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Predicting Failure Modes of RC Beams Strengthening with FRP-NSM System: A Statistical Approach

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Abstract

FRP strengthening using near surface mounted (NSM) is recognized as a highly effective method for strengthening structures using FRP material. However, there are some drawbacks associated with this technique. One of the challenges is concrete cover separation failure, which leads to premature material failure and restricts NSM technique applicability. To address this issue, multinomial logistic regression (MLR) analysis is used. This analysis aimed to investigate the factors (Total Equivalent Steel Ratio TESR%, Stirrup Steel Ratio%, and presence of an anchorage) that can be used to predict the failure modes of reinforced concrete beams strengthened with the FRP-NSM system using a previously published dataset consisting of 131 beam tests from 25 studies. By using odds ratios, which are exponential coefficients, the MLR results were interpreted. The study indicated that a reduction in the TESR% predictor or increase in Stirrup Steel Ratio%, deceases the probability of conversion from concrete cover separation to other failure modes such as flexural failure, FRP bar debonding, and FRP bar rupture. Moreover, the reinforced concrete beams strengthened with the FRP-NSM system with anchorage has a positive contribution on the expected the failure modes: flexural failure, FRP bar debonding, and FRP bar rupture compared to concrete cover separation. Based on the classification table analysis, the model's correct classification rate was 51.1%. The model is accurate in predicting failure modes, as its rate is higher than the chance accuracy rate of 36.4%.

1. Introduction

The strengthening of reinforced concrete (RC) structures is important for several reasons. These include structural defects, poor design, environmental conditions, earthquakes requiring repairs, and changes in the purpose or capacity of the structure. The use of fiber reinforced polymers (FRP) to strengthen RC structures has increased in recent years. This is because FRP offers advantages such as low strength, high strength, good strength in different environments, easy and quick installation, and low conductivity. There are several strategies for strengthening RC elements, the most prevalent of which is external bonding (EB) and near surface mounting (NSM). NSM has gained more attention compared to EBR recently due to its higher bond efficiency and ability to protect the FRP reinforcement from physical and environmental damage. NSM involves embedding FRP materials, such as bars and strips, into grooves cut into the concrete surface of RC members. This technique is suitable for harsh environmental conditions, enhances bond performance, and improves aesthetics.

However, the near surface mounted (NSM) method also has limitations. For instance, the beam width may not provide sufficient clearance around the edges or adequate spacing between adjacent NSM grooves. Several studies have been conducted to investigate the bond characteristics of NSM bars or strips in concrete using direct pull- out tests [1]– [7] or beam pull-out tests [8]– [11]. The flexural behavior of RC beams strengthened with the NSM technique using FRP bars has also been examined [12]– [85].

Hassan et al. [19] studied the bond behavior of Reinforced Concrete (RC) beams strengthened with near-surface mounted (NSM)- fiber-reinforced polymer (FRP) material. For this, nine RC beams were tested using monotonic static loading and strengthened with near-surface mounted (NSM)-Carbon Fiber-Reinforced Polymer (CFRP) strips. The results showed an increase in the load carrying capacity up to 53% with the requirement of sufficient anchorage for the bars. The authors also suggested that the maximum usable strain of the FRP bars should be limited from 0.7% to 0.8%. Similar testing was conducted by Teng and Lorenzis [20] testing FRP-reinforcement. they tested the same area of FRP reinforcement, and overall observed a greater debonding strain for the NSM specimen than the EB specimen, or, in a number of cases, no debonding at all for the NSM specimen.

Choi et al. [21] also studied the influence of the unbonded length on the deformability of reinforced concrete (RC) beams reinforced with near surface mounted (NSM) CFRP (Carbon Fiber Reinforced Polymer) bars. They concluded that deformability increases when the unbonded length increases. This fact was verified by Sharaky et al. [17] in rectangular beams with different materials, shapes and bonded lengths. They found that strength increases were proportional to the bonded length, especially when end anchorages were considered.

Obaidi et al. [22] studied the influence of different parameters enhancing the strengthening efficiency of NSM CFRP bars in rectangular RC beams such as size of bar, CFRP reinforcement ratio, and steel reinforcement ratio. One of the most significant findings of this study was negative impact of higher reinforcement ratios on strengthening efficiency. They also introduced a novel method of mechanical interlocking in the form of lateral grooves to enhance the load carrying capacity. However, this technique was not without its drawbacks since it resulted in reduced ductility which is an intrinsic problem of FRP materials due to their inherent lack of deformation capacity.

