Comparative Study on Proposed Models and Design Guideline for Flexural Strengthening of NSM FRP in RC Beams

● **Sangar J. Qadir**[1]**-** MSc ●
Dr. Serwan Kh. Rafiq[1]**-** Assist. Prof.
Daban Abdulthahir Muhedin[2]**-** MSc

[1] University of Sulaimani, College of Engineering, Department of Civil Engineering
[2] Koya University, Faculty of Engineering, Department of Geotechnical Engineering

Received : 01/05/2017 / Accepted : 07/01/2018
DOI Link: https://doi.org/10.17656/sjes.10064

Abstract

The retrofitting technique of near-surface mounting (NSM) fiber-reinforced polymer (FRP) is an alternative solution to externally bonded technique in strengthening of reinforced concrete (RC) elements, in particular a significant effect is due to improving high bond action between concrete and FRP bar. A comparative study on four theoretical models and two design guidelines for contribution of NSM FRP bars to RC beams is reported and evaluated in this study. A significant number of experimental results (71 tests) of RC beam specimens, reported in the literature have been collected to validate the accuracy of the theoretical models formula. The flexural strength equations of common guideline, Canadian standard and American guideline were also used to compare the strengthening capacity of RC beams based on the available experimental results. Apparently, theoretical models have provided accurate results compared to design guidelines, the equations showed a good match with test results by considering bond action. One of the proposed formulas is quite satisfactory concerning both test results and the prediction of different design guidelines.

Keywords: Near surface mounted (NSM), Fiber-reinforced polymer (FRP), Theoretical Models, Design Guideline, RC beams.

1- Introduction

The use of flexural strengthening technique of near surface mounted of fiber reinforced polymer NSM FRP has been common in many existing structures since the technique will enhance the structural capacity for resisting extra applying loads and prevent the deficient buildings from potential failure. This method is an alternative technique to boost flexural strengthening of deteriorated reinforced concrete members. Theses mechanism is effectively increase the durability and life serviceability of the structures and it will not need extensive surface preparation by cutting grooves along the side or soffit of the beam and inserting FRP bars to these grooves with epoxy material. Hence, minimum installation time is predicted as well as demolition and reconstruction can be avoided as it is economically inappropriate [1].

In addition, substantial research has been conducted to examine the flexural capacity of NSM FRP and eventually some of which created proposed model to predict peak strength of RC elements. It has been observed that the theoretical models are significantly dependent upon the bond actions between concrete, NSM FRP bars and resin material. For instance, higher performance of RC element can be obtained if appropriate bond is practically provided. This longitudinal bond stress can be observed when the structure is loaded and tensile force is transferred to the concrete. The bond actions mechanism are hugely affected by the shape and configuration of the FRP bars since deformed bars could significantly show better performance compared to smooth bars. Thus, the proposed models have taken into account many kinds of failure such as splitting failure, pull out and pull out by complete or partial shearing off that might occur.

However, using practical equations given in the design guideline and standards for flexural strengthening, predicts the flexural strength resistance imprecisely when compared with experimental data. The current codes such as, American[2] and Canadian[3] standard, are among the most common standards. Though, in Kurdistan region-Iraq, American standard[2] is used most widely among design engineers and design firms. American and Canadian code equations consider similar approaches in the calculation of flexural strength and the ways bond actions affect flexural strength. The flexural strength equations in the current building guidelines are driven from the stress compatibility, equilibrium of forces and controlling mode of failure. Besides, cover delimitation and debonding play an important role in reducing flexural strength capacity. In essence, the American[2] guideline tends to estimate this reduction of flexural strength by limiting the effective strain in FRP bar, while the Candian[3] approach is somehow similar in which the maximum tensile FRP strain shall not be greater than 0.007.

Provisions of major international guidelines and some suggested formulations on their calculation of flexural strength are presented in this study. The main objectives of the present study considered herein are to use a series of tests (71 tests) available in the literature to study the behaviour of RC beam strengthen with NSM FRP. The comparisons between experimental and theoretical results allow conclusions to be drawn on the consistency of flexural strength predictions of guidelines.

2- Research Significance

The present study provides analytical data, collected in the literature, on effect of NSM FRP bar on flexural strength resistance of RC beams. In addition, a comparison of flexural strengthening of current standards and some theoretical models is made with the test data (71 tests) taken from literature. The authors aim is investigating and selecting the accurate formulation in the literature to calculate flexural strength of strengthening beam with the NSM FRP and the equations have been verified against experimental data from literature.

3- Standard Equations for Strengthening of RC Beams Using NSM FRP

Guidelines and standards, which are currently available, provide similar formulae and approaches to determine flexural strength. The equations are same in terms of nominal moment capacity calculation as strain compatibility, internal force equilibrium and modes of failure shall be used to obtain peak strength. Whereas, different limitations are applied to strain that will be induced in the NSM FRP bars. The result of the nominal flexural strength will be different accordingly. This study considers the calculation of flexural strength which is under gravity loading with strengthening by NSM FRP as well as excluding all the safety factors in reinforced concrete beam. The analysis of the results given in this study is made in relation to ACI 4402R_08[2] and Canadian CAN.CSA.S806-09[3].

