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Performance of Concrete Beams Strengthened with Hybrid NSM-FRP Systems: A Review

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ABSTRACT

This article provides an overview of the study on the structural response of Near-Surface Mounted (NSM) FRP strengthened reinforced concrete beams within a hybrid reinforcement system. Although Fibre Reinforced Polymer (FRP) composites, such as CFRP and GFRP, have been extensively investigated, Basalt FRP (BFRP) is a relatively new but economically viable alternative material with high performance. This paper critically reviews the literature on bond enhancement of NSM-BFRP systems in flexural capacity, stiffness, and failure modes by internal reinforcement. A significant deficiency in the Application of these hybrid systems in NSC is also established, which lacks experimental data. The review concludes by emphasizing the need for codified design recommendations to enhance bond performance and ductility for hybrid NSM-BFRP systems.

1. Introduction

Structural sustainability and long-term durability of reinforced concrete is a main challenge in contemporary civil engineering. Electrochemical corrosion of the internal steel reinforcement is the main driver of structural decay and can be accelerated by exposure to chloride-based environments, industrial pollutants, or cyclic humidity [1]-[3]. This damage causes to the creation of Extensive oxidation products and creates an internal pressure on the concrete matrix, micro-crack initiation, loss of bond, and finally the spalling of concrete cover [4], [5]. As a result, the cross-section of the steel is compromised for overall structural safety and serviceability [6].

In order to overcome such inherent limitations of steel, Fiber Reinforced Polymer (FRP) composites have been integrated into the construction sector as a technically superior alternative. FRP materials are characterized by high strength-to-weight ratios, electrical neutrality, and exceptional resistance to chemical corrosion [7], [8]. Although CFRP and GFRP can be considered as the most used materials, Basalt Fiber Reinforced Polymer (BFRP), emerging as "an economical high-performance innovative material of composite reinforcement," has been recently developed [9]-[11]. BFRP is produced from natural volcanic rock via a one-step melting method, and in comparison with CFRP, it is more environmentally friendly and economically efficient. In addition, BFRP has significantly

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superior alkali resistance and heat resistance to that of GFRP [12]-[14].

However, the application of BFRP in RC beams is accompanied by certain structural complexities. Steel exhibits a ductile yielding stage, while the BFRP can be regarded as a linear elastic material, and sudden rupture takes place. These properties, along with a low modulus of elasticity (about 40-60 GPa), require the redefinition of design concepts, particularly in regard to deflection control and crack width limitation under service loads [15]-[17].In the field of structural strengthening, the Near-Surface Mounted (NSM) method has proved to be a preferred system over the classic Externally Bonded (EB) reinforcement technique [18]. The NSM method is completed by inserting FRP bars in pre-cut longitudinal slots at the cover depth and filling with high-strength adhesives [19]. This method enhances the bonding surface space and protects FRP with concrete encasement, so the premature debonding and fire-resistant, impact resistance risks can be reduced [19], [20].

One important frontier of current research is the "Hybrid Reinforcement System," which combines internal and NSM-strengthening in a synergetic way for an optimum between ultimate load capacity and structural ductility [21]. Although the performance of these systems is extensively documented in HSC, there is a significant scarcity of experimental values on (NSC) [22]. NSC is a brittle and porous matrix, directly affecting the stress transfer mechanism and Concrete Cover Separation failure mode [23]. This review paper aims to synthesize the existing knowledge while addressing a gap in the state of the art and research by specifically examining the behaviour of NSM-BFRP in hybrid systems with the aim of providing a valuable contribution for future standardization activities.

2. Previous Research

The evolution of structural strengthening has transitioned from traditional methods to advanced composite applications. This section provides a granular analysis of previous experimental works, focusing on the mechanical parameters, bonding interfaces, and the performance of hybrid configurations.