The flexural behavior of continuously reinforced concrete T-beams strengthened with near-surface mounted (NSM)- fiber-reinforced polymer (FRP) bars was investigated by Diab et al. [23], who observed a 33-36% increase in service load carrying capacity compared to that of the control specimens. The flexural behavior of RC beams strengthened with near-surface mounted (NSM)- fiber-reinforced polymer (FRP) bars was evaluated by Soliman et al. [24] using an experimental and finite element analysis approach. Four-point bending tests were performed on four beams having different steel reinforcement ratios and NSM FRP bar diameters. It was indicated that a lower steel reinforcement ratio results in an NSM FRP strengthening technique that is more efficient. Al Mahmoud et al. [15], [24] presented experimental results showing that using the Near-Surface Mounted (NSM) technique with Carbon Fiber Reinforced Polymer (CFRP) rods increased the ultimate strength of Reinforced Concrete (RC) beams. They noticed a minimum 50% increase of the ultimate strength compared to non-strengthened beams. They also observed that the failure mode changed from CFRP rod debonding to compressive concrete crushing, according to the ratio of combined CFRP cross-section and length to the compressive strength of the concrete.

Sharaky et al. [16] studied the flexural behavior of RC beams strengthened with partially and fully bonded CFRP and GFRP bars using NSM technique. The RC member with fully bonded reinforcement exhibited a substantial improvement in both strength and stiffness compared to that with partially bonded reinforcement. In addition, for NSM-CFRP strengthened beams the dominant failure mode was concrete cover separation, whereas for fully bonded NSM-GFRP beams, failure was either by debonding at the concrete-epoxy interface or by the splitting of concrete, depending on the number of grooves.

Khalifa [26] tested the effectiveness of NSM and Externally Bonded (EB) systems with CFRP reinforcement for improving the flexural strength of RC beams under four-point loading. He found that beams strengthened with NSM-CFRP strips showed significantly higher ultimate loads (ranging from 12% to 18%) than the ones strengthened by EB-CFRP sheets.

However, The FRP-NSM method has a typical drawback known as debonding failure, which tends to start at the ends of the FRP bars. debonding failure can occur in two ways: end interfacial debonding and end concrete cover separation, as seen in Fig. 1. interfacial debonding becomes more critical when the width of the concrete beam, is quite larger than the effective zone of the NSM FRP bonded to the concrete. Concrete cover separation is more common than interfacial debonding. Since the steel tension rebar causes stresses in the surrounding concrete, its plane is more crucial than the plane interfacial between the adhesive and the fibre [33], [34]. Due to the severity of the concrete cover separation failure, this failure has been the topic of numerous studies [35]–[37]. Moreover, this failure typically occurs before the fibers reach their maximum tensile strength, limiting the FRP's utilization to its full capacity.

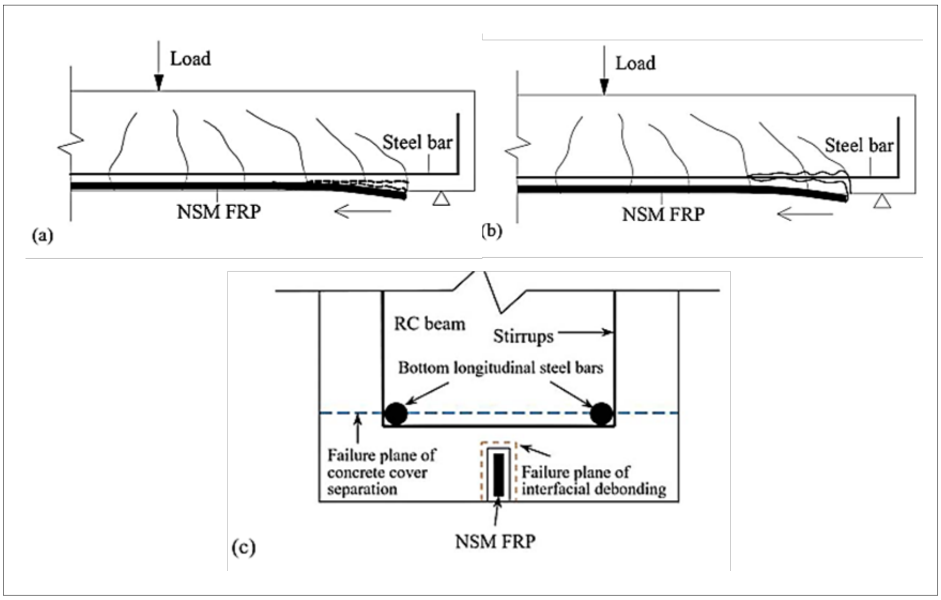

Fig. 1 *Schematic depiction of FRP debonding failures [19], as follows: (a) End interfacial debonding; (b) Concrete cover separation; (c) A sectional view*

To mitigate the risk of premature failure caused by concrete cover separation, various anchorage measures have been proposed and studied [33], [34], and [48]. Wu et al. [47] assessed a steel anchorage system on NSM-FRP strengthened RC beams. This involved steel sleeves for an NSM bar with steel hoops that were bolted on a beam. It was found that these steel devices provided effective prevention for end debonding failure and improved the load capacity by about 10% compared to the fiber-reinforced polymer (FRP)- near-surface mounted (NSM) strengthened control beam. While, Obaidat et al. [33] tested the performance of a new proposed system, which fixed an NSM-CFRP strip at the end with a steel clamped. The test results showed that the ultimate load capacity is increased, deflection behavior, stiffness, and toughness are better when the end is with a steel plate comparing with a horizontal CFRP strips with NSM-CFRP to beams.

