Strengthening of RC Members using NSM-CFRP Laminates: A Comprehensive Review of Bond Behaviour and Failure Mechanisms

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Abstract—**This paper reviews the literature on Near Surface Mounted (NSM) Carbon Fiber Reinforced Polymer (CFRP) strengthening of reinforced concrete (RC) members, highlighting experimental studies, analytical models and code guidance to better understand the bond mechanics and common failure modes. The review compiles evidence related to the effects of groove geometry, bond length, FRP axial stiffness, adhesive characteristics, and concrete strength and groove spacing on the bond–slip response and serviceability of NSM-CFRP systems. The summarized studies of the literature indicate that debonding, concrete cover separation, adhesive cohesive failure and the FRP rupture are the main failure mechanisms identified in laboratory tests, which are more highly dependent upon the strength of concrete, the groove dimension size and type and the adhesive characteristics. The literature compiled from experimental and analytical studies reveals that bond behaviour is the main parameter that influences the performance of NSM. The review also highlights the lack of uniform quantitative design rules for new CFRP profiles, long-term durability tests under environmental and cyclic loading, interaction effects between several grooves and reinforcement, and validated bond-slip formulations (groove perimeter, surface roughness). Failure mechanisms reported include failure at the interface, failure of the adhesive, failure of the concrete itself, and failure of the concrete cover. Finally, coordinated parametric testing, accelerated durability testing, and instrumented full-scale pilot retrofits are recommended to generate robust and code-ready guidance for NSM-CFRP strengthening.**

Index Terms—**Adhesive bond, CFRP laminates, debonding, near-surface mounted, reinforced concrete, failure modes.**

I. INTRODUCTION

Reinforced Concrete (RC) structures are a significant component in the modern infrastructure systems like buildings, bridges, flyovers, and Industrial structures because of their strength and durability as well as their economic benefits. Many of the existing RC structures, however, suffer from corrosion, exposure to the environment, overloading, ageing or inadequate maintenance and may deteriorate over time, leading to reduced structural performance and service life. Hence, for enhancing the safety and durability of existing structures, strengthening and retrofitting have been in trend for the past decade.

In the case of retrofitting of RC structures, the Near Surface Mounted (NSM) technique has been widely accepted, pertaining to its high strengthening efficiency, performance in bond, corrosion resistance and easy installation. Especially, CFRP laminates are being extensively used to improve the flexural performance of RC members. In some applications, a steel NSM reinforcement system is also used because of its ductile properties and cost-effectiveness. The bond behavior between concrete, adhesive and strengthening material is an important factor that greatly affects the performance of the NSM strengthened RC members and, consequently, the development of cracks, load transfer and failure mechanisms.

For strengthened RC members, the serviceability behaviour is also a critical issue to consider, particularly the crack width controlling performance, because excessive cracking may have negative impacts on the durability and long-term structural performance. There are some variations in design outcome due to various approaches mentioned in different international design codes like Bureau of Indian Standards IS456: 2000, American Concrete Institute ACI Guidelines and Eurocode Provision. There are several studies related to the strengthening of RC members by NSM-CFRP, but most of the previous studies have focused on the strength improvement of RC members, whereas comparatively less research work has been performed on bond behaviour, serviceability performance and comparison with code. Thus, a detailed literature review is essential to gain insight into the current limitations, the comparison of various design methods and future research directions of bond characteristics and failure modes of NSM strengthened RC members.

II. LITERATURE REVIEW

Existing structures, strengthening work done using FRP composite materials, have been carried out for many years, and are proven to be efficient in many research works across the globe. Considering a significant increase in the application of CFRP composites utilised for structural elements in flexure and shear because of their superior mechanical properties, such as high-strength to weight ratio, fatigue, corrosion resistance, ease of handling and durability. Internally applied FRP composites known as the Near Surface Mounted (NSM) Technique, in which the FRP composites are placed inside the grooves provided on the concrete surface in the tension zone with the help of compatible adhesives. The structural behaviour of FRP composites used for strengthening has been broadly studied over the last few decades, and these research studies have been incorporated in some design guidelines, such as Fib Bulletin 14-2001 [1]; CNR DT 200 R1/2013 [2], CNR-DT 200/2004 [3]; ACI 440.2R-08 [4]; TR55 [5]; ISIS Design Manual No. 3 2007[6]. The detailed review was done based on the research work that was assembled and presented.