2.1. Comparative Analysis of Strengthening Techniques (EB vs. NSM)

The EB to NSM change was attributed to addressing the challenges of premature debonding. De Lorenzis and Teng [24] were some of the early researchers who observed that bond mobilization in NSM is significantly larger because of the three-sided adhesion surface area with concrete and confinement offered by the surrounding matrix. The pre-fabrication and the installation of these bars into pre-sized grooves are depicted in Fig. 1[25], as supplemented with the explanation of the interlocking action performed by the adhesive.

In early comparative tests, Blaschko [26] observed that NSM strips were able to attain a significant portion of the full tensile capacity, while EB strips tended to fail at 20-30% of their ultimate strain capacity. El-Hacha and Rizkalla [27] investigated this aspect in more detail by testing RC beams strengthened with CFRP and stainless steel, observing that using the same volume of material, NSM systems increased ultimate load capacity by 4.8 times compared to 4.8 to EB systems. Types of strengthening in the studies are illustrated in Fig. 2[27].

2.2. Mechanical Performance of BFRP in Structural Applications

As mentioned in the introduction, BFRP can be classified as a “new generation” of FRP. Sim et al. [14] conducted comprehensive chemical durability tests of basalt fibers in different alkaline, acidic and saline solutions. They found that basalt fiber has better tensile properties than GFRP, especially in exposure to alkalinity. This durability is also supported by the results of Wu et al. [28]) are summarized in **Table 1** [28] which summarizes a tensile strength retention of BFRP bars following exposure to alkaline solutions at 55°C.

Table 2: provides a Detailed characterization of the mechanical properties of BFRP bars, as investigated by Adhikari [29], showing that tensile strength can exceed 1700 MPa for smaller diameters.

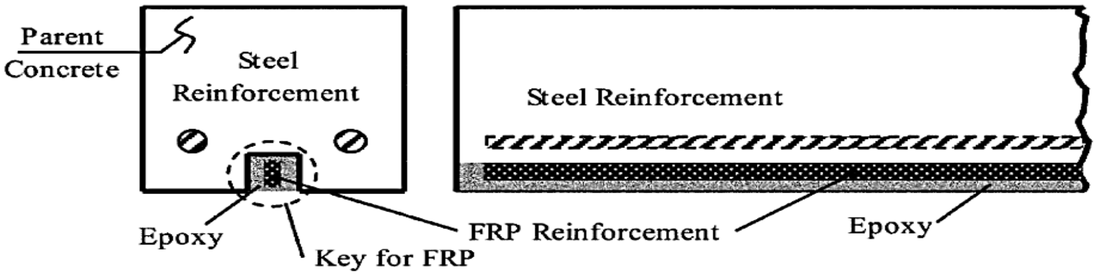

Figure 1: Strengthening of RC beams with NSM-FRP technique[25]

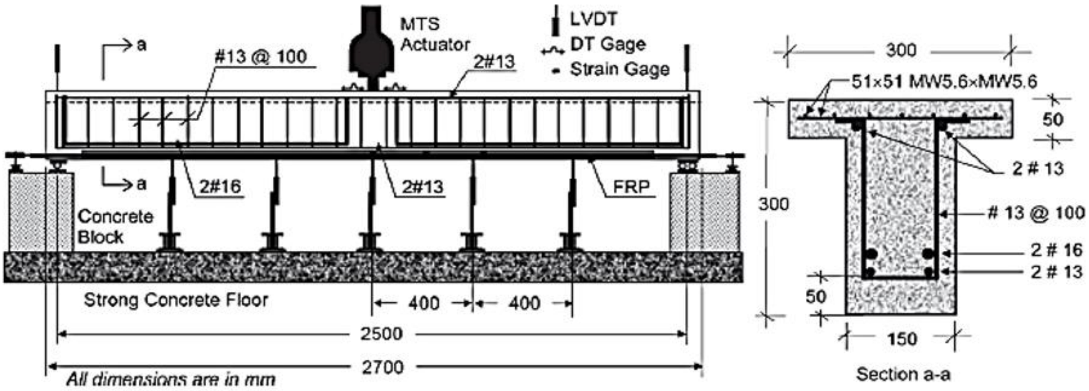

Figure 2: Beam details and test setup

Table 1: Results of the corrosion test of basalt FRP bar[28].

