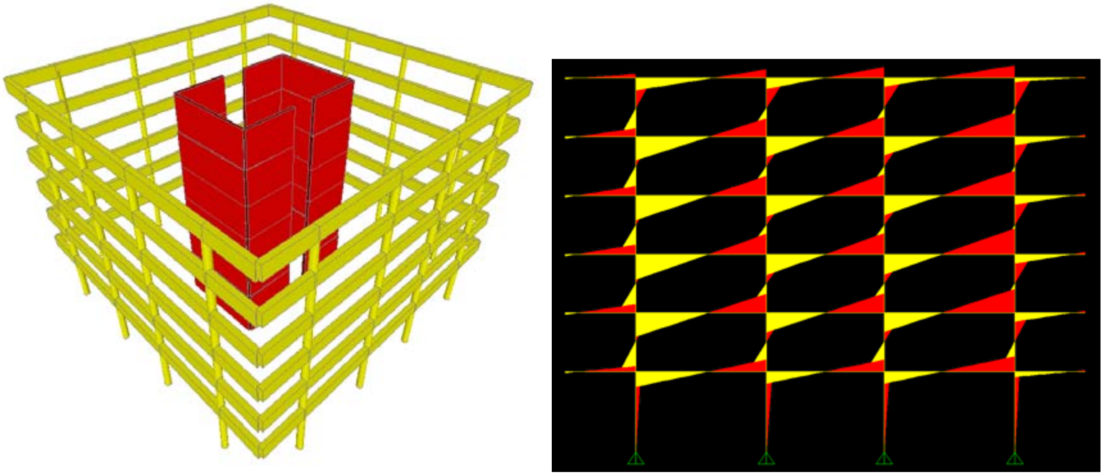

Figure 3: Structural model of the frames and shear walls using SAP2000 program and bending moment diagram in a typical frame due to seismic loads

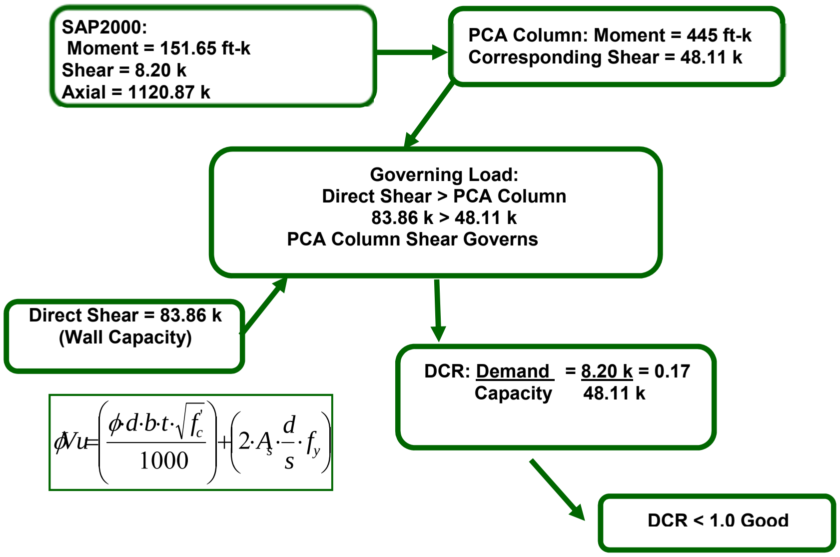

Figure 5: Typical calculation cycle for one of the structural members that is part of the lateral system

Findings

The structural analysis followed by the demand capacity ratio calculations revealed that the core shear walls have sufficient strength to meet the performance objective. On the other hand, the demand capacity ratios for the exterior shear walls indicated that the girders and columns do not have the sufficient strength to meet the desired performance objectives. It was also found that the girders are much stronger than the supporting columns, being driven by the architectural needs of deep beams to blend in with the style of the exterior glazing. It should be pointed out that FEMA 356 does not address the requirement of a strong-column-weak-beam condition; however, most model codes require this condition to be satisfied for moment frames. Having a stronger beam than the column in a building structure can lead to a situation where plastic hinges may form in the columns when the system is overloaded in a major earthquake. This can result in an unstable collapse mechanism in the exterior frames, which can cause substantial damage to the building.

Retrofit Strategies

Students explored two different approaches to address the deficiencies found in the moment frames. The first approach was based on the concept of reducing the seismic demands on the building to a level where the frames can resist the demands with its existing strength. This would have been achieved by adding viscoelastic dampers along the middle bay of each frame. The viscoelastic damper concept, if it were adopted, would reduce the seismic demands by reducing the base shear to the point where the demands in the moment frames would be within the existing strength. This retrofit strategy was faced with several challenges: the structure was found to be relatively stiff, and there was not enough displacement along the damper nodes to substantially reduce the seismic base shear to the level that would be required for the existing concrete frames to sustain the seismic demands. Adding the viscoelastic dampers would require the installation of steel braced frames along one of the frame bays, which would significantly alter the architecture appearance of the façade. Altering the appearance of the facade would not be allowed by the local planning department.

