Scientific Journal of Impact Factor (SJIF): 5.71

e-ISSN (O): 2348-4470
p-ISSN (P): 2348-6406

International Journal of Advance Engineering and Research Development

Volume 5, Issue 03, March -2018

FEA simulation approaches for Reinforced Concrete Beams strengthened with Fibre Reinforced Polymers

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Abstract — *Fiber reinforced polymers (FRP) have shown remarkable progress in civil infrastructures rehabilitation since last few decades. Despite the plethora of research on development of empirical models and design guidelines failure mechanism of FRP bonded reinforced concrete (RC) structures remains a challenge till date which often results in brittle and premature failure of FRP bonded RC structures in general and RC beams in particular – considering the range of failure modes. Analysis of detailed stress distribution and structural behavior of FRP retrofitted RC beams can solve this problem. This paper incorporates various approaches used in finite element models to simulate the behavior of reinforced concrete beams externally bonded with FRP. Variety of FRP strengthening schemes used for simulation in popular computer aided finite element analysis (FEA) tools - focused on parametric results such as load-strain plots, load-deflection plots, first-cracking loads, failure-loads and crack-patterns at failure to evaluate efficacy of modeling approach used to simulate the behavior of real-life structural applications - are ascertained.*

Keywords- *Fiber reinforced polymers, finite element analysis, RC beams, simulation.*

I. INTRODUCTION

The laboratory experimentations on full scale models of reinforced concrete beams have been an established practice for investigating their performance in various applications. The results from laboratory experimentations had been checked against different empirical equations developed and continuously refined by various researches from time to time. These empirical equations would provide a close approximation of various parameters like ultimate load, maximum deflection and ideas about the distribution of internal stresses and strains which with proper validation from experimental results would give solid grounds for supporting a particular concept under consideration. However, with advent of modern computational modeling capabilities, a new trend of using FEA along with routine laboratory experimentation has begun which has taken these investigations to a whole new level.

With Finite Element Analysis complicated problems are discretized into definite smaller and more comprehensible elements and records point to point variation of a particular phenomenon which was extremely difficult with conventional laboratory experimentations or empirical equations. This capability particularly suites the parametric investigation on behavior of reinforced concrete beams retrofitted with fiber reinforced polymers.

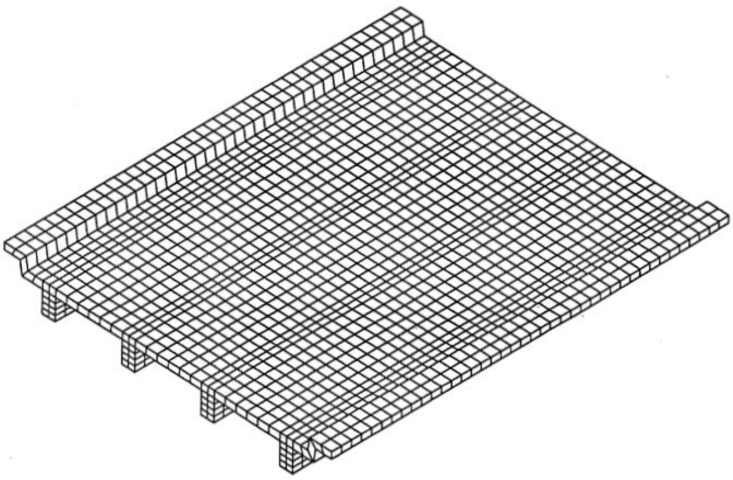
History of Finite Element Analysis goes way back into 1940s when it was first laid down by Richard Courant [2]. It gained valuable appreciation in field of aircraft and aerospace industries and undergone enormous developments since 1960s. The state of the art capabilities and expediency of Finite Element Analysis could not remain from revolutionizing structural engineering too. However, like always there were a few challenges before its successful implementation in civil engineering or infrastructural applications. For example, it had been extremely perplexing to model the effect of concrete's cracking and hence, the performance of reinforced concrete owing to its heterogeneous, composite and anisotropic nature. In the very earlier practices these effects were incorporated as geometric cutoffs or discontinuities between concrete elements by predetermining a definite path for crack propagation and accordingly the geometrical and spatial characteristics of the models were altered as the analysis progressed. Despite a very close definition of crack and possibility of modeling multidirectional and rotational cracks the continuous or step-wise alternations in topology made this approach very hectic and time consuming. This approach has been known as Discrete Crack Approach (DCA) which was presented by Ngo and Scordelis in 1967 [3].