A. Necessity of Strengthening, Retrofitting and Rehabilitation

With the population and infrastructure growth rate, rehabilitation, retrofitting and strengthening of existing reinforced concrete structures are becoming a growing requirement. The process of demolition of existing structures and rebuilding isn’t a sustainable option; strengthening methods are more economical and sustainable solutions to prolong the use of the structures and enhance their service life. In sustainable retrofitting, Menassa et al. 2014[13] reported that sustainable retrofitting offers substantial returns on investment, and Gholami et al. 2013[14] highlighted the need to obtain economical and high-performance structures by sustainable strengthening techniques.

When buildings are loaded, their function requirements are changed, their service life is extended, construction errors or design defects occur, or they are damaged by earthquakes, strengthening of the structures is needed. Singh et al. 1992[15] and Vijayakumar et al. 2011[16] discussed the rehabilitation of earthquake-affected structures. The handbook “Seismic Retrofitting of Buildings 2007” developed by IBC and CPWD in association with IIT Madras, gives the guidelines for the retrofitting of deteriorated RC structure which is subjected to seismic forces in India. Williams et al., 2009 [17] also noted that structural reliability, location and economics are factors that determine feasibility for seismic retrofitting.

B. Strengthening of RC beams using FRP composites under Near Surface Mounted (NSM) Technique.

The Near Surface Mounted (NSM) strengthening technique with FRP composites has been developed as an alternative technique to the externally bonded (EB) strengthening technique in the last two decades, which has been proven to be effective. The technique of NSM involves cutting grooves in the concrete and embedding FRP bars or strips in the openings with epoxy adhesive. The history of use of the NSM method dates back to the 1940s in European countries to strengthen old RC structures by installing steel reinforcement bars in cuts and filled with cement mortar.

A few benefits of the NSM technique over the EB technique were identified in the previous studies by Lorenzis et al. (2007) [117] and Parretti et al. (2004) [118]. The benefits are: less surface preparation time;

delayed debonding failure; easier installation of anchorages; and protection of FRP reinforcement from mechanical damage and fire exposure.

C. Bond parameter between FRP composites and concrete in NSM Technique

Bond is the composite action between the concrete and FRP, which was developed through the transfer of stresses during loading. The bond behaviour influences the load enhancement and serviceability requirements. The major problem with NSM strengthening is bond failure. Many research works (Cruz et al. 2004[119]; Lorenzis et al. 2007[117]; Seracino et al. 2007[120]; Lee et al. 2013[121]; Banthia et al. 2010 [122]; El-Gamal et al. 2016[123]; Hassan et al. 2003[124]; Mishad et al. 2017[125]; Seo et al. 2013[126]; Bilotta et al. 2011[127]) have been carried out in order to identify the parameters that influence the failure. The major factors that impact the bond failure are the grade of concrete, type of FRP reinforcement, surface treatment for grooves, dimension of groove, depth of FRP strip or diameter of FRP bar and the ratio between the FRP & groove dimensions.

- Effect of groove dimension on bond strength.

Fig. 1 shows the configuration of the NSM FRP strip as an external reinforcement. In the case of the NSM technique (L.D. Lorenzis et al. 2007[117]), the groove size or dimension plays a significant role in the bond performance in order to avoid the debonding failure. Blaschko et al. 1999[128] have suggested that the width and depth of the groove provided should be more than 3mm greater than the depth and thickness of the CFRP strip. Parretti et al. 2004[118] have recommended that the minimum width of the groove should not be less than three times the thickness of the strip, and the minimum depth of the groove should not be less than 1.5 times the depth of the strip/laminate. They have also recommended providing the bond along all 4 sides of the laminate surface by filling the groove with adhesives in order to ensure proper bonding between FRP and concrete. Barros et al. 2005[129] have suggested that the reduction in bond surface due to the large width of the groove to the thickness of the strip ratio was considered to be negligible. Zhang et al. 2013[130] have developed the model on the bond test. According to this model, the height-to-width ratio of the groove has a substantial effect on the bond–slip curve.

