



SEISMIC STRENGTHENING OF HARBORVIEW MEDICAL CENTER USING FRP REINFORCEMENT

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ABSTRACT

The North Wing at Harborview Medical Center in Seattle, Washington, houses portions of the Emergency Department and non-ambulatory nursing floors for the Pacific Northwest region's Level 1 Trauma Center. Originally constructed in the early 1970s, the cast-in-place concrete building structure does not meet current seismic design standards for Essential Facilities. Due to the facility's 24/7 occupancy and operations, the seismic upgrade solution requires minimal impact and interruption during construction. The use of Fiber Reinforced Polymers (FRP) for structural reinforcement is proposed to provide additional capacity to specific deficient elements. The lateral force-resisting system for the North Wing consists of concrete shear walls around the elevator and stair core and an exterior concrete frame/punched shear wall. The FRP reinforcement is designed to current standards where applicable and available. For strengthening structural elements that are not effectively covered by current standards, the application of FRP reinforcement has been designed based on results of a testing program utilizing scaled replicas of critical elements. The testing program includes the unique application of FRP to only one side of the spandrel beams, which are critical building elements. The placement of FRP on only one side was tested to replicate the application of the material to the outside of the building. The results of the test program were used to represent element behavior in a nonlinear, three-dimensional analysis. The design results in a building that will have the ability to respond in a predictable manner to seismic forces and will remain safe to occupy following the design-level seismic event. Furthermore, FRP reinforcement is very economical and can be applied with minimal interruption to building operations.

Introduction

Seattle's Harborview Medical Center is a critical community resource and the only regional Level 1 trauma center in a five-state area. To retain that status, the Harborview Bond Program calls for a seismic upgrade of the hospital's North Wing, which was designed in 1973.

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The North Wing houses critical emergency services and will serve as a vital physical link between the existing West Hospital and the new Inpatient Expansion Building. The performance of the North Wing in an earthquake therefore has to be consistent with the performance of newer construction, requiring an upgrade to current seismic performance for Essential Facilities.

When engineers at Magnusson Klemencic Associates (MKA) began the structural design for the seismic upgrade, the following goals were established:

- The building shall allow for "Immediate Occupancy" following a design-level earthquake (with Immediate Occupancy being defined as minimal post-earthquake damage and disruption, with some repairs and cleanup performed while the building remains occupied and safe).
- The seismic upgrade must be accomplished without closing off major portions of the building.
- Disruption to the critical functions within the building must be minimized during construction.
- An economical design solution—within the current bond budget—must be provided.

Seismically upgrading a full-to-capacity trauma center while it remains completely operational presented a significant challenge.

The earthquake-resisting system in the North Wing consists of concrete shear walls around the elevator core and perimeter concrete walls. The perimeter walls have 14-inch-thick vertical piers between the windows and 6-1/2-inch-thick concrete panels stacked on top of the windows, spanning between the vertical piers. Fig. 1 shows a typical framing plan for the North Wing. A computer analysis of the North Wing revealed that the building is very stiff but the thin concrete panels are at risk of cracking, yielding, and losing strength during an earthquake.

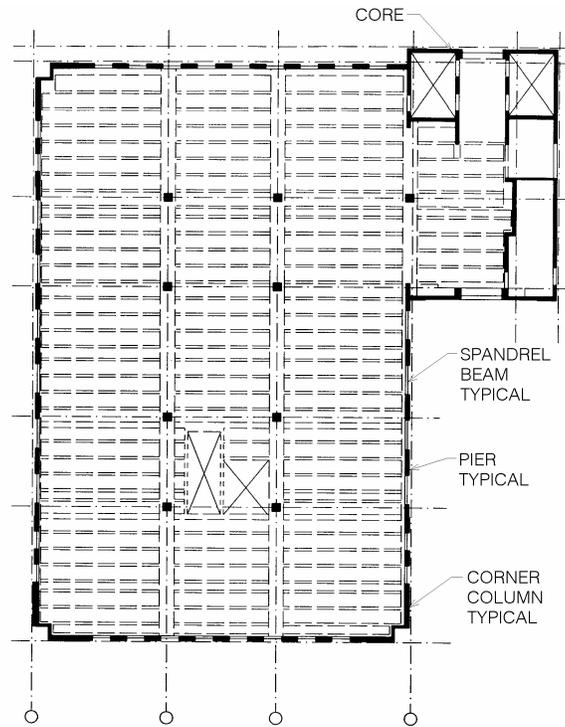


Figure 1. North Wing framing plan.

