ASSESSMENT AND PROPOSED STRUCTURAL REPAIR STRATEGIES FOR BRIDGE PIERS IN TAIWAN DAMAGED BY THE JI-JI EARTHQUAKE

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ABSTRACT

Taiwan, an island country with an area of approximately 14,000 square miles, was struck by a deadly earthquake, measuring 7.3 on the Richter scale, on September 21st, 1999. This earthquake struck the geographic center of Taiwan causing damage to most of the bridges in the region and prompting the need for repair and strengthening of these bridges. Shear failures were observed in many damaged piers. Some bridge piers apparently failed due to the large vertical seismic forces. A seismic retrofit program should aim at providing improved ductility to substructure members. Although steel jacketing has been used, due to constructability considerations, alternative strengthening methods using advanced composites are being considered. Retrofit procedures for vulnerable piers may use material systems made of aramid, glass and carbon fiber reinforced polymers. The characteristics of these composite retrofit systems include light weight, and high stiffness/strength to weight ratios. Confinement with FRP laminates allows the piers to form plastic hinges during the earthquake, limiting the amount of force distributed to adjacent members. This paper is concerned with proposing a combination of methods for seismic retrofit of bridge structures including near-surface mounted and externally bonded reinforcement. The intent of this methodology is not only to maintain safety for bridges subjected to a high magnitude earthquake, but also to control damage while accommodating large seismically induced deformations in order to maintain post-earthquake serviceability.
INTRODUCTION

Failure of concrete bridge piers may result from crushing of the concrete due to either a lack of confinement or the fracture of the transverse hoop reinforcement, and buckling of the longitudinal reinforcement [1]. For piers that are conventionally constructed, the maximum moments and strains occur at the ends of the column. In the event of an earthquake, all elements outside the plastic hinge zone of column may remain elastic. Damage is limited within the plastic hinge zone. Current bridge seismic design philosophy calls for ductile plastic hinges to form at the column ends. Inelastic action is limited to these well defined and detailed regions to prevent damage from occurring in the adjacent superstructure and footing.

Fiber reinforced polymer (FRP) reinforcement stands today as a viable alternative to conventional types of reinforcement and the use of FRP is gaining interest in the construction practice worldwide. The seismic retrofitting of chimneys, bridge piers, and building columns using light, high strength and high durability continuous fiber reinforcement such as aramid, glass, and carbon FRP has been developed and is now entering the stage of practical use.

This study proposes a column retrofit technique for strengthening damaged bridge piers using composite materials systems. To achieve this objective, a strengthening technology called near surface mounted rods is combined with the application of FRP jacketing for providing pier end region confinement, increased strength and ductility, and collapse prevention.

ASSESSMENT OF THE DAMAGED BRIDGE PIERS

Most of the damaged bridges due to the Ji-Ji earthquake in Taiwan observed in the epicentral region were constructed of prestressed concrete (PC) I-girders supported with or without bearings on reinforced concrete (RC) piers. Provisions, which presumably governed their design and construction, are set forth in the Standard Specification for Highway Bridges of Taiwan. Those specifications are based mainly on the American Association of State Highway and Transportation Officials (AASHTO) Standard Specifications. In particular, the first edition of the Taiwan specifications, published in 1960, was based on the 1953 AASHTO specifications; the 1987 edition was based on the 1977 AASHTO specifications; and the 1995 edition was based on the 1992 AASHTO specifications. The characteristics of the damaged bridge piers due to this severe earthquake can be summarized in the following:

- Most of the bridges built over the fault were seriously damaged even if designed and constructed recently.
- Several bridges near the fault region collapsed because of large embankment movement behind the abutment.
- Simply supported bridges were subjected to more damage compared with continuous span bridges.
Almost all the bridge bearings, with the exception of the elastometric bearings, were subjected to heavy impact so that the concrete bearing pads were crushed.

Almost all the bridge deck expansion joints were torn out due to seismic forces.