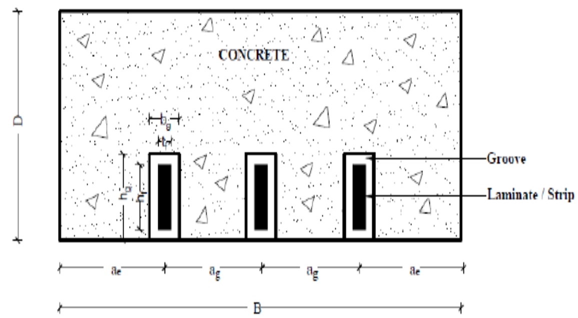

Fig. 1: NSM Technique using CFRP Strips/Laminates

- Effect of bond length on bond strength.

The pullout test and bending test were carried out (Cruz et al. 2004[119]; J.M.D.S. Cruz et al. 2006[131]; Seracino et al. 2007[120]; Saadi et al. 2016[132]; Barbieri et al.2016[133]) to evaluate the bond behaviour between concrete and CFRP strip. The study was made by varying the bond length. They have concluded that, as the bond length increases, the bond strength also increases up to a particular bond length; after this, the bond strength starts declining.

- Effect of concrete strength on bond strength.

Seracino et al. 2007[120], Teng et al. 2006[134]; Zhang et al. 2013[130] have concluded that, for the higher compressive strength of concrete (i.e., more than 50 MPa), the tension failure of FRP might occur. Whereas in lower compressive strength of concrete, the failure might occur at the interface of FRP and adhesive.

D. Failure modes in NSM Technique

In most of the cases, the expected type of failure mode was due to the development of an intermediate crack, which initiates cover separation and FRP rupture. In this method, the splitting of adhesive or the crushing of concrete was considered as the premature failure modes. Seo et al. 2016[135] suggested that the failure due to splitting of adhesive with FRP debonding was the common failure mode, which occurred due to the low adhesive tensile strength (less than concrete strength) and higher groove widths. The studies have been done on the failure modes by various researchers based on their experimental investigations for the NSM strengthened beams under flexure, and they are discussed below

- Failure due to interfacial debonding

Interfacial debonding is nothing but the adhesive cover splitting, which may appear at the FRP-adhesive interface near the anchorage zone.

- Failure due to concrete cover separation

This type of failure appeared to be the most common mode of failure in NSM strengthening. The concrete cover separation was caused by less spacing between the grooves. If the spacing between the grooves is less, the beam accommodates a larger number of grooves, which in turn reduces the tensile strength of concrete in the cover portion. According to the tests conducted by the researchers (Teng et al. 2016[136]; Lorenzis et al. 2002[137]; Barros et al. 2005[129]; Barros et al. 2007[138]; Bonaldo et al. 2008[139]; Ali et al. 2008[140]; Zhang et al. 2013[130]; Shukri et al. 2016[141]), the bond cracks developed at the beam soffit are inclined at almost 45 degrees with respect to the axis of beam which tends to propagate towards the top by maintaining 45 degrees up to the top of the cover portion. Then, these cracks tend to propagate horizontally close to the steel reinforcement, causing cover separation.

\- Strip/Laminate end cover separation

Cover separation is distinctive for the ends of NSM FRP strips, which were situated at some distance from the end supports. This type of failure was initiated from the beam bottom section and then propagates upwards up to the level of reinforcement as shown in Fig. 2, J.A.O. Barros et al. 2007[138]; M.S.M. Ali et al. 2008[140]; F.A. Mahmoud et al. 2007[142]; J.G. Teng et al. 2006[134]; I.G. Costa et al. 2010[143]; L.D. Lorenzis et al. 2002[137].