A traditional upgrade approach would be to add new structural elements for necessary seismic resistance. However, since the North Wing is already very stiff, the new structural elements would have to be even stiffer than the existing elements, or the existing perimeter wall would need to fail for the new elements to become effective. In addition, new structural elements, with associated foundations, would be prohibitively expensive and very disruptive to building occupants.

Retrofit Solution

After considering several approaches, MKA determined that the application of Fiber-Reinforced Polymer (FRP) directly to the surface of the existing concrete presented many advantages. FRP is a high-strength glass or carbon fiber fabric that is adhered to a concrete surface with an epoxy binder. FRP is becoming increasingly common in repairing and reinforcing existing concrete elements.

FRP appeared to be a very attractive method of reinforcing the concrete panels above and below the windows of the North Wing because it could be applied to the exterior of the building with minimal disruption to occupants. In addition, the FRP would provide reinforcing to existing elements without changing the building's overall seismic behavior. It would be important, however, to monitor the concrete panels as they were reinforced with FRP so that they did not become too strong and force cracking or yielding in the vertical piers. The goal was to increase the ability of the concrete panels to maintain their strength even if the concrete cracked and the reinforcing steel began to yield.

A computer analysis was performed to simulate the seismic performance of the North Wing with an FRP upgrade. The computer modeling requires that the properties of the building elements with the new reinforcement be defined and quantified with the development of cracking and yielding in order to evaluate the overall performance of the building. However, current design guidelines for FRP reinforcing, developed by the American Concrete Institute (ACI, 2002), address strength requirements but not post-cracking or yielding performance. While FRP reinforcing appeared to have many advantages, it was necessary to verify and quantify the post-cracking and yielding performance.

FRP Testing

Mock-up concrete panels were constructed and tested at the University of Washington's (UW's) Civil Engineering Department. The panels were tested first in an as-built condition and then with FRP applied in various configurations to determine the optimum reinforcement.

Due to a difference in aspect ratios between the two most representative spandrel beam types, it was decided that both sizes should be tested to fully understand the building's seismic performance. A total of five Type EW (located on the east and west building faces) beam specimens and three Type NS (north-south) beam specimens were constructed and tested at 3/4-scale. All testing material quantities (i.e., concrete, steel, and FRP) were scaled accordingly.

To simplify the testing apparatus and utilize the UW's laboratory capabilities, the spandrel beam specimens were rotated 90 degrees and tested upright. Loading from the ram was transferred through a steel "gooseneck" into the specimen's top pier. The bottom pier was anchored into the lab floor for stability and resistance. (Refer to Fig. 2.) This orientation simulates pier deformation and spandrel beam rotation under seismic loading.

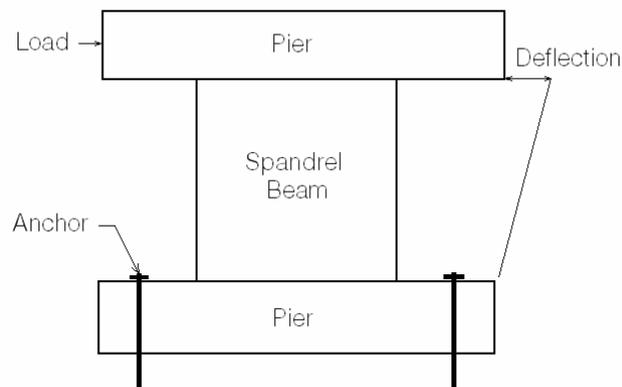


Figure 2. Test configuration.

