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Effect of Corner Radius on the Performance of Externally Bonded FRP Reinforcement

XINBAO YANG
Research Assistant, Department of Civil Engineering, University of Missouri-Rolla,
Rolla, MO 65409, USA

ANTONIO NANNI
V. & M. Jones Professor, Department of Civil Engineering, University of Missouri-Rolla,
Rolla, MO 65409, USA.

GENDA CHEN
Assistant Professor, Department of Civil Engineering, University of Missouri-Rolla,
Rolla, MO 65409, USA.

ABSTRACT

Externally bonded FRP reinforcement is wrapped around concrete members in order to provide confinement and/or shear strengthening. The need for bending the fibers over the member corners affects the performance of the FRP laminate and the efficiency of its confining/strengthening action. This paper presents an experimental study focusing on the effects of corner radius on FRP mechanical properties. A unique re-usable test device was designed and used for this purpose such that plies of FRP could be applied over interchangeable corner inserts. The radius of the inserts ranged from a minimum of 0 to a maximum of 50.8 mm, and one or two plies of carbon FRP were used. The monitored parameters were strain distribution in the FRP laminate and load. It was found that only a portion of the CFRP laminate capacity was developed when failure occurred at the corner. Increasing the number of plies from one to two slightly improved the efficiency of the laminate.

INTRODUCTION

Advanced composite materials have been extensively used in the rehabilitation of concrete structural members. One practice is to externally wrap beams and columns with fibers impregnated with a resin-based matrix to increase the strength and deformation performance of the member. For example, FRP jackets may be used to wrap the potential plastic hinge of bridge columns in seismically active regions, where fibers can be regarded as continuously distributed transverse reinforcement. The ultimate strain of concrete and its pseudo-ductility can be significantly increased with negligible cumulative damage to the composite jacket under cyclic loading.

Externally bonded laminates have to be bent when wrapped around columns and beams. Bending affects performance of the FRP laminate and the corresponding confinement action depending on the curvature radius of the corners (Rochettee et al. 2000, Restrepo et al. 2000). In this paper, an experimental investigation was conducted to study the effects of corner radius on the FRP performance. A unique reusable test device was designed for this purpose, around which FRP laminates can be wrapped. By changing its corner inserts, different curvatures in the laminate can be simulated. A tension test was then performed until failure of the FRP laminate.

EXPERIMENTAL PROGRAM

Material Properties

High tensile strength carbon fiber tow sheets (MBrace, 1998) were used and impregnated using a two-part epoxy polymer saturant provided by the manufacturer. The low bound mechanical properties of the resulting CFRP laminate according to manufacturer's literature are listed in Table 1. These properties are determined and the experimental results of this project are analyzed based on the fiber cross sectional area rather than the composite area. This is due to the following reasons: (a) the laminate is fabricated using the manual lay-up technique and it is rather difficult to control the amount of resin; (b) small variations in the amount of resin, provided that the fibers are fully impregnated, do not affect the composite mechanical performance, and (c) mechanical properties of the resin are significantly lower than those of fibers.

Table 1: Manufacturer provided CFRP properties

Ultimate strength (MPa)	4275
Design strength (MPa)	3790
Tensile modulus (GPa)	228
Ultimate strain (mm/mm)	0.017