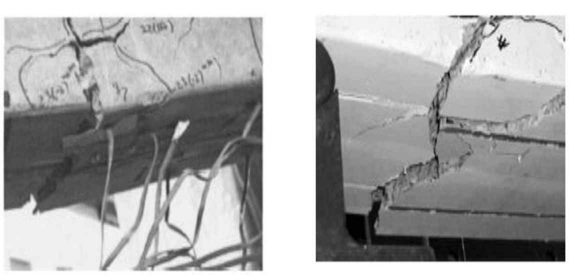

Fig. 2: Failure due to laminate end cover separation

\- Localised cover separation

This type of failure may occur due to bond cracks that were developed within or near the region where the bending moment is maximum. These cracks, along with the pre-existing flexural-shear cracks and flexural cracks, tend to detach the laminate from the beam.

\- Cover separation due to flexural cracks

In this failure, (Barros et al. 2005[129]; Barros et al. 2007[138]; Bonaldo et al. 2008[139]; Costa et al. 2010[143]; Rezazadeh et al. 2016[144]) the cover separation takes place due to flexural cracks which propagate vertically up to the top portion of the groove in the flexural zone, and then these cracks propagate horizontally towards one of the shear zones by separating the cover portion from the beam shown in Fig. 3.

Fig. 3: Cover separation due to intermediate crack debonding

\- Cover separation due to flexural-shear cracks

This type of failure was caused (Costa et al. 2010[143]) by increasing the depth of laminate/strip with respect to groove depth. In this case, the moment of inertia was relatively high. Hence, a longitudinal fracture takes place along the laminate/strip shown in Fig. 4.

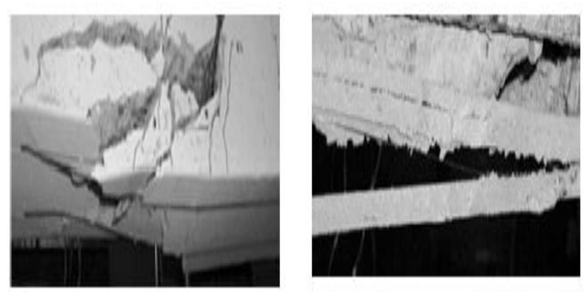

Fig. 4: Failure due to cover separation (a) propagation of flexural-shear cracks; (b) fracture along the laminate (Courtesy Costa et al. 2010[143])

\- Cover separation from beam edge.

This type of failure was caused (Costa et al. 2010[143]) by providing the NSM reinforcement to an entire length of the beam as shown in Fig. 5.

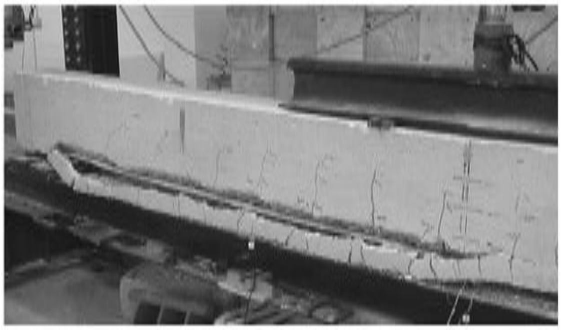

Fig. 5: Cover separation from beam edge (Courtesy Costa et al. 2010[143])

- Failure modes accompanying with debonding phenomenon

Based on the experimental results of the previous researchers, the probable modes of failure are discussed below

- Debonding failure at FRP laminate-adhesive interface

This type of failure (Lorenzis et al. 2002[137]; Coelho et al. 2015[145]) was identified by the virtual absence of epoxy adhesive in concrete. Since, the adhesive was completely stuck to laminate. It can be resisted by providing the essential degree of transverse confinement and proper bond length. This failure is more common in case of FRP bars than in FRP strip/laminate.

- Cohesive Failure with in the adhesive

This type of failure (Coelho et al. 2015[145]) was identified by the presence of adhesives which was stuck to the laminate and concrete surface. This failure may occur when the tensile strength of the adhesive exceeds the limit because of the concrete surrounding the adhesive was much stiffer and gives some confinement at adhesive-concrete interface. According to Mohr's principle, the failure mode due to pure sliding can be avoided in the adhesive-concrete interface. Hence, the failure was induced within the epoxy adhesive.

