The Use of Fiber Reinforced Polymer Composites to Retrofit Reinforced Concrete Bridge Columns

Scott Poveromo

12/08/03

In Partial Fulfillment of Course Requirements for MATE 115, Fall 2003

Course Instructor: Professor G. Selvaduray

ABSTRACT

A major problem in the construction industry is building a structure that can withstand cyclic axial and cyclic lateral loads during an earthquake. Reinforced concrete (RC) columns, which carry the largest load in many RC structures, are particularly vulnerable to failure during seismic activity. One solution to protect these columns from earthquakes is to retrofit the RC columns using fiber-reinforced plastic (FRP) composites. FRP composites offer many advantages to help earthquake-proof RC columns, including low life cycle costs due to zero maintenance and easy installation. The following paper will discuss the common failure modes which RC columns exhibit during an earthquake. It will then define what FRP composites are and discuss how they can protect RC columns from these failure modes. Finally, it will describe one type of retrofit application in which FRP composites are utilized via a wrapping method around a substandard RC column.

TABLE OF CONTENTS

LIST OF FIGURES

INTRODUCTION

Since the earthquake in San Fernando, CA, in 1971, designs of RC columns to support bridges have changed to address inherent reinforcement weaknesses, such as weak transverse reinforcement as well as insufficient seismic detailing [1]. However, many RC bridge columns were built before 1971 and, hence, do not pass the new design codes. In 1994 the Northridge earthquake damaged 40,000 structures including collapsing 7 major freeway bridges [2]. All seven of the destroyed bridges were built to the old design codes and could possibly have been saved if they had been properly seismic retrofitted [2]. Current substandard RC columns must be retrofitted in the near future in order to avoid potential catastrophic destruction during an earthquake. Typically, steel retrofits are used to improve flexural and shear strength of a RC column because steel has established structural design allowables and properties [3]. However, steel reinforcements corrode over time and require periodic maintenance. Although the material cost for purchasing the steel to be used in these retrofits is low, installation and regular maintenance is laborious and costly. For example, a four foot diameter, 22 foot high RC circular column takes two and a half days to retrofit using steel, not including site excavation and exterior painting [2]. A better solution to protect these columns from earthquakes is to retrofit the RC columns using fiber-reinforced plastic composites. FRP composites typically are at least twice as strong as steel and weigh 20 percent less [3]. Also, the ability to tailor FRP composites, by changing the orientation of the fibers, allows the user to strengthen a structure in preferential directions to meet performance requirements. The disadvantage of using FRP composites is that the material cost is usually high. However, prices per pound for fibers have been decreasing rapidly and material cost is a small portion of the total cost of a FRP composite retrofit [3]. Since steel corrodes and is heavier than a typical FRP composite, a steel retrofit will have a much higher installation and maintenance cost than a FRP composite retrofit. In many designs, FRP composites provide the most cost-effective solution when repairing a RC column [3].

PRINCIPLE/MECHANISM

During an earthquake, a RC column can fail in three main modes due to cyclic axial and lateral loads: shear failure, flexural plastic hinge failure, and lap splice failure [3]. Pre -1971 concrete bridge columns were constructed using long steel rods, which were attached longitudinally to the column, to increase flexural strength. However, rarely was there any transverse reinforcement or reinforcement through the thickness of the column [1]. Because seismic activity causes both axial and lateral movement, reinforcement in only the longitudinal direction will not suffice in protecting the column from shear failure [3]. Hence, RC columns under these old designs would exhibit catastrophic shear failure as shown in Figure 1a [3].