Type of FRP	Temperature Aging time (week)		Tensile strength			Elastic modulus		
			Mean (MPa)	CV (%)	Retention (%)	Mean (MPa)	CV (%)	Retention (%)
BFRP-6	Control		1325	0.71	100.00	56	2.16	100.00
	25°C	3	1021	0.45	77.10	55	0.31	98.36
		6	922	3.18	69.64	55	2.66	97.42
		9	919	7.84	69.38	55	0.45	97.77

	55°C	3	885	3.71	66.81	56	0.77	98.57
		6	818	4.47	61.72	54	1.93	96.40
		9	802	11.36	60.58	55	1.07	97.66
BFRP-12	Control		1089	5.66	100.00	46	3.84	100.00
	25°C	3	1036	15.21	95.18	48	2.86	103.73
		6	910	1.02	83.58	48	2.49	104.52
		9	893	6.22	82.03	47	4.62	103.12
	55°C	3	807	11.79	74.11	47	3.50	101.71
		6	681	15.76	62.55	47	3.14	103.05
		9	669	16.53	61.40	45	4.37	98.43
SFCB	Control		577	1.23	100.00	155	3.12	100.00
	25°C	3	565	2.88	97.97	147	8.62	94.73
		6	507	3.47	87.97	156	14.10	100.56
		9	488	1.70	84.67	140	2.06	90.34
	55°C	3	453	3.31	78.56	149	6.19	95.71
		6	414	2.25	71.82	156	14.85	100.50
		9	406	2.47	70.42	157	8.76	101.30

Table 2: Mechanical properties of BFRP rebars[29].

Bar Size In (mm)	Tensile strength ksi (MPa)	Elastic modulus, ksi (GPa)	Rupture strain, in./in
0.12 (3)	251.6 (1735)	12,000 (84)	0.016
0.20 (5)	252.2 (1739)	12,000 (84)	0.020
0.28 (7)	235.0 (1620)	12,000 (84)	0.020

Xing et al. [19], who concentrated only on the NSM-BFRP bar, the effects of different reinforcement ratios were examined. The results showed that, as compared to CFRP, BFRP has a relatively low modulus of elasticity and shows greater energy absorption characteristics along with a more “pseudo-ductile” mode of failure. Al-Nsour et al. [15] and Abdel-Jaber et al. [30] on the repaired heat-damaged RC beams using NSM-BFRP proved that the flexural capacity of those beams would be between 90-105% of the original value.

2.3. Hybrid Reinforcement Systems: Synergy and Ductility

A significant limitation of FRP-strengthened beams is the lack of a yielding range. Hybrid systems are proposed to resolve this issue by combining internal steel with NSM-FRP. Wu et al. [21] because the steel exhibits yielding behavior and thus compatibility, while FRP provides high ultimate strength. The stress-strain distribution throughout the hybrid cross-section at different failure modes (rupture vs. crushing) is illustrated in Fig. 3[31].

Experimental static loading results for these hybrid configurations, summarized in **Table 3** [32], show that strengthening with AFRP or CFRP can increase the ultimate load capacity by approximately 46% over control specimens