- Debonding failure at concrete-adhesive interface

This type of failure may arise as pure interfacial failure and this failure mode (Lorenzis et al. 2002[137]; Coelho et al. 2015[145]; Seracino et al. 2007[120]; Lorenzis et al. 2007[117]) was acute for the pre-cast grooves having smooth surface. Hence, relevant adhesion mechanism was low in this case, therefore the interface has small shear strength due to Mohr-coulomb effect because of the weakest link between concrete-adhesive.

- Cohesive Failure in concrete

This type of failure was caused (Costa et al. 2010[143]; Coelho et al. 2015[145]; Galati et al. 2009[146]; Ceroni et al. 2012[147]; Blaschko et al. 1998[128]) by providing the NSM reinforcement to an entire length of the beam. This can be easily avoided by providing or maintaining a nominal distance from the edge. This failure mode was common in low strength concrete. Cohesive failure in concrete (Coelho et al. 2015[145]) is also dependent on the degree of transverse confinement.

All the four failure modes are explained in the Fig. 6.

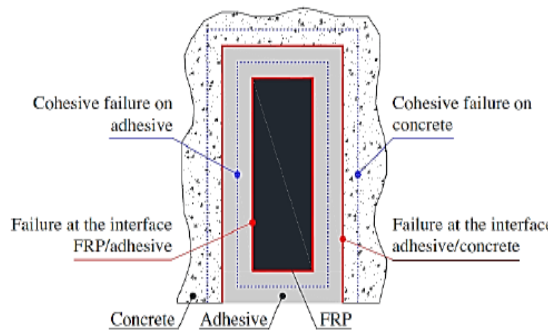

Fig. 6: Failure modes accompanying with debonding phenomenon (Courtesy Coelho et.al. 2015[145])

E. Debonding strain at the level of FRP laminate for strengthened beam under NSM technique.

Bilotta et al. 2014[148] have assessed the maximum debonding strain in NSM CFRP reinforcement by calibrating the selected experimental results from past research works where the debonding failure had occurred. The calibration was done by considering two relations. In the first relation, they have considered the axial stiffness of NSM CFRP reinforcement. Since, the debonding failure mainly dependent on the axial stiffness of CFRP reinforcement. According to power law, as the axial stiffness of CFRP laminate increases the maximum debonding strain decreases. In the second relation, they have considered the perimeter of the groove. For both relations, the numerical coefficients were assessed from experimental and theoretical data using least square method. By taking groove perimeter into consideration there was an improved fitting with the experimental results. They have derived the empirical formula for the assessment of debonding strain. According to ACI 440.2R-08 [4] code, the rupture strain is multiplied by 0.7 in order to obtain the debonding strain in case of NSM technique.

F. Summary of Literature Review

Current studies have shown that FRP composite laminates, especially CFRP, can be a viable solution in strengthening reinforced concrete (RC) members and that Near Surface Mounted (NSM) technique is a strong method alternative to externally bonded technique. Many research works have been conducted worldwide and existing structures and strengthening work carried out by FRP composite materials have proved to be efficient for many years. The Near Surface Mounted (NSM) strengthening technique using FRP composites has been developed in last 20 years as an alternative technique to the externally bonded (EB) strengthening technique that has been proven to be effective. The literature compiled from experimental and analytical studies reveals that bond behaviour is the main parameter that influences the performance of NSM, namely: bond geometry (width, depth and height to width ratio), bond length, axial stiffness of the FRP, adhesive properties, concrete strength and spacing of the grooves determine the bond-slip response and ultimate failure mode. Failure mechanisms reported include failure at the interface, failure of the adhesive, failure of the concrete itself, and failure of the concrete cover (end, localized, flexural and flexural-shear). High strength concrete can cause failure of the FRP, whereas, low strength concrete and smooth groove surfaces can cause failure at the interface or in the adhesive. There are empirical models for debonding strain that take into account the stiffness of the FRP and the perimeter of the grooved area, as well as models provided in the code, such as those in ACI reduction factors, but most of the results are still obtained by laboratory tests with different test configuration and material systems.

