Advantages of Incorporating Fiber Reinforced Polymers into the Earthquake Safety Program for the Bay Area Rapid Transit (BART)

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ABSTRACT

The Bay Area Rapid Transit (BART) system is a rail transit system in the San Francisco Bay Area that is located within close proximity to more than five active fault lines. For this reason, the BART Earthquake Safety Program was established in the early 2000's to protect the vital infrastructure through seismic retrofit. With two goals in mind - improving life safety during a seismic event and restoring operability shortly thereafter, it included addressing the vulnerability of many of the aerial and station structures built in the 1970's – BART began looking for cost-effective seismic retrofit options for these structures.

With BART's proactive approach to seismic retrofit, fiber-reinforced polymers (FRP) were soon considered as an alternate to conventional repair schemes such as steel jacketing and reinforced concrete built-out sections. The lightweight and high strength composite materials served as one potential repair option that could be quickly installed while having minimal impact on the public. Working with industry leaders, BART engineers developed a strict performance based specification for FRP systems that focused on designing the FRP's for a structural requirement. The specification also ensured the use of tested and proven materials, experienced and trained personnel performing the installations and consistent field quality control measures. This paper will examine the utilization of FRP's in seismic retrofit as a means of reducing the impact to the public, minimizing the aesthetic impact on the structure and increasing life safety, while minimizing the overall cost and construction time for the owner.

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Overview of BART

The Bay Area Rapid Transit (BART) network carries passenger traffic over roughly 104 miles of track within four counties of Northern California. Many residents within the San Francisco, Alameda, San Mateo and Contra Costa counties rely on the network to get to and from work on a daily basis. Furthermore, it is an excellent resource to avoid highway traffic congestion on the often crowded Northern California highways. With an average of 390,000 passengers a day who rely upon this system for their daily commute and as a means of more efficient travel, safety is of utmost importance for this major transportation system (San Francisco BART).

While the original BART system had been completed in the early 1970's, the system has continued to develop through the years as a major component of the regional transportation and economy (San Francisco BART). In addition, engineering codes had been advancing and more attention was being given to construction within seismic zones. After the 1989 Loma Prieta earthquake and considering the high probability of more earthquakes occurring along any of the region's major fault lines, safety of structures within the region began to be a more and more important topic.

The BART Earthquake Safety Program (ESP) was established in 2000 as an attempt to improve life safety and post-earthquake operability on this crucial transportation system and to mitigate any structural damage, which could occur in a large seismic event. In many cases, aerial structures – including columns and piers – were under designed, according to new codes, and were in need of additional shear or confining capacity. Traditionally, this additional capacity has been provided through several means – built out concrete jackets, steel jacketing or by simply replacing the under designed structure. The early 1990's also coincided with the development of fiber-reinforced polymers (FRP) being used for structural strengthening. After many successful lab performances with Caltrans and further successful field installations, in which highway columns wrapped with FRP's were able to perform well during seismic events, BART engineers began to consider an additional material to meet the performance deficiencies.

Figure 1: BART C-Line Aerial Structures

Fiber-Reinforced Polymer Material Overview

The use of FRPs to strengthen and repair reinforced concrete structures dates back to the early 1980s. Figure 2 demonstrates some of the early research conducted by Caltrans at the University of California at San Diego (Priestley et al 1994). Thousands of civil infrastructure projects have been completed around the world implementing advanced composite systems since this time. Transportation, commercial, industrial, waterfront, water transmission, and force protection markets continue to incorporate FRP composites into project specifications as cost-effective alternatives to the traditional strengthening options.