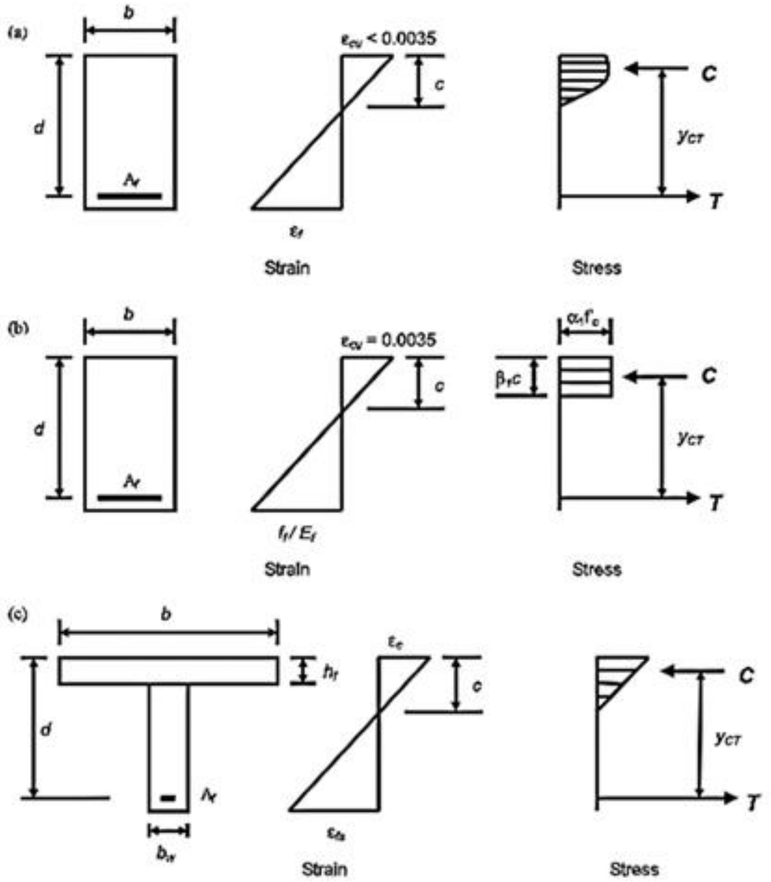

Figure 3. Stress–strain distributions in flexure: (a) failure by rupture of FRP; (b) failure by crushing of concrete; and (c) service condition with strain in FRP equal to ε_{fs} [31]

Table 3: Experimental results for static loading [32].

Specimen	Rebar yield load (kN)	Max. load (kN)
Beam NS	57 (1.0)	67 (1.0)
Beam AS	74 (1.30)	98 (1.46)
Beam CS	74 (1.30)	98 (1.46)

* The values in parentheses indicate the ratios with respect to the corresponding values of Beam NS.

2.4. Parameters Affecting NSM Bond Behavior

The performance of the NSM depends on several parameters, such as groove shape and surface preparation. Sharaky et al. [33] have proved that a groove width value up to 1.5 – 2 times the bar diameter is required. To investigate these bond mechanisms in detail, specific anchors and test arrangements like those described in Figure 4 and Figure 5 [29] (bellow) are used to isolate the bond-slip behavior. Al-Obaidi et al. [22] indicated that roughening the surface of BFRP bars 25–40% enhanced bond capacity. The results of pull-out tests, which distinguish between tension-failure and pure slip notation, are presented in **Table 4**. As observed in the experimental data [29], the failure mechanism is significantly influenced by the bar diameter. The smallest bars (3 mm) consistently failed due to tensile rupture, indicating that the bond strength exceeded the material's tensile capacity with bond stresses ranging between 3.8 and 4.3 MPa. Conversely, larger diameters (5 mm and 7 mm) exhibited a shift toward bond-slip failure, achieving higher bond stress values ranging from 6.1 to 8.7 MPa. This comparison highlights that while larger bars provide greater ultimate bond resistance, they are more susceptible to interface slip compared to the tensile rupture observed in thinner rods

Figure 4: Anchor for the Pull-Out Test [29]

Figure 5: PVC Conduits for the Pull-Out Cylinders at Both Edges [29]

Table 4: Pull-out test results of BFRP reinforcement bars [29].