G. Research Gap

Although much work has been done in the laboratory and some code guidance provided, there remain several areas of uncertainty that limit the ability to confidently make general design recommendations for NSM CFRP strengthening:

1. unified quantitative design rules that take into account the most modern CFRP profiles, realistic surface finishes and interaction with reinforcement layout;
2. systematic durability data and predictive models for the behaviour of the adhesive over the long-term (environmental and cyclic loading such as temperature, moisture, freeze–thaw, UV) and the influence of these on bond degradation and debonding strain;
3. predictive models for the interaction effects between multiple grooves, including cover integrity, spacing limits and effect of existing steel reinforcement;
4. comprehensive bond–slip formulations that incorporate groove perimeter, surface roughness, adhesive rheology and FRP axial stiffness;
5. optimized anchorage and termination details to limit end cover separation and local failures;
6. full-scale field validations and long-term monitoring to bridge the gap between lab results and code provisions. This will involve coordinated parametric experiments, accelerated durability programs, advanced multi-physics numerical modelling (calibrated using cohesive-zone approaches), and instrumented full-scale pilot retrofits to generate robust, code-ready design guidance addressing these gaps.

III. CONCLUSION

The literature compiled from experimental and analytical studies reveals that bond behaviour is the main parameter that influences the performance of NSM. Specifically, bond geometry (width, depth, and height-to-width ratio), bond length, axial stiffness of the FRP, adhesive properties, concrete strength, and groove spacing determine the bond-slip response and ultimate failure mode.

- Performance is under the control of bond behaviour. The effectiveness of NSM-CFRP strengthening is mostly controlled by the bond mechanics in the local area of the building (groove geometry, adhesive characteristics and axial stiffness of the FRP). Failure to consider these parameters can lead to soon-to-be debonded, covered or adhesive/cohesive failures.
- Failure modes are predictable-Systematic failures, such as failures at the interface, at the adhesion, at the concrete cohesion, and separation at the cover between the concrete and the FRP, are

typical and it can be seen that they are a function of concrete strength, and of the groove detailing and spacing; high strength concrete will cause failure at the rupture of the FRP, and low strength concrete will cause failure at the interface or adhesive, or at the concrete cohesion or cover separation.

- Available empirical rules are insufficient- Empirical relations currently exist that show trends such as stiffness and groove perimeter effects, but they are not general over the wide range of contemporary CFRP profiles, adhesive chemistries or realistic surface finishes.

REFERENCES

[1] FIB (2001). "Externally bonded FRP reinforcement for RC structures", Fib Bulletin-14, Task group 9.3-FRP reinforcement for concrete structures, International Federation for Structural Concrete.

[2] CNR-DT 200 R1/2013 (2013). "Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Existing Structures", CNR – Advisory Committee on Technical Recommendations for Construction, National Research Council, Rome.

[3] CNR-DT 200/2004 (2004). "Guide for the design and construction of externally bonded FRP systems for strengthening existing structures", CNR- Advisory committee of technical recommendations for construction, National Research Council, Rome.

[4] ACI Committee 440.2 R-08 (2008). "Guide for the design and construction of externally bonded FRP systems for strengthening concrete structures", Reported by ACI Committee 440.

[5] TR55 (2012). "Design Guidance for Strengthening Concrete Structures Using Fibre Reinforced Composite Materials", Network group for composites in construction, London.

[6] ISIS Design Manual (2007). "Reinforcing Concrete Structures with Fibre Reinforced Polymers", ISIS Canada research network, Version 2, Manual No. 3, ISBN 0-9689006-6-6.

[7] Carol C. Menassa and Brad Baer. "A framework to assess the role of stakeholders in sustainable building retrofit decisions", Sustainable Cities and Society, 10, 2014,207–221.

[8] Mehran Gholami, Abdul Rahman Mohd Sam, Jamaludin Mohamad Yatim and M. M. Tahir. "A review on steel/CFRP strengthening systems focusing environmental performance", Construction and Building Materials, 47, 2013, 301–310.

[9] D.P. Singh. "Repair and strengthening of reinforced concrete beams", Earthquake Engineering, Tenth World Conference, Rotterdam, 1992, 5217-5220.

[10] Vijayakumar. A and Venkatesh Babu. D.L. "A survey of methods and techniques used for Seismic retrofitting of RC buildings", International Journal of Civil and Structural Engineering, 2[1], 2011, 56-66.