Smear Crack/Continuous Approach (SCA), introduces by Rashid in 1968, is peer of DCA which assumed non-homogenous nature of concrete in three perpendicular directions (Orthotropic). This method considered the principal tensile strength of concrete, assuming that concrete will crack as it crossed the ultimate tensile strength of the concrete. As this limit is reached at a particular location the elastic modulus of material is automatically changed to zero at respective points. In SCA, the orthotropic nature of concrete model makes sure the zero value is only assigned parallel to the direction of the normal stress causing the cracking. This approach also included the interlocking effect between concrete surfaces along the crack which was not discussed in DCA which earlier defined crack as discontinuity in the concrete's geometry. Due to abovementioned advantages the smeared crack approach gained better recognition among the researchers around the globe since 1970s [3].

II. FEA SIMULATION APPROACHES

Finite element analysis of reinforced concrete and fiber reinforced polymers is very recent. Marco Arduini, et al. (1997) was among first researchers to attempt finite element analysis of fiber reinforced polymer bonded reinforced concrete beams. In his research, smeared crack approach was adopted and fiber reinforced polymer plates were simulated as 2-D plate elements to determine failure mechanism of different arrangements. Each arrangement was provided with particular thickness and length of FRP to address a range of failure mechanism covering ductile and brittle failure. Laboratory experimentation of full scale test beams was also performed to validate the results obtained from finite element analysis. Comparison of both results was in close conformity. The finite element analysis model could not successfully determine crack pattern of the test sample owing to the fact that FRP plates had been simulated as surface elements which have zero thickness hence; details of stress and strain distribution could not be obtained.

The researchers took the finite element analysis of FRP bonded reinforced concrete elements (beams) to the whole next level when complete structural systems were modeled to predict the behavior of whole structure after rehabilitation of a particular deteriorated component with layers of FRP plates/sheets. Among the first research ventures of this sort, was work of J. W. Tedesco et al. (1998) where he successfully simulated the FRP and RC concrete while working on a project of a 13-span RC bridge's rehabilitation. The bridge's T-beams girders had undergone excessive flexure cracks as it endured 40-years of vehicular traffic. GFRP and CFRP laminates were used for strengthening of T-beams. These beams were tested in field according Alabama Department of Transportation's (ALDOT) conventional truck load test. The same assembly was simulated through FEA tool for both static as well as dynamic analysis. However, various simplifications such as reduction in elasticity of concrete (modeled as eight node solid) was incorporated to take into consideration the effect of existing cracks, and modeling of both FRP as well as steel reinforcements using truss elements. Deflection in girders, stress in FRP and steel were analyzed and found in close agreement with the field load tests. The difference in simulated and experimental results for: mid-span deflection was less than 5 percent, stresses in FRP and steel bars less than 6.8 percent, and fundamental period of vibration was less than 2 percent, in all cases. It was further concluded that FRP reduced the max deflection and rebar stresses up to 20 percent and 22 percent respectively. Configuration of FEA model is shown is shown in Figure 1.