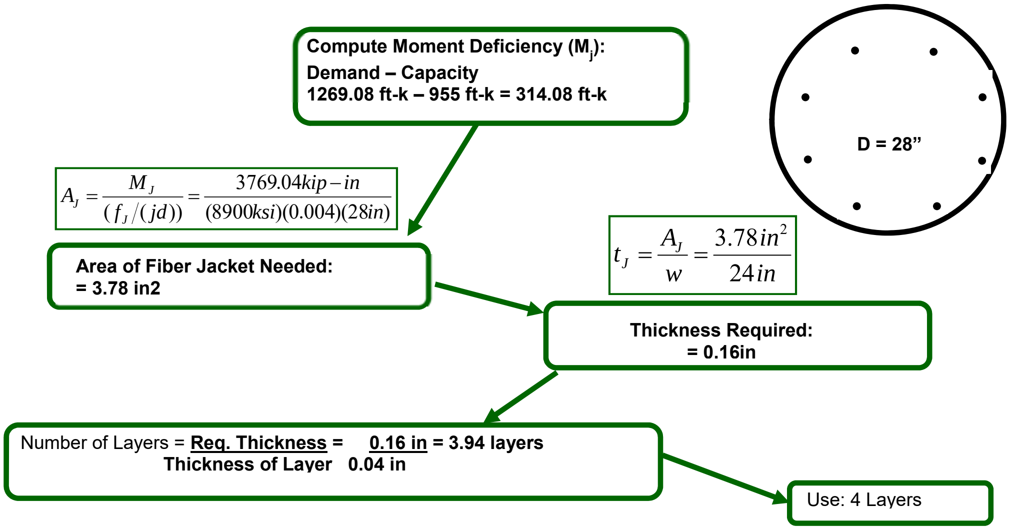

Figure 6: Typical calculation cycle for the FRP of one of the frame columns

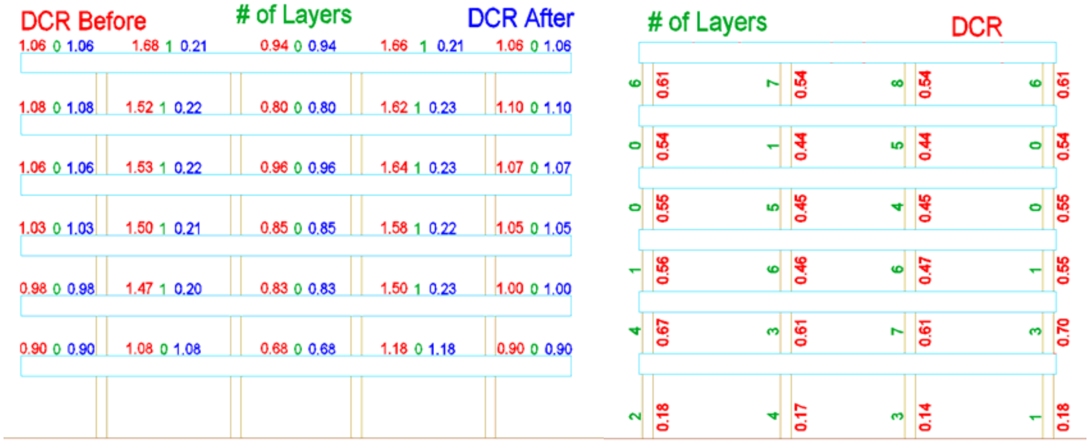

Figure 7: Demand-capacity ratio for one of the exterior frames

The second retrofit scheme, which was adopted in this project, utilizes fiberglass composite wrap (FRP) to increase the beam flexural strength and to increase the flexural capacity of the columns to a limit where strong-column-weak-beam conditions can be met. The FRP retrofit scheme has the advantage of not impacting the exterior façade appearance as it takes the same shape of the existing concrete girders and columns. The cost of installing the FRP per square foot of the building space was substantially less than the cost of installing the viscoelastic dampers and did not require adding any new foundations which would have been required for the viscoelastic damper frames. The installation of the FRP is relatively simple, and work can be done without major interruption to the normal business operation of the tenants who occupy the building. The FRP was found to be the most feasible retrofit strategy for this particular building.

Conclusions

In this project, students had the opportunity to apply knowledge they previously acquired in courses such as reinforced concrete design, earthquake engineering and structural analysis to tackle the advanced topic of assessing the condition of an existing building. Students had the opportunity to research the fiber composite wrapping of reinforced concrete members. This project also exposed students to the advanced study of supplemental damping devices and their performance characteristics. Students learned the fundamentals of performance-based design. This exposure was offered in an active learning environment where students would conduct their own research while being coached by the faculty advisors. The project offered an opportunity for students to explore earthquake engineering. One student was encouraged by this project and decided to pursue post-graduate studies in this field.

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