Several bridge piers apparently buckled due to the vertical seismic accelerations larger than one ‘g’.

All the bridge foundations without piles settled, apparently resulting in the large scale cracking on the bridge deck and wearing surfaces.

The horizontal and vertical alignment for almost all the bridges which remained standing after the seismic hazard were twisted and distorted.

More than 25 bridge piers were severely rotated due to the soil liquefaction.

Detailed safety inspections are definitely required after the seismic hazard since almost all the concrete bridges have extensive visible cracks.

Some bridges struck by this earthquake failed due to fault rupture beneath or adjacent to them. The Wu-Shi Bridge, located about 20 km NW of the epicenter, consisted of two parallel structures—the East Bridge constructed in 1981 and the West Bridge constructed in 1983 (Figure 1). The superstructure, comprised of 18 spans of PC I-girders, was supported on RC pier walls. The deck had an expansion joint at the north abutment, continuous joints for the next two piers, and another expansion joint over the third pier. Fault rupture passed through the foundation of the third pier, with an offset of approximately 1.5 m vertical. Damage included unseating of the PC spans of the East Bridge near the north abutment. The West Bridge is supported by smaller cross-section piers, which failed. The first and second piers, containing a vertical reinforcement ratio of approximately 2.5%, sustained apparent shear failures involving nearly complete fracture of the cross section along a failure surface. The third pier had cracking indicative of torsion failure. The damage patterns are consistent with rigid-body deformation involving in-plane rotation of the bridge deck. Figure 2 shows the damaged piers of the Wu-Shi Bridge.

Figure 1: Cross Sections of Wu-Shi Bridge.

Figure 2: Damaged Piers of the Wu-Shi Bridge.

**FRP COMPOSITES STRENGTHENING CONCEPT**

**Steel Jacketing**

Steel jacketing was originally developed for circular columns. It is effective for passive confinement. The lateral confining stress is induced in the concrete by flexible restraint as the concrete attempts to expand laterally in the compression zone as a function of high axial compression strains, or in the tension zone as a function of dilation of lap splices under incipient splice failure. However, jacketing rectangular columns has to be modified in order to obtain the desired response. The recommended practice is to use an elliptical jacket that provides a continuous confining action similar to that for a circular column but with a confining stress that varies around the circumference because of the continuous changing curvature of the jacket. The space between the jacket and column may be filled with normal conventional concrete rather than grout.

**Composite Jacketing**

In composites jacketing, rectangular and circular columns can equally benefit by obvious constructability advantages. FRP jackets can be erected more rapidly than their steel counterparts, resulting in time (cost) and effort savings. By wrapping a concrete column with an FRP jacket, the shear, moment, and axial capacity may be improved. In addition, the ductility of the member may also be significantly improved without affecting strength if this is necessary. The FRP jacket is formed by wrapping the column with the FRP fibers oriented in the transverse (hoop) direction. The jacket provides significant confinement to the concrete, which leads to the mechanical performance improvements. At low levels of longitudinal stress, the transverse strains are so low that the FRP jacket lends little confinement. However, as the longitudinal stress levels above the critical stress, the increase in transverse strains engages the FRP jacket and the confining pressure becomes significant. The effect of the confining pressure is to induce a triaxial state of stress in the concrete. It is well understood that concrete under triaxial compressive stress exhibits superior behavior in both strength and ductility. Composites jacketing with externally bonded sheets is limited by the fact that continuity of reinforcement cannot be provided at the foundation-column (or cap beam-column) intersection.

![Figure 3: Fiber Orientation of Composite Laminates.](image-url)
Constructability Considerations for FRP Jackets [2]

Depending on the circumstance, the condition of the existing concrete may range from excellent to very poor. Consideration for FRP jackets on the condition of the existing concrete should be made before the retrofit. For example, the nominal compressive strength of the concrete, $f'_{c}$, should be reduced if the existing concrete is damaged and repaired. If corrosion is present, its source must be investigated before any strengthening work is commissioned. This is especially critical considering that the FRP jacket would hide visual signs of corrosion. Similarly, other durability related concerns, such as the presence of efflorescence or exudation, any form of chemical attack, and non-structural cracking should be addressed and corrected prior to strengthening.

