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Near-surface mounted FRP reinforcement for structural strengthening

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ABSTRACT: This paper provides a critical review of recent studies on strengthening of reinforced concrete and masonry structures by near-surface mounted (NSM) fiber reinforced polymer (FRP) bars. In the past decade, the use of NSM-FRP bars has been on the rise. This is due to FRP composite materials' high strength and stiffness, noncorrosive nature, and ease of installation. Experimental investigations have confirmed the benefits associated with NSM-FRP flexural and shear reinforcements of existing concrete structures. Additionally, the bond behavior of the NSM-FRP bars-concrete interface which is a key factor in increasing the load capacity of structures has been explored. The use of NSM-FRP reinforcement for masonry is also an emerging area. Recent studies have revealed that this type of reinforcement can improve in and out of plane shear capacities of existing unreinfroced masonry (URM) walls along with increases in displacement capacity and ductility. Another topic of interest is the effect of temperature on strength and stiffness of NSM-FRP reinforced structures and bond performance. Preliminary findings suggest that as compared to externally bonded (EB) FRP sheets, NSM-FRP bars are less susceptible to fire damage due to concrete cover from embedment. In summary, the presented literature review provides an insight into the ongoing research on the use of NSM-FRP for strengthening of structural members and the trends for future research in this area.

1 INTRODUCTION

The use of fiber reinforced polymers (FRP) to retrofit structures to improve structural performance is a technique that has been established and implemented in numerous construction projects worldwide. Currently, the most common method of retrofitting is the external bonding reinforcement (EBR) method. This method has been employed in practical applications for quite some time and related guidelines have been established in various countries (e.g. ACI 440R 07, FIB bulletin 14, CNDR DT2005). On the other hand, near surface mounting (NSM) is a relatively recent retrofit technique that involves cutting out a groove on an existing concrete member, applying an appropriate adhesive, and then laying FRP bars or rods into the groove.

1.1 Benefits of the Near Surface Mounting Technique over Externally Bonded FRP

NSM-FRP is an appealing method to strengthen existing and new structures due to its advantages over EBR, primarily from the improved efficacy achieved from better strain distribution resulting in higher utilization of available strain (Seo et al. 2013), and its higher resistance to many environmental factors due to being embedded into concrete cover. Although temperature susceptibility is still moderately high for NSM-FRP, it is considerably reduced by changing the grout filler type. This is a newly emergent research topic area and is still under preliminary investigation (Bisby et al. 2013). NSM-FRP also provides low aesthetic impact, it is easy to install and has the ability to improve negative moments in the continuous slabs (De Lorenzis and Teng 2007).

These advantages have been the reason for a sudden increase in the experimental, numerical, and analytical research over the past few years (De Lorenzis and Teng 2007, Bianco et al. 2009). The main goal of this paper is to provide an overview of ongoing research on NSM-FRP reinforcement applications in the structural engineering field. In the following sections, greater emphasis is placed on more current and emerging topics, such as NSM-FRP applications for shear, masonry, and temperature effect. Other areas, such as flexural applications and bond factors, are briefly discussed, since they have already been explored in depth in a review by De Lorenzis and Teng (2007).

2 FLEXURAL APPLICATIONS OF NSM-FRP FOR CONCRETE MEMBERS

NSM-FRP rods can be highly effective method to improve the flexural capacity of RC beams. Experimental study performed by De Lorenzis et al. (2000) showed that NSM-FRP rods improved the load carrying capacity of RC beams ranging from 25.7% to 44.3%. Test results by Seo et al. (2013) also emphasized that NSM reinforcement allowed for more efficient use of FRP reinforcement. Concrete members strengthened through NSM reinforcement had almost 1.5 times higher bond strength as compared to EBR. Even with lower strain distribution, the actual value of strain in NSM-FRP is much higher than EBR, indicating higher material efficiency.

Long term tests over a two-year period performed by Astorga et al. (2013) indicated that NSM-CFRP strengthening improved the ultimate load bearing capacity of concrete bridge slabs by 41%, and yield load bearing capacity by 20% on average. Although they noticed a decrease in ductility, they also noted that strains were successfully transferred from concrete to NSM-CFRP, and allowed for full exploitation of ultimate strain of CFRP.