Some researchers [45], [43] utilized thermoplastic FRP bars with end hooks formed by bending the end parts of the bars to 90° to form the hooks for anchorage. It was observed in those studies that for such end-hook anchorage, concrete cover separation and interfacial debonding of NSM-FRP bars were successfully delayed. Hosen et al. [62] and Sharaky et al. [27] mentioned that FRP end concrete cover separation could be delayed by CFRP U-jackets, thereby increasing the load capacities (14.5%–33.1%) and mid span deflections (88.2%–150%) at failure over the strengthened control beam.

A more recent study Zhang et al. [48] evaluated CFRP U-jackets with different material and geometric configurations in full-scale RC beams strengthened with NSM CFRP strips. The experimental tests confirmed that CFRP U-jackets could delay or prevent concrete cover separation failure, and the strengthened beam's load capacity (3.6% to 33.9%) and deformation capacity (17.7% to 79.9%) were also greater than the control. The experimental study also illustrated the impact of the number and the amount of U-jackets and their inclination angle on the strengthened beam's performance. These measures aim to enhance the flexural capacity of beams and delay the occurrence of unexpected flexural failure to an acceptable extent.

However, the challenge of addressing premature failure due to concrete cover separation remains a significant concern for beams strengthened with near-surface mounted (NSM)- fiber-reinforced polymer (FRP) bars. The objective of this study is to perform a statistical analysis that explores the variables (Total Equivalent Steel Ratio (TESR%), Stirrup Steel Ratio%, and existence of an anchorage) that can predict failure modes of the RC beams strengthened with system of the near-surface mounted (NSM)- fiber-reinforced polymer (FRP) materials. To achieve this, we conducted a multinomial logistic regression analysis on the previously published data, which was executed using SPSS version 24.

2. Methodology

2.1 Data Analysis

A total of 131 beam tests from 25 different experimental programs detailed in Table 1 were collected and presented in this work. The dataset aimed to enhance reinforced concrete (RC) beams with the near-surface mounted (NSM) fiber-reinforced polymer (FRP) system in flexure, both with and without an anchorage configuration. All specimens were tested under two-point loading until failure.

The most common types of failure observed in the previous dataset were: (1) flexural failure; (2) FRP bar debonding; (3) concrete cover separation; and (4) FRP bar rupture. To conduct a statistical analysis, Table 1 included the variables: TESR%, Stirrup Steel Ratio%, and the existence of anchorage in the strengthening RC beams using the FRP-NSM system. To determine the variable Total Equivalent Steel Ratio (TESR%), we calculated the area of the composite material and determined an equivalent amount of steel using the modular ratio denoted as 'αi' in Eq. (1). This total equivalent steel ratio quantity was then expressed as a proportion of the total cross-sectional area, as given in Eq. (2).

Several structural design codes define the Stirrup Steel Ratio% [67], as demonstrated in Eq. (3). Where: 'Asv' represents the total area of stirrups in the beam's section, 'b' denotes the width of the beam, and 'S' is the spacing of the stirrups along the span of the beam.