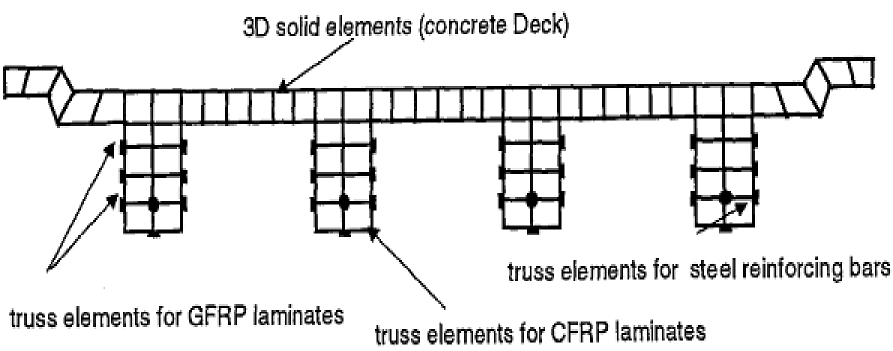
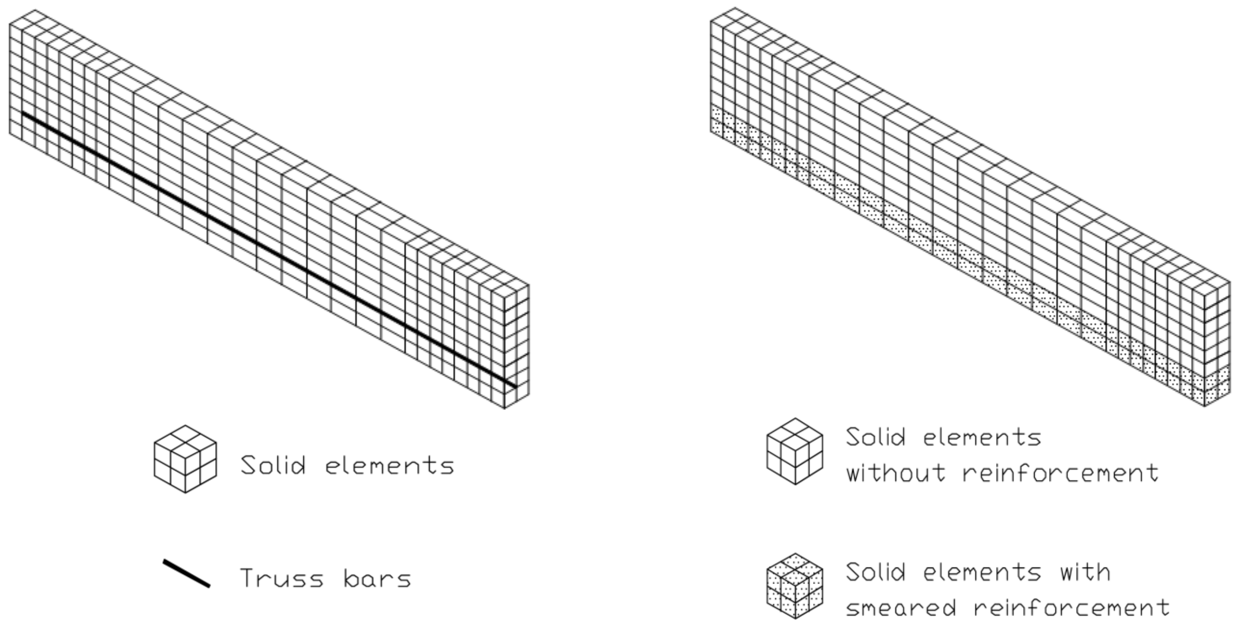


Figure 1. Isometric and cross-sectional details of FEA model [5].

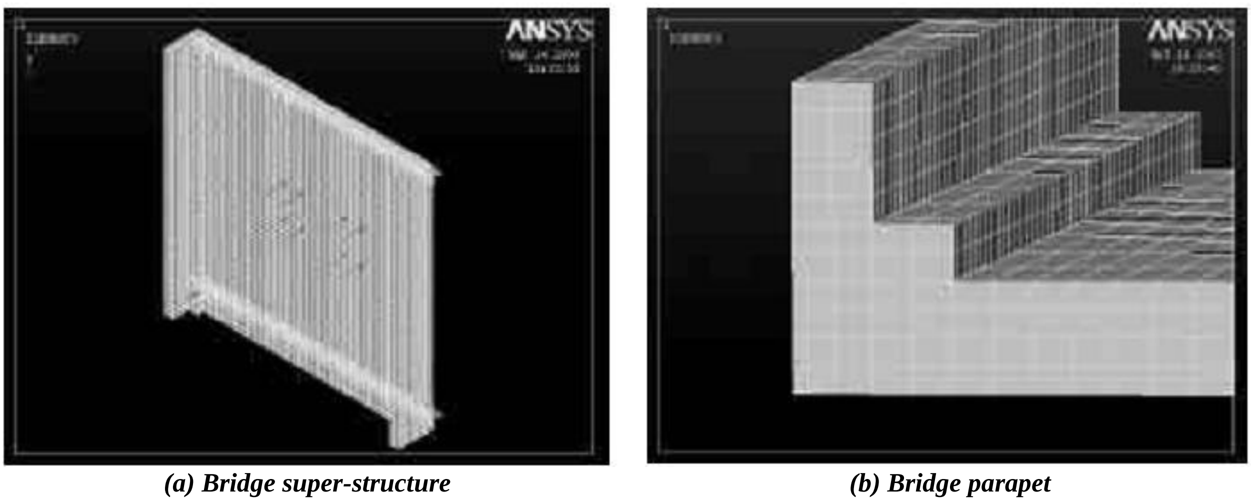
Antonio F. Barbosa et al. (1998) made a significant contribution towards nonlinear analysis of RC models. They modeled the steel reinforcement as smear and discrete elements in the same beam. In the prior case, they used truss element to simulate steel reinforcement whereas in later it was considered as distributed across the solid/concrete elements; both case shown in figure 2. They analyzed the compression-concrete elements in both models using four different approaches: Linear Elastic, Elastic Perfect Plastic, Multi-linear uniaxial stress strain (without crushing) and Multi-linear uniaxial stress strain (with crushing) models. The tension-steel elements were also modeled in both cases as: linear-elastic and elastic-perfectly. They computed and discussed load deflection plots from the foregoing cases and concluded these models can be used to predict behavior of real life RC concrete elements/structures. Moreover, the pattern of load-deflection plots for all cases for both smear and discrete modeling had close resemblance however, all material models except which incorporated non-linear compressive stress-strain relationship would fail to converge well below the ultimate load capacity of beam.