Barros et al. (2007) performed several tests on flexural strengthening capabilities of NSM-CFRP retrofitted RC beams and compared them to EB-CFRP retrofit. They noted that NSM reinforcement was the most effective technique in terms of ultimate load carrying capacity. However, the effectiveness was less profound with the increase of CFRP reinforcement ratio. This reduction in effectiveness is explained by numerical analysis that indicated a decreasing relationship of CFRP effective strain with an increase in the CFRP reinforcement ratio. Soliman et al. (2010) conducted flexural tests on NSM-strengthened RC beams. They observed that along with increase in the flexural capacity, the NSM-FRP system was particularly more effective with RC beams originally having low-steel reinforcement ratio of about 0.4 times the balanced steel reinforcement ratio.

3 SHEAR APPLICATIONS OF NSM FRP FOR CONCRETE MEMBERS

The NSM technique can be used to overcome drawbacks that occur during EB-FRP for shear strengthening due to premature debonding of FRP laminate resuling in very poor efficiency of the available FRP materials with high strain capacity (Hacha and Riskalla 2004).

Barros and Dias (2006) performed preliminary experiments by developing a NSM shear strengthening technique using CFRP strips. They noted that not only did the NSM retrofitting technique significantly improve the load carrying capacity of both unreinforced and reinforced concrete beams, but it was also the most effective shear strengthening method of the CFRP systems and provided highest deformation capacity at the failure point of the beam. Similar results were reported by Rizzo and De Lorenzis (2009). They revealed that the use of NSM retrofitting lead to a significant increase in load bearing capacity ranging from 22 to 44 percent as opposed to control models. In comparison to EB-FRP, the shear contribution of NSM was about 2.6 to 2.8 times higher.

Rizzo and De Lorenzis (2009) also noted that although stiffer bond between FRP-epoxy-concrete resulted in a higher FRP strain and more efficient use of FRP, it led to development of higher shear bond stress which was transferred to a certain portion of the FRP resulting in accelerated debonding failure cracks in the concrete for each single NSM-FRP bar. An epoxy with lower elastic modulus and tensile strength was also tested which showed a more ductile bond slip behavior. This provided lower bond-shear stress, higher failure load carrying capacity, and delayed crack initiation.

Increasing the spacing of the NSM bars led to more individual debonding of the bars from the concrete, whereas closer spacing or higher orientation of the bars led to mutual interaction of adjacent bars causing a debonding failure pattern which showed a lower failure load as compared to the individual debonding of each bar. In both cases, the failure mode was characterized by the separation of concrete side cover of internal stirrups. This kind of concrete cover failure occurred due to internal steel stirrups creating a vertical plane of weakness separating the steel bars and the concrete close to the NSM-FRP reinforcements, and was also observed by Barros and Dias (2006).

To overcome this failure, a recent study by Barros and Dias (2013) was conducted where they applied the NSM bars as deep as possible into the beam sections and noted a significant increase in the shear capacity. According to the authors, by increasing the depth of the NSM bars, the concrete fracture failure surface had a higher fracture area, resulting in higher concrete resisting fracture force and consequently higher shear strengthening effectiveness. Another contributing factor was that by increasing the depth of the FRP bars in the slit higher maximum pullout force was attained.

Barros and Dias (2013) also investigated the influence of various parameters including concrete compressive strength on the efficiency of NSM technique for RC beams. Higher strength concrete led to more efficient use of NSM, and changed the failure mode from concrete fracture to debonding of NSM-FRP. One of the key factors observed during the study was that, the force-displacement plot followed a similar pattern as the control model until the initial shear cracks were developed. Then the NSM-FRP came into effect by improving the shear stress transfer between the faces of the cracks. This meant that the load bearing capacity after shear crack initiation was increased significantly. Overall, the NSM-FRP provided more stiffness to RC beams.

4 NSM-FRP-CONCRETE BOND PERFORMANCE FACTORS

The bond behavior of the NSM reinforcing is of critical importance in determining the effectiveness of this method (De Lorenzis and Teng 2007). The strength of the NSM technique is dependent on a number of factors which control the bond-slip behavior, such as material properties, surface treatment of the FRP and grooves, the type of adhesive, groove and FRP dimensions (Seracino et al. 2007, Bianco et al. 2009). As previously mentioned, bond performance factors have been briefly investigated in this paper. More detailed review can be found in De Lorenzis and Teng (2007).

