A Hybrid Composite System for Strengthening Concrete Columns

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ABSTRACT

Strengthening existing concrete columns using fiber-reinforced polymers (FRP) in the form of longitudinal near-surface-mounted (NSM) bars has not gained that much attention due to the possibility of premature crushing and/or buckling of NSM bars. This paper investigates a hybrid system using both NSM and wrapping methods to prevent the premature failure and extend the contribution of NSM bars due to extended strain of confined concrete. A total of 21 plain concrete cylinders (150 mm x 300 mm) were prepared, strengthened, and tested to characterize the performance of the hybrid system. Multiple glass FRP (GFRP) bars (#4) were mounted in 20 mm by 20 mm surface grooves, and unidirectional basalt FRP (BFRP) was used to wrap the specimens. The specimens were instrumented with multiple strain and displacement gauges and loaded under uniaxial compression. It was shown that the wrapping system effectively prevented the premature failure and extended the contribution of NSM bars, significantly.

INTRODUCTION

The structural engineering profession has seen a shift in focus towards durability, structural maintenance and rehabilitation. Aging steel-reinforced concrete infrastructure creates a great demand for this research, especially structural members exposed to harsh environments. Strengthening concrete beams and slabs using fiber-reinforced polymers (FRP) near-surface mounted (NSM) has gained a lot of research interest due to promising results (De Lorenzis and Nanni 2001; Hassan and Rizkalla 2003). However, the method has not been effectively implemented for concrete columns due to the possibility of buckling of NSM bars/strips. On the other hand, FRP-wrapping has been successfully used to enhance axial capacity of concrete columns with limited effect on bending performance. As a majority of columns are subjected to both combined axial load and bending moment, it is crucial for practicing engineers to enhance both axial and bending capacities. The longitudinal NSM bars provide flexural strength and the transverse FRP wraps provide lateral support for the NSM bars and confinement for the concrete core. The FRP wrap also provides additional shear strength and protects the concrete core and existing steel bars against harsh environments. The hybrid system can provide a durable and cost-effective solution for rehabilitation of bridge and waterfront structures.

ACI 440.2R (2017) defines a NSM system as circular or rectangular bars or plates installed and bonded into grooves made on the concrete surface. Two common FRP bar types have been used for NSM applications, namely round bars and rectangular bars/plates/strips. They are usually manufactured using pultrusion processes and typically delivered to the site in the form of either single bar or a roll. A suitable adhesive should be used to bond the FRP bar into the groove to be cured in-place. The adhesive provides a shear transfer between the concrete substrate and the NSM FRP. ACI 440.2R considers FRPs only in tension and ignores any contribution of FRP bars/strips in concrete under direct compression. Per ACI 440.2R, while FRP materials can support compressive stresses, there are numerous issues surrounding the use of FRP for compression. Microbuckling of fibers can occur if any resin voids are present in the laminate. Laminates themselves can buckle if not properly adhered or anchored to the substrate, and highly unreliable compressive strengths result from misaligning fibers in the field. It is acceptable, however, for FRP tension reinforcement to experience compression due to moment reversals or changes in load pattern. The compressive strength of the FRP reinforcement, however, should be neglected. ACI 440.1R (2015) also neglects the compressive contribution of internal FRP bars based on the same approach.

On the other hand, there are numerous experimental studies indicating that internal FRP bars can support a significant level of compressive strain if sufficient lateral support is provided. Tobbi et al. (2012) tested large-scale columns and concluded that glass FRP (GFRP) bars could be used in compression members if adequate transverse bars are provided to eliminate bar buckling. Recently, Karim et al. (2016) found that longitudinal GFRP bars improved the peak load and the ductility of the columns. Also, Hadhood et al. (2017) reviewed and discussed the compressive contribution of GFRP bars and found that ignoring the contribution of the compression GFRP bars underestimated the nominal axial load and moment capacity of the tested columns. More recently, Fillmore and Sadeghian (2017) found that the elastic modulus of GFRP bars in compression is slightly higher than that in tension; however, the compressive strength was obtained at 67% of tensile strength. Moreover, Khorramian and Sadeghian (2017) showed that GFRP bars can be considered as load bearing longitudinal reinforcement of concrete columns and ignoring their effect is not necessary.

In terms of a NSM system for strengthening reinforced concrete (RC) columns, there are very limited studies. Bournas and Triantafillou (2009) demonstrated that NSM FRP reinforcement is a viable solution toward enhancing the flexural resistance of RC columns subjected to seismic loads. This was especially the case when the retrofitting scheme combines epoxy-bonded NSM bars with local confining jackets with textile-reinforced mortars (TRM). El-Maaddawy and El-Dieb (2010) found that the effectiveness of the NSM GFRP reinforcement was greatly affected by the FRP confinement level and the load eccentricity.