$$\alpha i = \frac{(\mathrm{E_{FRP}})\mathrm{i}}{E_{Steel}} \tag{1}$$

$$TESR\% = \sum \frac{100(A_S + \alpha i A_{FRP})}{bd} \tag{2}$$

$$Stirrup\ Steel\ Ratio\% = \frac{A_{sv}}{bs} \tag{3}$$

Table 1 *Database of the previous studies*

References	Reference ID	Stirrup steel ratio %	TESR%	Anchorage type	Failure Modes
El-Hacha ,2004 [45]	B1	1.5	1.871	No Anchorage	Concrete Cover Separation
	B2	1.5	1.874	No Anchorage	FRP bar Rupture
	B3	1.5	1.874	No Anchorage	FRP bar Rupture
	B4	1.5	1.874	No Anchorage	Concrete Cover Separation
Y.Zhang,2021 [46]	JG-LG8S14C20M	1.4	1.381	Anchorage	Flexural Failure
	JG-LG8S12C40M	1.4	1.037	Anchorage	Flexural Failure
	JG-LG8S12C20M	1.4	1.037	Anchorage	Flexural Failure
	JG-GG8S14C20M	1.4	1.381	Anchorage	FRP bar debonding
	JG-GG8S12C40M	1.4	1.037	Anchorage	FRP bar debonding
	JG-GG8S12C20M	1.4	1.037	Anchorage	FRP bar debonding
	JG-LC8S12C20M	1.4	1.236	Anchorage	Concrete Cover Separation
	JG-LG8S12C20	1.4	1.037	No Anchorage	Concrete Cover Separation
	JG-LG10S12C20M	1.4	1.087	Anchorage	Concrete Cover Separation
	JG-LG6S12C20M	1.4	0.998	Anchorage	Flexural Failure
Wu,2014 [47]	B11	1.3	1.244	No Anchorage	Flexural Failure
	B21	1.3	1.346	No Anchorage	Concrete Cover Separation
	B22-u	1.3	1.346	Anchorage	Concrete Cover Separation
Ke, 2023 [34]	SB	1.0	0.885	No Anchorage	Concrete Cover Separation
	UB	1.0	0.885	Anchorage	Concrete Cover Separation
	E-C-2-120-90	1.0	0.885	Anchorage	Concrete Cover Separation
	E-G-2-120-90	1.0	0.885	Anchorage	Concrete Cover Separation
	E-C-4-120-90	1.0	0.885	Anchorage	Concrete Cover Separation
	E-C-4-120-45	1.0	0.885	Anchorage	Concrete Cover Separation
	E-C-4-200-45	1.0	0.885	Anchorage	Concrete Cover Separation
	E-C-8-200-45	1.0	0.885	Anchorage	Concrete Cover Separation
S.S.Zhang,2021 [48]	S1	1.0	0.884	No Anchorage	Concrete Cover Separation
	S1-C-1-100-90	1.0	0.884	Anchorage	Concrete Cover Separation
	S2	1.0	0.884	No Anchorage	Concrete Cover Separation
	S2-C-1-50-90	1.0	0.884	Anchorage	Concrete Cover Separation
	S2-C-1-100-90	1.0	0.884	Anchorage	Concrete Cover Separation
	S2-G-1-100-90	1.0	0.884	Anchorage	Concrete Cover Separation
	S2-C-1-100-45	1.0	0.884	Anchorage	Concrete Cover Separation

	S2-C-2-50-90	1.0	0.884	Anchorage	Concrete Cover Separation
	S2-C-2-100-90	1.0	0.884	Anchorage	Concrete Cover Separation
	S2-C-2-100-45	1.0	0.884	Anchorage	FRP bar Rupture
Saeed,2018 [49]	SL	0.9	1.319	No Anchorage	FRP bar debonding
	RL	0.9	1.340	No Anchorage	FRP bar debonding
	RB	0.9	1.267	No Anchorage	FRP bar debonding
Jung,2017 [50]	R-TR-10	0.8	0.445	No Anchorage	FRP bar Rupture
	R-PL-15	0.8	0.445	No Anchorage	FRP bar Rupture
	R-PL-25	0.8	0.468	No Anchorage	FRP bar debonding
	R-RD-9	0.8	0.486	No Anchorage	FRP bar debonding
	R-PL-25∗2-S	0.8	0.524	No Anchorage	Concrete Cover Separation
	R-PL-25∗2-2S	0.8	0.524	No Anchorage	Concrete Cover Separation
	R-RD-9∗2-S	0.8	0.560	No Anchorage	FRP bar debonding
	R-RD-9∗2-2S	0.8	0.560	No Anchorage	Concrete Cover Separation
Zeng,2019 [51]	B1-3EB	0.8	0.965	No Anchorage	FRP bar debonding
	B2-3NSM	0.8	0.988	No Anchorage	FRP bar debonding
Obaidat, 2020 [33]	S1-H	0.8	0.755	No Anchorage	Concrete Cover Separation
	S1-V	0.8	0.755	No Anchorage	Concrete Cover Separation
	S1-H-SC	0.8	0.755	Anchorage	FRP bar Rupture
	S2-H	0.8	0.826	No Anchorage	Concrete Cover Separation
	S2-V	0.8	0.826	No Anchorage	Concrete Cover Separation
	S2-H-SC	0.8	0.826	Anchorage	FRP bar Rupture
	S3-H	0.8	0.897	No Anchorage	Concrete Cover Separation
	S3-V	0.8	0.897	No Anchorage	Concrete Cover Separation
	S3-H-SC	0.8	0.897	Anchorage	FRP bar Rupture
Tahmouresi,2021 [52]	LB-NG	0.8	0.928	No Anchorage	Flexural Failure
	LB-NGS	0.8	0.928	Anchorage	FRP bar Rupture
	LB-NGS-CE	0.8	0.928	Anchorage	FRP bar Rupture
	LB-NGS-CM	0.8	0.928	Anchorage	FRP bar debonding
	LB-NGS-A2	0.8	0.928	Anchorage	FRP bar Rupture
	LB-NGS-A3	0.8	0.928	Anchorage	FRP bar Rupture
Boutlikht,2022 [53]	SB1NSM	0.6	1.648	No Anchorage	Concrete Cover Separation
	SB2NSM	0.6	1.648	No Anchorage	Concrete Cover Separation
	SB1EBR	0.6	1.648	No Anchorage	FRP bar debonding
	SB2EBR	0.6	1.648	No Anchorage	FRP bar debonding
Ali ,2022 [63]	G-B1	0.6	0.487	No Anchorage	Concrete Cover Separation
	G-B2	0.6	0.547	No Anchorage	Concrete Cover Separation
	G-S2	0.6	0.547	No Anchorage	Concrete Cover Separation
	G-B1-UC-S	0.6	0.487	Anchorage	FRP bar Rupture
	G-B2-UC-S	0.6	0.547	Anchorage	FRP bar Rupture
	G-S2-UC-S	0.6	0.547	Anchorage	FRP bar Rupture
Elgamal,2016 [54]	CN1	0.5	0.520	No Anchorage	FRP bar debonding
	CN2	0.5	0.605	No Anchorage	FRP bar debonding
	GN1	0.5	0.472	No Anchorage	Flexural Failure
	GN2	0.5	0.509	No Anchorage	FRP bar Rupture
	CHYB	0.5	0.811	No Anchorage	FRP bar Rupture
	GHYB	0.5	0.763	No Anchorage	FRP bar Rupture
	CN1-II	0.5	0.954	No Anchorage	FRP bar debonding
	CN2-II	0.5	1.040	No Anchorage	FRP bar debonding
Xing,2018 [55]	GCB-3	0.5	1.075	No Anchorage	Concrete Cover Separation
	GCB-1	0.5	0.723	No Anchorage	Concrete Cover Separation
	GCB-2	0.5	0.770	No Anchorage	FRP bar debonding
Darain,2016 [56]	CBC8P1	0.5	1.038	No Anchorage	FRP bar Rupture
	CBC8P2	0.5	1.125	No Anchorage	FRP bar Rupture
	CBC10P1	0.5	1.119	No Anchorage	FRP bar Rupture
	CBC10P2	0.5	1.206	No Anchorage	FRP bar debonding
	CBC10P2A	0.5	1.380	No Anchorage	Flexural Failure
Sabau,2018 [64]	B300	0.5	0.994	No Anchorage	Concrete Cover Separation
	B250	0.5	0.994	No Anchorage	Concrete Cover Separation

