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EVALUATION OF PARAMETERS EFFECTIVE IN FRP SHEAR STRENGTHENING OF RC BEAMS USING FE METHOD

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ABSTRACT

Shear strengthening is required when an RC beam is found deficient in shear, or when its shear capacity falls below its flexural capacity after flexural strengthening. A recent technique for the shear strengthening of RC beams is to provide additional FRP web reinforcement, commonly in the form of bonded external FRP strips/sheets. Over the last few years, several experimental studies have been conducted on this new strengthening technique, which has established its effectiveness. While experimental methods of investigation are extremely useful in obtaining information about the composite behaviour of FRP and reinforced concrete, the use of numerical models such as the one presented in this paper helps in developing a good understanding of the behaviour at lower costs. In the study presented in this paper, ANSYS finite element program is used to examine the response of beams strengthened in shear by FRPs. The FE model is calibrated against test results performed at the University of Kentucky. Once validated, the model is used to examine the influence of fibre orientation, compressive strength of concrete, area of tensile and compressive reinforcements, and amount and distance between stirrups on the strength and ductility of FRP strengthened beam.

Keywords: reinforced concrete, finite element model, shear strengthening, FRP laminates

1. INTRODUCTION

The use of externally bonded fibre-reinforced polymer (FRP) composite strips/sheets for the strengthening of reinforced concrete (RC) structures has become very popular in recent years. This popularity has been due to the advantages of FRP composites, including their high strength-to-weight ratio and corrosion resistance. One of the major strengthening applications of FRP composites is as additional web reinforcement of various forms for the enhancement of shear resistance of RC beams. Shear strengthening is required when an RC beam is found deficient in shear, or when its shear capacity falls below its flexural capacity

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after flexural strengthening. Compared to flexural strengthening of RC beams, shear strengthening studies have been rather limited. Most of studies are also experimental and numerical modelling has not been used widely.

A comprehensive review of the experimental and design model development studies on shear strengthening has been provided by Professor Teng of Hong Kong Polytechnic University [1]. Elaborate models explaining the behaviour are also provided in [2] and [3]. According to Teng et al [1], most experimental results revealed one of two failure modes: tensile rupture of the FRP, which starts in the most highly stressed FRP strip, followed rapidly by the rupture of other FRP strips intersected by the main shear crack and debonding of the FRP from the concrete, involving a process of sequential debonding starting from the most vulnerable strip. Before the tensile rupture or the complete debonding of at least one end of the most vulnerable strip, there is generally a process of debonding propagation starting from the main shear crack. The FRP rupture failure mode has been observed in almost all tests on beams with complete FRP wraps and some tests on beams with FRP U-jackets, while the debonding failure mode has been observed in almost all tests on beams with FRP side strips and most tests on beams with FRP U-jackets. Mechanical anchors can be used to prevent debonding and thus change the failure mode from debonding to rupture.

While experimental methods of investigation are extremely useful in obtaining information about the composite behaviour of FRP and reinforced concrete, the use of numerical models helps in developing a good understanding of the behaviour at lower costs. Successful use of ANSYS for modelling of FRP strengthened beams has been reported in the past [4]. In this paper, a FEM for FRP shear strengthening of beams is presented. The model makes use of the commercial software ANSYS to evaluate the effects of different parameters that are important in the response of the strengthened beam in shear. The model is calibrated with the results of tests performed at the University of Kentucky [5] and is later used in a parametric study in order to evaluate these effects. The model is explained in the following. More information can be found in [6].

2. NUMERICAL MODEL

The numerical model represents only a quarter of the full size beams used in the tests at University of Kentucky. The symmetry and anti-symmetry boundary conditions are used at the boundaries in order to simulate the full beam adequately. As is seen in Figure 1, the beam length is 2.13m and its clear span 1.83m. The height of the beam is 38cm and it's width 23cm. Reinforcements include two compression reinforcements of 9mm diameter, two tension reinforcements of 25mm diameter together with $\phi 9$ stirrups at 30 cm. Beams tested at Kentucky include 2 control beams, 4 strengthened beams with 90 degrees fiber orientation, 2 strengthened beams with one 90 degree fiber and one 0 degree layer overlapped, 4 strengthened beams with 45 degrees fiber orientation, 2 strengthened beams with one 45 degrees and one 0 degrees overlapped.