3.1. ACI 4402R_08[2]

The ACI 4402R[2] committee report has employed the similar equation for flexural strengthening calculation as ACI-318[4]. The strain compatibility, internal equilibrium force and controlling mode of failure shall be used to calculate nominal flexural strength of NSM FRP-strengthened RC members. However, there are some points which are different from ACI-318[4]. Firstly, the linear elastic stress-strain relationship shall be assumed to the NSM FRP bar. Secondly, any slip which may occur between concrete and NSM FRP shall be neglected. Finally, shear deformation of the resin shall not be considered since the resin is very thin. Thus, the nominal flexural strength of NSM FRP-strengthened RC members can be calculated, shown in figure1 and (Eq.1).

$$Mn = A_s\, f_s\, (d \;\; \beta_1 c/2) + A_f\, f_{fe}\, (h \;\; \beta_1 C/2) + A_{s'}\, f_{s'}\, (\beta_1 C/2 - d') \; \ldots \; (1)$$

It should be noted that the nominal flexural moment shown in (Eq.1) is governed by mode of failure introduced in ACI 4402R. GangaRao and Vijay[5] were proposed some modes of failure which has been followed by ACI 440-2R[2]. Firstly, over reinforcement failure, crushing of concrete before yielding tensile reinforcement, shall be taken into account when strain in the compressive zone of the concrete reaches maximum ultimate strain (ε_{cu} = 0.003). Secondly, NSM FRP rapture can occur if NSM FRP strain reaches its design strain ($\varepsilon_f = \varepsilon_{fu} = f_f / E_f$). Thirdly, yielding of tension rebar followed by concrete crushing shall be investigated. Finally, concrete cover delamination and NSM FRP debonding shall be considered if the force in the NSM FRP cannot be resisted by the concrete substrate and the effective strain (ε_{fd}) in NSM FRP shall be limited to seventy percent of ultimate strain (ε_u) to prevent such a failure ($\varepsilon_{fd} = 0.7\ \varepsilon_u$). Thus, the mode of failure can be investigated.

$$[\varepsilon_{fe} = \varepsilon_{cu}\left(\frac{d_f - c}{c}\right) - \varepsilon_{bi} \le \varepsilon_{fd}] \qquad \ldots\ldots\ldots\ldots\ (2)$$

3.2. CAN.CSA.S806-02[3]

Canadian Standard CSA[3] has recently become effective in design and construction of building components with Fibre-Reinforced polymer. The design flexural strength requirements for concrete beam strengthening are taken into account through considering strain compatibility and equilibrium of internal forces. Clear distinctions of CSA are concrete compressive strain that shall be no greater than 0.0035 and the bond between concrete, rebar and NSM FRP assumed to be perfect as well as the maximum NSM FRP strain limited to 0.007, assuming no anchorage failure.

But, CSA [3] is likely to pay no attention to the crack debonding between concrete and resin filler as well as between resin and NSM FRP. In the presence of intermediate cracks, CSA[3] has only limited strain in NSM FRP to take into account the influences of debonding. However, researchers have pointed out that high resistance at the epoxy-bar interface achieved through using high tensile strength epoxy and considerable cover for groove filler by which epoxy split failure was prevented and concrete split failure was predominant.

3.3. Other Standards

There are some other standards which can be applied to calculate the flexural strengthening of R.C beam with NSM FRP. Consideration of other standards such as, FIB Bulletin 14[6] and ISIS[7] define similar methods for the calculation of flexural strengthening capacity of R.C beam. For example, the FIB 14[6] and ISIS[7] standard are in the similar approach as ACI 4402R[2] committee report and Canadian Standard[3] for flexural strengthen calculation. While, the standards were mainly proposed to examine the strengthening of externally bonded FRP, it has been modified and used for calculation of NSM FRP of R.C elements. Thus, the other methods shall be modified and applied to study the behaviour of strengthened beam with NSM FRP without ignoring the effects of interfacial debonding between resin and bar.

4- Researchers Proposed Equations

Various researchers have attempted to obtain and reach a flexural strengthening equation to predict explicitly the experimental data of flexural strengthening of RC beam. Different methods were applied to estimate the flexural strengthening capacity with variety of parameters in design.

Similar to guidelines of practice, a model to predict the maximum capacity of strengthened beams for which near surface mounted strips were employed to increase the peak capacity of the beam is published by Hassan and Rizkalla[8]. It has been reported that the model has been developed based on a model, which derived for externally strengthened element by Malek et al.[9]. The Malek's formulation were taken one side of the plate and due to the fact that NSM strip have two bonded surfaces, this has been taken into consideration by Hassan and Rizkalla [8] formulation. Concrete cracking leads to decrease the flexural stiffness of the element that is why the previous researchers consider effective moment of inertia of the section. In the model formulations, the authors were suggested that both bending and shear stresses could be investigated individually. The form of failure that has been considered in this model is where the near surface mounted strips are terminated; this is because maximum stress is generated in this position. The following equation is used to find the maximum shear stress in the beam:

$$\tau = \frac{t_f}{2}\left[\frac{nPl_o y_{eff}}{2I_{eff}} we^{-wx} + \frac{nPl_o y_{eff}}{2I_{eff}}\right] \ldots\ldots\ldots\ldots(3)$$

Where: τ : is the shear stress at the end of the NSM FRP strips. n: modular ratio between FRP and concrete. P: is the concentrated failure load. y_{eff}: is the distance from the neutral axis of the beam to the NSM FRP strips. I_{eff} : is the effective moment of inertia of enhanced element. $W = \sqrt{\frac{G_a}{t_a t_f E_f}}$, G_a: shear modulus of adhesive. t_a: adhesive thickness. t_f :NSM FRP strip thickness. E_f: elastic modulus of FRP strips. x: is the distance between the end of the NSM FRP strip to the beam support.

