Analysis for FRP Composite Beams Using Finite Element Method

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Abstract--- *Advances in finite element methods and analysis of strengthened reinforced concrete beams using fiber reinforced polymers (FRP) are reviewed in this paper with reference to numerical analysis and modeling of fiber reinforced polymer (FRP) composite concrete beams. The possibilities of future research on finite element analysis of FRP strengthened RCC beams are also presented.*

This review is required to have better understanding of stress distribution on concrete matrix due to strengthening with FRP elements. This will also help in understanding the various strains occurring on different elements. These parameters help in limiting stresses within permissible limits.

Keywords--- *Finite Element Modeling of RCC Beam, Strengthening with FRP.*

I. Introduction

NUMEROUS experimental studies and field applications proved that the application of FRPs (typically glass FRPs and carbon FRPs) as internal reinforcements or external strengthening is effective to improve the structural durability and performance of concrete structures. In particular, the FRP strengthening technique by bonding FRP plate to the tension regions of concrete structures is proving to be very competitive with regard to both structural performance and costs (Godat et al. 2007)[10].

Experimental tests on FRP strengthened beams have identified a number of possible modes of failure including tensile rupture of the composite laminate, de-bonding failure between the FRP laminate and the concrete substrate, concrete cover failure, and concrete crushing (ACI 2002).

To accurately predict the ultimate load carrying capacities and observe the de-bonding failures, it is essential to understand the mechanics of bond and interfacial failure behavior between FRP and concrete. Thus a large number of researches on finite element modeling of FRP concrete beam are concentrated on the model development of de-bonding and the interface behavior between the FRP and concrete. Some papers assume perfect bonding between FRP and concrete. Most of studies on FRP composite beams were carried out by experimental investigations due to the complexity of numerical modeling of concrete structures.

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Finite element method is one of the most versatile and powerful numerical modeling tools and have been employed successfully for nonlinear finite element analysis of RC structures including FRP composite concrete beams.

II. Analysis of FRP Concrete Beams

Concrete beams are modeled as a 3D beam element, with reinforcement modeled as truss element. For an effective and accurate finite element analysis, a geometric model is used to model the FRP composite beams reinforced/strengthened for concrete beams. De-bonding failure play significant roles in making the analysis more practical. Material models are used to model the nonlinear material characteristics of concrete, concrete cracking and tension stiffening effects, and a bond-slip for de-bonding between FRP and concrete.

A. Geometric Models

Various FEM-based geometric models have been proposed for finite element analysis and modeling of the behavior of FRP reinforced/strengthened RC beams, and generally they can be classified as 1-D models, 2-D models, 3-D models and layered shell models. In the layered shell models, the concrete is modeled by a series of layers and the rebar is usually treated as an smeared equivalent layer with stiffness only in the bar direction (Ebead & Marzouk 2005)[7], (Ferreira et al. 2001)[9], (Nitereka & Neale 1999)[25], (Takahashi et al.1997)[32], (Zhang & Zhu 2010)[38]. Perfect bonding is usually assumed in the layered finite element model. In the 1-D models, both the concrete and rebar and FRP sheet is modeled by a unified 1-D element (Faella et al.2008)[7]. In the 2-D and 3-D models (Hoque et al. 2007)[13], the rebar is usually modeled by one dimensional bar elements or truss element, the concrete is modeled by 2-D plane elements or 3-D solid elements, and the FRP sheet is usually modeled as plane element or shell element. To model de-bonding behavior, the interface between FRP and concrete is usually modeled using nonlinear spring elements.