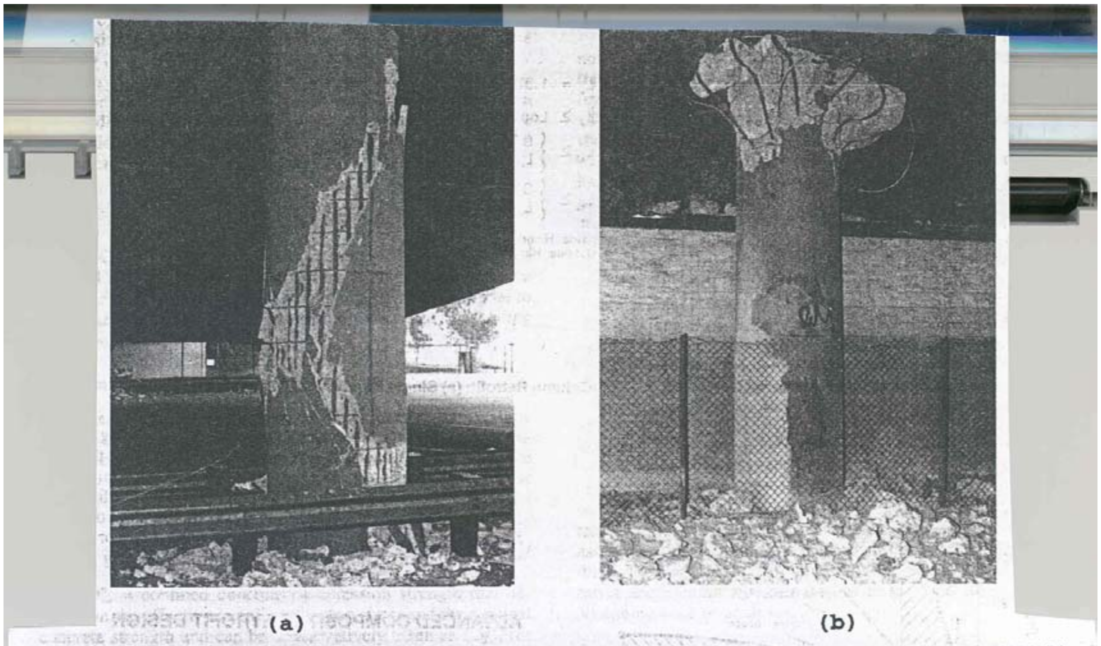

FIG. 1. Typical Column Failure Modes: (a) Progressive Shear Failure, I-10 Santa Monica Freeway, Northridge Earthquake 1994; (b) Flexural Plastic Hinge Failures, I-10 La Cienega and Venice, Northridge Earthquake, 1994

Shear failure is one of the most undesirable failure modes because it is brittle. This means the RC column will exhibit very little plastic deformation. A typical stress strain curve for a brittle material is shown in Figure 2.

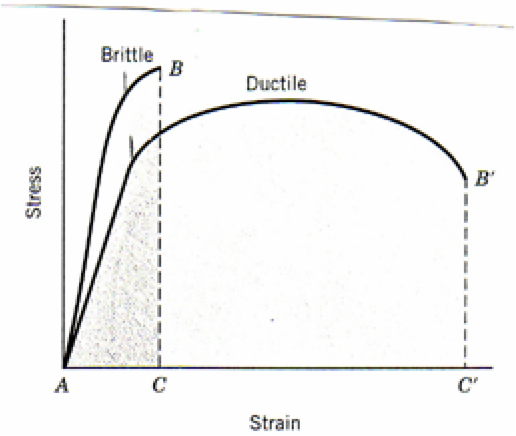

Figure 2. Stress-Strain curves for brittle and ductile materials loaded to fracture [4].

As you can see, minimal plastic deformation is seen before fracture. The area underneath the stress strain curve is also small. This correlates to a material that has low fracture toughness. In order to increase the fracture toughness of a material, the ultimate tensile strength must be very high or the material must be able to plastically deform over a wide range of strain values.

The second type of failure mode that is typical of RC columns is a flexural plastic hinge failure [3]. This is a ductile failure where the plastic deformation is large before reaching fracture (see Figure 2) [3]. A ductile failure is therefore not catastrophic and would be more desirable than a shear failure. Plastic hinge failure is seen either at the interface of the column and the bridge or the column and the ground. Characteristics of this failure are spalling of concrete at the ends of the column as well as buckling of longitudinal steel reinforcements due to repeated bending during an earthquake [3]. Figure 1b shows the interface between the column and the bridge where concrete has spalled and reinforcing steel rods have all buckled and detached from the column.

Finally, the third type of failure is a lap splice failure. This type of failure is dependent on how steel reinforcement rods are attached longitudinally and laterally along the column. Many of the older RC column designs have steel rods lap spliced together [3]. The lap splice joint created is a stress raiser. If the length of the lap splice is too small, it will debond during cyclic loading. If this weak joint breaks during seismic activity, the steel reinforcements will lose their structural integrity and the columns flexural strength will sharply decrease [3]. The RC columns flexural strength will then be based upon the concrete's low tensile strength.