Mohr-Coulomb line was used to obtain the shear strength of the strengthened beam after knowing the compressive and tensile strength of concrete by using Equation 4. This achieved shear stress is used in Equation 3 to find the load, which leads to the failure of the beam.

$$\tau_{\max} = \frac{f_c' f_{ct}}{f_c' + f_{ct}} \ldots\ldots\ldots\ldots(4)$$

Where: $\tau_{\max}$: is ultimate shear stress. f_c': is the concrete compressive strength. f_{ct}: is the concrete tensile strength.

In addition, Seracino et al.[10] developed a model to estimate the intermediate crack debonding load and it can be employed for both EB and NSM methods. Its derivation is carried out by taking compatibility and equilibrium of plate to concrete joint, which is shown in figure 1.

The equation derived in this model that is the function of geometric and material properties is:

$$P_{IC} = \alpha_p 0.85\varphi_f^{0.25} f_c^{0.33}\sqrt{L_{per}(EA)_p} \text{ ....(5)}$$

Where: α_p: equal to 1. $\varphi_f = \frac{d_f}{b_f}$: is the aspect ratio. $L_{per} = 2d_f + b_f$. d_f : is the depth of the groove plus (x). b_f: is the width of the groove in addition to (2x).
Moreover, Oehlers et al.[11] improved previous model and altered it to account for group effect of NSM FRP bars, decreasing axial rigidity of concrete has been taken into account as a result of cracking. The modified equation is provided below:

$$P_{IC} = \alpha_p 0.85\varphi_f^{0.25} f_c^{0.33}\sqrt{L_{per}}$$

$$\sqrt{n(EA)_p + k_{EAC}(EA)_c} \text{ ....(6)}$$

Where: n: is the number of NSM FRP strips used to strengthen the beam. EA_p: Axial rigidity of NSM FRP. EA_c: Concrete axial rigidity. k_{EAC}: is a coefficient that takes into account decreases in the axial rigidity due to the cracking of concrete and it is considered to be 0.2 for beam[10].

5- Flexural Strengthening of R.C. Beams Database

The experimental data collected from available literature, conducted by different researchers, is a total of 71 reinforced concrete beam strengthened by NSM FRP subjected to vertical load. The data results are presented in the Table 1. All the experimental specimens were reinforced concrete rectangular beam and T-beam. The concrete's compressive strength, fc', for the analysed database lies within 21 to 67 MPa, yield strength of steel reinforcement, fy, has a value of minimum of 337 to maximum of 788 MPa, the FRP strength, f_{fu}, 512 to 3700 MPa , whereas the ratio of flexure reinforcement, ρ, is between 0.21% to 1.7% as well as ratio of FRP, ρFRP, is between 0.04% to 0.96% . Moreover, the beam dimension (b x h) ranges from 100mm to 550mm for width and a 170mm to 400mm for depth. Length of beams is ranged within 900mm to 4000mm. The purpose is to examine the influence of NSM FRP on flexural strengthening capacity. In the present study the flexural strengthening resistance was calculated for four theoretical models and two guidelines.

Failure modes

FR-CC: FRP rupture followed by concrete crushing, FP: CFRP bar pull-out, CP: concrete peeling off, CC: concrete crushing, CCS: concrete cover splitting, C+D+FR: concrete crushing followed by concrete-epoxy interface debonding and NSM GFRP rupture, CR:CFRP rupture, CCD: concrete cover delamination, P+CC: peeling off the NSM bars/ strips with concrete cover, S+R: slipping followed by rupture of NSM bars/ strips, CD: concrete cover separation, S/D-FRP: shear failure followed by debonding of FRP bar, S/R-FRP: FRP bar rupture after shear failure. CC/ECS: concrete crushing followed by splitting of epoxy paste, D: Debonding failure, R: rupture of FRP bar/ Strip, D-FRP, R-FRP: debonding and rupture of CFRP strips.

6- Statistical Comparison of Theoretical Models and Standards

Two guide lines ACI440-2R[2] and CAN.CSA.S806[3] as well as four theoretical models Seracino et al.[10], Oehlers et al.[11], Hassan and Rizkalla[8] and Al-Muhamad et al.[12] have been compared against the existing experimental results shown in Table 3. This comparison has been made by comparing mean (μ), standard deviation (σ) and coefficient of variation. In addition, Table 2 shows the data Frequency analysis results. Frequency can be defined as how often values occur within a range of values. For instance, the number of test result will be repeated six times if $P_{exp.}/P_{CSA.}$ is equal to one. Hence, the statistical data analysis have been shown and compared.

7- Comparison between Theoretical Models and Guidelines

The mean value, the standard deviation and the coefficient of variation are explained in Table 3 for $P_{Exp}/P_{guidelines}$, $P_{Exp}/P_{eq.}$. The mean value obtained by Al-Muhamad et al.[12] is the lowest value (0.52) and the standard deviation is (0.38), whereas the mean value provided by Hassan and Rizkalla[8] is the highest value (1.79) and the standard deviation is (1.27). This indicates that the estimated values by Hassan and Rizkalla[8] equation are close to experimental values. The coefficients of variation in CAN.CSA.S806[3] and ACI440-2R[2] are 55% and 48%, respectively. The highest value of coefficient of variation obtained by Al-Muhamad et al.[12] means the equation is not in close agreement with test data. The coefficient of variation of Oehlers et al.[11] is 51 %, while for Hassan and Rizkalla[8] is 71%.