An increase in spandrel deformation capacity, rather than an increase in strength capacity, is the desired test outcome. Therefore, the test regime used on the specimens was based on deformation rather than force targets. A recommended loading sequence from the Federal

Emergency Management Agency's *Prestandard and Commentary for the Seismic Rehabilitation of Buildings* (FEMA 356) was used as the loading protocol (ASCE, 2000). Each applied load step represents a specific spandrel rotation. Loads were applied in both the positive and negative directions to a target displacement and then were cycled two or three times before increasing the target displacement for the next load step. Specimens were loaded to failure to better understand the failure mechanism of each spandrel beam with its corresponding FRP configuration.

Initial tests applied a sheet of FRP over the entire surface of the concrete panel. The FRP bonded well to the surface of the concrete, but once the concrete panel began to crack, the surface fractured off, taking the FRP sheet with it. Once the concrete surface and FRP sheet began to pull away, the entire sheet would pull off suddenly like a zipper. While the FRP reinforcement did increase strength, the sudden failure mode was undesirable.

The second round of tests replaced the full sheet of FRP with individual strips separated by bare concrete. Speculation was that the separation between strips would stop the zipper effect. In these tests, each strip of FRP behaved independently, but once a strip began to pull away from the body of the panel, the entire strip would lose effectiveness. The strips provided better post-cracking and yielding performance, but not yet as desired.

The next round of tests added FRP anchors, which provided a shear connection between the FRP strips and the body of the panel. With the addition of the anchors, the tendency of the FRP to pull away from the surface of the panel was limited to the length of strip between the anchors. By varying the location of the anchors, MKA engineers were able to tune the performance of the FRP reinforcement. (Refer to Fig. 3.)

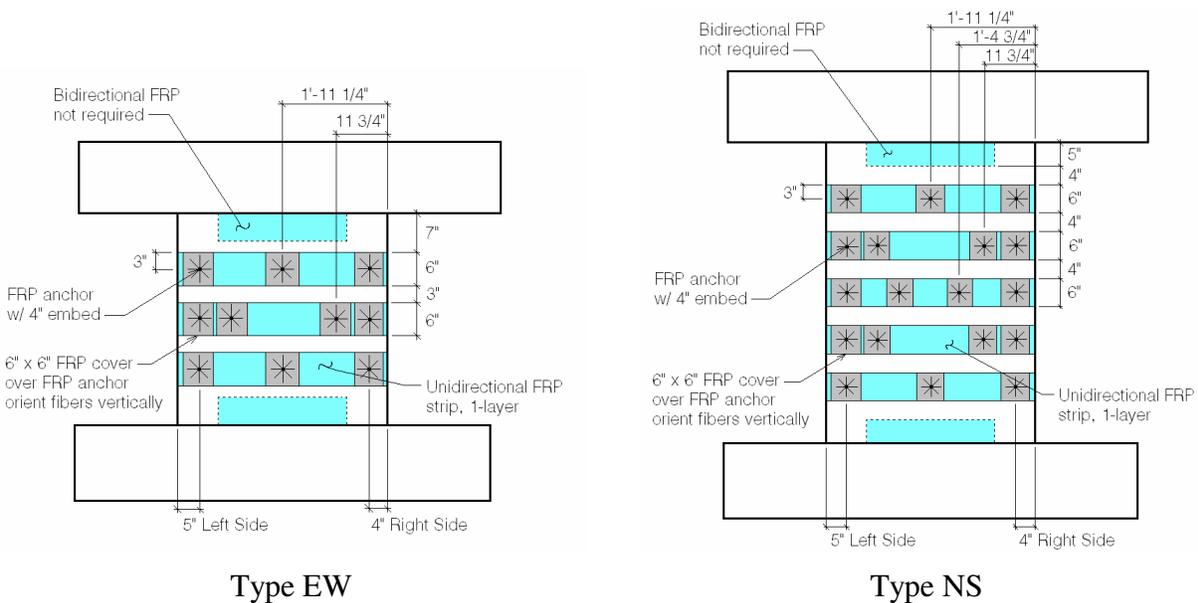


Figure 3. Final FRP configurations.

