

# An Overview of Sprayed FRP Retrofitting and Strengthening of RC Structures

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## SUMMARY

The present paper summarizes an overview paper (Lee and Ha, 2007) recapitulating representative papers regarding the previous and on-going researches on sprayed FRP retrofitting and strengthening of RC structures. A series of experiments to characterize tensile strength, shear bond behavior and anchor/bond capacities of the sprayed FRP coating are summarized. Application of sprayed FRP coating to full-scale RC structures conducted by researchers is then reviewed to assess the applicability of sprayed FRP retrofitting and strengthening method.

**Keywords:** *Sprayed FRP Coating; Strengthening and retrofitting performances; RC structures*

## INTRODUCTION

The existing concrete structures in service may have been damaged by increased external loads, insufficient maintenance and chemical processes caused by harsh environmental conditions, etc. (Capozucca and Cerri, 2002). In response to growing needs for strengthening and rehabilitation of concrete structures, many researchers have considered application of fiber-reinforced polymer (FRP) (laminated) sheets/strips as an effective strengthening and rehabilitation method. FRP sheets/strips have many advantageous engineering characteristics such as high strength-to-weight and stiffness-to-weight ratio, corrosion resistance, easy application and construction (Young and Harries, 2000).

Many researchers (Meier, 1987; Ritchie et al., 1991; Triantafillou and Plevris, 1992; Saadatmanesh and Eshani, 1991; Sharif et al., 1994; Al-Sulaimani et al., 1994; Chajes et

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al., 1995; Takeda et al., 1996; Alexander, 1996; Arduini and Nanni, 1997; Norris et al., 1997; Garden and Hollaway, 1998; Khalifa and Nanni, 2002; Karbhari, 2004) have conducted various experiments on concrete structures strengthened with FRP sheets/strips. The method using carbon FRP plates to strengthen concrete structures was suggested firstly by Meier (1987) at Swiss Federal Laboratory for Materials Testing and Research (EMPA). Saadatmanesh and Eshani (1991) experimentally investigated the effectiveness of glass-FRP plates on tension face of the RC beams. The influence of plate end anchorage in carbon FRP plates installed to strengthen RC beams was investigated by Garden and Hollaway (1998). From their study, it was shown that the anchorage benefited composite action between the plate and the beam by providing better structural stiffness. Khalifa and Nanni (2002) examined the shear performance and failure modes of rectangular simply supported RC beams designed with shear deficiencies.

FRP sheets or plates exhibit relatively small strains at rupture and behave in a linear manner to rupture (Kestner et al., 1997). Further, anchorage is generally needed to obtain a good bonding between the FRP sheets or plates and concrete, resulting in conservative design parameters and the use of large amounts of expensive materials with expensive installation (Lee and Hausmann, 2004).

Since the mid-90s, a new method of retrofit using composites in an innovative technique, the use of composites in a spray gun with a chopper unit, has been studied for strengthening and rehabilitation of deteriorated concrete structures (Banthia et al., 1996, 2002; Caibal et al., 2003; Harries and Young, 2003; Lee and Hausmann, 2004; Ross et al., 2004; Lee, 2004; Lee et al., 2005; Kanakubo et al., 2005; Boyd et al., 2006; Lee et al., 2007). The present paper summarizes an overview paper (Lee and Ha, 2007) recapitulating representative papers regarding the previous and on-going researches on sprayed FRP retrofitting and strengthening of reinforced concrete (RC) structures. A series of experiments conducted to characterize tensile strength, shear bond behavior and anchor/bond capacities of the sprayed FRP coating are summarized. Application of sprayed FRP coating to full-scale RC structures conducted by researchers is then reviewed to assess the applicability of sprayed FRP retrofitting and strengthening method.