FRP composites can be used to protect RC columns from the major failure modes during an earthquake. A FRP composite consists of two main constituents: a reinforcing agent (usually a fiber) and a matrix (the glue that holds the fibers together). The fibers are usually high strength ceramic materials such as carbon or glass. These ceramic fibers have a high tensile strength because dislocations are pinned in ceramic materials restricting plastic flow. Also, ceramic fibers usually are extensively cold worked which causes an increase in dislocation barriers. As a result, the fiber has a higher strength, but also becomes more brittle. The fibers can be continuous or discontinuous; and depending on their length, diameter, and volume fraction in the composite, they can exhibit a variety of mechanical properties. However, fibers are brittle and small in size, and they alone would not make a useful engineering material. The matrix in a FRP composite is usually a polymeric resin that can be a thermoset or a thermoplastic. These resins act as binders to hold the fibers together to create a monolithic structure. An example of a FRP composite would be fiberglass. Fiberglass combines the strength of the ceramic glass fibers, with the toughness and ductility of a resin, such as an epoxy.

FRP composites utilize dislocation motion in the polymer matrix to transfer the applied load from the matrix to the high strength fibers. The strength of the composite will be dependent on the orientation of the fibers. If the fibers are all pointed in the zero direction, the strength of the composite will have very good mechanical properties in that direction and very weak mechanical properties in the 90-degree orientation. This is because in the 90 degree direction the matrix, not the fibers are carrying the load. FRP composites can be easily designed to meet load requirements in specific directions [4,5,6].

When constructing a FRP composite to meet specific performance requirements, three mechanical properties are used: strength, Young's modulus, and toughness [6]. It is important to know the modulus and strength properties for the fiber and the matrix in order to calculate what these properties should be for the composite as a whole. First, if we assume we are using continuous fibers at or above the critical volume fraction, we can calculate the fracture strength of the composite (σ_c) using the Rule of Mixtures shown as Equation 1 below [6].

$$\sigma_c = \sigma_f V_f + \sigma'_m(1 - V_f) \qquad \text{Equation 1}$$

V_f = volume fraction of fibers
σ_f = Tensile strength of fibers
σ'_m = Tensile stress in the matrix

Since the fiber tensile strength will be much higher than the matrix tensile strength ($\sigma_f >>>> \sigma'_m$), the higher the fiber volume is, the higher the fracture strength will be for the composite. Then, the modulus of the composite can be computed by multiplying the fracture strength of the composite by its strain to failure. Toughness is also an important property to determine of the composite when selecting materials that will need to withstand seismic loadings. Toughness is defined as the work per unit volume needed to cause fracture [5]. This property may be determined by calculating the area underneath the true stress-true strain curve

[5]. The typical stress-strain curves are shown in Figure 3 for a carbon fiber reinforced polymer (CFRP), a graphite fiber reinforced polymer (GFRP), and mild steel. Figure 3 shows that carbon fiber reinforced polymers are the toughest of the three materials based on the areas underneath their respective curves. As a result, CFRPs will perform the best as a retrofit in increasing the toughness of a RC column.

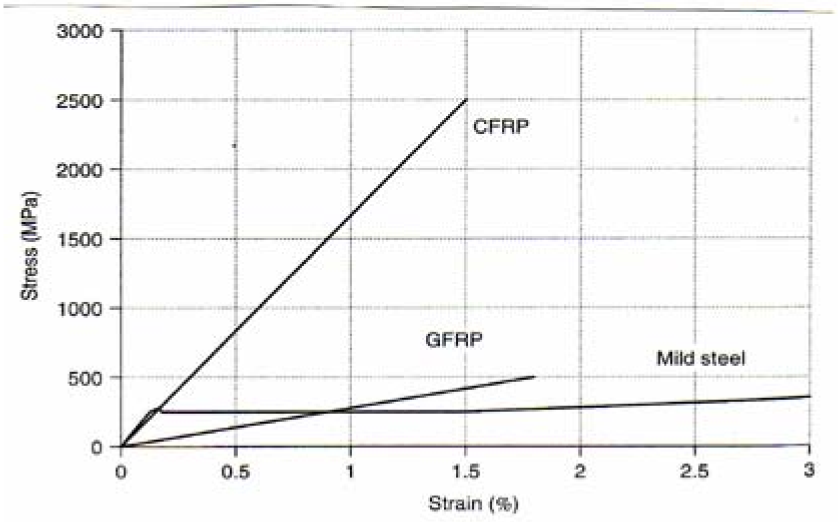

Figure 3. Typical CFRP, GFRP, and mild-steel stress-strain curves [3].

