Seismic Retrofit with Fiber Reinforced Polymers

Using ASCE-41 to Retrofit a Multi-Story Concrete Building

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Aging infrastructure and stricter seismic design guidelines cause many structures to need seismic upgrading. This is especially true in the Pacific Northwest, where the Puget Sound area is prone to large magnitude subduction zone earthquakes. Most recently, the 2001 Nisqually Earthquake, one of the largest earthquakes in Washington's recent history, caused over $2 billion in damage and resulted in hundreds of injuries. The tremors could be felt as far away as Spokane in the eastern part of the state.

While seismic retrofits provide a significant reduction in life-safety and financial risks, most upgrades are only undertaken when they are mandated by jurisdictional or investor/lender requirements. Significant renovations or building improvements, building alterations, unsafe building ordinances, or requirements by financial institutions are the most common triggers. Older buildings may go through a number of seismic upgrades during their lifespans. One recent project was the seismic retrofit of the Sunset House in downtown Seattle, the subject of this article, where Fiber Reinforced Polymers (FRP) were successfully employed.

Fiber Reinforced Polymers

Fiber Reinforced Polymers are well recognized as an effective seismic retrofit material for existing concrete buildings. This segment of the strengthening industry is more than twenty years old and several successful projects have been installed. Some of these retrofitted buildings have experienced significant earthquakes and performed as designed, demonstrating the effectiveness of the technology. Extensive laboratory testing and actual earthquakes have led to the development of reliable design methodologies and guidelines for FRP to be used by the engineering community.

There are many methods available for the seismic retrofit of buildings including section enlargement with concrete and/or steel, adding more members such as new shear walls, beams or columns, base isolation or braced frames. While these methods are very effective at improving the building performance, they may result in lost space, long shutdown times during construction or cause a large impact on day-to-day operations of an occupied building. For more than twenty years in the United States, FRP has been used as an alternate method of structural reinforcing for existing buildings and has gained acceptance as a structural repair method throughout the world.

FRP materials consist of high strength fibers in a polymer matrix. The fibers provide the strength and stiffness, and the matrix provides load transfer and environmental protection to the fibers. The most commonly used fibers are glass and carbon. FRP design is based on the composite properties of both of these materials when combined. Design professionals can ensure they specify well tested products by requiring the materials to have an ICC Listing. ICC AC 125, *Acceptance Criteria for Concrete and Reinforced and Unreinforced Masonry Strengthening Using Externally Bonded Fiber-Reinforced Polymer (FRP) Composite Systems*, has a comprehensive test program that includes environmental durability to ensure materials can be consistently designed and perform as expected. The American Concrete Institute (ACI) has also published material specification for FRP, ACI 440.8R-13, *Specification for Carbon and Glass Fiber-reinforced Polymer (FRP) Materials Made by Wet Layup for External Strengthening of Concrete and Masonry Structures*. This is the first code document in the United States for externally bonded wet layup FRP materials.

FRP materials have high strength-to-weight ratios, which make them an ideal material for seismic retrofit. They do not add significant mass to a structure, while they can be designed to add ductility, confinement, moment or shear capacity to existing structural members. This allows for local strengthening without concerns of transferring the added weight to the foundation. FRP can also be designed to add strength without changing the stiffness, minimizing the extent of additional analysis of the structure after strengthening. FRP materials add minimal depth to the structure, with an average application less than ¼-inch thick.

FRP materials are designed as tension members that work in conjunction with the existing member. Currently, there are several design codes and recommendations for these materials throughout the world. In the United States, ACI 440.2R-08, *Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Concrete Structures*, provides a widely used design guideline for the materials. It was first published in 2002 and republished in 2008. However, this document currently does not cover seismic retrofit design.

Seismic Retrofit Design Standards

At the time the Sunset House building project was undertaken, the *International Existing Building Code* (IEBC) had not been formally adopted as a standard in Seattle and the primary standards were ASCE 31-03 (evaluation) and ASCE 41-06 (retrofit). Seattle has now adopted the IEBC with local amendments and ASCE 41-13 now incorporates the previous two documents (ASCE 31-03 and ASCE 41-06) into one document.

The IEBC currently allows for two approaches to analyzing and strengthening existing buildings. The first is to review the structural system relative to the current *International Building Code* (IBC) with a reduction in force and detailing requirements in recognition of the strength of the original structures and the shorter expected remaining life-spans. Alternatively, the second method permitted in the IEBC is ASCE 41-13, *Seismic Rehabilitation of Existing Buildings*.

In the past, engineers were confronted with a discrepancy between the force levels derived from the two approaches. The two approaches handle the material and structural behavior quite differently, making the IBC loads appear to be significantly less than the ASCE 41 loads. Generally, the structural solutions will be similar to the ASCE 41 approach, providing a more detailed approach for existing buildings. The ASCE 41 approach provides performance objectives based on the desired performance of the building. The *Basic Performance Objective for Existing Buildings* (BPOE) is intended to provide requirements for existing buildings that produce performance equivalent to the reduced IBC loads approach.

Currently, ASCE 41-13 does not address FRP as a material used as part of a seismic system, i.e. the *deformation-controlled* elements with m-factor force reductions, so some judgement and a solid understanding of the design approach used to produce the loads is required until FRP is included in future editions. FRP can currently be used as a *force-controlled* element based on the maximum load it will be subjected to.

