Chapter 2

Literature Review

There is a wide range of research pertaining to the use of FRP in bridge repair. Rebar, grating into concrete, and wrapping around columns and piers are just a few examples of the broad applications of these composites (Norris & Saadatmanesh, 1994). This literature review will be limited to research of FRP material externally bonded to the tensile face of concrete beams. In particular, research studying the effect of externally applied FRP materials on the flexural performance of reinforced concrete beams will be reported.

2.1 Analytical Studies

2.1.1 An et al.

An et al. (1991) developed a model to predict the stresses and forces of a reinforced concrete beam with externally applied glass fiber reinforced plastics (GFRP). Their study was based on five assumptions: 1) linear strain distribution throughout the beam; 2) small deformations; 3) tensile strength of concrete was ignored; 4) shear deformation was ignored; 5) perfect bond between concrete and GFRP. Using classical flexural theory and strain compatibility, effects of variables such as material strength, modulus of elasticity, and reinforcement ratios of the steel and GFRP were compared with experimental results of a previous test (Saadatmanesh & Ehsani, 1991). The behavior of the beams were predicted with reasonable accuracy using the model.

2.1.2 Triantifillou & Plevris

Triantifillou & Plevris (1991) used strain compatibility and fracture mechanics to analyze reinforced concrete beams applied with externally bonded carbon fiber reinforced plastics (CFRP). The same assumptions as An et al. (1991) were used with the inclusion of an rectangular compression stress distribution in the concrete at failure. The applied moments that would cause each of the three failure modes were predicted. The failures were yielding of the steel reinforcement followed by CFRP rupture; yielding of the steel reinforcement followed by the crushing of the concrete compression zone; and concrete crushing before either tensile component fails. These models were compared with experimental studies and deemed creditable.

2.1.3 Bhutta

Moment, stiffness, and deflection models of reinforced concrete beams with applied FRP were developed by Bhutta (1993). Glass, carbon, and kelvar fiber reinforced plastics were utilized. Beams reinforced with kelvar showed the highest increase in moment capacity and stiffness, while the smallest was the beams reinforced with glass. The moment capacity of beams reinforced with carbon fell between these two composites.

2.1.4 Naaman and Jeong

Naaman and Jeong (1995) developed a new definition for the measurement of the ductility index. According to Naaman and Jeong, the conventional definition, which is based on yielding of the reinforcement, is inappropriate for evaluating concrete beams that are reinforced with FRP. This is due to the inability of most FRP materials to yield. The new definition is expressed with a ratio of the total energy of beam and the elastic energy released at failure. This index is applicable to concrete beams reinforced with steel tendons, FRP tendons, or a combination of both.

To evaluate the proposed ductility index, a series of 24 prestressed concrete beams, which were previously tested by Naaman and Jeong and other researchers, were studied. The results showed the FRP prestressed concrete beams have less ductility than prestressed concrete beams with steel strands. Also, the proposed ductility index accurately predicted the ductility of the beams.

2.2 Experimental Studies

2.2.1 Meier et al.

Experimental studies involving bonded CFRP to reinforced concrete beams has been performed by Meier et al. since 1985 at the Swiss Laboratories for Materials Testing and Research. This program envisions the replacement of steel plates with FRP laminates for repairing and strengthening reinforced concrete beams. Examining the strength and stiffness of beams with unidirectional CFRP plates is a primary focus of their past research.

An earlier study (Meier et al., 1991) encompassed externally bonding CFRP sheets to twenty-six concrete beams. Each beam (6”x10”x79”) was minimally reinforced with steel (two 5/16” diameter bars) on top and bottom and included shear reinforcement (¼” spaced every 8 ½”). The test set-up consisted of a four point loading on simple supports.

The maximum load increased over 100% compared to the control beam (unstrengthened) by applying a unidirectional CFRP laminate sheet (0.012”x8”x79”) to the tensile side of the specimens. Also, the deflection of the strengthened beam was 50% less than the control beam. The cracks in the repaired beams were small and closely spaced along the length of the member. This differed from the control beam, which showed a classic reinforced concrete crack pattern of fewer and larger cracks. This study presented the first evidence that FRP laminates could help in the repair of deteriorated concrete beams.