4.1 Surface Treatment of FRP bars or rods

In general, surface properties of NSM reinforcements provide frictional forces and mechanical interlocking which affect the bond behavior. According to bond tests performed by Lee et al. (2012), from the highest to lowest in terms of strain achieved from surface treatments are sand coated, ribbed, roughened, spirally sand coated, and smooth. Each type of surface treatment accounted for various levels of damage to concrete and epoxy, and there are at least 9 different failure modes, including a combination of cracking, splitting and breakage.

4.2 Adhesive Types

Sharaky et al. (2013) conducted test using resin and hardener based epoxy with higher ductility and noticed improved load capacity and better stress distribution along the bond length. This prevented sudden failure and increased the efficiency of having longer bond length. Earlier studies suggest that use of cement based epoxies is limited due to significantly lower tensile strengths (De Lorenzis and Teng 2007). Soliman et al. (2011) tested a fast curing mix of resin plus cement based epoxy which was capable of resisting a high range of temperature and compared it to a high strength resin epoxy. The cementitious based epoxy showed a failure load of only 40-56% of that of the high strength epoxy due to concrete and adhesive splitting. In the case of shear strengthening using NSM bars, tests performed by Rizzo and De Lorenzis (2009) revealed that the epoxy with lower elastic modulus and tensile strength led to a significantly higher failure load and showed twice as much FRP contribution compared to high strength epoxy. According to the authors, using this type of lower strength epoxy resulted in a weaker, but more compliant and ductile bond slip behavior which led to load distribution over a longer length of the FRP bar. This lowered the bond shear stress and delayed crack initiation and debonding failure.

4.3 NSM Groove & Bar Dimensions

According to Lee et al. (2012), increasing the dimensions of the groove generally led to increased bond strength between NSM-FRP and concrete but had no effect on the failure mode. Similarly, Sharaky et al. (2013) performed pullout tests using NSM-FRP bars in concrete blocks and reported that increasing the width of the groove by 33.3% improved the failure capacity by 8.85% (small increase) in general. Pullout tests by Soliman et al. (2011) however showed that when using cementitious adhesive, the increase in the groove size resulted in in a reduction in the load capacity due to the shrinkage of cement in bigger grooves. A groove width greater than 1.5 times NSM-FRP bar diameter is not recommended. Their findings also indicated that decreasing the NSM groove size led to increase in space between NSM-FRP rods and steel rebars which showed an increase in the load capacity. The pullout tests by Sharaky et al. (2013) using NSM-FRP bars also observed that increasing the diameter of CFRP bars from 8 mm to 9 mm resulted in an increase of 21.95% in the load capacity. In the case of GFRP bars, increasing the diameter from 8 mm to 12 mm also resulted in 72% loading capacity increase.

4.4 Bonded Length

The pullout tests by Soliman et al. (2010, 2011) on NSM-FRP systems using FRP bars and epoxy had also confirmed that increasing the bonded length of NSM reinforcement resulted in higher stress distribution along the length and reduced the bond stress. This led to higher load carrying capacity, up to an approximate length limit of 48 times the diameter of the NSM bar. In the pullout tests performed by Sharaky et al. (2013) use of CFRP bars, increased the bond length by 25% and the failure load by 17.2%.

5 NSM-FRP APPLICATIONS FOR MASONRY WALLS

Due to the susceptibility to seismic impacts and brittle failure mechanisms, URM walls can benefit from NSM retrofitting as it is a cost effective and minimally-invasive retrofit technique. NSM bars achieve higher axial strains, along with previously mentioned benefits over EB retrofit applications, resulting in improving flexural and shear capacities, as well as overall ductility.

5.1 In Plane Shear

Dizhur et al. (2013) performed several tests with various NSM-CRFP retrofitting and repair schemes on URM walls. They reported that NSM-CFRP retrofitting led to an increase in the maximum shear strength ranging from 1.3 to 2.6 times for retrofitted walls, and 1.3 to 3.7 times for repaired walls, as compared to the as-built masonry wall. Ductility also increased substantially, ranging from 2.6 times for walls retrofitted on one side to 25.5 times for the walls with retrofit on both sides, and 2.5 to 10 times for repaired walls. In tests using diagonally oriented CFRP strips, higher axial strain was noted due to high compressive loads normal to the strips. In general it was noted that higher ratio of vertical NSM-CFRP led to a linear increase in wall panel shear strength.