Testing of the specimens enabled refinement of the FRP configuration from two layers of solid FRP sheets wrapped around the edges to one layer of individual strips with FRP anchors. The bidirectional FRP was found to be unnecessary, which greatly improves the architect's flexibility on finish and decreases costs. The architectural finish is also improved by not wrapping the unidirectional FRP around the edges but rather anchoring the FRP strips with FRP anchors. The final layout demonstrated ductility through good crack distribution in both the positive and negative directions without a significant amount of increase in strength capacity. The overall deformation capacity of the retrofitted spandrel beams was therefore increased.

Fig. 4 shows the increased deformation performance of the retrofitted Type NS spandrel beam in comparison to the existing condition. The "X" indicates the maximum usable displacement. These hysteresis loops were used to extrapolate backbone curves for the building performance analysis.

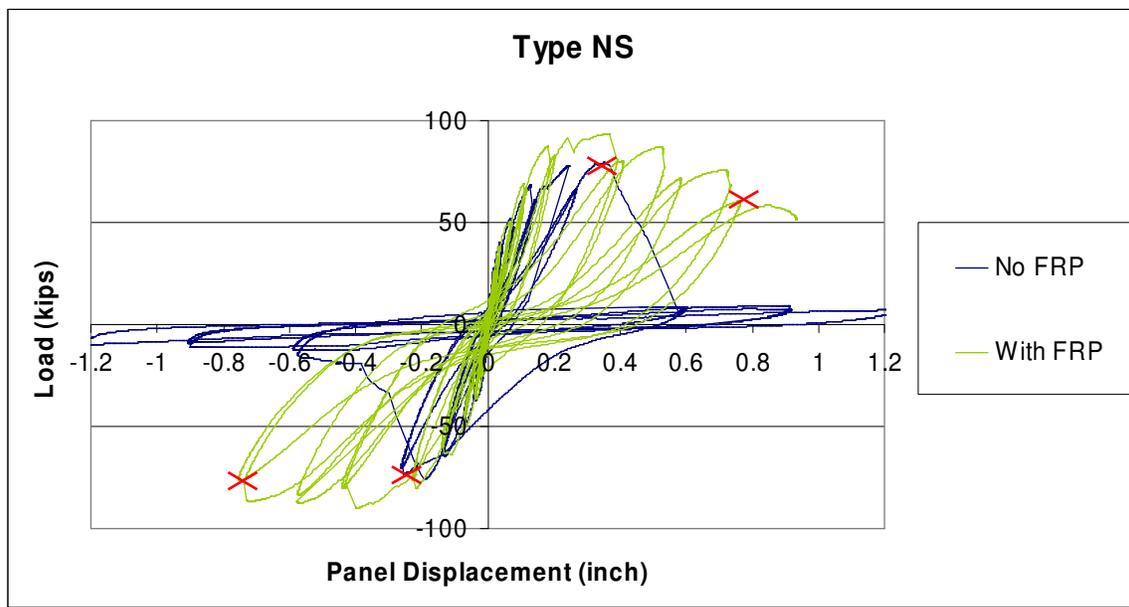


Figure 4. Type NS deformation performance – existing versus retrofitted.

Computer Model

Once the material properties of the FRP-reinforced concrete panels were determined, the final step was to apply the properties to the computer model to verify performance and post-earthquake stability. The computer analysis demonstrated that following the cracking and yielding in the structure, the existing (non-FRP-reinforced) structure lost strength, which could lead to progressive failure of the building. However, with the application of FRP reinforcement, the structure was able to maintain its capacity to carry earthquake forces well after the onset of cracking and yielding—which is essential for an Immediate Occupancy structure.