	B200	0.5	0.994	No Anchorage	Concrete Cover Separation
	S300	0.5	0.994	No Anchorage	FRP bar deboning
	S250	0.5	0.994	No Anchorage	FRP bar deboning
	S200	0.5	0.994	No Anchorage	FRP bar deboning
hadi,2022 [57]	CFRP sheet	0.4	0.818	No Anchorage	FRP bar Rupture
	NSM CFRP bar	0.4	0.772	No Anchorage	Flexural Failure
	Laminate CFRP	0.4	0.831	No Anchorage	Flexural Failure
	Hybrid	0.4	0.862	No Anchorage	Flexural Failure
Imjai,2022 [58]	TB2	0.4	0.813	No Anchorage	Flexural Failure
	TB3	0.4	0.910	No Anchorage	Flexural Failure
AL-Ameedee,2020 [66]	NCb	0.4	0.88	No Anchorage	Concrete Cover Separation
	NGb	0.4	0.853	No Anchorage	Concrete Cover Separation
abdallah,2020 [59]	BC1-SR	0.3	0.708	No Anchorage	Flexural Failure
	BC2-SR	0.3	0.708	No Anchorage	Concrete Cover Separation
	BC3-SM	0.3	0.708	No Anchorage	FRP bar debonding
	BC4-SM	0.3	0.708	No Anchorage	FRP bar debonding
	BC5-UR	0.3	0.708	No Anchorage	Flexural Failure
Dias,2018 [60]	S1L	0.3	0.412	No Anchorage	FRP bar Rupture
	S2L	0.3	0.443	No Anchorage	FRP bar debonding
	S3L	0.3	0.474	No Anchorage	FRP bar debonding
Nuraiah,2010 [61]	A-1G	0.3	0.747	No Anchorage	Flexural Failure
	A-2G	0.3	0.824	No Anchorage	Flexural Failure
Al-Thairy, 2023 [65]	F2G10	0.3	0.8204	No Anchorage	FRP bar deboning
	FS2G10	0.3	0.8204	No Anchorage	FRP bar deboning
	F1G10	0.3	0.7318	No Anchorage	FRP bar deboning
	F1G10.L1000mm	0.3	0.7318	No Anchorage	FRP bar deboning
	F1G10 E.E-M.M	0.3	0.7318	No Anchorage	Flexural Failure
EL-Emam,2020 [31]	B1.8-B	0.3	0.35	No Anchorage	Concrete Cover Separation
	B1.15-B	0.3	0.35	No Anchorage	FRP bar deboning
	B0.55-B	0.3	0.35	No Anchorage	FRP bar deboning
	B1.8-C	0.3	0.804	No Anchorage	Concrete Cover Separation
	B1.15-C	0.3	0.804	No Anchorage	FRP bar deboning
	B0.55-C	0.3	0.804	No Anchorage	FRP bar deboning
Sharaky,2014 [16]	LB1C1	0.3	0.668	No Anchorage	FRP bar Debonding
	LB1G1	0.3	0.6025	No Anchorage	Concrete Cover Separation
	LB2C1	0.3	0.771	No Anchorage	Concrete Cover Separation
	LB2G1	0.3	0.64	No Anchorage	Concrete Cover Separation
	LA2C1	0.3	0.771	No Anchorage	Concrete Cover Separation
	LA2G1	0.3	0.64	No Anchorage	Concrete Cover Separation
	LB1G2	0.3	0.6497	No Anchorage	FRP bar Debonding