It can be noticed from Table 2 that the result of the Hassan and Rizkalla[8] equation is more close to the experimental results, which percent of pass is 79%, while Al-Muhamad et al.[12] overestimates the values in considerable amount of the data, which percent of pass is only 11%. In addition, the results of all data show that Oehlers et al.[11] equation gives accurate match with experimental data, while the CAN.CSA.S806[3] and ACI440-2R[2] overestimate by a large margin. However, it should be noted that the CAN.CSA.S806[3] and ACI440-2R[2] have been used for the entire cases of the test results, whereas the Hassan and Rizkalla[8] and Oehlers et al.[11] shall not be applied for all cases. This is owing to the fact that the first model was developed to predict the ultimate capacity of the beams which had been strengthened by NSM FRP strips, and was used to assess beams which were not strengthened for the whole length and failed at the cut-off point. This model would overestimate the predicted maximum loads, when the ends of NSM FRP strips were close to the support. Nevertheless, the later model depends on the geometrical and material properties of the strengthened beams; it provides the same result when the strengthening length is changed.

8- Conclusion

The objective of this study is to provide a comparison result for flexural strengthening of reinforced concrete beam. The results of 71 beam specimens collected from literature were used to compare the four theoretical models and equations of guidelines.

There are many approaches in the guidelines to predict the flexural strengthening of reinforced concrete beam, whilst the methods appear to be unsafe. The prime focus of this paper is the flexural strengthening, particularly in the presence of near surface mounted FRP. Hence, it is vital that beams should be carefully investigated to take into account the effect of NSM FRP.

The comparative study made in this work incorporates the investigation of reinforced concrete beam under static loading and strengthening with NSM FRP. The study examines the comparison of four theoretical models and two standards. The results have been examined and compared with experimental data. The following conclusions can be drawn in this research.

1- To begin with, a bond action between NSM FRP and concrete can play a crucial role in reducing flexural strengthening resistance by switching the design results from overestimation to underestimation. Therefore, the bond action influence cannot be ignored. This does not coincide with previous design Guideline equations that paid no attention to the effects of tie between concrete, resin and FRP.
2- In addition, it has been observed that both Hassan and Rizkalla[8] and Oehlers et al.[11] equations are safe with regard to the design of flexural strengthening of RC beams, which percent of passed results are 79% and 72% respectively, whereas Al-Muhamad et al.[12] equation is unsafe and prediction of safe result is only 11%. Both CAN.CSA.S806[2] and ACI440-2R[3] provide unsatisfactory results 31% and 33% accordingly.
3- The analytical results have shown that the effects of some parameters, such as the increase in the length of NSM FRP and the thickness of the concrete layer between the steel and NSM FRP will enhance the ultimate capacity of the strengthened beam, while Concrete compressive strength, bar to groove perimeter ratio, groove spacing, the distance between grooves and the edge of the beam might not lead to the clear enhancement of the flexural resistance.

References

1- Tanarslan, H.M., 2011. The effects of NSM CFRP reinforcements for improving the shear capacity of RC. Construction and Building Materials, 29, p.2663–2673.
2- ACI 440-2R-08 committee, (2008). Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Concrete Structures. American Concrete Institute, Farmington Hills, Michigan.
3- CAN/CSA-S806-02 committee, (2009). Design and Construction of Building Components with Fibre-Reinforced Polymers. The Canadian Standards Association, 5060 Spectrum Way, Suite 100, Mississauga, Ontario, Canada.
4- ACI 318-14 committee, (2014). Building Code requirements for Reinforced Concrete and Commentary. American Concrete Institute, Farmington Hills, Michigan.
5- GangaRao, H. V. S., and Vijay, P. V., 1998, “Bending Behavior of Concrete Beams Wrapped with Carbon Fabric,”Journal of Structural Engineering, V. 124, No. 1, pp. 3-10.
6- FIB Bulletin 14, (2001). Design and use of externally bonded fibre reinforced polymer reinforcement (FRP EBR) for reinforced concrete structures. Task Group 9.3 FRP.
7- ISIS (2007). “Reinforcing Concrete Structures with Fibre Reinforced Polymers”, Design Manual, Canadian

Network of Centres of Excellence on Intelligent Sensing for Innovative Structures.

8- Hassan, T. & Rizkalla, S., 2003. Investigation of Bond in Concrete Structures Strengthened with Near Surface Mounted Carbon Fiber Reinforced Polymer Strips. Composites for Construction, 7, pp.248-57.

9- Malek, A.; Saadatmanesh, H.; and Ehsani, M., 1998, "Prediction of Failure Load of R/C Beams Strengthened with FRP Plate Due to Stress Concentrations at the Plate End,"
ACI Structural Journal, V. 95, No. 1, Jan.-Feb., pp. 142-152.

10- Seracino, R., Oehlers, D.J. & Saifulnaz, M.R.R., 2005. Towards a Generic Model of
The Intermediate Crack Debonding Resistance of Plates Adhesively Bonded to Concrete. International Institute for FRP in Construction, pp.263-68.