The computer program RamPerform-3D was used to analyze the inelastic behavior of the reinforced North Wing structure. Target displacements are determined in accordance with FEMA 356 utilizing building stiffness and associated periods from the reinforced structure. The target displacements are determined for both the Design Basis Earthquake (DBE) and the Maximum Considered Earthquake (MCE) seismic events in both the north-south and east-west directions. The building frames are then analyzed as they are deflected incrementally until the target displacements are met. At each increment of displacement, the stiffness of all of the inelastic elements is determined to reevaluate the building properties for the application of the next increment of load. Through this incremental application of seismic displacements, the first occurrence of structural yielding can be identified. Then, as subsequent increments are added, the progression and extent of yielding can be observed. Documenting the progression of yielding in the structure with the application of increasing seismic loads provides a very good understanding of the condition of the building structure at target displacements for the DBE and MCE events.

Based upon the behavior of the reinforced spandrel panels, some damage is anticipated in the panels. The degree of damage and potential repair procedures will depend upon the location of the spandrel panel in the building and the intensity of the earthquake.

As a point of reference for evaluating the beneficial contribution from the FRP reinforcement, first consider the building performance after all other reinforcements have been applied except for FRP on the spandrel panels. Fig. 5 shows the resulting spandrel panel conditions for the DBE event. The panels marked as "less than A" will require a level of repair from no repairs to minor epoxy injection. The panels marked as "A" will require minor to moderate levels of epoxy injection. The panels marked as "B" will require extensive epoxy injection, and the panels marked as "C" will require rebuilding-in-place following the DBE event. In addition, Fig. 5 shows the pushover force-deflection curve for the same frame in the unreinforced spandrel condition. The negative slope of the pushover curve after initial yielding indicates that the building is losing strength faster than it is losing stiffness. This is an unsafe condition and can lead to progressive collapse from subsequent seismic events (aftershocks).

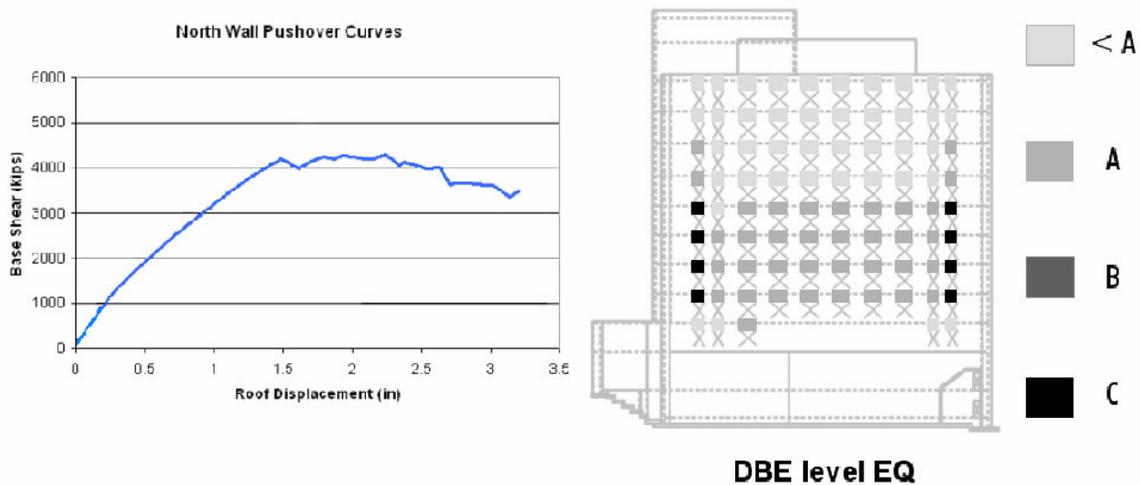


Figure 5. Unreinforced north wall pushover curve and north elevation.