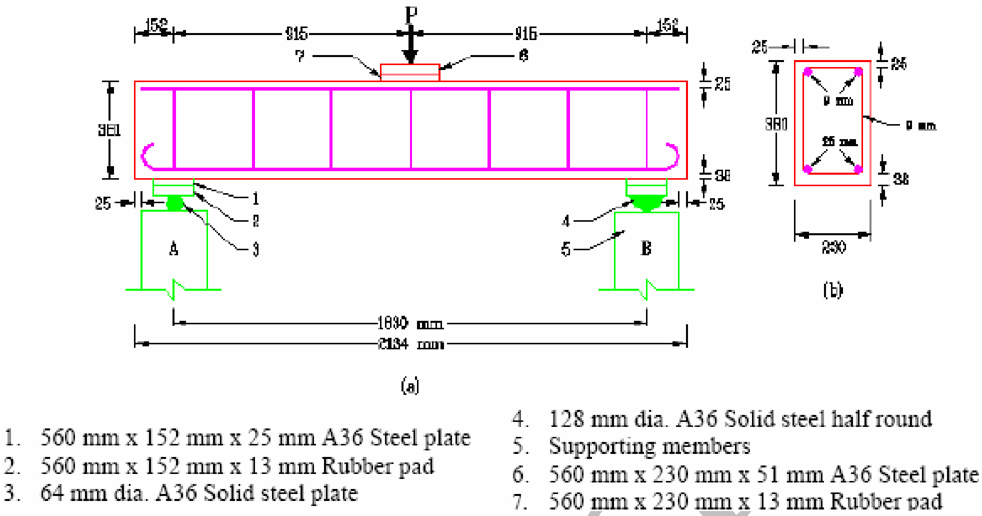

Figure 1. Beams geometry and reinforcements array [5]

Concrete compression strength is 31MPa and yield stress of reinforcements is 414MPa, concrete modulus of elasticity is calculated from $E_c = 4750\sqrt{f'_c}$ and concrete cracking stress or rupture module is taken as $f_t = 0.6\sqrt{f'_c}$ while the Poisson's ratio for concrete is considered as $\nu = 0.2$. Steel modulus of elasticity is taken as 200GPa, and it's Poisson's ratio as $\nu = 0.3$. It is further assumed that steel behaves in an elastic perfectly plastic manner while strain hardening is ignored. Properties used for carbon fibre materials are as shown in Table 1 below.

Table 1. CFRP properties

CFRP Fabric	**Thickness (mm)**	**Ultimate tensile Stress (MPa)**	**Modulus Of Elasticity (GPa)**	**Ultimate Strain (%)**
	0.18	490	228	1.8

These properties are for fiber in major orientation considering orthotropic conditions. FRP modulus of elasticity in minor orientation equal 10 to 15 percent of that of the major orientation and shear modulus for orthotropic material are calculated from Eq. (1).

$$G_{xy} = \frac{E_x E_y}{E_x + E_y + 2\nu_{xy} E_x} \quad (1)$$

ANSYS models concrete with its element SOLID 65. SOLID65 is a cubic element with eight nodes at each of its corners each having three translational degrees of freedom (Fig. 3).

SOLID65 is capable of cracking in tension, crushing in compression, and plastic deformation. It also comes with a rebar capability in which rebars can be defined within the element itself. As for cracking, here a smeared crack model is adopted [7].

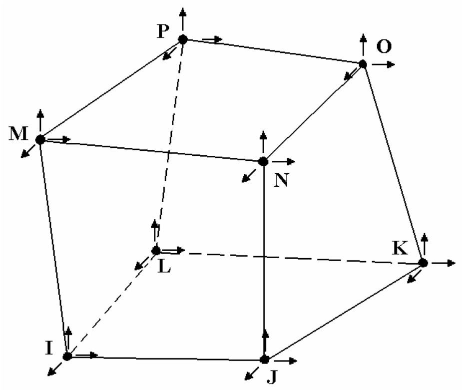

Figure 2. Element SOLID 65 and its degrees of freedom

Reinforcement bars can also be modelled separately from SOLID65 using an element called LINK8. This element is a 3-dimentional spar and a uniaxial tension-compression element with three degrees of freedom at each node. In addition, FRP wraps are modelled by SHELL43 as an elastic material and steel plates below the loading points and on the supports by SOLID45 as an elastic perfectly plastic material without strain hardening. It is also assumed that the slip between concrete and reinforcement and also between concrete and FRP is zero. The mesh geometry is shown in Figure 3.