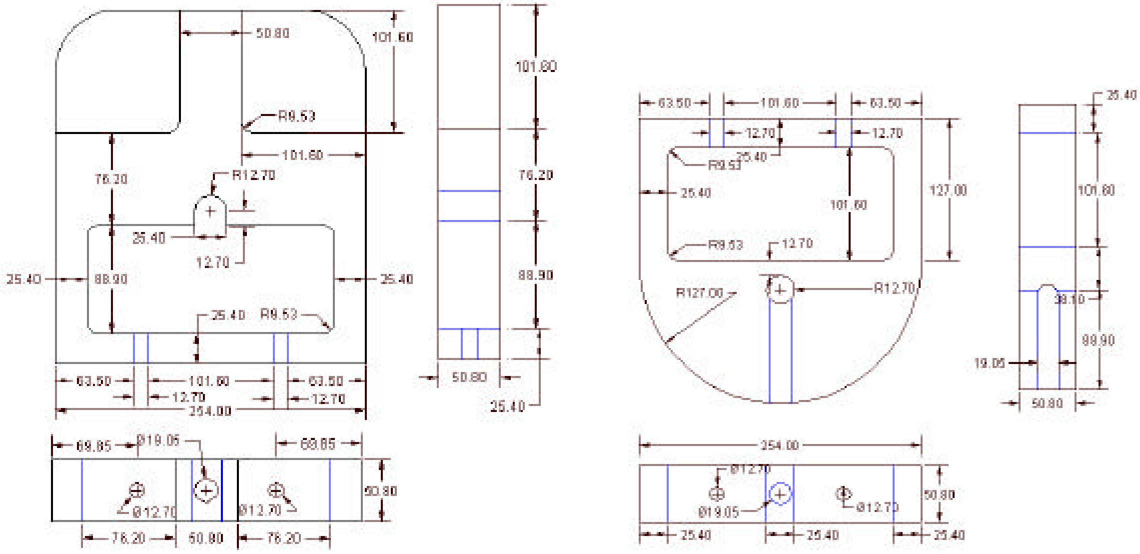
Design of Test Specimen

In order to simulate the force transfer mechanism of FRP wrapping a cross section via running tension test, a unique reusable test device is designed and manufactured based on the following considerations: (a) the mechanical interaction between FRP laminate and device should be similar to that of wrapped concrete members for a meaningful correlation; (b) the device should be suitable for different corner radii; and (c) failure should occur in the test zone. A detailed drawing of the two-part steel device is illustrated in Figure 1.

The upper part is designed as the test zone with two interchangeable aluminum corner inserts separated by a 51 mm wide steel. It has a uniform thickness of 51 mm while the overall width and height are 254 mm and 292 mm, respectively.

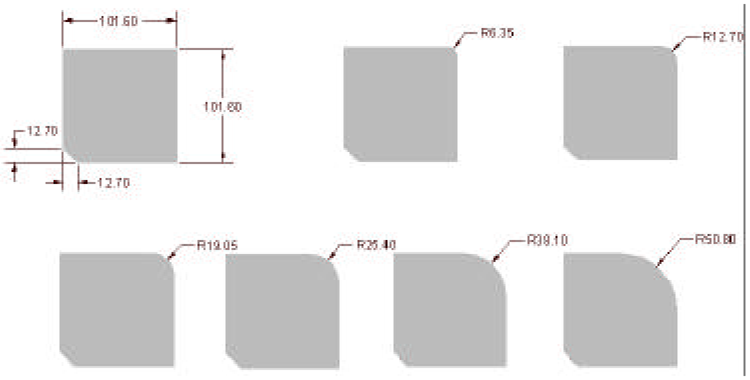
The corner inserts are made of aluminum and have overall dimensions of 102 x102 mm. The corner radii investigated in this research include: 0.00, 6.35, 12.70, 19.05, 25.40, 38.10, and 50.80 mm. The largest radius of 50.80 mm corresponding to half of the width of the corner insert can be used to simulate a circular cross section. The corner inserts are glued to the steel part to prevent any movement during testing.

The lower part of the device is designed to anchor the FRP laminate. The semi-circular bottom steel block has a radius of 127 mm under which the FRP laminate is terminated with a lap splice length of 152 mm. Because the radius of the semi-circle is considerably larger than that of all corner inserts, no failure would be expected within the anchor zone.



Upper part

Lower part



Interchangeable corner inserts

Fig. 1 Test apparatus (Unit: mm)

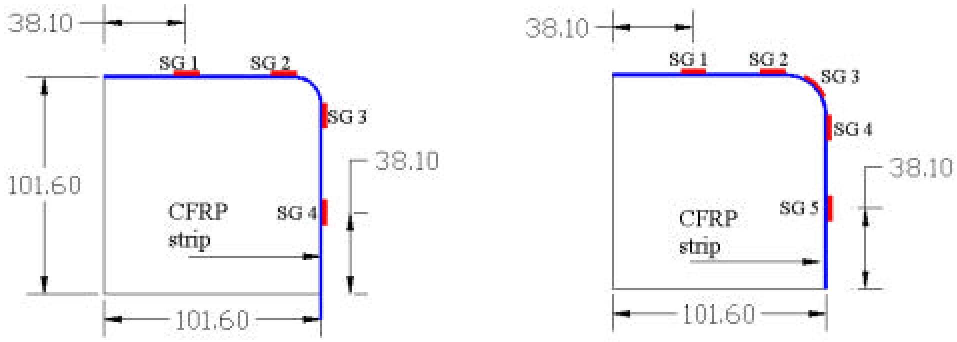
Prior to the installation of the FRP laminate, these two parts are joined using two through bolts. After the device is installed on the testing machine, the nuts on these bolts are loosened so that the tensile load is transferred to the FRP laminate. The loose bolts were also used as safety feature to hold the device after rupture of the laminate.