(a) Discrete elements ***(b) Smeared element***

Figure 2. FEA model with discrete and smeared reinforcement [6].

Paolo Casadei et al. (2003) used near surface mounted CFRP bars and laminates to mitigate excessive cracks in a three span RC concrete bridge namely Martin Spring Bridge in Italy. They also validated their experimental finding by FEA of bridge system. However, their simulation too, had some over simplifications in the form of both: the geometry where they adopted simplified geometry for modeling parapets, and material models where they defined the concrete element as isotropic and linear elastic. The simplified material model was explained with the fact that applied loads were well below the limit-states. There mesh size was also considerably large (3.5in x 5in x 6in); perhaps owing to computational restraints. To take into consideration the effect of previous cracking, they assumed reduced modulus of elasticity of central elements by a thousand times. Despite retaining these limitations their FEA results - for stresses and deflection at central and side passing of truck load - were in close agreements with physical testing. Figure 3 shows glimpses of FEA model.

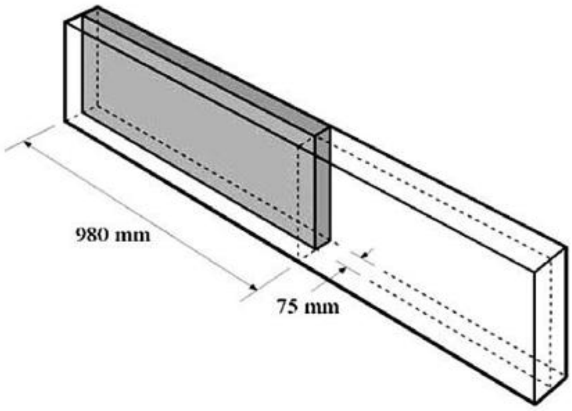


(a) Bridge super-structure ***(b) Bridge parapet***

Figure 3. FEA model for bridge super-structure and parapets [7].

Y. M Obaidat et al. (2009) investigated CFRP and CFRP to concrete interface models. In this study, concrete, steel reinforcement and CFRP were all modeled as four node tetrahedral elements whereas interface between concrete and

CFRP were modeled as eight node solid elements. The material model for concrete was defined with uniaxial liner elastic tensile stress-strain relation and uniaxial non-linear compressive stress-strain relation; for steel as elastic-perfectly plastic; for FRP as linear elastic isotropic and then liner elastic orthotropic. The bond between steel and concrete was assumed as perfect bond whereas bond between concrete and FRP-to-concrete interface elements was first considered as perfect bond and afterwards defined as bond-slip model. Presence of previous cracking was also introduced as geometrical discontinuity. The double symmetry of samples was exploited by simulation of only quarter of the beam specimen. The load-deflection response, crack pattern, failure modes and stresses from FEA were ascertained and found in close agreement with experimental results. Although the load deflection curves from all FEA simulations were similar during initial stages of loadings, prior to cracking; however, after cracking the perfect-bond assumption lead to higher stiffness than bond-spit model. Perfect bond assumption also failed to exhibit tension softening and debonding modes of failure. Moreover, the results from isotropic and orthotropic FRP material models were also closely similar. Figure 4 depict the FEA model of a beam sample.



(a) Double symmetry of beam specimen

(b) Meshed model of quarter beam

Figure 4. FEA model and actual beam specimen [8].