The finite element model is run until a displacement convergence criterion set at the beginning is satisfied.

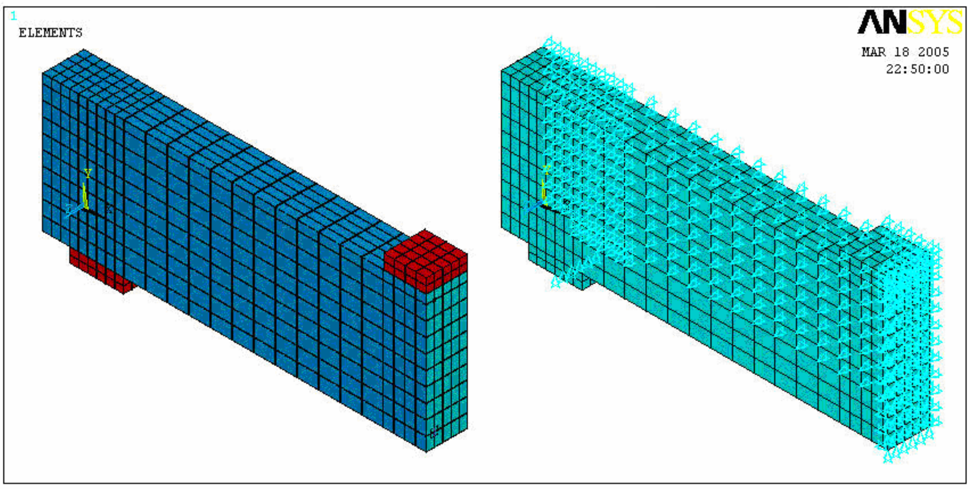

Figure 3. Geometry of model in ANSYS program, considering symmetry

3. CALIBRATION OF THE MODEL

The control beams tested at the University of Kentucky were weak in shear. Test results have shown that they failed in a brittle manner without any prior warning signal as the combination of shear and flexure cracks spread along the beam causing concrete to crush at the loading point. The FRP strengthened beams mostly failed by FRP rupture and the follow up delamination. The separation of CFRP fabric was observed near the support and extended towards the mid-span.

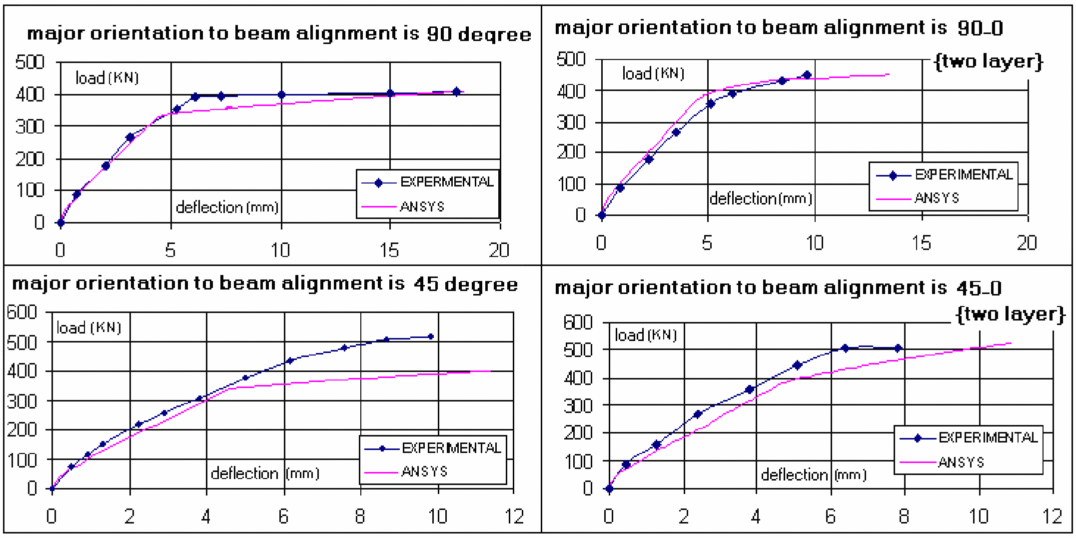

Figure 4. Comparing the model with experiments

As is seen, the model predictions are in agreement with the experiments. The model can therefore be used with confidence in the following parametric study to evaluate the effects of different parameters that may be effective in FRP shear strengthening.