Fig. 6 shows the same frame after FRP has been applied to the spandrel panels with the corresponding force-deflection curve. The shading of the spandrels illustrates the level of cracking that is anticipated following the DBE seismic event. The positive slope of the curve within the range of the DBE and MCE events indicates that the building remains structurally stable and capable of resisting additional seismic forces from subsequent seismic events (aftershocks). Therefore, the building remains safe to occupy following the DBE event.

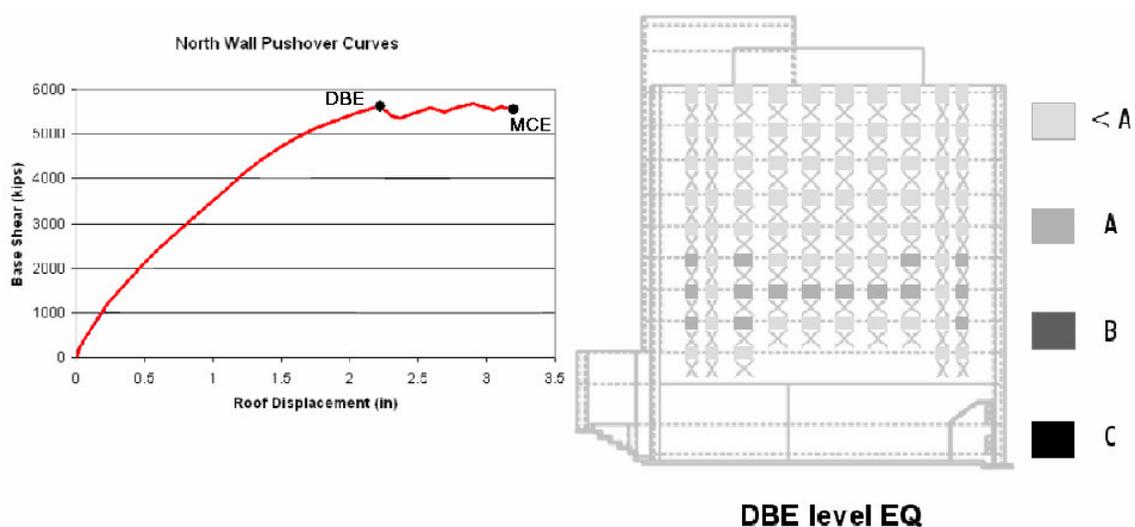


Figure 6. Reinforced north wall pushover curve and north elevation.

Conclusions

The Harborview Medical Center North Wing seismic upgrade will meet Immediate Occupancy performance standards for the DBE seismic event with the strategic application of FRP and structural steel reinforcements.

A material testing program verified the contribution of FRP reinforcement toward improved inelastic behavior and provides reliable performance properties for the hybrid elements. An inelastic analysis of the structure before and after the application of the reinforcements demonstrates the potential instability of the existing structure versus the stability and reserve capacity of the reinforced structure. The proposed reinforcements satisfy the following stated goals:

- Satisfy Immediate Occupancy performance for the DBE seismic event, demonstrated by inelastic analysis.
- Maintain nearly full operations within the building during construction. FRP is applied mostly to the exterior of the building, which minimizes interruptions on the interior floors.

- Minimize construction noise and activities that may be disruptive to patients and staff. Procedures have been tested and specified to minimize construction noise inside the building.
- Provide a cost-effective design. The combined FRP and structural steel reinforcements are substantially less expensive than the much more intrusive concept of adding new structural elements into the building to carry the seismic forces.

The design of the seismic reinforcements for the North Wing, incorporating project-specific material testing in concert with inelastic analysis of building performance, will result in a building that will meet the stated criteria in a reliable and predictable fashion.

References

American Concrete Institute, 2002. *Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Concrete Structures* (ACI 440.2R-02), Farmington Hill, MI.

American Society of Civil Engineers (ASCE), 2000. *Prestandard and Commentary for the Seismic Rehabilitation of Buildings* (FEMA 356), Reston, VA.