2.2 Multinomial Logistic Regression (MLR)

Multinomial logistic regression (MLR) is a statistical technique commonly used instead of discriminant analysis due to its independence from assumptions of normality, linearity, and homoscedasticity. MLR aims to establish connections between multinomial outcomes in a dependent variable and a set of independent variables known as predictors. It is an extension of binary logistic regression, in which the relationship between a dependent and a set of independent variables with two possible outcomes is analyzed [86], [87].

Multinomial logistic regression (MLR) is particularly useful when the dependent variable does not indicate an ordered category. In this method, one category is selected as the reference point against which all other groups are compared. By interpreting the results relative to this reference group, valuable insights can be obtained regarding the effects being examined.

3. Results

In order to achieve our research objective, we utilized multinomial logistic regression analysis to explore the independent factors that predicted failure modes. As mentioned earlier, this statistical modeling technique is employed when the dependent variable consists of more than two categories. In our specific case, the dependent variable was failure modes, which were categorized as: (1) flexural failure, (2) concrete cover separation (3) FRP bar debonding, and (4) FRP bar rupture. The predictor or independent variables included Total Equivalent Steel Ratio (TESR%), existing of anchorage, and the covariate variable was Stirrup Steel Ratio% (as a continuous variable). Following the definition of the variables, it was crucial to further investigate their relationship. There are two commonly used tests for individual independent variables: the likelihood ratio test, which assesses the overall relationship between an independent variable and dependent variables (failure modes), and the final odds ratio model. Based on the above discussion and referring to Table 2, we observed a significant relationship between the dependent variable (failure modes) and all the independent variables: Total Equivalent Steel Ratio (TESR%) (p-value = 0.003 < 0.05), existing of anchorage (p-value = 0.024 > 0.05), and covariate variable (Stirrup Steel Ratio %) (p-value = 0.002 < 0.05).

Table 2 *Likelihood ratio tests*

Effect	**Model Fitting Criteria**	**Likelihood Ratio Tests**		
	-2 Log Likelihood of Reduced Model	**Chi-Square**	**df**	**Sig.**
Intercept	161.076a	.000	0	.
Stirrup Steel Ratio%	176.437	15.360	3	.002
TESR%	186.101	25.024	9	.003
Anchorage	170.556	9.479	3	.024

The chi-square statistic is the difference in -2 log-likelihoods between the final model and a reduced model. The reduced model is formed by omitting an effect from the final model. The null hypothesis is that all parameters of that effect are 0.

a. This reduced model is equivalent to the final model because omitting the effect does not increase the degrees of freedom.

Table 3 shows the final model of the odds ratio (OR). The odds ratios in this model, which were derived from multinomial logistic regressions, represent the likelihood of an event happening versus it not happening. The reference category of our model is the concrete cover separation, as it is the most prevalent failure mode in RC beams reinforced with the FRP-NSM system. Other failure modes, like flexural failure, FRP bar debonding and FRP bar rupture, are evaluated in relation to the separation of the concrete cover.

In multinomial logistic regression, the standard interpretation states that if we increase the predictor variable by one unit while keeping all other predictors constant, the odds ratio of the dependent variable compared to the reference category is expected to change by the parameter estimate associated with that predictor variable. The odds ratios are deemed statistically significant when their corresponding p-values at the 95% confidence level are less than 0.05. If the odds ratio is greater than 1.0, it indicates a positive correlation between the predictors and the dependent variable (failure modes). Conversely, if the odds ratio is smaller than 1.0, it suggests a negative correlation.

To clarify, when the odds ratios are greater than 1.0, it means that the predictors increase the likelihood of failure modes occurring at that specific level. This shows a positive contribution. On the other hand, when the odds ratios are below 1.0, it means that the predictors decrease the likelihood of failure modes occurring at that level, indicating a negative contribution.