11- [11] Oehlers, D.J., Rashid, R. & Seracino, R., 2008. IC debonding resistance of groups of
FRP NSM strips in reinforced concrete beams. Construction and Building Materials,
p. 1574–1582.

12- Al-Mahmoud, F., Castel, A., François, R. & Tourneur, C., 2010. RC beams strengthened with NSM CFRP rods and modeling of peeling-off failure. Composite Structures, 92, p.1920–1930.

13- Almusallam, T.H., Elsanadedy, H.M., Al-Salloum, Y.A. & Alsayed, S.H., 2013. Experimental and numerical investigation for the flexural strengthening of RC beams using near-surface mounted steel or GFRP bars. Construction and Building Materials, 40, p.145–161.

14- Soliman, S.M., El-Salakawy, E. & Benmokrane, B., 2010. Flexural behavior of concrete beams strengthened with near surface mounted fibre reinforced polymer. NRC research press, 37, pp.1371-81.

15- Wang, B. et al., 2009. Strain monitoring of RC members strengthened with smart NSM FRP bars. Construction and Building Materials, p.1698–1711.

16- Yost, J.R., Gross, S.P., Dinehart, D.W. & Mildenberg, J.J., 2007. Flexural Behavior of Concrete Beams Strengthened with Near-Surface-Mounted CFRP Strips. ACI Structural Journal, 104, pp.430-37.

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

18- Castro, E.K., MELO, G.S. & NGATO, Y., 2007. Flexural Strengthening of RC "T" Beams With Near Surface Mounted (NSM) FRP Reinforcements. pp.1-10.

19- Barros, J.A.O., Ferreira, D.R.S.M., Fortes, A.S. & Dias, S.J.E., 2006. Assessing the effectiveness of embedding CFRP laminates in the near surface for structural strengthening. Construction and Building Materials, pp.485-91.

20- Tang, W.C., Balendran, R.V., Nadeem, A. & Leung, H.Y., 2006. Flexural strengthening of reinforced lightweight polystyrene aggregate concrete beams with near-surface mounted GFRP bars. Building and Environment, 41, p.1381–1393.

21- Hassan, T.K. & Rizkalla, S.H., 2004. Bond Mechanism of Near-Surface-Mounted Fiber-Reinforced Polymer Bars for Flexural Strengthening of Concrete Structures. ACI Structural Journal, 101, pp.830-39.

22- El-Hacha, R. & Rizkalla, S.H., 2004. Near-Surface-Mounted Fiber-Reinforced Polymer Reinforcements for Flexural Strengthening of Concrete Structures. ACI Structural Journal, 101, pp.717-26.

دراسة مقارنة في النماذج المقترحة والمعايير التصميمية لتقوية الانحناء في الجسور الخرسانية المسلحة باستخدام طريقة الرصع القريب من السطح المعززة بالياف البوليمر

سەنگەر جمال قادر[1] - ماجستير
د. سيروان خورشيد رفيق[1] - استاذ مساعد
دابان عبدالظاهر محي الدين[2] - ماجستير
[1] جامعة السليمانية -كلية الهندسة - قسم الهندسة المدنية
[2] جامعة كويه - قسم هندسة الجيوتكنيك

المستخلص :

ان تقنية اعادة التهيئة بطريقة الرصع القريب من الوجه باستخدام البوليمر المقوى بالألياف هو حل بديل للتقنيات المستخدمة للتقوية الخارجية للعناصر الخرسانة المسلحة ، هناك تاثير كبير من الناحية العملية بسبب تحسين تاثير الربط العالى بين الخرسانة والبوليمر المقوى بالالياف . تم في هذة الدراسة مقارنة أربعة نماذج نظرية مقترحة مع اثنين من المدونات التصميمية (المدونة الكندية- ومدونة الخرسانة الامريكية) لمعرفة المساهمة بين البوليمر المقوى بالالياف بطريقة الرصع القريب من الوجة والجسورالمحسوبة . لقد تم جمع عدد كبير من النتائج التجريبية (71 نموذج) من الجسور الكونكريتية ، التي تمت الاشارة اليها فى متن البحث للتحقق من صحة النماذج التصميمية النظرية المقترحة. تم استخدام معادلة قوة الانحناء للمدونات التصميمية في المعيار الكندى ومدونة الخرسانة الامريكية ايضا لمقارنة كفاءة التقوية للنماذج العملية للجسور الخرسانية المسلحة في الدراسة الحالية. اثبتت دراسة النماذج النظرية نتائج دقيقة مقارنة الى قواعد المدونة التصميمية. ان المعادلات المقترحة من قبل (سيراسينو واخرون في 2007 وحسن ورزكالة في 2003) اعطت نتائج جيدة مع نتائج الفحوصات العملية عندما يؤخذ تاثير الربط بنظر الاعتبار. اقترح (سيراسينو واخرون في 2007) معادلة متطابقة تماما حيث اخذ بنظر الاعتبار النتائج العملية والتنبؤ لمختلف القواعد الارشادية التصميمية.

الكلمات المفتاحية: تقوية مثبتة على السطح ، البوليمر المقوى بالألياف ، النماذج النظرية ، المبدأ التوجيهي للتصميم ، العتبات الخرسانية المسلحة.