Bar Size In (mm)	Bond stress, psi (MPa)	Concrete strength, ksi (Mpa)	Failure mode
0.12 (3)	554 (3.8)	4.65 (32.06)	Tension-Failure
	595 (4.1)	4.65 (32.06)	Tension-Failure
	621 (4.3)	4.65 (32.06)	Tension-Failure
	609 (4.2)	4.65 (32.06)	Tension-Failure
0.20 (5)	878 (6.1)	4.62 (31.85)	Pure Slip-Failure
	981 (6.8)	4.62 (31.85)	Slip followed by Tension
	999 (6.9)	4.62 (31.85)	Pure Tension-Failure
	1016 (7.0)	4.62 (31.85)	Slip followed by Tension
0.28 (7)	996 (6.9)	4.65 (32.06)	Pure Slip-Failure
	1004 (6.9)	4.65 (32.06)	Pure Slip-Failure
	1001 (6.9)	4.65 (32.06)	Pure Slip-Failure
	1261 (8.7)	4.65 (32.06)	Pure Tension-Failure

2.5. Failure Mechanisms in Normal-Strength Concrete (NSC)

Modes of failure are more intricate when NSC is used because the fracture toughness of the matrix is much lower. Oehlers et al. [23] identified "Concrete Cover Separation" (CCS) as the main failure. Two representative bond failure mechanisms: sliding or slipping of the bar in the concrete matrix are presented in Fig. 6[34]. Moreover, Fig.7 [35]. illustrates the cracks and failure modes under different loading situations (static or impacting). 7, showing the typical, more brittle shear-flexural cracks in NSC relatively to High-Strength Concrete.

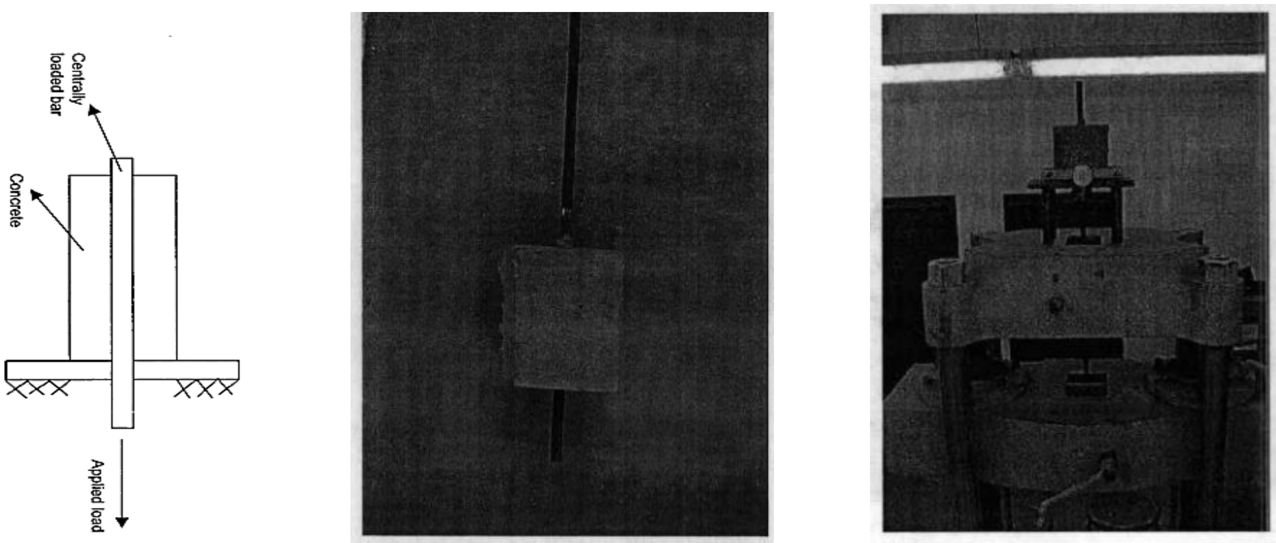

Figure 6: The bond failure of the plain basalt rebar reinforced specimen due to slip[34]