Installation of Laminate

After placing two identical aluminum corner inserts, the side surface of the device was covered with polyethylene tapes. The polyethylene tape was used as the release film to facilitate detaching of the FRP laminate from the steel surface after completion of the test. A strip of FRP laminate was 38.1 mm wide and 1.68 m long. The laminate was applied by the manual lay-up procedure. The two-part saturant was thoroughly mixed and a thin layer was applied on both the polyethylene tape and the carbon fiber sheet using a sponge brush. Through careful handling, the carbon fiber ply was wrapped around the specimen and lap-spliced at the bottom. Then, the backing paper was removed after application of gentle pressure. A plastic roller was used to remove the air entrapped between fiber ply and saturant. After approximately 30 minutes, a second layer of saturant was applied and the plastic roller was used again to work the resin into the fibers. The wet laminate was left to cure for three days and then strain gages were attached. Two or three identical specimens were manufactured for each set of corner inserts.

Instrumentation

Strain gages were used to measure the strains at multiple points around each corner. The first gage was placed 38.10 mm away from the root of the corner on the flat part of the upper and side surfaces. Another two gages were positioned with one end exactly at the curvature changing point of the upper and side surfaces, respectively. For those laminates with corner radius larger than 19.05 mm, a fifth strain gage was attached at the center of the corner arc. Load was monitored by the built-in load cell in the testing machine. The strain gage arrangements for laminates with different corner radius are shown in Figure 2 and an instrumented specimen ready for testing is shown in Figure 3.



R=12.70mm R=19.05mm

Fig. 2 Strain gage arrangement

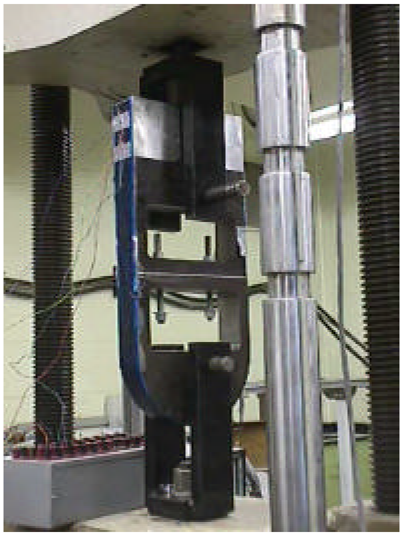


Fig. 3 Test setup

TEST RESULTS

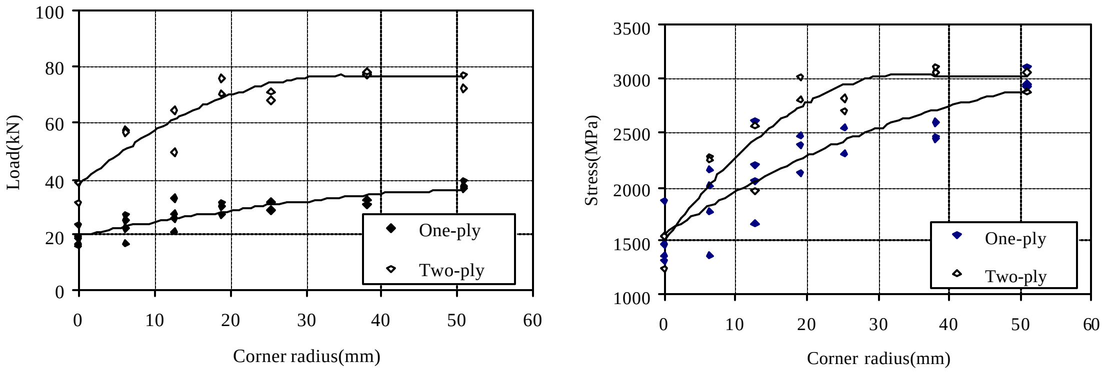
Strength of CFRP laminates

The average ultimate load carried by CFRP laminates for different corner radii is shown in Table 2. The individual data points of load and stress versus corner radius are depicted in Figures 4(a) and (b). The average ultimate load increases with corner radius for both one and two-ply laminates. The ultimate load capacity of two-ply specimens is more than twice that of the corresponding one-ply specimen with two exceptions: corner radii of 0 and 50.80 mm, which represent the square and circular section, respectively.