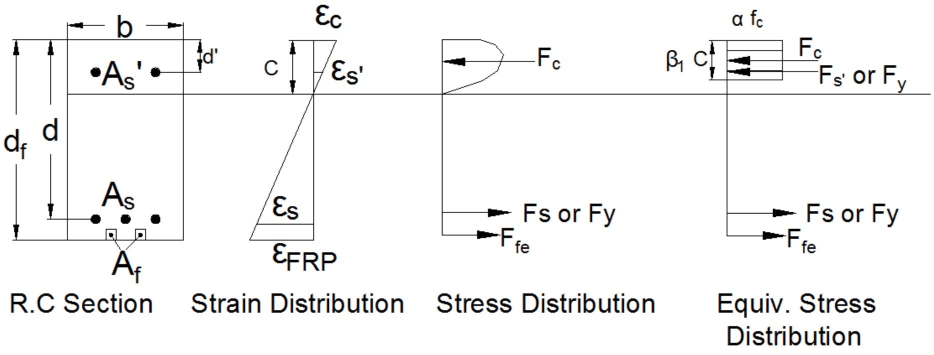

Figure1 : Stress-Strain distribution for rectangular RC beams strengthened with NSM FRP. (by researchers and guidelines)

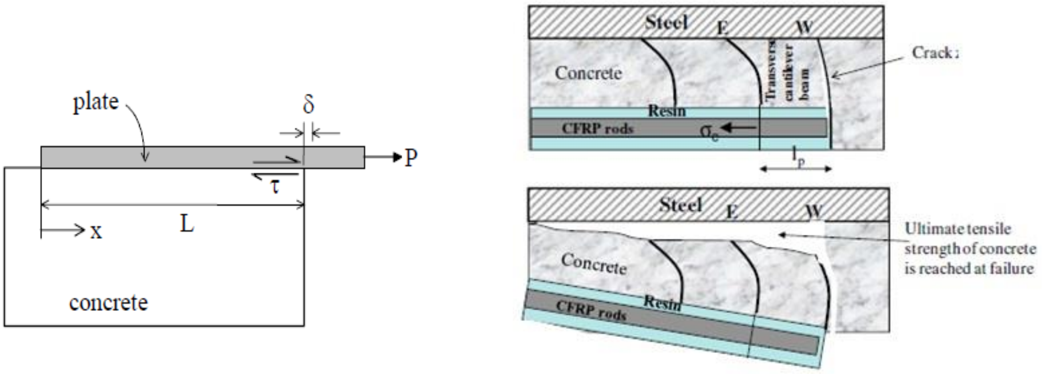

Figure 2 : Push-pull specimen model[10]

Table 1: Reinforced rectangular beam and T beam under gravity load and strengthened by NSM FRP. (by researchers and guidelines)