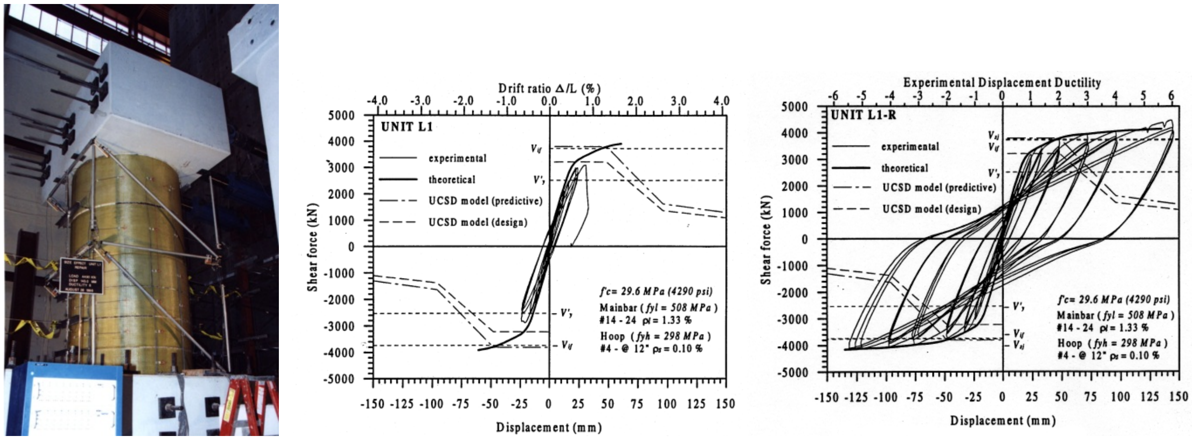

Figure 2: Caltrans UCSD Testing

Common reasons for implementation of FRP composites include seismic upgrades, corrosion mitigation and structural repairs which include restoring or increasing the shear strength, flexural resistance, confinement, and axial load capacity of the structural elements. Elements including slabs, beams, columns, pier caps, walls, piles, and pipelines have been reinforced throughout the last three decades using FRP composites. Building materials strengthened with FRP's consist of concrete, steel, masonry, and wood. The most common FRP's used in the industry are wet-layup systems which consist of unidirectional carbon or E-glass fabrics saturated with high grade, 100% solids epoxy resins to form the composite system.

There are many advantages to FRP composites in structural applications. The materials are corrosion resistant, high strength, light weight, easy to install and maintain the existing dimensions of a structure. When utilized in a project, the FRP's must provide a long-term solution that can withstand any harsh environment to which they may be subjected. ICC AC 125 sets forth standard exterior exposure testing requirements that FRP composites shall be compliant with, prior to use. One thousand, three thousand and ten thousand hour exposure tests and acceptance conditions are defined within this document, some of which include freeze-thaw, humidity, ultraviolet exposure (UV), alkali soil, fuel, water, saltwater, and dry heat resistance. Verifying that the physical and mechanical properties of the fiber-reinforced composite systems chosen can remain constant through not only the test of time, but through these long term exposure conditions, allows the designer the confidence in utilizing that system. Similarly, through material reduction factors laid out in ACI-440.2R-08 along with design strain limitations, owners and engineers are able to design systems to last the life of the existing structure.

FRP Strengthening Design Background

This paper will provide information regarding FRP strengthening as an effective alternative to traditional means of retrofit within BART's Earthquake Safety Program. One of the primary goals for the C-Line Aerial and Station Structures projects was to provide additional shear capacity to the pier columns as specified in the bid-documents.

For these aerial and station structures, the primary elements being strengthened were reinforced concrete hexagonal columns. Design goals included providing additional shear capacities as per ACI-440.2R-08. The FRP material selected to satisfy these design requirements was a unidirectional Carbon Fiber-Reinforced Polymer (CFRP) due to the high strength and low weight of the material.

FRP materials are used to provide additional tension reinforcement to structures, providing strengths comparable to those contributed by steel. Various design codes and guidelines have been created to address the use of FRPs and their contribution to the strength of an element. Among these documents is the guideline selected for use on these bridges, ACI 440.2R-08, "Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Concrete Structures"[3]. This publication covers material qualifications, structural design and detailing, construction procedures, and quality control methods for externally bonded wet-layup FRP systems on concrete. In addition to these design guidelines, the long term durability exposure test requirements from the ICC AC 125 document mentioned earlier were incorporated into the contract documents to ensure that a long lasting rehabilitation solution was achieved. The contract documents also required fire resistance testing to ASTM E-84, to meet BART's fire safety requirements for smoke and flame spread.

The strength contribution of FRPs is governed by the allowable strain and modulus of the cured composite system. Unlike steel reinforcement, composites remain linear elastic until rupture, not experiencing the yielding effect that is typical of steel. Therefore, the materials continue to develop tension capacity until the ultimate strain is reached. Ultimate FRP strains are in the range of 0.80% to 2.00%. However, often times, the ultimate strengths of these materials will not be reached and other failure modes will govern the tension capacity reached in the composite reinforcement. Possible failure modes that shall be considered are FRP rupture, concrete crushing, FRP debonding, and concrete cover delaminations. The governing failure mode will limit the fiberwrap design strain that can be developed, in turn governing the additional capacity provided by the FRP. Designs of these systems are based on standard principles of mechanics, with equations that are very similar to those in adopted codes for all construction materials. In addition to the usual strength reduction factors, which are used in the capacity calculations, supplemental reduction factors are placed on the force resistance of the FRP to incorporate an additional factor of safety into the design.

Case Study – BART C-Line Aerial and Station Structures

For the BART C-Line Aerial and Station Structures, the degree of deficiencies varied from pier to pier, with the columns requiring anywhere from 150 kip to 1100 kip of additional shear strength. Due to these high seismic shear demands, conventional construction methods would require large amounts of reinforced concrete to be added around the existing columns and beams to meet these demands. This led directly to the exploration of a low profile and high strength composite system.