Figure 1. Limited work area for installation of FRP for tension loads.

Structural Evaluation of Sunset House using ASCE 41

The Sunset House building is a ten-story, 1970s era residential structure built with precast concrete plank floors and a combination of reinforced concrete and masonry shear walls (*Figure 1*). The seismic evaluation was required as part of a major rehabilitation of the building. This evaluation was performed using ASCE 41-06, *Seismic Retrofit of Existing Buildings*. A Tier 1 checklist, a Tier 2 evaluation and a Tier 3 linear dynamic analysis were used to identify and mitigate the seismic issues in the building.

ASCE 41 provides significant performance-based guidance to designers in evaluating and upgrading existing buildings, incorporating damage observations from past seismic events and laboratory testing. The seismic performance objectives can be customized depending on the occupancy, owner objectives, type of building, etc.

The retrofit of the Sunset House was performed to meet a *Life-Safety Performance Objective* with identified deficiencies in the tensile capacity of boundary details in some of the shear walls and in the shear capacity at some of the link beams in the corridor walls. While these deficiencies were fairly isolated, potential impact to the performance of the structure would have likely been significant.

Design of FRP for Sunset House

The location of the deficient structural elements relative to the corridors and living spaces significantly limited the size of the solutions used for the strengthening. After exploring a variety of potential strengthening methods, FRP was selected based on cost effectiveness, as well as the minimal architectural impact to the living spaces. FRP not only provided minimum impact to the space, but also provided the required strength without a significant increase in stiffness (an increase in stiffness on this project would have affected the distribution of lateral loads and would have likely required strengthening of additional elements). Other options, such as adding steel and concrete to the walls, were not feasible due to the space constraints.

The FRP was designed for the two major components of the retrofit design, adding shear and overturning capacity to walls and increasing the shear capacity of the coupling beams over several of the doorways. Increasing the overturning capacity of the shear walls required increasing the tensile capacity at the wall boundary connections. This was provided by adding bonded layers of carbon and glass fibers to connect the walls between the floor levels. Shear capacities at the walls were similarly strengthened with bonded glass fiber sheets applied to connect the top and bottoms of the walls to the floor slabs. Coupling beams' capacities were increased by bonding FRP to the faces of the wall. The FRP was extended beyond the ends of the coupling beams to develop the strength of the fibers.

The seismic system m-factors used in ASCE 41 to represent the expected ductility are not specified for systems including FRP, such as shear walls. However, the design team felt that FRP was a good option. Design coordination among the project team allowed the FRP to be utilized and provided the best retrofit option for the building.

As ACI 440.2R does not have a seismic section, the design equations for wall shear from ICC AC 125 were the basis of FRP design for the shear walls. The shear wall boundary elements and coupling beams were design based on appropriate design strains developed from expected movement in the walls and the composite behavior with the FRP. Reduction factors were chosen by looking at the development of the design loads and commonly used FRP reduction factors.

Figure 2. Existing slab is cut back to allow the FRP to be installed continuously from floor to floor.

Installation

The Sunset House was an occupied facility during the installation of the FRP strengthening. This created construction challenges for both scheduling and coordination among the occupants. Installation was phased with access to only certain floors and work areas at a given time. The corridors were narrow and access to each living unit needed to be maintained during construction (*Figure 2*).

Work began with protection of the work area and removal of the existing wall finishes. One sided wall applications of FRP are bond critical in that all the force of the FRP is transferred through the bond into the substrate. For bond critical applications, the surface preparation is the most important step in the installation process. It is necessary to control and capture the dust created by the mechanical abrasion of the concrete surface. The use of HEPA vacuums and negative air machines were used, enabling this process to proceed without the release of dust into the public areas, reducing the impact on the occupants.

Following surface preparation, the concrete surface is primed with a system compatible epoxy. As the facility was occupied, a primer epoxy was used that had no volatiles and no toxic odors. Additionally, negative air machines were used as ventilators to keep fresh air movement within the working areas.

Following the priming of the surface, the FRP fabrics are saturated with the epoxy matrix and placed onto the prepared wall surface.

The retrofit design included vertical fibers that needed to run continuously from upper floors down to the foundation to ensure load path continuity. While there are options to use steel plates or fiber anchors for transferring the forces through the slab, the design was detailed to cut back the slab and allow access for the fiber to be continuously installed on the wall and floor (*Figure 3*). While removing small sections of the slab, the existing rebar remained in place. Once the fiber was installed, the concrete was replaced and the connection between the wall and slab was not damaged. This avoided any steel plates in the corridor and other connection details that have a more significant profile.

The final installation of the FRP system was less than ½-inch thick and maintained the required width of the egress routes. The facility remained occupied and the work was completed on time. The FRP strengthening significantly increases the ductility of the critical connections, as the shear walls and coupling beams and resulting building performance is expected to be significantly better than it's previous as-built condition.

Future Developments for FRP

The Sunset House demonstrates how ASCE 41 and FRP can be effectively used in conjunction for seismic retrofit design. Moving ahead, the ACI 440 committee is working to incorporate a seismic design chapter into the ACI 440.2R document. This chapter will reference ASCE 41, providing more guidance to the design engineer on using FRP to retrofit structures. In addition, the industry needs to look at developing appropriate m-factors for these strengthened members.▪

Figure 3. Exterior view of Sunset House.