At load levels near ultimate, the damage to the concrete in the form of significant cracking in the radial direction may occur. The FRP jacket contains the damage and maintains the structural integrity of the column. The FRP jacket would only act during overloads that are temporal in nature. To insure that radial cracking will not occur under service loads, the strain in the concrete should remain below $\varepsilon_{cr}$ (transverse strain corresponding to the onset of transverse cracking in the concrete) at service load levels. This corresponds to limiting the stress in the concrete to $0.65 f'_{c}$. In addition, the stress in the steel should remain below $0.60 f_{y}$ (60% of the tensile yield strength) to avoid plastic deformation under sustained or cyclic loads. By maintaining the specified stress in the concrete at service, the stress in the FRP jacket would be virtually zero. The jacket is only stressed when the concrete is strained above $\varepsilon_{cr}$ and the rate of transverse expansion becomes large.

Near Surface Mounted FRP Rods [3,4]

To increase flexural capacity of piers, the technique referred to as Near-Surface Mounted (NSM) FRP rods is proposed. Embedment of the rods is achieved by grooving the surface of the member to be strengthened along the desired direction. Continuity with foundation, flare or cap beam is obtained by drilling a hole into such member. The groove is filled half way with epoxy paste. The FRP rod is then placed in the groove and lightly pressed, so forcing the paste to flow around the bar and fill completely between the bar and the sides of the groove. The groove is then filled with more paste and the surface is leveled. Details of the final product are shown in Figure 4a. After completing the installation of NSM reinforcement, an FRP jacket is provided with the purpose of confining both concrete and rods.

The use of NSM FRP rods increases the flexural and the shear strength of deficient bridge piers and can be more convenient than using externally bonded FRP laminates in the negative moment regions of a deck. In this case, the externally bonded reinforcement would be subjected to mechanical and environmental damage and would require protective cover which could interfere with the presence of floor finishes.

PIER CAPACITY AFTER STRENGTHENING

In Figure 5, the load-moment interaction diagram (P-M diagram) of a rectangular bridge pier is shown. In the region between A and B, failure initiates by crushing of the concrete on the compression side of the member; between points B and C, failure initiates by yielding of the tension steel. After the NSM rods are installed, the P-M diagram expands rightward in proportion to the increase of vertical reinforcement ratio (Figure 6) in the tension controlled region. Conversely, with the application of a composite jacket, the capacity of concrete to carry axial load increases as the composite jacket contributes confinement to the cross section (Figure 7). Figure 8 shows that the combination of NSM rods and externally bonded reinforcement enhances the strength of a member, in both compression and tension controlled regions. In addition, the presence of the jacket contributes to the stability of the rods and controls epoxy paste cracking.

Figure 4: Installation of Near Surface Mounted Rods Followed by FRP Jacketing

Figure 5: P-M Diagram before Strengthening

Figure 6: P-M Diagram after Installation of NSM Rods
CONCLUSIONS

- Although the use of composite materials for seismic retrofit in Taiwan is a relatively new area, its potential for success is very high.
- Strengthening using FRP laminates is an effective retrofit technique which provides improved ductility to reinforced concrete piers.
- Combination of FRP jacketing and NSF rods could be used for improving the flexural capacity of damaged or undamaged columns.

ACKNOWLEDGEMENT

This research study was sponsored by the National Science Foundation Industry (NSF)/University Cooperative Research Center on Repair of Buildings and Bridges with Composites (RB2C). Special thanks are extended to Center for Bridge Engineering Studies, Feng Chia University, Taiwan, and Mr. Dong-Son Wu for field investigation and valuable opinions.

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