B. Material Models

To simulate the real response and the failure mechanisms of the FRP concrete beam, it is important to accurately model the crack propagation behavior in concrete, the bond–slip relationships between reinforcing bar and concrete and interfacial bond behavior of FRP–concrete interface in addition to the constitutive behaviors of concrete, steel, and FRP sheets. In most of the finite element analysis, the rein-forcing steel is treated as a linear elastic–perfectly plastic material. The FRP sheets and the rebar are assumed to be linear elastic. Various nonlinear constitutive models were used to model the material characteristics of concrete. Concrete cracking and propagation of cracks are important aspects of concrete behavior that considerably affects the overall response of concrete structures. Generally, two approaches have been employed to model the concrete cracking, i.e. smeared crack approach and discrete crack approach. For a rational and accurate analysis of concrete structures, it is often important to also include the post-cracking resistance of concrete, thus an accurate tension stiffening model for FRP reinforced/strengthened concrete, such as the model developed by (Nayal et al. 2006)[22], should also be included.

C. Bond-Slip Models

For accurate numerical modeling of the de-bonding between FRP and concrete, an efficient mechanical characterization is required to model the adhesive between FRP to concrete. Accurate and effective bond-slip models have been developed such as the bi-linear shear stresses-slip relationship (Holzenkaempfer 1994)[12] and the accurate bond-slip models based on the predictions of a meso-scale finite element model Lu et al. (2007)[21].

III. Finite Element Analysis for FRP Reinforced Concrete Beams

The deflections and stresses in concrete and rebars of perfectly bonded FRP reinforced concrete beams was predicted by a geometric and material nonlinear finite element analysis using a layered discretization of the laminate materials (Ferreira et al. 2001)[8]. The bond behaviour of FRP rebars with concrete was investigated by (Achillides and Pilakoutas 2006)[1] by modelling the concrete using 4-node plane square elements, FRP bars using 2-noded square bar elements, and the interface between concrete and FRP bars using nonlinear spring elements. Some simply supported carbon FRP reinforced/strengthened concrete beams are modeled using a non-linear finite element model which is analysed with the help of 2D isoparametric plane stress elements, in which the concete crack was considered as an orthotropic material and the crack formation is simulated as smeared cracks (Rafi et al. 2007)[29]. The nonlinear response of concrete structures reinforced with internal and external FRPs was studied by using a refined 3-D hypoelastic constitutive model for the nonlinear behavior of concrete (Nour et al. 2007)[26]. The reinforcing bar-concrete interaction was simulated implicitly using tension-stiffening factors modified according to the nature of reinforcement.

A. FRP Strengthened RC Beams with Perfect Bonding

(Hu et al.2004)[14] used 27-node solid elements to model the reinforced concrete beams, while FRPs were modeled by using 8-node shell elements. A fictitious crack approach was adopted by (Wu and Davies 2003)[34] to estimate the equivalent bridge effect of the fracture process zone of concrete for a beam subjected to three-point bending and externally reinforced with unidirectional FRP plate near the bottom surface of the tensile zone. The rebar/concrete interface de-bonding of FRP-strengthened concrete beams is assumed as perfect bonding between the concrete and FRP plate under fatigue load which was investigated by (Zhang and Shi 2008)[37].