Similar results were observed in experimental study performed by Petersen et al. (2010). URM walls were tested in diagonal tension/shear according to ASTM E519-93, and were strengthened using either vertical, horizontal, or a combination of NSM-CFRP strips. The use of vertical NSM-FRP strips resulted in a 28% increase in load capacity when the strips were applied only to one side, and a 46% increase when applied to both front and back sides of the URM walls. The vertical strips also proved to be effective in preventing sliding URM failure, and showed tensile strain, indicating that the strips resisted opening of the sliding cracks. When both horizontal and vertical NSM strips were employed, the horizontal strips prevented opening of diagonal cracks and the vertical strips prevented sliding failure. A 32% increase in loading capacity was also observed.

5.2 Out of Plane flexure

Griffith et al. (2012) tested 15 NSM-FRP strengthened masonry walls and noted that the spacing of NSM-FRP strips played an important role in increasing the out of plane flexural bending capacity. In one wall with 3 FRP strips and spacing of 357 mm, the vertical one-way bending capacity improved up to 20 times over the control wall. Displacement was also increased by more than 60%. Increase in the NSM-FRP reinforcement ratio resulted in an increase in the strength and a reduction in the displacement. Failure load was directly related to the perimeter of debonded failure plane given by $L_{per} = (b + 2\text{ mm}) + 2(d + 1\text{ mm})$ where b and d are the thickness and width of the NSM-FRP strip (in mm) and the '1 and 2 mm' terms account for the fact that the failure surface occurs in the brick unit and not at the FRP-adhesive interface. Here it was assumed that the failure surface is 1 mm away from the FRP strips. Closer spacing with smaller FRP strips led to an increase in load capacity as long as the FRP strips did not rupture prematurely.

Dymtro et al. (2014) performed out of plane shear tests on clay URM walls retrofitted vertically with NSM-CFRP strips and reported significant improvement of about 3.05 to 6.21 times in flexural strength as compared to the as-built URM wall. In all specimens tested, the ductility was also improved. Anchorage systems tested by Lunn et al. (2012) showed that specimens loaded out of plane indicated had 1.6 to 7.2 times increase in loading capacity and 0.6 to 4.5 times increase in ductility over the control wall. Shear sliding along the interface between masonry infill and beams which led to debonding of NSM-FRP was observed as the failure mode.

6 NSM-FRP APPLICATIONS UNDER TEMPERATURE

Apart from the mechanical strengthening advantage, the use of NSM-FRP over EB-FRP reinforcement can provide protection from environmental and fire damage due to additional embedment from concrete cover (Sena-Cruz and Barros 2004). Kodur and Yu (2014) stated that the NSM-CFRP strips and bars themselves provided better resistance to high temperature in comparison to external FRP laminates and internal FRP reinforcement.

In order to study the effect of the temperature ranging from 20 to 600°C, on the tensile strength and elastic modulus, Kodur and Yu (2014) have performed tests on NSM-CFRP reinforcing strips and rods. Their results showed three stages of tensile strength degradation. (1)In the first stage, the temperature ranged from 20 to 200°C, and the CFRP tensile strength degraded slowly to about 80% to that of room temperature. (2) In the second stage of temperature ranging from 200 to 400°C, the degradation of tensile strength was rapid, and was mainly due to decomposition of polymer resins at 300° C. By now the tensile strength was reduced to 50%. (3) In the third stage, when the temperature varied between 400 to 600°C, the degradation of tensile strength was also fast, and down to 10% to that of original. The effect of the temperature on elastic modulus followed a similar trend, but was more directly based on the decomposition of the polymer resin. It was also noted, that with the increase in temperature, the ultimate strain of CFRP reduced leading to a reduction in ductility.

However, the guidelines for design of FRP-strengthened structures (American Concrete Institute 4402R-08, 2008 and International Federation for Structural Concrete Bulletin 14 2001) state that the strength of FRP is to be ignored unless a fire protection system or insulation is in place. Therefore, the FRP system temperature can be maintained under lowest critical temperature which is mainly the glass transition temperature (T_g) of the epoxy adhesive (Palmieri et al. 2012). Bisbi et al. (2013) conducted experiments to study various factors affecting the performance of insulated NSM-strengthened RC beams at elevated temperature and reported that adhesive type can have a significant effect on the load carrying capacity. The use of cementitious grout in place of regular resin epoxy was able to provide better durability over four hours at 100°C and over 70 minutes at 200°C. The observed failure was the pull out of NSM-FRP strips from the grout, similar to that of ambient temperature. It was also observed that it is not necessary to insulate the full length of NSM-FRP to provide fire protection. Insulation of only short length of NSM-FRP strips may be sufficient to maintain effectiveness of bond-critical FRP-strengthening systems.