For example, Example-wise, Table 3 considers an examination of the Stirrup Steel Ratio% predictor as it relates to the failure modes (flexural failure, FRP bar debonding, and FRP bar rupture compared to concrete cover separation. The odds ratios for these failure modes are notably less than 1.0 (0.111, 0.031, and 0.035, respectively). That means that an increase in the Stirrup Steel Ratio% by one unit with all other predictors constant leads to a decrease in the occurrence of the failure modes flexural failure, FRP bar, bar debonding and FRP bar rupture relative to concrete cover separation. In addition, these odds ratios are statistically significant at 95% confidence level because p-values (0.001 and 0.009) are less than 0.05 for the failure types; FRP bar debonding and FRP bar rupture, however an odds ratio of flexural failure is not statistically significant at 95% confidence level because p-value (0.075) is greater than 0.05.

The performance of the TESR% predictor was evaluated for three different failure modes: flexural failure, FRP bar debonding, and FRP bar rupture. In each failure mode, odds ratios were computed for TESR 1, TESR 2, and TESR 3 levels with respect to the TESR 4 level. These odds ratios were all less than 1.0, indicating that a decrease in the TESR% predictor from the TESR 4 level to TESR 1, TESR 2, and TESR 3 reduces the probability of changing from concrete cover separation to a different failure mode (flexural failure, FRP bar debonding, and FRP bar rupture). One important note is that all of these odds ratios were not statistically significant at the 95% confidence level since their p-values were all greater than 0.05.

However, one condition has emerged to reverse this: the TESR% predictor decreasing from TESR 4 level to TESR 3 actually increases the odds ratio for FRP bar rupture type failure (1.005). However, it is not statistically significant at the 95% confidence level as its p-value exceeds 0.05 (p-value = 0.997). In other words, the contribution of TESR% predictor to the occurrence of FRP bar rupture failure mode is expected to increase by 1.005 times when the TESR% predictor decreases from TESR 4 level to TESR 3 given that all other predictors remain constant.

Table 3 *Parameter estimates*

Failure Modes[a]		**Std. Error**	**df**	**Sig.**	**OR**	**95% Confidence Interval for OR**	
						Lower Bound	**Upper Bound**
Flexural failure	Intercept	1.458	1	.254			
	Stirrup Steel Ratio%	1.230	1	.074	.111	.010	1.241
	[TESR1=<= .57]	1.410	1	.108	.104	.007	1.645
	[TESR2=.58 - .89]	1.088	1	.119	.183	.022	1.544
	[TESR3=.90 - 1.21]	1.033	1	.724	.695	.092	5.261
	[TESR4=1.22+]	.	0	.	.	.	.
	[Ancorchage1.0= Anchorage]	.893	1	.678	1.448	.252	8.334
	[Ancorchage2.0=No Anchorage]	.	0	.	.	.	.
FRP bar debonding	Intercept	1.262	1	.004			
	Stirrup Steel Ratio%	1.088	1	.001	.031	.004	.258
	[TESR1=<= .57]	.955	1	.135	.240	.037	1.558
	[TESR2=.58 - .89]	.966	1	.004	.064	.010	.423
	[TESR3=.90 - 1.21]	.901	1	.491	.538	.092	3.141
	[TESR4=1.22+]	.	0	.	.	.	.
	[Ancorchage1.0= Anchorage]	.824	1	.795	1.238	.246	6.224
	[Ancorchage2.0=No Anchorage]	.	0	.	.	.	.
FRP bar rupture	Intercept	1.483	1	.219			
	Stirrup Steel Ratio%	1.283	1	.009	.035	.003	.432
	[TESR1=<= .57]	1.161	1	.902	.867	.089	8.432
	[TESR2=.58 - .89]	1.149	1	.053	.108	.011	1.030
	[TESR3=.90 - 1.21]	1.066	1	.997	1.005	.124	8.115
	[TESR4=1.22+]	.	0	.	.	.	.
	[Ancorchage1.0= Anchorage]	.856	1	.008	9.822	1.836	52.552
	[Ancorchage2.0=No Anchorage]	.	0	.	.	.	.

a. The reference category is: Concrete Cover Separation.
b. This parameter is set to zero because it is redundant.

Moreover, the odds ratios of the presence of anchorage in the strengthening of RC beams using the FRP-NSM system as a predictor for the all of failure modes (flexural failure vs. concrete cover separation, FRP bar debonding vs. concrete cover separation, and FRP bar rupture vs. concrete cover separation) are more than 1.0 (1.448, 1.238, and 9.822), respectively. This means that strengthening of RC beams using the FRP-NSM system with anchorage will tend to occur their failure modes of flexural failure, FRP bar debonding and FRP bar rupture relative to concrete cover separation.