[11] Ryan J. Williams, Paolo Gardoni and Joseph M. Bracci. "Decision analysis for seismic retrofit of structures", Structural Safety, 31, 2009, 188–196.

[12] De Lorenzis and J.G. Teng. "Near-surface mounted FRP reinforcement: An emerging technique for strengthening structures", Composites: Part B, 38, 2007, 119–143.

[13] Renato Parretti and Antonio Nanni. "Strengthening of RC Members Using Near-Surface Mounted FRP Composites: Design Overview", Advances in Structural Engineering, 7[5], 2004, 1-16.

[14] Jose Manuel de Sena Cruz and Joaquim Antonio Oliveira de Barros. "Bond Between Near-Surface Mounted Carbon-Fibre-Reinforced Polymer Laminate Strips and Concrete", Journal of Composites for Construction, 8[6], 2004, 519-527.

[15] Rudolf Seracino, Nicola M. Jones, M. S. M. Ali, Mark W. Page and Deric J. Oehlers. "Bond Strength of Near-Surface Mounted FRP Strip-to-Concrete Joints", Journal of Composites for Construction, 11[4], 2007, 401-409.

[16] Dongkeun Lee, Lijuan Cheng and Jason Yan-Gee Hui. "Bond Characteristics of Various NSM FRP Reinforcements in Concrete", Journal of Composites for Construction, 17[1], 2013, 117-129.

[17] Nemkumar Banthia, Aidin Abdolrahimzadeh, Marc Demers, Aftab Mufti, and Shamim Sheikh. "Durability of FRP-Concrete Bond in FRP-

Strengthened Bridges", ACI Journal, 32[8], 2010, 45-51.

[18] S.E. El-Gamal, A. Al-Nuaimi, A. Al-Saidy, A. Al-Lawati. "Efficiency of near surface mounted technique using fibre-reinforced polymers for the flexural strengthening of RC beams", Construction and Building Materials, 118, 2016, 52–62.

[19] Tarek Hassan and Sami Rizkalla. "Investigation of Bond in Concrete Structures Strengthened with Near Surface Mounted Carbon Fibre Reinforced Polymer Strips", Journal of Composites for Construction, 7[3], 2003, 248-257.

[20] Amiruddin Mishad, Mohd Hisbany Mohd Hashim, Azmi Ibrahim and Mudrika Nafis. "Flexural performance of reinforced concrete beams strengthened with a double vertical carbon fiber reinforced polymer (CFRP) plate using near-surface mounted (NSM)" Advanced Science Letters, 23[5], 2017, 4458-4462.

[21] Soo-Yeon Seo, Luciano Feo, David Hui. "Bond strength of near-surface-mounted FRP plate for retrofit of concrete structures", Composite Structures, 95, 2013, 719–727.

[22] A. Bilotta, F. Ceroni, M. Di Ludovico, E. Nigro, M. Pecce and G. Manfredi. "Bond Efficiency of EBR and NSM FRP Systems for Strengthening Concrete Members" Journal of Composites for Construction, 15[5], 2011, 757–772.

[23] Blaschko, M and Zilch.K. "Rehabilitation of concrete structures with CFRP strips glued into slits", Technische Universität München, Munich, Germany, 1998, 7 pages.

[24] J.A.O. Barros and A.S. Fortes. "Flexural strengthening of concrete beams with CFRP laminates bonded into slits", Cement & Concrete Composites, 27, 2005, 471–480.

[25] S.S. Zhang, J.G. Teng and T. Yu. "Bond–slip model for CFRP strips near-surface mounted to concrete", Engineering Structures, 56, 2013, 945–953.

[26] Jose M. Sena Cruz, Joaquim A. O. Barros, Ravindra Gettu, and Alvaro F. M. Azevedo. Bond Behavior of Near-Surface Mounted CFRP Laminate Strips under Monotonic and Cyclic Loading", Journal of Composites for Construction, 10[4], 2006, 295-303.