There are a few FRP bonding schemes that can be used to improve the shear and flexural strength of a RC column. However, the most effective bonding scheme used in seismic retrofits is a FRP composite 'wrap' [3]. The wrap is made of layers of fibers pre-impregnated with resin, called pre-preg. Each layer may have the fibers oriented in multiple directions to protect the column from reverse cyclic loading or other loadings due to seismic activity [3]. To do this, the fibers can be oriented in the 0 degree direction in the first layer, the 60 degree direction in the second layer and the 120 degree direction in the third layer. This 0/60/120 pattern maybe repeated until the desired wrap thickness is achieved. As long as the fibers are not exactly parallel to the shear cracks, shear crack propagation will be controlled and the shear capacity of the column will improve [3]. Seible reports that, to increase shear strength, the ‘wrap’ bonding scheme may be applied on the column in the hoop or in the horizontal direction with its fibers oriented 90 degrees from the column axis [1]. The composite wrap must be wrapped around the entire column with adequate overlap preferably in the hoop direction, not the longitudinal direction [3]. This overlap area will provide added transverse reinforcement if performed around the circumference of the column, which will in turn increase the shear strength [3]. The fibers in the wrap can be applied as pre-preg sheets or strips [3]. The sheets are easier to apply and protect the column from the environment because they cover its entire surface area [3]. The strips allow more flexibility in regulating the amount of material used and, hence, should lower the material cost, but the application process is more laborious [3].

The composite wrap method also protects the RC column from the flexural plastic hinge failure mode. Assuming continuous fibers are used, the wrap helps prevent concrete spalling and provides lateral support to the steel longitudinal reinforcements [1]. The uniform ‘confinement’, provided by the composite wrap, enhances both the strength and ductility of the concrete [1]. The wrap acts as a jacket around the column providing support in all the principal load directions. The wrap also does not have joints or lap-splices, such as in longitudinal steel reinforcements, which could debond during an earthquake. The shape of the RC column also plays a key role in determining the flexural strengthening effectiveness of the fiber wrap. A FRP composite retrofit works well when applied to circular columns. However, if the RC column cross section is square, the FRP composite retrofit will have reduced stiffness and ductility benefits [7]. The reduction in stiffness and ductility is a function of the corner radii of the square cross section: as the corner radii decreases, the mechanical properties of the retrofit also decrease

[7]. Finally, to increase flexural strength, the composite wrap must be applied over the entire column in order to achieve uniform confinement. If areas on the column are left exposed, the failure modes will shift to that location [1]. Usually, the only gap in composite wrap designs is left between the bottom of the bridge (cap beam) and the start of the RC column [7]. This gap, which is roughly a few inches, is left for the formation of a plastic hinge without the cap beam creating interference [7].

APPLICATION

One of the advantages of using FRP composites to seismically retrofit bridge columns is ease of application. The company XXsys Technologies has developed a speedy method for applying a FRP composite wrap to RC columns. XXsys designed a machine called the Robo-Wrapper that constructs a hoop-wrapped jacket around a RC column using tows of continuous carbon fiber pre-impregnated with resin. The Robo-Wrapper is a programmable two-axis machine that can wrap pre-preg tow to precise dimensions around highway and bridge columns. The machine rotates around the column while it moves up and or down, encasing the entire column with carbon fiber pre-preg. Because the carbon fiber is continuous, the wrap created provides uniform confinement of the concrete. This ensures there are no weak spots where the shear strength and flexural strength would be low. XXsys also designed a radiant heat oven, which cures the resin at high temperatures. During the cure, the resin cross-links and forms a hard shall. The resin also acts as an adhesive and bonds to the concrete forming a tight structure around the entire cross section of the column [2].

Figure 4. Xxsys' Robo-Wrapper I [8].