Table 2 Average ultimate results

One-ply							
R (mm)	0	6.35	12.70	19.05	25.4	38.10	50.80
Load (kN)	19.03	22.92	26.86	29.39	30.56	31.46	37.72
Stress (MPa)	1513	1822	2135	2336	2429	2501	2999
Percentage of reference strength*	33	40	47	52	54	55	66
Strain(%)**	0.65	0.96	1.05	1.01	1.00	0.98	1.10
Elastic Modulus (GPa)	233	188	203	234	243	255	273
Failure mode***	I	I	I	I or II	II	II	II
Two-ply							
R (mm)	0	6.35	12.70	19.05	25.4	38.10	50.80
Load kN)	34.92	57.00	56.94	73.24	69.62	77.62	74.73
Stress (MPa)	1388	2266	2263	2911	2767	3086	2970
Percentage of reference strength*	31	50	50	64	61	68	66
Strain(%)**	0.50	0.96	0.92	1.12	1.18	1.25	1.25
Elastic Modulus (GPa)	278	236	246	260	234	247	238
Failure Mode***	I	I	I	I	II	II	II

* 4525MPa, ** average from all gages, *** I: at corner, II: at flat portion



(a) Ultimate load

(b)Stress

Fig. 4 Ultimate load and stress vs. corner radius

The performance of the laminate is analyzed by comparing the stress-strain relationships with the reference one obtained through direct tension testing of CFRP coupons (Yang et al. 2000). The strain values reported in Figure 5 are those measured on the flat part of the side surface. It can be seen that even though the diagrams (with the exception of two-ply R = 50.80 mm) are almost the same for all specimens, only 67% of the reference strength (or strain) can be attained. When R is equal to 6.35 mm, only half the strength was developed, corresponding to a strain of less than 1%. The laminate stiffness (modulus of elasticity) when wrapped is less than that of the straight form.

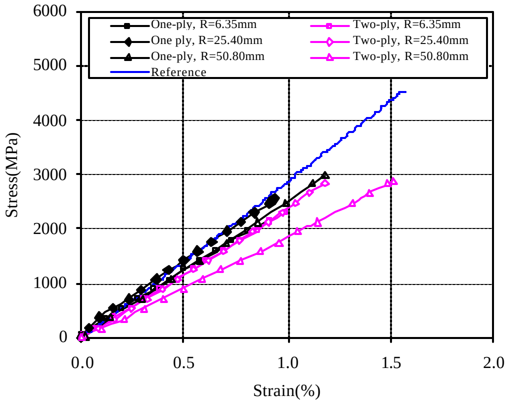
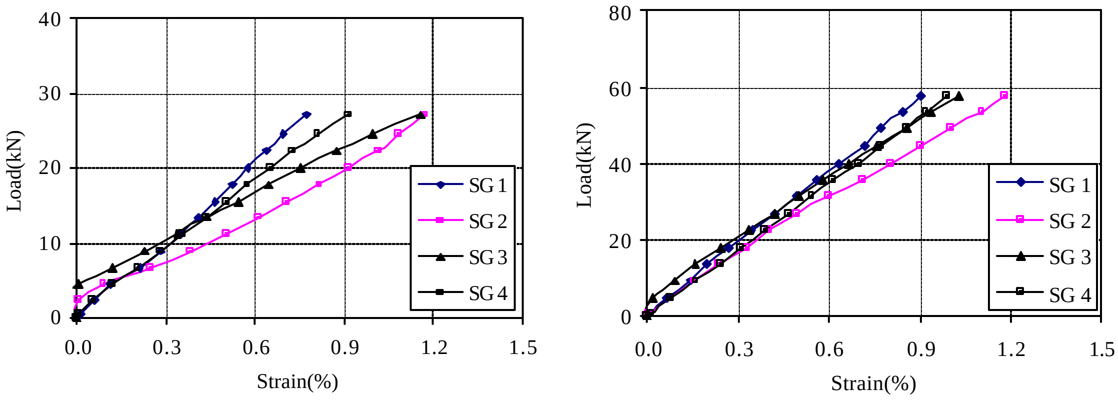