[27] Nihad Tareq Khshain Al-Saadi, Riadh Al Mahaidi and Kamiran Abdouka. "Bond behaviour between NSM CFRP strips and concrete substrate using single-lap shear testing with cement-based adhesives", Australian Journal of Structural Engineering,17[1], 2016, 28–38.

[28] Gaia Barbieri, Luigi Biolzi, Massimiliano Bocciarelli, Sara Cattaneo. "Size and shape effect in the pull-out of FRP reinforcement from concrete", Composite Structures, 143, 2016, 395–417.

[29] J.G.Teng, L. De Lorenzis, Bo Wang, Rong Li, T. N. Wong and Lik Lam. "Debonding Failures of RC Beams Strengthened with Near Surface Mounted CFRP Strips", Journal of Composites for Construction, 10[2], 2006, 92-105.

[30] Soo-yeon Seo, Ki-bong Choi, Young-sun Kwon, and Kang-seok Lee. "Flexural Strength of RC Beam Strengthened by Partially De-bonded Near Surface-Mounted FRP Strip", International Journal of Concrete Structures and Materials, 10[2], 2016, 149–161.

[31] J.G. Teng, S.S. Zhang and J.F. Chen. "Strength model for end cover separation failure in RC beams strengthened with near-surface mounted (NSM) FRP strips", Engineering Structures, 110, 2016, 222–232.

[32] Laura De Lorenzis, Andrea Rizzo and Antonio La Tegola. "A modified pull-out test for bond of near-surface mounted FRP rods in concrete", Composites: Part B, 33,2002, 589–603.

[33] J.A.O. Barros, S.J.E. Dias and J.L.T. Lima. "Efficacy of CFRP-based techniques for the flexural and shear strengthening of concrete beams", Cement & Concrete Composites, 29, 2007, 203–217.

[34] Everaldo Bonaldo, Joaquim António Oliveira de Barros and Paulo B. Lourenço. "Efficient Strengthening Technique to Increase the Flexural Resistance of Existing RC Slabs", Journal of Composites for Construction, 12[2], 2008, 149-159.

[35] M.S. Mohamed Ali, D.J. Oehlers, M.C. Griffith and R. Seracino. "Interfacial stress transfer of near surface-mounted FRP-to-concrete joints", Engineering Structures, 30, 2008, 1861–1868.

[36] A.A. Shukri and M.Z. Jumaat (2016). "Simulating concrete cover separation in RC beams strengthened with near-surface mounted reinforcements", Construction and Building Materials, 122, 2016, 1–11.

[37] Firas AL-mahmoud, Arnaud Castel, Raoul Francois and Christian Tourneur. “Effect of surface pre-conditioning on bond of carbon fibre reinforced polymer rods to concrete”, Cement & Concrete Composites, 29, 2007, 677–689.
[38] Ines G. Costa and Joaquim A.O. Barros. “Flexural and shear strengthening of RC beams with composite materials – The influence of cutting steel stirrups to install CFRP strips”, Cement & Concrete Composites, 32, 2010, 544–553.
[39] Mohammadali Rezazadeh, Szymon Cholostiakow, Renata Kotynia, Joaquim Barros. “Exploring New NSM Reinforcements for the Flexural Strengthening of RC Beams: Experimental and Numerical Research”, Composite Structures, 141, 2016, 132–145.
[40] Mario R.F. Coelho, Jose M. Sena-Cruz and Luís A.C. Neves. “A review on the bond behavior of FRP NSM systems in concrete”, Construction and Building Materials,93, 2015, 1157–1169.
[41] Donatella Galati and Laura De Lorenzis. “Effect of Construction Details on the Bond Performance of NSM FRP Bars in Concrete”, Advances in Structural Engineering,12[5], 2009, 683-700.
[42] Francesca Ceroni, Marisa Pecce, Antonio Bilotta and Emidio Nigro. “Bond behavior of FRP NSM systems in concrete elements”, Composites: Part B, 43, 2012, 99–109.
[43] Antonio Bilotta, Francesca Ceroni, Emidio Nigro and Marisa Pecce. “Strain assessment for the design of NSM FRP systems for the strengthening of RC members, Construction and Building Materials, 69, 2014, 143–158