R. A Havileh et al. (2012) validated the published experimental results of Al-Tamimi et al. (2011) through FEA simulation. They modeled concrete as solid elements, reinforcement as link elements and CRFP plate as shell elements. The epoxy at interface of concrete and FRP was also modeled as solid element. They unlike other previous researchers, did not assume a perfect bond between concrete and steel reinforcement, and concrete and FRP; and rather bond-slip approach was incorporated using spring elements and cohesive interface-elements at steel-concrete and concrete interface respectively. Concrete material model was defined with compressive nonlinear stress-strain relation and tension cut-off criterion. Steel and FRPs were modeled as elasto-plastic and orthotropic material. They successfully validated the load deflection plots and failure modes obtained from experimental results through FEA. The difference in FEA and experimental results for ultimate load and corresponding deflections, in all six cases, were less than 2.4 percent and 3.6 percent respectively. Figure 4 portrays FEA model of a beam used in this study

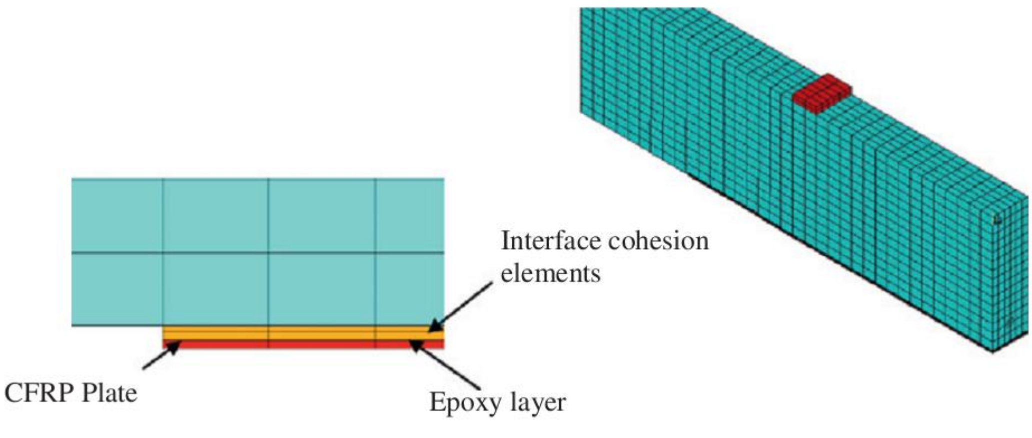


Figure 4. FEA model for RC beam specimen bonded with CFRP [9].

S. Dirar et al. (2013) used FEA simulation to validate their previous experimental work on shear strengthening of RC T-beam. Figure 5 shows calibration of a beam model used in this study. It was among pioneer FEA studies to simulate pre-cracked RC T-beams. In this study an effort was made to simulate real life structure as closely as possible. The FEA models were prepared and processed in such manner to cover at stages of initial damaging loading, unloading for sake of repair, repairing and finally re-loading after repair is done. In their models they used solid brick elements (and wedge elements at chamfer location) for concrete and interface b/w steel and concrete, and truss elements for steel reinforcement and CFRP sheets. Material model for concrete was defined with compressive stress strain relationship and von mises yield criteria. Similarly steel was defined as elastic-perfectly plastic, FRP as elastic brittle and FRP-concrete interface with bond-slip model. Phased-analysis which allows the user to apply changes geometric and boundary conditions at the end of a certain stage in the solution was performed. Initially the FRP and interface between the FRP and concrete was intentionally made inactive and the model was loaded to 70 percent shear capacity to make it substandard. The model was then reloaded till 40 percent point and FRP and interface elements were activated to replicate the real life retrofitting. A comparison was made between the FEA and experimental results for different parameters such as shear stresses & strains and shear force & deflections. They also used their FEA findings for approximating failure mode of the RC beams.