Palmieri et al. (2012) investigated the performance of protected RC beams with NSM reinforcement subjected to service loads and fire exposure. They reported that RC beams were capable of achieving two- hour fire endurance rating, even after adhesive temperature exceeded the glass transition temperature, as long as they were well insulated. It was also noted that the residual strength of the FRP-strengthened RC beam was equivalent to the flexural load capacity of the control RC beam, as long as the temperature during fire testing was maintained below 140°C for concrete and 570°C for steel. Palmieri et al. (2012) then conducted one-hour fire tests and observed that despite adding higher service load, the NSM-FRP strengthening showed no obvious reduction of strength. The insulation systems could maintain low temperatures of 130°C for epoxy and 167°C for mortar. The insulated RC beam was able to achieve residual strength of 77% as compared to the beam at room temperature and, 127% as compared to the control beam.

7 CONCLUSIONS

NSM-FRP reinforcements are capable of achieving higher strains than EBR, resulting in more efficient use of the FRP material, and thus improving flexural and shear capacities and ductility of RC beams. NSM-FRP reinforcements are also more effective when used in RC beams with lower steel reinforcing ratios. Different surface treatments can lead to various degrees of concrete and epoxy damage, and FRP strain utilization; specifically, sand coated and ribbed FRP bars provided the highest strain utilization. Use of more ductile adhesive resulted in better stress distribution along the bond length. Higher bonded length in NSM-FRP systems generally led to higher stress distribution and improved performance, up to a limit related to the diameter of FRP bars. In general, groove dimensions have relatively low impact on increasing failure capacity.

Premature debonding in external flexural and shear reinforcing scenarios can be avoided through NSM-FRP replacement. For shear strengthening NSM-FRP bars could be used along with high strength concrete and a lower strength epoxy for more compliant and ductile bond slip behavior. This could change the failure mode from concrete cover failure to debonding of FRP and help shear stress transfer between faces of cracks, resulting in further improved loading capacity.

NSM-FRP could significantly improve in plane shear and out of plane flexural capacities and ductility of URM walls. A higher ratio of vertical NSM-FRP provided an increase in shear strength of the wall panel, whereas a combination of horizontal and vertical NSM-FRP prevented opening of diagonal cracks and sliding failure during in plane shear loading. For out of plane flexural testing, it was noted that closer spacing of vertical NSM-FRP led to increase in load capacity. Whereas increasing reinforcement ratio led to increase in load capacity, but a decrease in displacement.

NSM-FRP strips and bars also provided better fire resistance than FRP laminates and internal FRP bars. Only short insulation length was required to prevent the temperature to exceed adhesive glass transition temperature which was required to maintain structural effectiveness based on the guidelines for design of FRP-strengthened structures. Even if the glass transition temperature exceeded, as long as the structure was well insulated and the temperature for steel and concrete was maintained relatively low, it could provide a two hour fire rating.

Future research could be focused on NSM-FRP shear strengthening and shear design equations with appropriate bond models consideration. Long term performance monitoring of concrete beams and slabs with NSM-FRP reinforcement is another possible area of research. Finally, the use of various bonding materials such as cementitious grouts and modified resins can be explored in more details to improve the fire endurance of RC structures.

8 REFERENCES

Astorga, A., Santa Maria, H., & Lopez, M. 2013. Behavior of a concrete bridge cantilevered slab reinforced using NSM CFRP strips. *Constr. and Build. Mater.*, *40*, 461-472.

Barros, J. A., & Dias, S. J. 2006. Near surface mounted CFRP laminates for shear strengthening of concrete beams. *Cem. and Concr. Compos.*, *28*(3), 276-292.

Barros, J. A., Dias, S. J., & Lima, J. L. 2007. Efficacy of CFRP-based techniques for the flexural and shear strengthening of concrete beams. *Cem. and Concr. Compos.*, *29*(3), 203-217.

Barros, J. A., & Dias, S. J. 2013. Assessment of the effectiveness of the NSM shear strengthening technique for deep T cross section RC beams, *FRPRCS-11.*

Burke, P. J., Bisby, L. A., & Green, M. F. 2013. Effects of elevated temperature on near surface mounted and externally bonded FRP strengthening systems for concrete. *Cem. and Conc. Compos.*, *35*(1), 190-199.