Based on the literature, it is concluded that NSM FRPs are also effective for concrete columns under significant bending, and their effectiveness increases by applying FRP wraps. However, due to limited data, the behavior of the hybrid system with the approach of extending the contribution of NSM FRPs beyond the typical strain level of concrete in compression has not been studied. In this study, a total of 21 plain concrete cylinders (150 mm x 300 mm) were prepared, strengthened, and tested to isolate the effects of each method individually as well as to characterize the performance of the hybrid system. Multiple GFRP bars (#4) were mounted in 20 mm by 20 mm surface grooves, and unidirectional basalt FRP (BFRP) was used to wrap the specimens. Test parameters were, number of NSM GFRP bars (4, 6, and 8) and number of BFRP layers (0 and 2). The specimens were instrumented with multiple strain and displacement gauges and loaded under uniaxial compression to failure.

EXPERIMENTAL PROGRAM

Test Matrix

A total of 21 concrete cylinders with a diameter of 150 mm and a height of 300 mm were prepared and tested under uniaxial compression loading. The testing matrix consisted of control groups of plain and GFRP NSM-reinforced concrete specimens, and GFRP NSM-reinforced concrete specimens wrapped with two layers of BFRP. NSM bars were placed in 4, 6, and 8 bar arrangements with nominal diameters of 13 mm (#4). Table 1 shows the test matrix. Three identical specimens per group were prepared and tested.

Table 1. Test matrix

Group #	Specimen ID	Number of identical specimens	Number of NSM bars	Number of FRP wrap layers
1	**Plain**	3	0	0
2	**NSM-4**	3	4	0
3	**NSM-6**	3	6	0
4	**NSM-8**	3	8	0
5	**NSM-4-W**	3	4	2
6	**NSM-6-W**	3	6	2
7	**NSM-8-W**	3	8	2

Material Properties

Ready mix concrete with maximum aggregate size of 13 mm and slump of 100 mm was delivered. The average compressive strength of concrete at the time of test was 40 MPa. Round GFRP bars with nominal diameter of 13 mm (#4) and nominal cross-sectional area of 126.7 mm^2 were used as NSM bars. The guaranteed tensile strength, elastic modulus, and rupture strain of 758 MPa, 46 GPa, and 1.64%, respectively, as per the manufacturer. A compatible adhesive was used as the bonding material to attach the NSM bars into the groove of the concrete specimens. The tensile strength, compressive elastic modulus, ultimate tensile strain, and the bond strength were 27.6 MPa, 3.06 GPa, 1.0%, and 13.8 MPa, respectively, as reported by the manufacturer. For wrapping, a unidirectional basalt fabric and epoxy resin were used. For resin, a mixture of epoxy resin and slow hardener was used, which was reported by the manufacturer to have the tensile strength, tensile modulus, and maximum elongation of 50 MPa, 2.8 GPa, and 4.5%, respectively. The epoxy resin was reinforced by a unidirectional basalt fabric with the areal weight of 300 g/m^2 and nominal thickness of 0.115 mm. The tensile strength, tensile modulus, and rupture strain of basalt fibers were 2100 MPa, 105 GPa, and 2.6%, per manufacturer.

Specimen Fabrication

Standard plastic molds with the inner diameter of 150 mm and height of 300 mm were used for the fabrication of concrete specimens. Due to the high risk of working with a concrete saw, it was decided to install 300-mm long wooden sticks with 25 mm x 25 mm cross-section to the inner surface of the plastic molds with a radial arrangement accommodating 4, 6, or 8 NSM grooves. Figure 1 shows the procedure. The fresh concrete was placed and consolidated in two layers using scoops, a vibration table, and then the surface was carefully troweled smooth. The consolidated concrete was left in the molds and covered to moist cure for 4 days before the molds were removed and the specimens were relocated to the laboratory. After at least 28-days, the wooden sticks were removed and the specimens were left in the lab to cure and dry. Then the groves were cleaned with a wire brush for the strengthening procedure.

Figure 1. Specimen fabrication - Courtesy of Pedram Sadeghian

Strengthening Procedure

As shown in Figure 2, the grooves were partially filled with the adhesive, the NSM bar was placed into the center of the grove, and then the groove was filled with adhesive. A blade was used to make the surface of the groove flat and compatible with the curvature of the concrete cylinder. After at least a 7-day curing, two layers of the unidirectional basalt fabric was continuously applied in the hoop direction using the epoxy resin. An overlap of 100 mm was applied to the last layer. Also, a 25-mm strap of basalt fabric was applied at each end of cylinders to ensure the ends are strong enough to prevent localized end failure. The specimens then were capped with a Sulphur compound for uniform loading.