Two main machines, the Robo-I and the Robo-II, are used to retrofit RC columns of all sizes. The Robo-I, shown in Figure 4, can complete a composite wrap for an average freeway circular column, four feet in diameter and 20 feet high, in 8 to 12 hours! The Robo-II has the capability of wrapping two 22 foot tall circular columns per day, which includes machine set-up, the actual wrapping, and then removing the equipment from the site. The Robo-I uses up to six spools of pre-preg tow while the Robo-II uses twice as many spools and can wind 4 to 5 times faster. The XXsys' wrap system is well equipped for handling seismic retrofits of structurally deficient bridge columns. A typical retrofit process would follow three general steps: column preparation, operation of the Robo-Wrapper, and the curing system. During the first step the columns surface area is cleaned of dirt and dust. All defects in the concrete are fixed to ensure as close to a contamination-free surface as possible. The less contamination on the surface the better the composite wrap will bond to the concrete column. The second step involves assembling the Robo-Wrapper machine, programming the machine, and wrapping the column. The Robo-Wrapper is made up of two segments that are lifted to the appropriate location and bolted together. Once in place, the machine is programmed and then activated. The final step is the curing system. The curing system, shown in Figure 5, is constructed after each column is wrapped. The curing oven is made up of radiant curing panels that are bolted together around an eight-foot section of the column. The panels are insulated and the power source is a diesel electric generator. The cables shown in Figure 5 are the electric power cables connecting the generator to the curing panels. Thermocouples are used to measure the actual temperature of the

Figure 5. XXsys'curing system [8].

part accurately. When the job is finished a detailed report showing what was done, such as jacket thickness in specific areas, etc., can be reviewed. XXsys Technologies has performed several successful demonstrations in the field and in the lab. Seismic retrofits performed using the Robo-Wrapper have improved the ductility and strength of substandard RC columns. The XXsys method of FRP composite application is an example of how time and cost efficient seismic retrofitting can become [2,8].

CONCLUSION

It is estimated that one in three bridges in the United States requires some form of repair or retrofit [2]. Many of these bridges have RC columns with poor transverse reinforcement making them vulnerable to earthquakes. FRP composites offer many advantages over other materials in seismic retrofitting applications, including better mechanical properties and lower installation costs. FRP composites can potentially enhance the shear strength, flexural strength, toughness, and ductility of RC columns. Using a ‘wrap’ method, FRP composites protect the RC columns from the major failure modes. XXsys Technologies has developed an automated FRP composite wrapping system which has increased the speed and accuracy of constructing seismic retrofits on structurally deficient RC columns.

REFERENCES

1. F.Seible, M.J.N. Priestley, G.A. Hegemier and D. Innamorato*, "Seismic Retrofit of RC Columns With Continuous Carbon Fiber Jackets,"* Journal of Composites For Construction, **1,** 52-62 (1997).

2. G. Ma, "*The Use of Space Age Materials and Technology for Infrastructure Renewal: State of the Art Seismic Retrofit and Corrosion Rehabilitation in the United States,"* in Carbon Fibers 98: Meeting the Composite Challenge, edited and sponsored by INTERTECH CONFERENCES (San Antonio, Texas, 1998).

3. J.G. Teng, J.F. Chen, S.T. Smith and L. Lam, FRP Strengthened RC Structures, (John Wiley and Sons. West Sussex, England, 2002), pp. 1-10, 100-108, 148-236.

4. W.D. Callister, Jr., Materials Science and Engineering an Introduction, 6th ed. (John Wiley & Sons, Inc. New York, NY, 2003), pp. 120-132.

5. D. Hull and T.W. Clyne, An Introduction to Composite Materials, 2nd ed. (Cambridge Univ. Press. Cambridge, England, 1996), pp. 1-10.

6. C.R. Barrett, W.D. Nix and A.S. Tetelman, The Principles of Engineering Materials, (Prentice-Hall, Inc. Englewood Cliffs, New Jersey, 1973), pp. 193-213, 316-325.

7. I. Gergely, C.P. Pantelides, R.J. Nuismer and L.D. Reaveley, *"Bridge Pier Retrofit Using Fiber-Reinforced Plastic Composites."* Journal of Composites for Construction, **2,** 165-174 (1998).

8. Photos from website: http://www.xxsys.com/rwfp.html. Collected (December 2003).

.