4. EVALUATING THE EFFECT OF DIFFERENT PARAMETERS

In this section, the effects of parameters such as the influence of fibre orientation, compressive strength of concrete, area of tensile and compressive reinforcements, amount and distance between stirrups on the strength of FRP strengthened beams are examined.

4.1 Effect of fibre orientation

Figure 5 shows the load deflection curves obtained from ANSYS for beams with the geometry mentioned previously strengthened with only one layer FRP at different fibre orientations. As is seen, the 90 degrees orientation provides the highest strength gain and a more favourable (ductile) failure. Further investigation related to the behaviour of beams area therefore carried out considering a 90 degrees orientation.

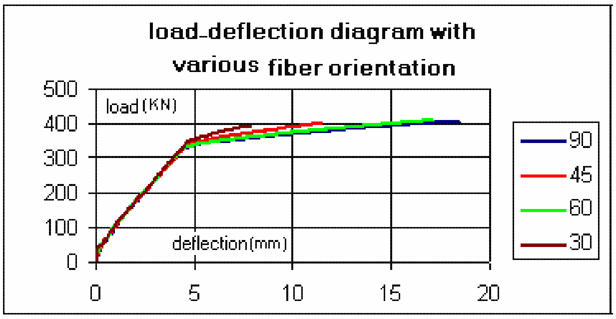

Figure 5. Load-deflection diagram for beams strengthened with FRP

4.2 Effect of concrete compressive strength

The concrete used in the tests was a 31Mpa concrete. To evaluate the effect of concrete strength, two other strengths of 21MPa and 41MPa are tried keeping the rest of the parameters constant and the fibre orientation at 90 degrees. Figure 6 contains the results.

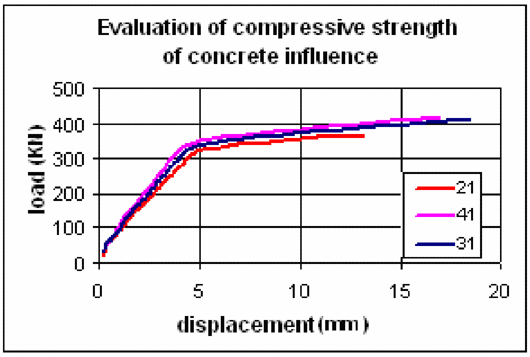

Figure 6. Load versus mid-span displacement

As is seen, the ductility is highest at the mid strength of 31MPa. This is due to preferable distribution of stresses between different components at this stress level. As is shown in Figure 7, the stresses in FRP arrive at their maximum at a larger mid-span deflection comparing to the 21MPa and 41Mpa cases.

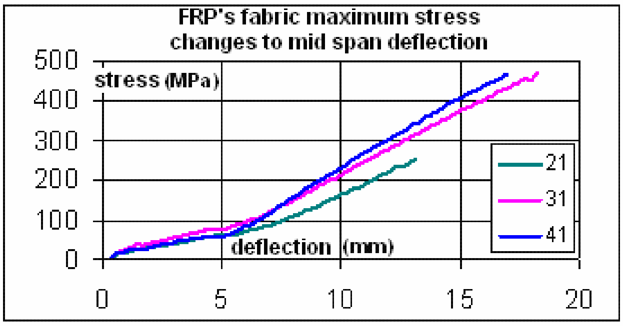

Figure 7. FRP's fabric maximum stress versus midspan deflection

4.3 Effect of longitudinal tensile reinforcement

The load versus mid-span deflection is shown in Fig. 8a for different amounts of tensile reinforcements from two size 12 to two size 36 mm in diameter. Variation of stresses with respect to the mid-span deflection is also recorded in Fig. 8b. As is seen, there is quite a distinctive range for which the ductility remains almost constant. Here, for T12 to T30, there is not much change in the ductility. The T36 however tends to make the beam brittle. There is a shift from flexure to shear failure at this level of tensile reinforcing. The stress variations shown in Fig. 8b are quite natural and predictable as larger size rebars arrive at their peak stress at higher deflections.