Figure 2. Hybrid strengthening procedure - Courtesy of Pedram Sadeghian

Instrumentation and Test Setup

As shown in Figure 3, the axial deformation of the specimens was measured using two linear variable differential transformer (LVDT) units fixed to the cylinder using aluminum brackets. The LVDTs were placed on opposite sides to measure average axial strain over 150 mm gauge lengths. Two NSM bars per specimens were also instrumented with 12 mm longitudinal strain gauges each, which were bonded to flat surfaces machined in-house into the outward facing sides of the bars. The strain gauges were also protected by a protective coating and covered with aluminum tape.

In each wrapped specimen, four more strain gauges were installed on the BFRP wrap, two in the axial direction and two in the hoop direction at locations 90 degrees apart. For unwrapped specimens, two horizontal LVDTs were also placed at mid-height of each specimen in a radial direction at locations 180 degrees apart. The surface of the wrapped specimens was also painted with a spackled pattern to measure the surface strain using a digital image correlation (DIC) technique. The compressive testing was done on a 2 MN test frame and was programmed to deform the specimens at a rate of 0.6 mm per minute. The specimens were compressed until either the internal reinforcement began to crush, the FRP wrap ruptured, or until it did not seem safe to deform the specimen any further.

Figure 3. Instrumentation and test setup - Courtesy of Pedram Sadeghian

RESULTS AND DISCUSSION

Failure Modes

Figure 4 shows some of the specimens after the test. The control group of plain concrete specimens all failed along a shear plane, and some light tapping with a hammer revealed that fractures were developed all around the upper and lower shear cones. NSM specimens' failure was controlled by concrete crushing. As concrete passed its crushing strain and started to bulge significantly, NSM bars buckled and some of them crushed, as shown in Figure 4. Overall, NSM bars did not show any signs of crushing until the concrete bulged and cracked significantly.

The behaviour of NSM-wrapped specimens was completely different than NSM specimens without wrapping. NSM bars were continued, contributing to the load bearing system, and did not buckle until the FRP wrap was ruptured in the hoop direction, long after the other specimens. In some specimens, before the FRP wrap rupture, the NSM bars started to crush making noise and dropping the load. FRP wraps were typically ruptured at the location of the NSM bars, indicating lateral concentrated pressure on the FRP wrap can control the rupture. Overall, FRP wraps were effective on extending the contribution of the NSM bars.

Figure 4. Failure modes - Courtesy of Pedram Sadeghian

Behaviour of NSM Specimens

Figure 5 shows the average axial load vs. axial strain curves of three identical specimens of each group of control plain and NSM specimens. As shown, all NSM and control specimens had almost the same curve until the axial load of about 700 kN and axial strain of about 0.0028 mm/mm. Plain specimens lost their stiffness and went to a softening branch. However, the NSM specimens continued gaining load and after a peak load slightly larger than plain specimens they started their softening branch. The peak load and strain corresponding to the peak load increased as the amount of NSM reinforcement increased. The strain at peak load was affected more than the peak load itself.

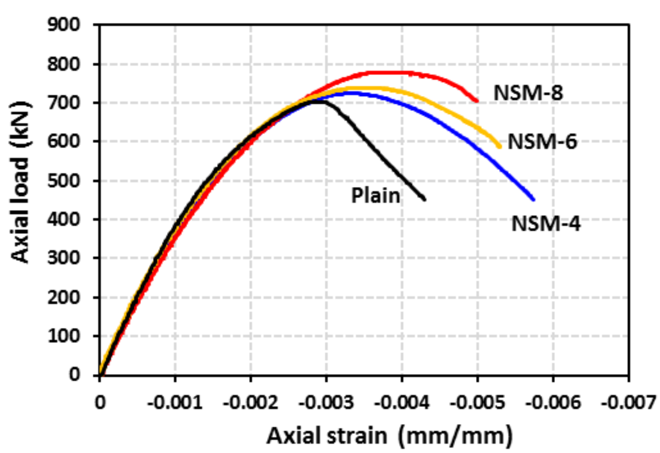

Figure 5. Axial load vs. axial strain behavior of NSM specimens (note: each curve is the average of three identical curves).

Effect of Wrapping on NSM Specimens

Figure 6 shows the average axial load vs. axial strain curves of three identical specimens of each group of plain, NSM, and NSM-wrapped specimens. As shown, FRP wrap changed the behaviour of the NSM specimens significantly, increasing both peak load and its corresponding strain. There is clearly an interaction between the wrap and NSM bars as a hybrid system also changed the stiffness of the NSM specimens even before plain concrete reached its peak load. The effect is more pronounced for specimens with more NSM bars. It means the NSM bars of NSM specimens started to buckle even before the peak load of plain concrete and the FRP wrap controlled the buckling and kept the NSM bars straight contributing to the axial stiffness of the specimens. The little drops in NSM-wrapped specimens' curve indicate the crushing of at least one NSM bar, which was compatible with noise during the tests. Even after crushing of one NSM bar, the specimens kept resisting until more bars crushed, and finally the FRP wrap was ruptured in the hoop direction. The FRP wrap was more effective on specimens with 6 NSM bars than 8 NSM bars. This indicates that over-reinforcing the concrete specimens with longitudinal NSM bars made the integrity of the concrete less solid, which weakened the lateral support of concrete for the NSM bars making them more vulnerable to axial crushing.