Meier et al. (1991) also studied the failure modes related to FRP repaired beams. A preliminary study dealt with three different failures:

1. Tensile failure of the CFRP sheets.
2. Classical concrete failure in the compressive zone.
3. Continuous peeling-off of the CFRP sheets due to an uneven concrete surface

Tensile failure of the CFRP is described as very sudden and explosive, but is easily predicted due to cracking sounds. Peeling-off of the laminate is caused by vertical displacement across shear cracks in the concrete.

Within the next year, Meier et al. (1992) expanded the possible failure modes to nine. The additional six failures are as follows:

1. Shearing of the concrete in the tensile zone.
2. Interlaminar shear within the CFRP sheet.
3. Failure of the reinforcing steel in the tensile zone.
4. Cohesive failure within the adhesive.
5. Adhesive failure at the interface CFRP sheet/adhesive.
6. Adhesive failure at the interface CFRP concrete/adhesive.

The latter three were not observed but described as “theoretically possible”.

2.2.2 Saadatmanesh & Ehsani

The first full-scale FRP repaired beam test conducted in the United States were at the University of Arizona (Saadatmanesh & Ehsani, 1991). The tests consisted of six large concrete beams; five rectangle cross-sections (8”x18”) and one T-beam (3”x24” flange, 8”x18” web). All the specimens were 192” long and tested as a simple span in four point loading. Steel reinforcement ratios, shear reinforcement, and cambering were varied in the six beams. However, the externally applied GFRP was identical for each beam (1/4”x10”x168”).

The research concluded adding GFRP plates improved the strength and stiffness of the specimens. The tests showed the GFRP sheets carried a portion of the tensile force, which decreased the stress in the steel reinforcement. This was particularly evident with the smaller steel reinforcement ratios.

2.2.3 Deblois et al.

Unidirectional and bi-directional GFRP sheets bonded to concrete beams using epoxy adhesive and a combination of epoxy and bolts were investigated by Deblois et al.

(1992). A series of specimens (5”x5”x40”) reinforced with steel (two 7/16” diameter bars) in the tension region and shear reinforcement consisted of one of the following lay-ups for the GFRP:

1. Bi-directional sheets with epoxy bonding.
2. Bi-directional sheets with combination epoxy and bolt bonding.
3. Unidirectional sheets with epoxy bonding.
4. Combination of unidirectional and bi-directional sheets with epoxy and bolt bonding.

The unidirectional sheets increased the ultimate load by 58% over the control beam, while the bi-directional laminate resulted in a 32% increase. However, the maximum load was reached with a combination of the two sheets. The maximum load of this specimen was 77% larger than the control beam.

The two bonds used with the bi-directional sheets caused very little difference in the ultimate load. The beam bonded with the inclusion of bolts only increased the ultimate load 2% as compared to the epoxy-bonded beam.

Additionally, a larger specimen (8”x12”x160”), strengthened using the combination of the two GFRP sheets, was tested. Similar to the previous results, the maximum load increased 66% over the control beam. Due to the GFRP sheet, the ductility of all the beams decreased along with the deflection at maximum load.

2.2.4 Ritchie et al.

Ritchie et al. (1992) tested sixteen concrete beams (6”x12”x108”) with minimum steel reinforcement (two ½” diameter bars) to study the effects of external strengthening using three different types of FRP; glass, carbon, and aramid fibers. The beams were tested in flexure under four-point loading. Also, an analytical model was developed to predict the strength and stiffness of the FRP strengthened beams.

The results showed an increase in stiffness from 17% to 99% and an increase in strength of 40% to 97% based on the type, amount, and orientation of FRP that was applied to the beam. Also, the predicted and actual behavior showed good agreement, except that the analytical model predicted a slightly stiffer response than was achieved during the tests.

Ritchie et al. also investigated anchorage methods for the FRP. Since the beams in the initial tests failed at the ends of the FRP plate instead of at the constant moment region, a series of anchorage types were developed in hopes to shift the failure to the constant moment region. The first consisted of anchoring the ends of the plate with fiberglass angles. This led to a larger load capacity, but the failure was still located at the ends of the plate. The second method consisted of wrapping FRP plates around the beam at the ends. This type also raised the load capacity, but was unsuccessful in transferring the failure to the constant moment region. The final method consisted of extending the plates up to the supports. This method was very successful in both increasing the load capacity and shifting the failure to the constant moment region.