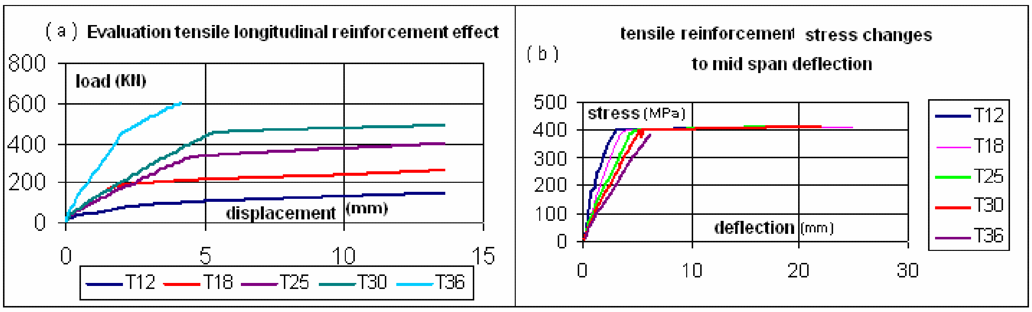

Figure 8. Load versus mid span deflection for various amounts of tensile longitudinal reinforcement

4.4 Effect of longitudinal compressive reinforcement

As more compressive reinforcements are introduced to the system, the failure mode can shift from shear to flexure and the opposite of what happened in the previous section may happen here. Table 2 below contains the results showing an almost constant strength gain at and after 2 size 12 bars are used in the compressive region. The failure mode in all of these cases is a shear failure not influenced much by the amount of compressive reinforcement.

Table 2. Effect of compressive longitudinal reinforcement

compressive reinforcement		compressive bar ratio	stress in compressive reinforcement in strengthened beam	$\bar{\rho}_{min}$	$\bar{\rho}_{max}$	FRP's laminate distribution in ultimate load	ultimate deflection	control beam		strengthened beam		incearse in strength percent
diameter	section area mm^2	ρ'	(MPa)				mm	moment KN-m	ultimate load KN	moment KN-m	ultimate load KN	
0	0	0	0	0.0193	0.0234	9	15.25	162	354	180	393	11
$2\phi9$	127.2	0.00175	389	0.0211	0.0252	11	18.4	165	361	186	407	13
$2\phi12$	226.2	0.0031	400	0.0224	0.0265	14	15	158	348	182	397	14
$2\phi16$	402.2	0.0056	313	0.0249	0.0289	13	13.7	150	340	178	390	15
$2\phi20$	628.4	0.0087	249	0.028	0.032	15	16.65	145	337	181	395	17
$2\phi25$	981.8	0.0136	163	0.0329	0.0369	15	12.3	137	329	178	388	18

4.5 Effect of transverse reinforcement

Table 3 shows that there is a complex interaction between amount and distance of stirrups and the FRP laminates. From the results shown, it can be said that as the role of internal shear reinforcement in shear strengthening increases (distance between stirrups reduces or sizes increase), the role of FRP in shear strengthening decreases. The reason for this is in the development of shear cracks that are better inhibited by FRP laminates compared to stirrups. FRPs can control the shear cracks a lot better than stirrups do as they provide a distributed inhibiting mechanism.

5. CONCLUSIONS

In this paper FRP shear strengthening of reinforced concrete beams was examined numerically using ANSYS. The results showed the following.

- ANSYS was capable of producing results in good agreement with previously published test results. It can therefore be confidently used in design and analysis situations.
- In all numerical models investigated in this study, the stresses in FRP laminates increased gradually until major cracks occurred after which concrete crushed locally and reinforcements yielded. At this stage FRP stress increased at a relatively large rate to rupture.
- 90 degree FRP alignment was found to be the most rewarding configuration as for the strength gain while the 0 degree alignment only helped with controlling the propagation of shear cracks to some extent and not the strength.
- The interaction of different cross-sectional parameters and the FRP were investigated and the trends explained in relevant graphs and tables. The results show that FRP shear strengthening is quite viable and by choosing the parameters carefully adequate ductility can be obtained in addition to reasonable strength gains.

Table 3. Comparing ultimate loads for various amounts and distances of stirrups

Transverse reinforcement (stirrup)	@15cm		@30 cm		@ 45 cm	
	Deflection mm	Ultimate load KN	Deflection mm	Ultimate load KN	Deflection mm	Ultimate load KN
$\phi 6$	22.8	424	24.1	423	26.3	430
$\phi 9$	16	406	18.4	407	19.5	409
$\phi 12$	15.9	404	18.3	418	15.2	398

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