## OVERVIEW OF SPRAYED FRP COATING

A new method of strengthening system using the sprayed FRP coating was firstly introduced by Banthia and his group at the University of British Columbia in 1996. The innovative method consisted of resin (e.g., epoxy or polyester resin) and short, randomly distributed fibers in a polymer matrix (Young and Harries, 2000; Banthia, 2002; Hausmann, 2003; Lee and Hausmann, 2004). The epoxy base and activator resins (polyester resin and catalyst) are transferred separately to the mixing part where they are mixed well and moved to a spray gun, and then epoxy system was sprayed as a single stream (Banthia, 2002; Lee et al., 2007). Simultaneously, glass fibers are fed to a chopper unit fixed on the spray gun, where one or two strands of glass fiber goes through between a rubber roller and a steel roller with several rolling blades placed at equal distances

(Banthia, 2002; Lee et al, 2007). The two streams of chopped fiber and epoxy resins were mixed in the air and applied onto the surface to concrete then sprayed FRP coating layer on the surface of concrete (Banthia, 2002; Lee et al, 2007). Details of application of the sprayed FRP coating can be found in Young and Harries (2000), Banthia (2002) and Lee and Hausmann (2004).

## CHARACTERIZATION OF SPRAYED FRP COATING

### Tensile strength test

A series of tensile tests were conducted by Caibal et al. (2003) to investigate the mechanical properties of sprayed FRP coating. From the tests conducted in accordance with JIS K 7054 Testing Method for Tensile Properties of Glass Fiber Reinforced Plastics, the stress-strain relationship of the sprayed FRP coating was obtained. The stress of the sprayed FRP coating was determined by dividing the measured load by the ruptured section. Three different fiber lengths (13mm, 26mm, 52mm) and a fixed volume fraction of fibers (20%) were used in their study. Five specimens for each fiber length were tested by 300kN testing machine. Little deviations were observed from the stress-strain curves of the specimens having 13mm fiber length, while the specimens having 52mm fiber length showed a modest deviation in their stress-strain curves (Caibal et al., 2003).

High elastic modulus was observed with the specimens having 52mm fiber length, whereas high strain value at failure was observed with the specimens having 26mm fiber length (Caibal et al., 2003).

### Shear bond test

Shear bond test was also carried out by Caibal et al. (2003) to measure the shear stresses along the interface between the concrete and sprayed FRP coating. A total of sixteen strain gauges were used to measure the strain and Pi gauge was used to measure the displacement at the center of the sample, and the maximum load, elastic modulus, average thickness and stiffness of the sprayed FRP were computed from the shear bond test (Caibal et al., 2003).

The experimentally measured maximum load and highest stiffness of the sprayed FRP coating were 40.2 kN and 32.92 kN/mm, respectively (Caibal et al., 2003). They also demonstrated that the stiffness of the sprayed FRP coating was increased as the maximum loads continued to increase.

### Anchor/bond test

Kanakubo et al. (2005) investigated the effectiveness of FRP filled slits as an anchor. The test variable was the size of slits. The concrete prism specimens (100 x 100 x 600mm)

for the anchor/bond test was cracked at the center after strengthening with the sprayed FRP coating (see Figure 6 of Kanakubo et al. (2005)). As seen from the figure, the two steel bars were not connected and the two prisms were connected through the sprayed FRP coating.

Specimens in Group 1 were designed to have no slits to measure the pure bonding strength between the sprayed FRP coating and concrete. Specimens in Groups 2, 3 and 4 had sprayed FRP filled slits having a depth of 5, 10 and 20 mm, respectively. Three specimens were cast for each group. The tests were conducted under displacement control at a constant head-loading rate. Specimens in Group 1 were fractured by debonding between the sprayed FRP coating and concrete. Specimens in Groups 2, 3 and 4 were failed by rupture in the sprayed FRP coating or shear failure in concrete. The measured maximum load of specimens in Group 1 was 20.6kN (on average), but the anchoring strength of the sprayed FRP filled slit was not determined since specimens in Group 2, 3, 4 were failed by rupture in the sprayed FRP coating or shear failure in concrete (Kanakubo et al., 2005).