2.2.5 Norris and Saadatmanesh

Norris and Saadatmanesh (1994) cast thirteen concrete beams for flexural tests to compare three different fiber/epoxy systems and several orientations of fiber. The beams (5”x8”x96”) contained close to the minimal amount of steel reinforcement (two 3/8” diameter bars) and were over-designed against shear. Some beams were pre-cracked before the application of the CFRP to see if pre-cracking caused any substantial differences in behavior. Two types of fiber were tested with 0°, 90°, and ±45° orientations, and the third fiber was used with orientations of 0°/90° and ±45° with respect to the longitudinal axis. The same fiber weight was applied to every beam.

The research showed little difference in the results between the fiber types or the behavior between pre-cracked and uncracked beams, but the different fiber orientations provided amiable results. The unidirectional fibers (0°) yielded the largest strength and stiffness increase and deflection decrease with respect to the control beam. These beams failed very abruptly due to the peeling-off of the CFRP. The 0°/90° fibers had a maximum strength which was 20% less than the unidirectional, but showed much more ductility and deflection (40% greater than 0°). They also failed less explosively than the unidirectional fibers. A 45% decrease in strength and stiffness occurred with the ±45° laminate compared to the 0° orientation. However, the ±45° laminate experienced much more ductility than the other lay-ups. Failure of the beam applied with ±45° laminate acted in such a slow, ductile manner that loading had to be stopped.

Norris et al. concluded that off-axis CFRP laminates need to be studied at length. Use of different orientations could increase the strength and stiffness of concrete beams without causing catastrophic, brittle failures associated with unidirectional laminates. Also, they may provide ductile yielding properties that are very important in the civil engineering field.

2.2.6 Shahawy et al.

Shahawy et al. (1995) assessed the effectiveness of external reinforcement in terms of the cracking moment, maximum moment, deflection, and crack patterns. Four beams (8”x12”x108”) were tested using minimum steel reinforcement (two ½” diameter bars) and varying the layers of unidirectional CFRP. Also, non-linear finite element computer model was used to compare to the results of the experiment.

The cracking moment of the CFRP repaired beams was much larger than that of the control beam. For one, two, and three layers of GFRP, the cracking moment increased 12%, 61%, and 105%, respectively. The maximum moment also became larger and corresponded well to the theoretical data. A 13%, 66%, and 105% increase was observed for the three different layers. This showed the CFRP behaved similarly before and after cracking of the beam.

The deflection and cracking patterns showed results similar to experiments previously discussed. The deflection decreased inversely with the number of CFRP layers on each beam. This, alternatively, caused the stiffness to increase. The cracking patterns between the control and the CFRP repaired beams exhibited different patterns. The control had wider cracks while the repaired beams showed smaller cracks at relatively close spacing. This shows an enhanced concrete refinement due to the CFRP sheets.

2.2.7 M'Bazaa et al.

The research by Bazaa et al. (1996) was based on optimizing the length and orientation of the CFRP to increase beam strength and ductility. Eight beams (8"x12"x120') were minimally reinforced with steel (two 7/16" diameter bars) and over-designed for shear to cause a flexural failure. One beam was used as a control while the others were bonded with three layers of CFRP (0.012"x6.6"). The sheets varied in length and orientation of the fibers. Four had unidirectional fibers with different lengths, and the other three had various fiber directions with regard to the longitudinal direction (±6°, ±9°, ±12°).

The results of the experiment showed an increase in strength and stiffness and a decrease in deflection as compared to the control beam. All failures occurred at a load at least 57% higher than the control beam. The stiffness was similar until the cracking moment. At this point, less deflection was observed in the repaired beams. The load versus deflection plots exhibit three different section modulus; the start of the experiment to first crack, first crack to yielding of the steel began, and yielding of the steel to failure of the member.

The use of small angle, off-axis laminates and different CFRP sheet lengths had no effect on strength or stiffness of the repaired beams. However, the off-axis CFRP provided improved warning of failure due to a cracking sounds.

2.3 Need for Research

Past research concluded applying FRP to the tensile face of a reinforced concrete beam increases the stiffness and load capacity and decreases the deflection of reinforced concrete beams. An important property in the civil engineering field that has not been the focus in much of the previous experimental research is ductility. This thesis will focus on examining the ductility and strength of reinforced concrete beams applied with different amounts of cross-ply and off-axis CFRP.

Also, a common trend found with most of the research is the use of minimum steel reinforcement in the design of the experimental beams. Although this procedure provides the largest percent increase in load capacity and stiffness, the effect of FRP on beams with larger amounts of steel reinforcement should also be studied. This thesis will use specimens with a relatively larger amount of steel reinforcement than seen in a majority of the past research.