Ref.	Specimen No.	Beam span (mm)	Beam size	Groove No. & size (mm)	fc` (MPa)	ρ (%)	ρFRP (%)	$P_{exp.}$ (kN)	$P_{exp.}/P_{calculated.}$						Failure Mode
			bxh (mm)						CSA 2009	ACI 440-2R -2008	Seracino et al. (2005)	Ohlers et al. (2008)	Hassan & Rizkalla (2003)	AL Mahmud F. et al. 2010	
[14]	B-1GFRP	2000	150x200	1x30x30	36.6	0.63	0.28	48.53	0.90	0.72	1.02	0.94	-	-	FR-CC
	B-2 GFRP	2000	150x200	2x30x30	36.6	0.31	0.56	51.17	1.04	0.68	0.54	0.51	-	-	FR-CC
[13]	B-6-LS-3	2800	150x280	2x12x12	36.1	0.63	0.14	146.25	1.36	1.23	2.09	2.10	-	-	FP
	B-6-LS-2.7	2800	150x280	2x12x12	36.1	0.63	0.14	133.25	1.24	1.12	1.90	1.91	0.55	0.29	FP
	B-6-LS-2.4	2800	150x280	2x12x12	36.1	0.63	0.14	119.00	1.10	1.00	1.70	1.71	1.89	0.52	FP
	B-6-LS-2.1	2800	150x280	2x12x12	36.1	0.63	0.14	110.00	1.02	0.92	1.57	1.58	3.03	0.72	CP
	B-12-LS-3	2800	150x280	2x12x12	36.1	0.63	0.14	163.50	1.18	1.10	1.68	1.51	-	-	CC
	B-12-HS-3	2800	150x280	2x12x12	67.1	0.63	0.14	183.00	0.90	1.10	1.53	1.34	-	-	FP
[15]	AC1	2600	200x300	1x19x19	41.0	0.39	0.12	67.00	0.53	0.51	0.99	0.98	2.43	0.33	CCS
	AC2	2600	200x300	1x19x19	41.0	0.39	0.12	73.00	0.57	0.56	1.08	1.06	2.22	0.31	CCS
	AC3	2600	200x300	1x19x19	41.0	0.39	0.12	94.00	0.74	0.72	1.39	1.36	1.75	0.27	CCS
	AC4	2600	200x300	1x19x19	41.0	0.39	0.12	96.00	0.76	0.74	1.42	1.39	1.24	0.21	CCS
	AC5	2600	200x300	1x14x19	41.0	0.39	0.12	88.00	0.69	0.67	1.49	1.47	2.83	0.40	CCS
	AC6	2600	200x300	1x14x19	41.0	0.39	0.12	94.00	0.74	0.72	1.60	1.57	1.88	0.29	CCS
	AC7	2600	200x300	1x14x19	41.0	0.39	0.12	102.00	0.80	0.78	1.73	1.71	1.40	0.24	CCS
	AC8	2600	200x300	1x25x25	41.0	0.39	0.12	74.00	0.49	0.48	0.71	0.69	1.91	0.26	CCS
	AC9	2600	200x300	1x25x25	41.0	0.39	0.12	109.00	0.72	0.70	1.05	1.02	1.16	0.24	CCS
	AG10	2600	200x300	1x25x25	41.0	0.39	0.12	75.00	0.64	0.62	1.21	1.17	1.65	0.15	CCS
	AG11	2600	200x300	1x25x25	41.0	0.39	0.12	112.00	0.95	0.93	1.81	1.75	1.00	0.20	CCS
	BC1	2600	200x300	1x19x19	41.0	0.39	0.12	135.00	0.75	0.73	1.99	1.96	3.57	0.43	CCS
	BC2	2600	200x300	1x19x19	41.0	0.39	0.12	61.40	0.85	0.83	2.28	2.24	2.51	0.33	CCS
	CC1	2600	200x300	1x19x19	41.0	0.39	0.12	41.60	0.91	0.90	3.36	3.30	5.45	0.84	CCS
	CC2	2600	200x300	1x19x19	41.0	0.39	0.12	45.30	0.92	0.90	3.39	3.33	5.06	0.79	CCS
	CC3	2600	200x300	1x19x19	41.0	0.39	0.12	49.43	0.94	0.92	3.46	3.40	4.73	0.74	CCS
	CC4	2600	200x300	1x19x19	41.0	0.39	0.12	79.10	1.02	1.00	3.76	3.69	3.21	0.52	CCS
[16]	B2600	3000	150x300	1x15x15	37.5	0.57	0.18	81.50	0.53	0.46	2.30	2.21	1.29	0.16	C+D+FR
	B2800	3000	150x300	1x15x15	37.5	0.57	0.18	80.60	0.53	0.45	2.27	2.19	0.67	0.10	C+D+FR
	B3200	3000	150x300	1x15x15	37.5	0.57	0.18	81.90	0.54	0.46	2.31	2.22	-	-	C+D+FR
[17]	A-1CFRP	2743	152x190	1x19x6	37.2	1.71	0.14	49.66	0.41	0.42	0.91	0.88	-	-	CC
	A-2CFRP	2743	152x190	2x19x6	37.2	1.71	0.27	53.88	0.39	0.42	0.49	0.56	-	-	CC
	B-1CFRP	2743	229x190	1x19x6	37.2	1.09	0.09	56.44	0.44	0.43	1.03	1.00	-	-	CC
	B-2CFRP	2743	229x190	2x19x6	37.2	1.09	0.19	74.10	0.51	0.48	0.68	0.71	-	-	CC
	C-1CFRP	2743	305x190	1x19x6	37.2	0.82	0.07	62.02	0.43	0.42	1.13	1.10	-	-	CR
	C-2CFRP	2743	305x190	2x19x6	37.2	0.82	0.14	83.54	0.46	0.52	0.76	0.74	-	-	CC
[18]	B1-1CFRP	900	120x170	1x15x5	44.2	0.22	0.07	79.90	1.66	2.05	1.20	2.13	-	-	CCD
	B2-2CFRP	900	120x170	2x15x5	44.2	0.38	0.14	93.30	2.31	1.61	1.40	1.44	-	-	CCD
	B3-3CFRP	900	120x170	3x15x5	44.2	0.57	0.20	96.60	1.63	1.35	0.97	1.24	-	-	CCD
[19]	A1-3C-S	4000	550x400	3x18x5	49.5	0.32	0.04	245.6	1.00	0.97	1.51	2.02	-	-	P+CC
	A2-3C-S	4000	550x400	3x18x5	45.0	0.32	0.04	250.0	1.02	0.99	1.53	2.00	-	-	P+CC
	B1-2G-B	4000	550x400	2x25x25	50.1	0.32	0.11	250.0	1.06	1.04	2.02	1.50	-	-	P+CC
	B2-2G-B	4000	550x400	2x25x25	35.2	0.32	0.11	226.0	0.96	0.95	2.05	1.63	-	-	P+CC
	C1-1C-B	4000	550x400	1x20x20	52.7	0.32	0.03	253.4	1.14	1.11	3.00	2.94	-	-	S+R
	C2-1C-B	4000	550x400	1x20x20	50.1	0.32	0.03	249.6	1.12	1.09	3.00	2.95	-	-	S+R
[20]	S1-1FRP	1500	100x170	1x12x4	46.1	0.36	0.08	50.3	1.36	1.33	1.64	1.57	0.91	0.12	CD
	S2-2FRP	1500	100x177	2x12x4	46.1	0.52	0.16	78.5	2.11	1.42	1.28	1.46	1.26	0.31	CD
	S3-2FRP	1500	100x175	2x12x4	46.1	0.66	0.16	81.9	2.01	1.45	1.34	1.52	1.31	0.28	CD
	S4-3FRP	1500	100x180	3x12x4	46.1	0.92	0.24	94.9	1.61	1.33	1.03	1.43	1.37	0.38	CD
[21]	B-S40-G5-A	1200	180x250	2x20x20	21	1.10	0.93	115.0	0.57	0.61	0.87	1.11	-	-	S/D-FRP
	B-S20-G5-A	1200	180x250	2x20x20	37	1.10	0.93	144.0	0.56	0.62	0.91	1.12	-	-	S/R-FRP
	B-S20-G3-A	1200	180x250	2x15x15	37	1.10	0.32	131.0	0.69	0.67	1.55	1.61	-	-	CC/ECS
	B-S50-G5-A	1200	180x250	2x20x20	58	1.10	0.93	149.0	0.53	0.50	0.81	0.98	-	-	S/R-FRP
	B-S50-G5-B	1200	180x250	2x20x20	58	1.10	0.93	159.0	0.56	0.54	0.86	1.04	-	-	S/R-FRP
[22]	B-D-300	2500	300x300	1x30x18	48	0.21	0.08	56.0	0.28	0.27	0.65	0.63	1.23	1.85	D
	B-D-1100	2500	100x177	1x30x18	48	0.21	0.08	67.0	0.33	0.32	0.77	0.75	0.95	1.49	D
	B-D-1600	2500	100x175	1x30x18	48	0.21	0.08	73.0	0.36	0.35	0.84	0.82	0.68	1.12	D
	B-D-2400	2500	100x180	1x30x18	48	0.21	0.08	79.0	0.39	0.38	0.91	0.88	0.11	0.35	D
	B-K-1100	2500	100x170	1x30x18	48	0.21	0.08	59.0	0.29	0.28	0.68	0.66	1.04	1.31	D
	B-K-1600	2500	100x175	1x30x18	48	0.21	0.08	70.0	0.34	0.34	0.81	0.78	0.81	1.07	D
	B-K-2400	2500	100x175	1x30x18	48	0.21	0.08	76.0	0.37	0.37	0.88	0.85	0.12	0.34	D
[23]	B1-C-A	2500	150x300	1x30x18	45	0.69	0.16	93.8	0.49	0.48	1.06	1.03	-	0.36	D
	B2-C-S	2500	150x300	2x19x6	45	0.69	0.15	99.3	0.53	0.51	0.91	0.91	-	0.45	R
	B3-C-S	2500	150x300	2x25x6	45	0.69	0.14	110.2	0.51	0.50	0.84	0.79	-	0.46	R
	B4-G-S	2500	300x300	3x25x6	45	0.35	0.14	102.7	0.46	0.45	0.59	0.82	-	0.48	D
[8]	B-300	2500	150x300	1x25x5	48	0.55	0.07	53.0	0.40	0.39	0.77	0.69	1.53	0.90	D-FRP
	B-500	2500	150x300	1x25x5	48	0.55	0.07	54.0	0.41	0.39	0.78	0.71	1.42	0.84	D-FRP
	B-1000	2500	150x300	1x25x5	48	0.55	0.07	60.0	0.45	0.44	0.87	0.79	1.18	0.73	D-FRP
	B-1500	2500	150x300	1x25x5	48	0.55	0.07	74.0	0.56	0.54	1.07	0.97	0.98	0.64	D-FRP
	B-1700	2500	150x300	1x25x5	48	0.55	0.07	79.0	0.59	0.58	1.15	1.04	-	0.57	R -FRP
	B-1900	2500	150x300	1x25x5	48	0.55	0.07	75.0	0.56	0.55	1.09	0.98	-	0.43	R -FRP
	B-2100	2500	150x300	1x25x5	48	0.55	0.07	80.0	0.60	0.58	1.16	1.05	-	0.35	R -FRP
	B-2400	2500	150x300	1x25x5	48	0.55	0.07	80.0	0.60	0.58	1.16	1.05	-	0.18	R -FRP