## **STRENGTHENING PERFORMANCE OF SPRAYED FRP COATING**

### **Bending test of beams strengthened with sprayed FRP coating**

Lee and Hausmann (2004) investigated the strength and ductility aspects of damaged and undamaged RC beams retrofitted with sprayed FRP coating and to assess the feasibility of using sprayed FRP coating for repair/strengthening of RC beams. The dimension of RC beams was 100x100x450 mm, complying with ACI446 and ASTM C293 requirements. “Some of the RC specimens were precracked to model deteriorated concrete structures. The initial crack was induced by using the MTS machine at a loading rate of 0.375 mm/s and the maximum limit of applied load of 10 kN” (Lee and Hausmann, 2004).

“The concrete surface receiving sprayed FRP coating was sandblasted to remove any debris and etches so that a high quality of bond process between the concrete surface and sprayed FRP coating can be assured. The resin used in this procedure was T-301 Epoxy Spray System developed by Warren Environmental, which is highly chemical resistant and has a high thixotropic index that allows a buildup of up to 6.25 mm (1/4 in.) on vertical surfaces without sagging. The fibers used in this study were multi-filament E-glass strand roving and pitch-based carbon fibers. The specimens were tested after two weeks of curing, as recommended by the manufacturer. The loading capacity and energy absorption are dependent on many parameters. The parameters under this investigation include coating thickness (3.2 and 6.4 mm), fiber volume fraction (15% and 30%), fiber type (E-glass and carbon fibers), fiber length (13 and 26 mm) and precracked and uncracked specimens. The findings of the experimental study can be summarized as follows:

1. Coating thickness has a significant influence on the peak load, ductility and energy absorption capacity of RC beams. A more ductile failure with a significant increase in energy absorption capacity was observed with a thicker coating.
2. An appropriate fiber length near 26 mm will maximize the increase in load carrying and energy absorption capacities of RC beams.
3. Moderate volume fraction of fibers (up to 30%) is desirable for increasing the ductility and energy absorption of RC beams.
4. Carbon fibers lead to higher increase in load carry ability and lower increase in energy absorption for both damaged and undamaged RC beams due to their brittle characteristics compared to E-glass fibers.
5. The variation of the temperature on the epoxy resin during sprayed FRP application affects in a significant manner the performance of the retrofitted specimen.” (Lee and Hausmann, 2004)

The effectiveness of anchorage used to enhance the bonding capacity between the sprayed FRP coating and the application face was investigated by Lee (2004). A series of three point bending tests were carried out on notched plain concrete (PC) specimens retrofitted with sprayed FRP layer and anchors. From the load deflection curves of the specimens having a anchor spacing of  $l_a = 100\text{mm}$  and the specimens having a anchor spacing of  $l_a = 200\text{mm}$ , it was shown that 115% and 152% increases in average peak load over the notched PC control beams were observed with specimens having a anchor spacing of  $l_a = 100\text{mm}$  and 200mm, respectively (Lee and Hausmann, 2004).

### **Anti-symmetrical loading test of columns strengthened with sprayed FRP coating**

Anti-symmetrical loading test of columns strengthened with sprayed FRP was conducted by Kanakubo et al. (2005). The dimension of four specimens was 300mm (wide)  $\times$  300mm (deep). Four different retrofitting schemes were used: a sprayed carbon FRP coating, a sprayed glass FRP coating, a carbon fiber sheet with one layer, and glass fiber sheets with four layers (Kanakubo et al., 2005). Anti-symmetrical bending moment in a cyclic manner was applied on each specimen.

The results showed that the glass FRP sheets showed the most superior deformation capability. The deformation capabilities were declined in the order of the sprayed carbon FRP coating, the sprayed glass FRP coating, and the carbon FRP sheet. The findings of their study are the following (Kanakubo et al., 2005).