As seen in the hysteresis loops in Figure 2, increases in ductility are provided to the column through the use of composite wraps and "increases in shear strength… to the extent that brittle shear failures modes are converted to ductile inelastic flexural deformation modes" can be designed for (Priestley et al 1994). Therefore, an effective, durable carbon composite FRP was selected, with multiple layers applied at each location (as required) to achieve the desired accumulated thickness and strength. The FRP wraps were applied transverse to the longitudinal axis of the columns, with a 6-inch minimum overlap in the primary fiber direction. As carbon fabrics are typically manufactured in 24-inch wide rolls, small overlaps or gaps in the horizontal plane were provided to adjust the shear capacity, rather than just adding more layers.

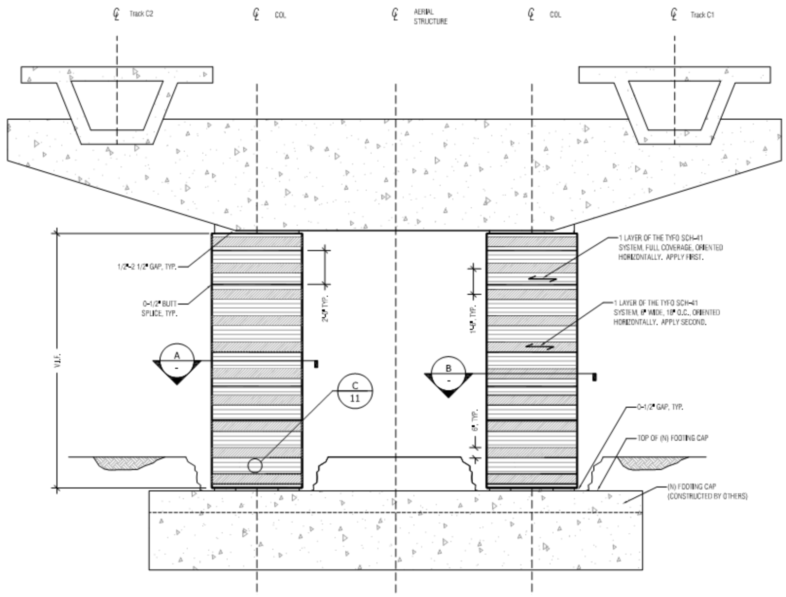

Figure 3: Bart C-Line Submittal Drawings

Prior to application of the FRP composite materials, the existing concrete substrate must be prepared. Whenever the composite is able to fully encase an element, as detailed at the columns to be wrapped, the sheets are able to wrap back onto themselves classifying this as a contact-critical application. This installation process requires minimal surface preparation, which includes rounding the existing corners to a ¾" minimum radius and ensuring that all contact surfaces are free from dust, debris and any sharp edges. Bay Area Rapid Transit engineers elected to be a bit more conservative in this process and classified all installations as bond critical, in order to better control the size and distribution of shear cracks for these relatively large columns.

Figure 4: Surface Preparation

Figure 5: Excavation of Column

Bond critical applications occur when the FRP composite is not able to fully wrap around a member and back onto its self. In these instances, the surface preparation will be more intensive, requiring grinding or other abrasive methods to properly expose the substrate. For all of the columns to be wrapped, the surface was prepared by means of mechanical grinding (Figure 4). Additionally, the FRP strengthening was to continue down below the base of the columns. Figure 5 shows the excavation required to achieve this.

Once the surface had been prepared, the epoxy could then be mixed on site, and a prime coat applied to the substrate was allowed to become tacky to the touch before a thin coat of thickened epoxy was installed to ensure that there were no voids behind the first layer of fully saturated fiberwrap. In figure 6, one can see the top layer of the column already wrapped with FRP, while the middle layer has had the primer applied. Once the primer coat and first layer of FRP has been applied, subsequent layers were then installed until the desired number of layers shown on the approved shop drawings was achieved. All seams and edges were finished with a coat of thickened epoxy to feather out these locations and provide good installation detailing.

Figure 6: Surface Preparation

The final step to the FRP installation was the application of a high-solid polyurethane finish coating for ultraviolet (UV) and long term durability protection. Finish coats should be applied within twelve to seventy-two hours of mixing the epoxy (depending on ambient curing conditions) to allow the coating and the epoxy resin to cure simultaneously, also called a chemical bond. If the coating is applied after this time period, a light sanding of the cured epoxy is required to achieve a proper mechanical bond between the cured epoxy and the top coat. All composite surfaces on this structure were then painted to best match the existing structures color.

CONCLUSION

Over the last twenty-five years, FRP composite strengthening systems have developed into a reliable alternative to traditional structural repair materials and seismic retrofit methods for reinforced concrete bridge and other transit structures. With the low-impact, cost-effectiveness and ease of installation of these materials, the number of projects with FRP composites being specified for rehabilitation, strengthening, and protection of structural elements is continually growing. The BART C-Line Aerial and Station Structures seismic strengthening project provides one example in the efficiency in utilizing fiber-reinforced composite systems on bridge structures. In this case, high seismic demands were able to be designed for and the FRP system was installed in a cost-effective and rapid rehabilitation manner. When designed, detailed and installed correctly, FRP materials can provide a long lasting, effective strengthening solution with minimal impact on the existing structure and its surroundings.

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