XFEM Modelling of Reinforced Concrete Beam with FRP Rebars

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ABSTRACT: Advanced computing technology has led to fast and accurate predictions from finite element analysis (FEA) modelling framework. Six models were developed in current work following reported experimental series with combination of reinforcement types (steel, CFRP amd GFRP) and concrete grades (Grade 40 and 60). All 3D models were idealized from four-points bending testing set-up. Physically-based material model were incorporated using Extended Finite Element Method (XFEM) technique to perform strength prediction using traction-separation relationship and later validated against experimental datasets. Discrepancies between 23% - 31% in all testing were obtained, underprediction values was mainly due to several assumptions during modelling idealization phase. The unmeasured friction values was employed within concrete matrix and reinforcements where improper reinforcement slippage within concrete matrix. Secondly, governing failure only limited to occur within cracked concrete sections. If both assumptions were properly captured, better predictions may exhibit.

Keywords: *XFEM; RC Beam; Bending Test*

1. INTRODUCTION

Recently, few studies employed Fiber Reinforced Plastic (FRP) as rebars with advantages of low manufacturing cost and low specific strength (and stiffness). The FRP rebar cost are based on per unit weight (or force carrying capacity) is high compared to steel rebar. Furthermore, in large projects, low weight of FRP materials makes it easy for rebar installation and excellent durability as an ideal alternative to conventional steel rebar. Nevertheless, FRP materials exhibited brittle failure and relatively weak in transverse and shear resistance.

There are many closed-forms available in the literatures, however they are problem-specific expression which has limited applicability to concrete grades (and/or reinforcement types) usually applicable to specified beam dimensions. Finite element analysis (FEA) is the most powerful numerical tool available, however its accuracy and numerical convergence is largely dependent upon modelling selections during pre-processing stage. Concrete damage plasticity (CDP) requires crack opening-displacement datasets or stress-inelastic strain (Lee *et. al*., 2020) from experimental datasets. Good agreements were obtained but requires comprehensive experimental data which are laborious and time-consuming. These inelastic stress and strain are dependent upon intrinsic factor such as concrete grade and rebar configurations.

The objectives of this paper is to develop strength prediction framework of reinforced concrete beams subjected to flexural load and validated against experimental datasets (after Kim and Kim, 2019).

2. METHODOLOGY

Fracture and failure of reinforced concrete is perform using extended finite element method (XFEM) technique. The XFEM formulation is embedded in ABAQUS CAE extension from basic FEA displacement which is integration of an enriched function. This enriched function consists of near-tip asymptotic functions to capture singularity around the crack-tip to allow displacement jump between crack faces during crack propagation.

Traction-separation relationship is physically-based constitutive model to incorporate within XFEM technique. The testing series is following experimental programme conducted by Kim and Kim (2019) with variation of reinforcing types and characteristic concrete strength. The geometries of the concrete beam with shear link spacing of 100 mm are shown in Figure 1. The red colour indicates the steel reinforcement which is constant but blue colour specified different rebar type indicated in the testing series. i.e., steel, CFRP or GFRP associated to different diameter bar size at most bottom tension rebar. Another variation is two concrete grades, namely 40 and 60 MPa where combination with different reinforcement types gives a total of six testing beams.

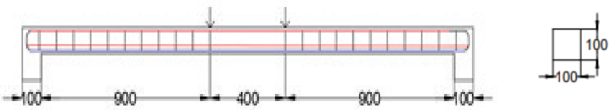

Figure 1: Concrete beam with different type of reinforcement.

As the mesh density increases demand more computational time and efforts, necessitating a balance between accuracy and computational cost in order to provide a practical and useful numerical model (Ahmad *et. al*., 2021). In this work, sensitivity study to adopt suitable mesh refinement and damage stabilization coefficient to assure strength predictions are free from these parameters. All simply-supported beam models were assigned as pin and roller at their left and right supports, respectively.