Fig. 5 Stress-strain curves of CFRP laminates

Strain Distribution

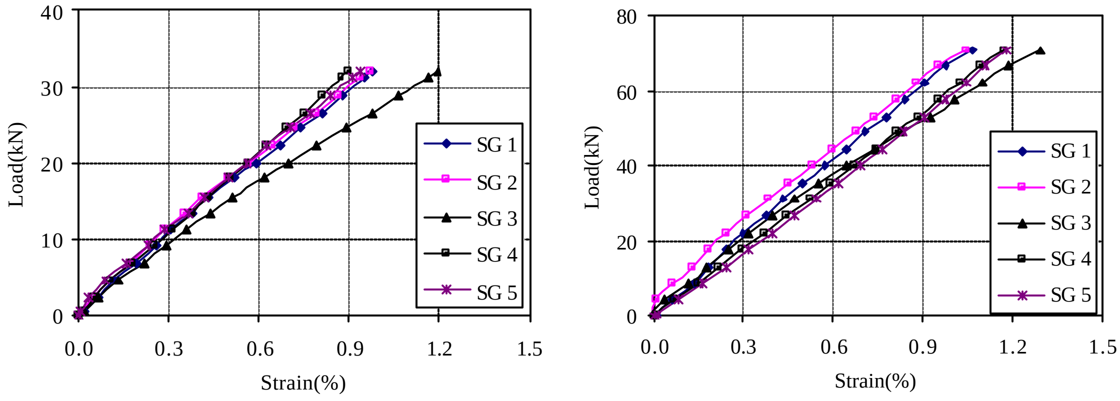
The strain at various locations around the corner is presented in Figure 6 for different corner radii of 6.35, 25.4, and 50.80 mm and different numbers of plies. Generally, the difference in strain values is insignificant and the ultimate strains are between 0.9% and 1.2%, which is smaller than the design value of 1.7% (MBrace 1998). For the small corner radius (R=6.35 mm), the largest strain occurs at the corner indicating the occurrence of stress concentration. As radius of the corner inserts increases, the location of the maximum strain shifts from the center of the corner (R=25.4 mm) to the flat portion of the side surface (R=50.80 mm). The strain difference at various locations is smaller for larger corner radii. One possible reason for this phenomenon is the presence of the release agent, which made the friction between CFRP laminates and the steel surface small and created a relatively smooth force transfer.



One-ply, R=6.35mm

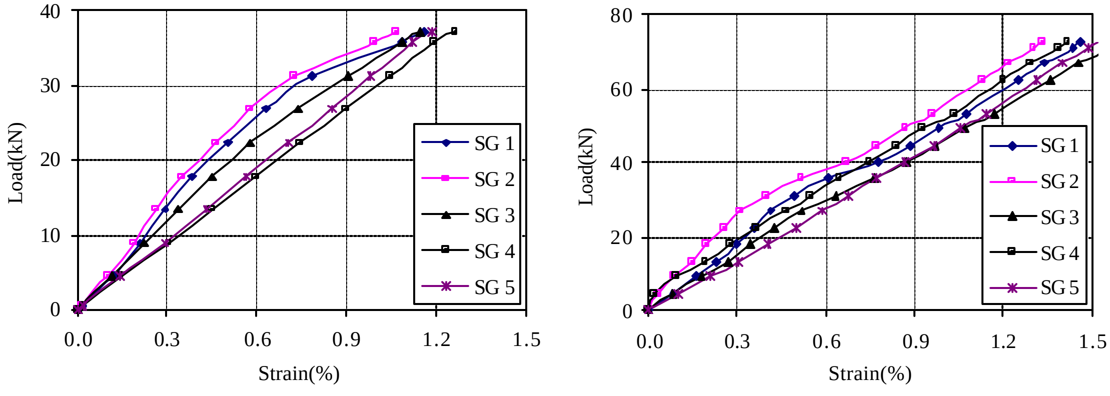
Two-ply, R=6.35mm

Fig. 6 Strain distribution around a corner



One-ply R=25.40mm

Two-ply R=25.40mm



One-ply R=50.80mm Two-ply R=50.80mm

Fig. 6 Strain distribution around a corner (cont.)

Failure Modes

One- and two-ply CFRP strips failed in a brittle manner. Three different failure modes were identified: fracture at one corner; simultaneous fracture at both corners; and fracture at the flat portion of the surface. The first failure mode mainly happened in cases of small corner radius. The other modes were typical in laminates bent around larger radii. The fractured laminates for different corner radius are illustrated in Figure 7.

R=0.0 mm R=6.35 mm R=19.05 mm

Fig. 7 Failure modes of CFRP laminates

R=25.4 mm R=38.10 mm R=50.80 mm

Fig. 7 Failure modes of CFRP laminates (cont.)

CONCLUSIONS

The experimental investigation on the effect of corner radius on the performance of CFRP laminates yielded the following conclusions:

- Corner radius plays an important role on the mechanical properties of CFRP laminates. Test results indicate that at best only 67% of the ultimate laminate strength can be developed when wrapped around a circular section. As the corner radius decreases, the efficiency of FRP wrapping further reduces.
- Multiple placement of FRP plies can slightly increase the strength of bent CFRP laminates and improve the overall strengthening performance except for the square or rectangular sections.

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