De Lorenzis, L., Nanni, A., & La Tegola, A. 2000. Strengthening of reinforced concrete structures with near surface mounted FRP rods. *Int. Meeting on Compos. Mater., PLAST 2000, Proceedings, Advancing with Composites* (pp. 9-11).

De Lorenzis, L., & Teng, J. G. 2007. Near-surface mounted FRP reinforcement: An emerging technique for strengthening structures. *Compos. Part B: Eng.*, 38(2), 119-143.

Dizhur, D., Griffith, M., & Ingham, J. 2013. In-plane shear improvement of unreinforced masonry wall panels using NSM CFRP strips. *J. Compos. Constr.*, *17*(6).

Dizhur, D., Griffith, M., & Ingham, J. 2014. Out-of-plane strengthening of unreinforced masonry walls using near surface mounted fibre reinforced polymer strips. *Eng. Struct.*, 59, 330-343.

Dong, J., Wang, Q., & Guan, Z. 2013. Structural behaviour of RC beams with external flexural and flexural–shear strengthening by FRP sheets. *Compos. Part B: Eng.*, 44(1), 604-612.

El-Hacha, R., & Rizkalla, S. H. 2004. Near-surface-mounted fiber-reinforced polymer reinforcements for flexural strengthening of concrete structures. *ACI Struct. J.*, 101(5).

Griffith, M. C., Kashyap, J., & Ali, M. M. 2012. Flexural displacement response of NSM FRP retrofitted masonry walls. *Lateral*, *17*(2.95), 0-17.

Lee, D., Cheng, L., & Yan-Gee Hui, J. 2012. Bond characteristics of various NSM FRP reinforcements in concrete. *J Compos. Constr.*, *17*(1), 117-129.

Lunn, D. S., Rizkalla, S. H., Maeda, S., & Ueda, T. 2012. FRP anchorage systems for infill masonry structures. *Proceedings of 3rd Asia-Pacific conference on FRP in structures, Hokkaido, Japan*.

Palmieri, A., Matthys, S., & Taerwe, L. 2012. Experimental investigation on fire endurance of insulated concrete beams strengthened with near surface mounted FRP bar reinforcement. *Compos. Part B: Eng.*, *43*(3), 885-895.

Palmieri, A., Matthys, S., & Taerwe, L. 2012. Fire endurance and residual strength of insulated concrete beams strengthened with near-surface mounted reinforcement. *J. Compos. Constr.*, *17*(4), 454-462.

Petersen, R. B., Masia, M. J., & Seracino, R. 2010. In-plane shear behavior of masonry panels strengthened with NSM CFRP strips. I: Exp. investigation. *J. Compos. Constr.*, *14*(6), 754-763.

Rizzo, A., & De Lorenzis, L. 2009. Behavior and capacity of RC beams strengthened in shear with NSM FRP reinforcement. *Constr. and Build. Mater.*, *23*(4), 1555-1567.

Seracino, R., Jones, N. M., Ali, M. S., Page, M. W., & Oehlers, D. J. 2007. Bond strength of near-surface mounted FRP strip-to-concrete joints. *J. Compos. Constr.*, *11*(4), 401-409.

Seo, S. Y., Feo, L., & Hui, D. 2013. Bond strength of near surface-mounted FRP plate for retrofit of concrete structures. *Compos. Struct.*, *95*, 719-727.

Sharaky, I. A., Torres, L., Baena, M., & Miàs, C. 2013. An experimental study of different factors affecting the bond of NSM FRP bars in concrete. *Composite Structures*, *99*, 350-365.

Soliman, S. M., El-Salakawy, E., & Benmokrane, B. 2010. Bond performance of near-surface-mounted FRP bars. *J. Compos. Constr.*, *15*(1), 103-111

Soliman, S. M., El-Salakawy, E., & Benmokrane, B. 2010. Flexural behaviour of concrete beams strengthened with near surface mounted fibre reinforced polymer bars. *Canadian J. Civil Eng.*, *37*(10), 1371-1382.

Yu, B., & Kodur, V. 2014. Effect of temperature on strength and stiffness properties of near-surface mounted FRP reinforcement. *Compos. Part B: Eng.*, 58, 510-517.