B. FRP Strengthened RC Beams with De-Bonding

(Arduini et al. 1997)[2] examined the nonlinear behavior and early concrete cover de-lamination and end plate failure of FRP strengthened RC concrete beams using a smeared crack model for concrete.A 3-D elasto-plastic finite element analysis method was developed to simulate the load-carrying capacity of RC beams failed in the FRP sheet peel off mode (Kishi et al. 2005)[15]. The nonlinear behavior of FRP-strengthened beams was examined using the smeared crack model for concrete, and the mixed mode of failure due to the combined shear and concrete cover de-lamination was addressed through modeling end plate and shear crack discontinuities using the discrete crack approach (Pešic & Pilakoutas, 2003)[27]. Using a discrete crack model for concrete crack propagation and a bilinear bond-slip relationship with softening behavior is used to represent FRP-concrete interfacial behavior. (Niu and Wu 2005)[25] performed a nonlinear fracture mechanics-based finite element analysis to investigate the effects of crack spacing and interfacial parameters such as stiffness, local bond strength, and fracture energy on the initiation and propagation of the de-bonding. A 2-D frame finite element was presented by (Barbato 2009)[4] to estimate the load- carrying capacity of FRP strengthened RC beams. (Wang and Zhang 2008)[33] examined the de-bonding between the FRP plate and concrete using linear elastic Euler-Bernoulli's beam and a bilinear law for the modeling of the nonlinear bond-slip behavior. (Baky et al. 2007)[3] used 2-D and 3-D models to simulate the FRP strengthened RC beams. In addition, (Neale et al. 2006)[23] investigated the load-deformation behavior and de-bonding phenomenon of FRP strengthened concrete beams and slabs. Great efforts have been made to model the interactive behavior between concrete and FRP. (Qiao and Chen 2008)[28] used a bilinear model cohesive zone model to simulate the nonlinear cohesive fracture behavior of the FRP–concrete bonded interfaces in a three-point bending beam. (Li et al. 2009)[19] analyzed the interfacial stresses between the concrete and the FRP of RC beams strengthened with hybrid carbon fibers and glass fibers and the de-bonding process of the FRP sheets. (Yang et al. 2004)[35] studied the interfacial stress distribution and evaluated the effect of the structural parameters on the interfacial behavior in FRP-reinforced concrete hybrid beams. Intermediate crack de-bonding was simulated by a finite- element model based on the smeared crack approach for concrete by (Lu et al. 2007)[21]. (Leung et al. 2006)[18] determined the nonlinear softening behavior at FRP composite/concrete interface. In addition interfacial stresses in structural members bonded with a thin plate were predicted by (Zhang and Teng 2010)[38].

C. Governing Equation for the Validation of Experimental and Analytical Models

FRP's are susceptible to deterioration under various static and dynamic loading. Reinforced/strengthened RC beams needs to be validated depending upon the different governing equation framed under limit state of serviceability. The formulation of equation should be validated depending upon the end boundary condition prevailed. The equations need to be verified for site/laboratory conditions that prevail. The governing equation will help in laying definite procedure in understanding the modes of failure for different beam cases viz. un-cracked beam, cracked beam and failed beam.

D. FRP Composite Concrete Beams under Elevated Temperatures

FRPs are susceptible to deterioration under elevated temperatures or fire conditions with mechanical and bond properties decreasing sharply at elevated temperatures. Although significant research has been conducted to investigate various aspects of the behavior of FRP RC beams, few studies on the performance of FRP concrete beams subjected to fire exposure have been reported. Among the few are the study of response of a reinforced RC beam in the entire range of loading up to collapse under fire (Kodur & Dwaikat 2008a,b)[16], the nonlinear 3-D finite element model presented by (Rafi et al. 2008)[30] for the prediction of response and crack formation and propagation of steel and FRP reinforced concrete beams under a combined thermal and mechanical loading up to failure, the prediction of the fire behavior of FRP- strengthened RC beams by (Gao et al. 2009)[9], and the modeling of insulated CFRP-strengthened reinforced concrete T-beam exposed to fire (Hawileh et al. 2009)[11].

IV. FUTURE RESEARCH

In the research carried so far, very few researches on the performance of the FRP concrete beams under static, fire condition, environmental effects, and dynamic loading have been reported so far. To predict the structural and failure behavior of FRP concrete beams in the real environmental conditions are listed below. An effort may be made in this regard;

1. Accurate and reliable predictions of the behavior of FRP concrete beams at high temperatures.
2. Governing equations for behavior of beam and FRP to determine stresses and deflection.
3. Further investigations on the material properties at elevated temperature, especially with respect to the strength and stiffness of FRP materials.
4. Interface damage behavior between FRP and concrete, such as de-bonding and etc.
5. More realistic material and bond models at elevated temperature
6. Research on the tension stiffening stress-strain relationship for FRP reinforced/strengthened RC beams.
7. Long term structural performance under environmental effects, such as moisture, cycling temperature.
8. Structural performance under cyclic and dynamic loading.

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