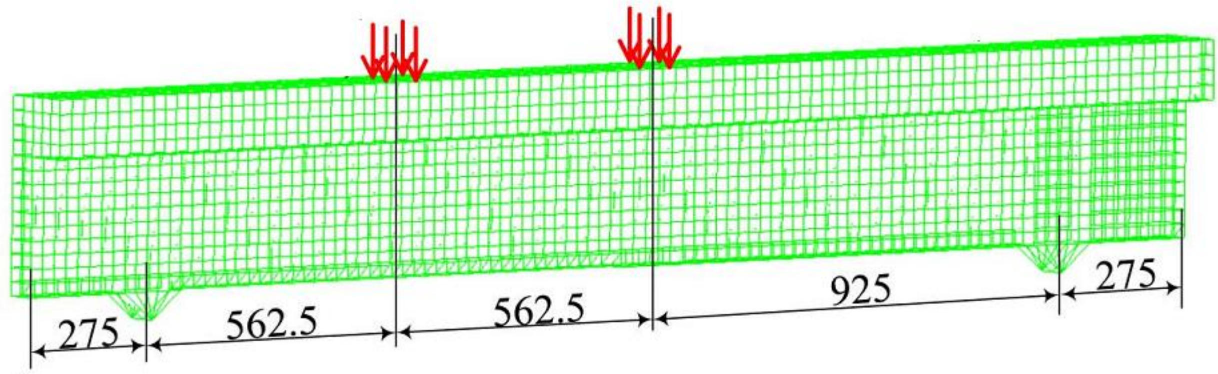


Figure 5. Calibration of the complete beam with double symmetry [10].

V. Vitanov (2016) validated the experimental work performed by Garden et al. (1998). Externally bonded FRP applied to soffit were simulated through FEA program and comparison was made between load deflection plots obtained from experimental results and FEA. The results were in close agreement corroborating the effectiveness of FEA simulation techniques used in the study. The researcher assumed the steel reinforcement as well as FRP to be smeared across the concrete elements. This technique allowed to divide the cross-sectional area of the concrete beam into three distinct regions of concrete elements, concrete elements smeared with steel reinforcement and concrete elements. These regions are shown - color coded – in Figure 6. The concrete element model was considered as linear-elastic and orthotropic before and after the occurrence of crack respectively. Fore steel, bilinear model with strain hardening was used whereas the FRP material model was defined as elastic brittle. Taking advantage of the symmetry only half of the beam was modeled and analyses.

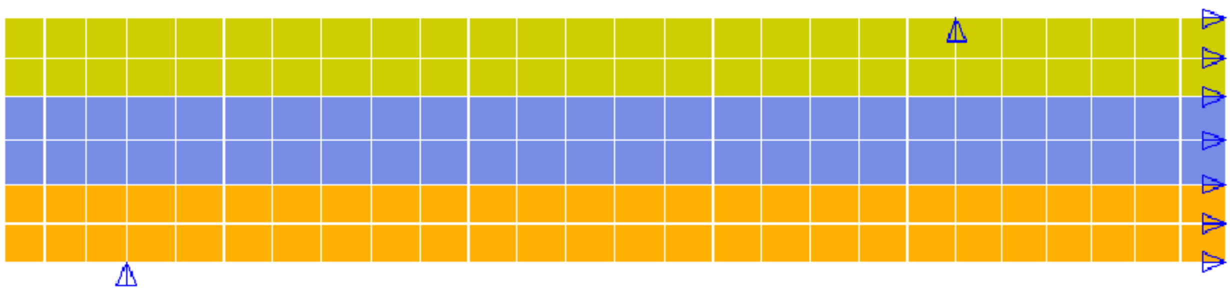


Figure 6. Beam specimen showing concrete elements (top), smeared with steel (middle) and FRP bottom [11].

III. CONCLUSION

Use of FRPs in strengthening of RC members is still under development as the renowned institutions such as American Concrete Institute continue to strive for development and improvement of design guidelines. These guidelines are primarily based on the empirical models developed from notable researched around the globe however, there are some issues such as long-term behavior of strengthened system which are still not completely understood therefore, guidelines put very strict threshold on allowable stresses and strains in FRP. Such limitations coupled with multitude of failure modes of FRP bonded RC structures in general and RC beams in particular mandate detailed finite element analysis during design process.

FEA of FRP bonded RC members itself is a complicated process and requires means to address complexities in their material models and failure criteria considering the heterogeneous nature of materials and their complicate interface. Owing to these limitations, design engineer often hesitate to perform FEA and tilt towards conventional investigations through laboratory testing of models which itself necessitate great financial endowments.

Selection of appropriate FRP materials and suitable strengthening scheme also becomes very convenient once FEA is performed during initial design stages. It can help in focusing time, serenity and equity on more sustainable strengthening scheme. For this reason a growing trend among researches is being seen to supplement their experimentation with FEA.
Notwithstanding the complexities of FEA, several simplifications and idealizations – as articulated in the foregoing section – have been performed by researches which have been amply corroborated through comparison with experimental findings. These interventions can be adopted by contemporary research projects depending on the nature and complexity of the problems at hand and proficiency of researches in FEA.
Foregoing in view, use of appropriate FEA approach can significantly improve the potential use of FRPs for strengthening of RC structural members.

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