However, When the predicting failure modes (flexural failure and FRP bar debonding) in the strengthening of RC beams using the FRP-NSM system is considered present of anchorage, the odds ratios are not statistically significant at the 95% confidence level as p-values are over 0.05 (p-values = 0.678 and 0.795). However, when the predicting failure mode (FRP bar rupture relative to concrete cover separation) in the strengthening of RC beams using the FRP-NSM system is considered the presence of anchorage, the odds ratio is statistically significant at the 95% confidence level as a p-value is < 0.05 (0.008). This indicates that the strengthening of RC beams using the FRP-NSM system with anchorage would be 9.822 times the contribution to the occurrence of FRP bar rupture failure relative to concrete cover separation.

To evaluate the accuracy of MLR models, classification tables are employed. The overall correct percentage is compared with the chance accuracy rate, as demonstrated in Table 4. The chance accuracy rate is determined by summing up the marginal percentages of the dependent variable from the case processing summary, squaring them, and adding them together to obtain a proportional chance accuracy rate. If there is a 25% improvement over this chance rate, it is considered satisfactory. To assess a 25% prediction improvement and calculate the proportional chance accuracy rate, we can utilize the marginal frequencies provided in Table 5's case processing summary:

$$0.137^2 + 0.405^2 + 0.282^2 + 0.176^2 = 0.291 \text{, then } 1.25 \times 0.293 = 0.364 .$$

In this particular case, the model achieved an overall correct classification rate of 51.1%, exceeding the proportional chance accuracy rate of 36.4%. Consequently, we can conclude that this model exhibits sufficient accuracy.

Table 4 *Classification table*

Observed	Flexural Failure	Concrete Cover Separation	FRP bars debonding	FRP bar Rupture	Percent Correct
Flexural failure	0	14	4	0	0
Concrete cover separation	0	41	12	0	77.4%
FRP bar debonding	0	18	18	1	48.6%
FRP bar rupture	0	10	5	8	34.8%
Overall Percentage	0.0%	63.4%	29.8%	6.9%	51.1%

Table 5 *Case processing summary*

		N	Marginal Percentage
Failure Modes	Flexural failure	18	13.7%
	Concrete cover separation	53	40.5%
	FRP bars debonding	37	28.2%
	FRP bar rupture	23	17.6%
TESR%	<= 0.57	23	17.6%
	0.58 -0.89	58	44.3%
	0.90 - 1.21	32	24.4%
	1.22+	18	13.7%
Anchorage	Anchorage	36	27.5%
	No Anchorage	95	72.5%
Valid		131	100.0%
Missing		0	
Total		131	
Subpopulation		25[a]	

4. Conclusions

- The multinomial logistic regression (MLR) analysis reveals that a significant association takes place among the failure modes (dependent variable) of RC beams reinforced with the FRP-NSM system (with or without anchorage) and all predictor variables such as the Total Equivalent Steel Ratio (TESR%) and the presence of anchorage, as well as the covariate variable Stirrup Steel Ratio% (as a continuous variable).
- Increases in the Stirrup Steel Ratio% predictor by one unit, while holding all other predictors constant, decreases the odds of flexural failure compared to concrete cover separation and FRP bar debonding compared to concrete cover separation and FRP bar rupture compared to concrete cover separation by a factor of 0.60, a factor of 0.77, a factor of 0.85, respectively.
- The TESR% predictor was inspected with regard to the mode of failure distribution. Three failure modes were considered flexural failure, FRP bar debonding, and FRP bar rupture. All odds ratios were established to be below 1.0, which indicates that as the TESR% predictor value decreased (from TESR 4 to TESR 1, 2, or 3), there was lower likelihood of conversion the type of failure from from separation of concrete cover to any alternative mode (flexural failure, FRP bar debonding, FRP bar rupture).
- The odds ratios for the presence of anchorage in flexural strengthening of RC beams using the FRP-NSM system as a predictor to all failure modes (flexural failure vs. concrete cover separation, FRP bar debonding vs. concrete cover separation and FRP bar rupture vs. concrete cover separation) is greater than 1.0. The likelihood of flexural failure is 1.448 times higher than concrete cover separation; FRP bar debonding is 1.238 times higher; and for FRP bar rupture is 9.822 times higher.

- Furthermore, the analysis of the classification tables shows that the overall correct classification rate of the model is 51.1%. This exceeds the proportional chance accuracy rate of 36.4%, indicating that the model has adequate accuracy.

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Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

Author Contribution

The authors confirm contribution to the paper as follows: ***study conception and design:*** *Diyaree Jalal Ghaidan, Hasan Jasim Mohammed, Ali Ihsan Salahaldin;* ***data collection:*** *Diyaree Jalal Ghaidan;* ***analysis and interpretation of results:*** *Diyaree Jalal Ghaidan, Hasan Jasim Mohammed, Ali Ihsan Salahaldin;* ***draft manuscript preparation:*** *Diyaree Jalal Ghaidan, Ali Ihsan Salahaldin. All authors reviewed the results and approved the final version of the manuscript.*

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