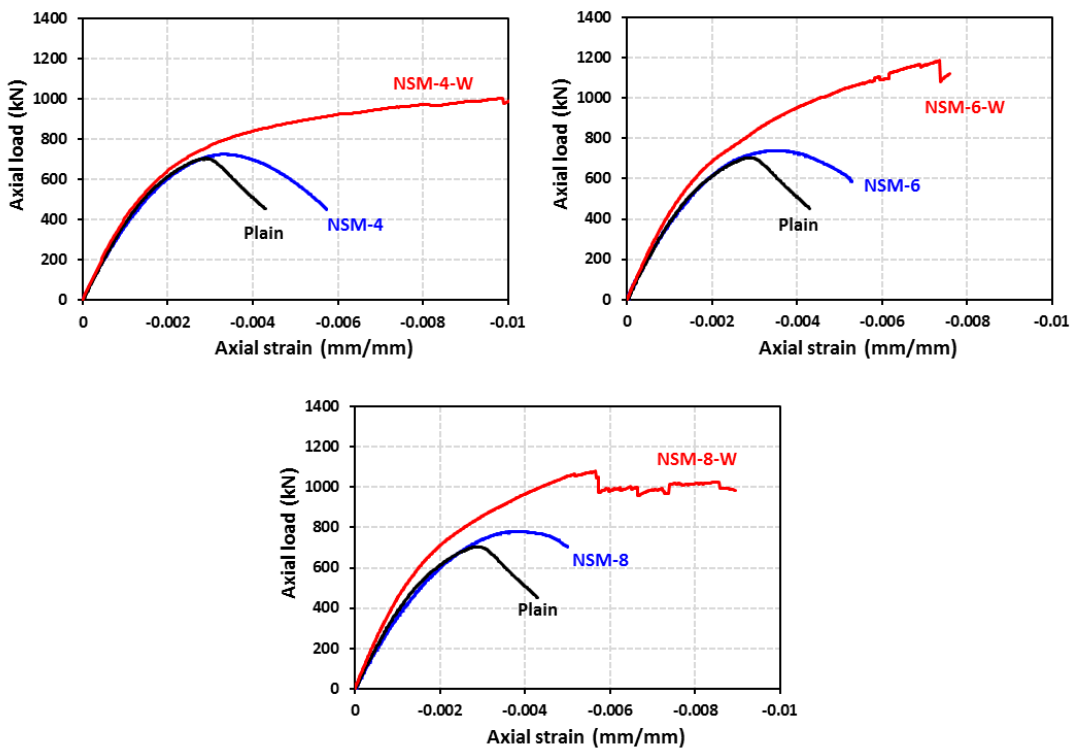

Figure 5. Effect of FRP wrapping on behavior of NSM specimens (note: each curve is the average of three identical curves).

Overall, the hybrid system of longitudinal NSM GFRP bars and lateral BFRP wrapping was effective on upgrading the performance of the concrete specimens. More research is needed on the behaviour of concrete columns with internal steel bars strengthened with the hybrid system under pure axial and combined axial-bending loadings. Also, the effectiveness of FRP wrap (Pessiki et al. 2001; Chen et al. 2011; and Sadeghian and Fam 2015) and effect of confinement (Mirmiran and Shahawy 1997; De Luca et al. 2010; Sadeghian and Fam 2015; and Bai et al. 2017) need to be compared to concrete specimens wrapped with FRPs without NSM bars.

CONCLUSION

In this paper, a total of 21 cylindrical concrete specimens were strengthened with a hybrid system of NSM GFRP bars and BFRP wrapping system. The specimens were tested under axial compression until failure. The following conclusions can be drawn from the study:

- In concrete specimens with NSM bars, the bars did not show any signs of crushing until the concrete bulged and cracked significantly.
- The FRP wrap changed the behaviour of the NSM specimens significantly, increasing both peak load and its corresponding strain via preventing the buckling of NSM bars and extending the contribution of NSM bars.
- The hybrid system of longitudinal NSM GFRP bars and lateral BFRP wrapping was effective on upgrading the performance of concrete specimens.
- The effectiveness of FRP wrap and effect of confinement need to be studied more in depth through comparing the behaviour of NSM wrapped concrete specimens with concrete specimens wrapped with FRPs without NSM bars.

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