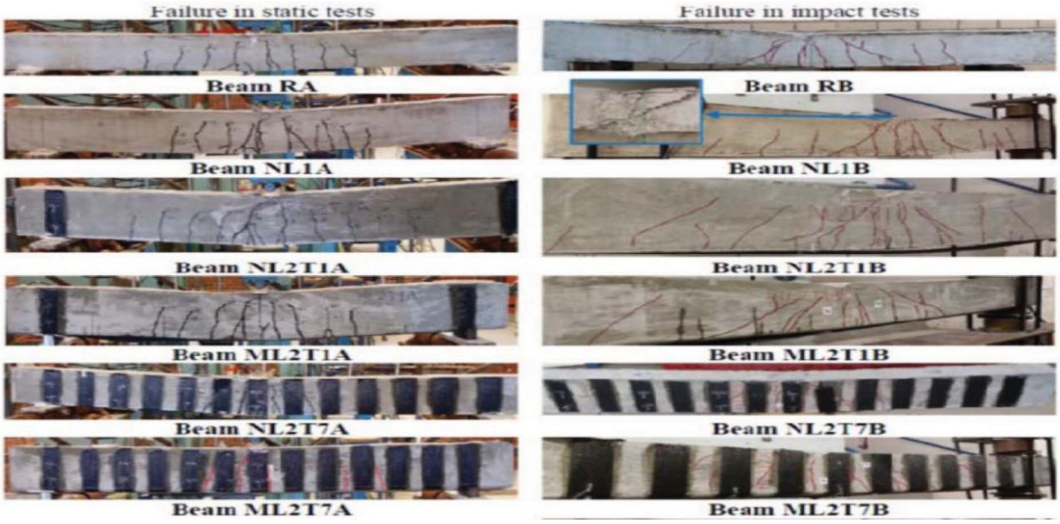

Figure 7: Failure modes of tested beams [35]

2.6. Long-term Durability and Environmental Impacts

The influence of several environmental factors on NSM systems is critical. Benmokrane et al. [1] presented long-term data about BFRP bars in alkaline media, aged by BFRP bars durability of 70% strength gain. Valerio et al. [36] showed that fatigue-induced debonding occurs less frequently for NSM system in comparison with EB systems. This is demonstrated by the failure patterns of flexural behavior in Fig. 8[36], i.e., NSM rods exhibited superior debonding resistance than EB sheets under cyclic loading.

Figure 8: flexural failure mode [36]

3. Conclusions

Based on the extensive review of previous experimental and analytical studies concerning the strengthening of RC beams, the following conclusions are synthesized:

1. BFRP has proven to be an effective and economical alternative to traditional reinforcement. It possesses a high tensile strength that significantly exceeds that of steel, making it ideal for structural applications, especially in corrosive environments.
2. The NSM technique is superior to the EB method in terms of bond mobilization. Embedding the BFRP bars within the concrete cover provides greater confinement, which effectively delays debonding and allows the strengthening material to reach higher strain levels before failure.
3. The combination of internal reinforcement and NSM-BFRP bars (hybrid system) successfully balances strength and ductility. This approach mitigates the brittle nature of FRP by utilizing the yielding characteristics of internal bars, resulting in a substantial increase in the ultimate load-carrying capacity.
4. In NSC members, the bond performance is highly sensitive to the porous and brittle nature of the matrix. Failure is predominantly governed by concrete cover separation or bar slip, occurring at lower stress levels compared to high-strength concrete applications.
5. BFRP exhibits high durability and strength retention when exposed to alkaline and saline conditions. This ensures the long-term integrity of the strengthened RC elements compared to other fiber types like GFRP.
6. There is a clear deficiency in the literature regarding the specific interaction of hybrid NSM-BFRP systems within an NSC matrix. Future studies should focus on establishing precise design determinants for this configuration to optimize serviceability and ultimate performance

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