Table 1 Material properties of reinforcing bars and shear link (after Kim and Kim (2019)).

	d (mm)	Area (mm^2)	E (GPa)	f_y (MPa)	f_u (MPa)
Steel-D10 /links	9.5	71.3	173	446	577
GFRP-D13	12.7	126.7	48	-	1118
CFRP-D9	9.5	71.3	103	-	1655

3. RESULTS AND DISCUSSION

It is regarded as good agreements has reached if the discrepancies between strength predictions and experimental datasets lower than 20%. However, as seen in Table 2, it was found that much larger discrepancies from experimental work reported by Kim and Kim (2019). Beam series with concrete grade 60 gives larger discrepancies than grade 40 counterparts. Respective to rebar type of similar concrete grade, CFRP series give the largest discrepancies followed by GFRP and steel.

Table 2: Comparison of XFEM with experimental datasets.

Concrete Beam Designations	Experimental Peak Load, $P_{max,Exp}$ (kN)	XFEM $P_{max,XFEM}$ (kN)	XFEM Error (%)
C40-Steel	58	58	24
C40-GFRP	92	74	23
C40-CFRP	102	76	23
C60-Steel	72	58	31
C60-GFRP	117	75	28
C60-CFRP	140	78	29

The underpredictions predominantly due to earlier assumptions made. Firstly, the plasticity in steel (also in CFRP and GFRP) were ignored. Bear in mind that measured steel plasticity is not readily available in open literatues and measured plasticity dataset (i.e., plastic stress versus plastic strain) are regarded as independent material properties. Hypothesis that led to current modelling idealization is that governing failure only limited to occur within cracked concrete sections. Secondly, no measured friction values were adopted within concrete matrix and steel reinforcements (also CFRP and GFRP bar) which may not exhibit proper reinforcement slippage within concrete matrix. Current model adopted friction coefficient of 0.33, similar values used in Ahmad *et. al*., (2020).

Figure 2 showed the crack growth from beam mid-span where only one governing crack was modelled following a prominent crack path to beam separation as observed from experimental work (Kim and Kim, 2019)) in order to provide easier solution for modelling convergence. However, there are few crack formations were formed within bending of beam tension zone under experimental observations. Few attempts has been made to model few cracks within the model, but requires expensive computational effort and time. As expected, these few other cracks developed at the vicinity of governing crack may reduce the stress exhibited within cracked concrete section to improve load carrying capacity of the concrete beam under flexural. Current approach only model a governing crack and ignore the existance of minor neighbouring cracks associated to lower prediction of ultimate flexural load.

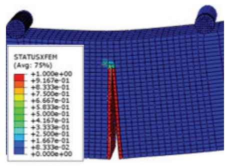

Figure 2: Crack growth tracked from XFEM model

Another interesting finding is good predictions was obtained with a combination of lower concrete grade and steel rebar (i.e., given as C40-steel concrete beam designations). Lower concrete grade may not much affected the fracture energy value incorporated (current work used similar fracture energy values to both concrete grades) where it is expected that larger fracture energy may exhibit in higher concrete grade due to better compressive strength and concrete density. Current work employed homogeneous isotropic materials for both composite materials which may appears as inappropriate selections. Nevertheless, material anisotropy of both composite materials are not clearly given in Kim and Kim (2019), only homogeneous properties were reported and employed in the current work.

4. CONCLUSION

All developed XFEM models exhibited physical behavior as seen from experimental observations. From experimental observations, it is clearly that the crack is present due to stress concentration and as progressive macro-cracks has reached to a certain distance (known as fracture zone length) gives catastrophic failure to beam separation. More than 20% discrepancies in all testing were obtained parly due to improper friction values were measured within concrete matrix and rebar to exhibit improper rebar slippage within concrete matrix which requires independent value from additional experimental set-up. Better prediction may be obtained if the model able to capture frictional load transfer in a proper manner.

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