Table 2: Frequency Result Analysis. (by researchers and guidelines)

Data (Frequency)	$P_{exp.}/P$ CSA.S806-2009	$P_{exp.}/P$ ACI440-2R-2008	$P_{exp.}/P$ Seracino et al. (2005)	$P_{exp.}/P$ Oehlers et al. (2008)	$P_{exp.}/P$ Hassan & Rizkall (2003)	$P_{exp.}/P$ AL Mahmud F. et al. 2010
0.5	18	23	1	0	2	29
0.7	20	17	5	6	3	4
0.9	9	9	13	12	1	7
1	6	8	6	7	4	0
1.25	10	7	14	12	5	2
1.75	5	6	16	18	9	2
2	0	0	3	3	3	1
2.25	2	1	3	7	1	0
% Pass	33	31	69	72	79	11

Table 3: Statistical Result Analysis. (by researchers and guidelines)

Formula	Mean (μ)	Standard Deviation (σ)	Coefficient of Variation (%)
$P_{exp.}/P_{CSA.S806\text{-}2009}$	0.79	0.44	55
$P_{exp.}/P_{ACI440\text{-}2R\text{-}2008}$	0.74	0.36	48
$P_{exp.}/P$ Seracino et al. (2005)	1.42	0.75	53
$P_{exp.}/P$ Oehlers et al. (2008)	1.43	0.73	51
$P_{exp.}/P$ Hassan & Rizkalal (2003)	1.79	1.27	71
$P_{exp.}/P$ AL Mahmud et al. 2010	0.52	0.38	73