1. Both repair systems using sprayed carbon FRP coating and sprayed glass FRP coating with vinyl ester resin were shown to be effective in strengthening of RC structures.
2. Overall, similar deformations and ultimate strengths were observed with the columns reinforced with the sprayed FRP coating and the carbon FRP sheet.
3. The FRP filled slit was shown to be effective as an anchor system.

## **APPLICATION OF SPRAYED FRP COATING TO FULL-SCALE RC STRUCTURES**

### **Channel Beam**

Ross et al. (2004) investigated two different types of glass FRP retrofit materials (a traditional fabric warp and a sprayed coating) experimentally and numerically. Three different channel beams were tested. One channel beam was tested without retrofitting, one beam was retrofitted with sprayed glass FRP coating, and one beam was retrofitted with a bonded glass FRP fabric system (Ross et al., 2004).

The elastic (tensile) modulus, ultimate tensile strength and ultimate tensile elongation capacity of sprayed glass FRP coating were 12,000 MPa, 110 MPa and 1.25%, respectively (Ross et al., 2004). The sprayed glass FRP coating was isotropic, whereas the glass fiber wrap was orthotropic. Each beam had different level of damage prior to testing for comparison. 25% and 41% increases in flexural stiffness were observed with the sprayed glass FRP coating and the bonded glass FRP fabric system, respectively (Ross et al., 2004). It was shown from the investigation that the use of two different types of glass FRP retrofit materials significantly increased the ultimate flexural capacity of channel beam bridge girders (Ross et al., 2004).

98% and 36% increases in ultimate flexural capacities were observed with the sprayed glass FRP coating and the bonded glass FRP fabric system, respectively (Ross et al., 2004). The effectiveness of retrofitting with a sprayed glass FRP coating having a thickness of 10 mm and two layers of glass FRP wrap having 0°/90° orientation were also compared, and it was seen that the sprayed glass FRP coating had a better retrofitting capacity than the glass FRP wrap (Ross et al., 2004).

### **PC Girders**

Boyd et al. (2006) investigated the flexural stiffness and capacity, and deflection of the prestressed concrete (PC) girders to determine whether the sprayed FRP coating was an appropriate repair system for PC girders subject to impact damage. Each girder contained 22 prestressing strands, oriented in three layers within the bottom portion of the section (Boyd et al., 2006).

The first girder was an undamaged control beam, and remaining two girders were subjected to a procedure designed to affect the damage caused by over-height vehicles striking (Boyd et al., 2006). The second control specimen was subjected to the simulated damaging procedure but received no FRP retrofit, and the last girder having the simulated damages was retrofitted by the sprayed FRP coating (Boyd et al., 2006).

Significant increases in initial stiffness (up to 89.5%), cracking load (up to 95.4%), and ultimate load (up to 95.0%) were observed with the sprayed FRP coating, and mid-span deflection of the girders were also measured at both the cracking and ultimate loads (Boyd et al., 2006).

## CONCLUSION

An overview of sprayed FRP retrofitting and strengthening of RC structures has been presented. A series of experiments to characterize tensile strength, shear bond behavior and anchor/bond capacities of the sprayed FRP coating, and application of sprayed FRP coating to full-scale RC structures conducted by researchers (Banthia et al., 1996, 2002; Caibal et al, 2003; Harries and Young, 2003; Lee and Hausmann, 2004; Ross et al., 2004; Lee, 2004; Lee et al., 2005; Kanakubo et al., 2005; Boyd et al., 2006; Lee et al., 2007) are reviewed to assess the applicability of sprayed FRP retrofitting and strengthening method.

The results showed that the sprayed FRP retrofitting and strengthening method was very effective in increasing the load carrying and energy absorbing capacities of the concrete structures. However, significant research work still needs to be conducted in the future to accelerate the introduction of sprayed FRP coating to the repair and strengthening of bridges and other civil infrastructures.

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