Journal of Applied Sciences

ISSN 1812-5654

Journal of Applied Sciences 10 (9): 738-744, 2010
ISSN 1812-5654

Numerical Analysis of Bonding Between Concrete and Reinforcement using the Finite Element Method

Petru Mihai, Ioan Hirhui and Bogdan Rosca
Faculty of Civil Engineering and Building Services, 43 Dimitrie Mangeron Blvd., Iasi, 700050, Romania

Abstract: In this study, characteristics of the bond between concrete and reinforcement are estimated with the finite element method and improvements to the method are proposed. Because the reinforced concrete elements work in conjunction with the material cracking behavior, the bonding process is very complex and depends on the shape of the reinforcement, mechanical characteristics of the materials and the intensity of loads. In general, the finite element method cannot emulate this complex process because the connection between elements at the node is fixed and slip behavior of reinforcement is not allowed. For this reason, the results obtained with the finite element method do not correctly describe the phenomenon. To address this, the study propose an improvement on the finite element method to eliminate the deficiency and describe the process with more accuracy.

Key words: Bond, concrete, reinforcement, finite elements, numerical analysis

INTRODUCTION

One of the most important influences on the bearing capacity of reinforced concrete members is the bond between concrete and reinforcement (Weibe and Holschemacher, 2003). A good bond between reinforcement and concrete is required so that the two materials are able to act together in a synergistic way (Vandewalle, 2004).

The modulus of elasticity, the ductility and the yield or rupture strength of the reinforcement must be considerably higher than those of the concrete to raise the capacity of the reinforced concrete section to a meaningful level (Nawy, 2008). At the same time, the reinforcing element (such as a reinforcing bar) must undergo the same strain or deformation as the surrounding concrete to prevent discontinuity or separation of the two materials under load (Kovacevic, 2006).

Many materials have been used over time as reinforcement, but only steel and fiberglass possess the necessary principal factors of yield strength, ductility and bond value.

FACTORS AFFECTING THE BOND STRENGTH

The bonding behavior is mainly dependent on the profile of the reinforcement bar, the concrete covering on the bar, the position of the bar during the concrete pouring and the quality of the concrete.

Bond strength results from a combination of several parameters, such as the mutual adhesion between concrete and steel interfaces as well as the pressure of hardened concrete against steel bar or wire due to shrinkage from drying of the concrete (Barnes and Mays, 2001). Additionally, friction interlock between bar surface deformations or projections and concrete, which is caused by micro movements of the tensioned bar, yields an increased resistance to slippage. The total effect of these influences is known as bond strength. In summary, bond strength is controlled by the following major factors (Nawy, 2008):

- Adhesion between concrete and reinforcing elements
- Gripping effect resulting from shrinkage during drying of the surrounding concrete as well as the shear interlock between bar deformations and surrounding concrete
- Frictional resistance to sliding and interlock behavior that the reinforcing element is subjected to under tensile stress
- Effect of concrete quality and strength under tension and compression
- Mechanical anchorage effect on the ends of bars from development length, splicing, hooks and crossbars
- Diameter, shape, bond length and spacing of reinforcement in regards to their effect on crack development

---

Corresponding Author: Petru Mihai, Faculty of Civil Engineering and Building Services, 43 Dimitrie Mangeron Blvd., Iasi, 700050, Romania Tel: +40-788-690691 Fax: +40-332-107053

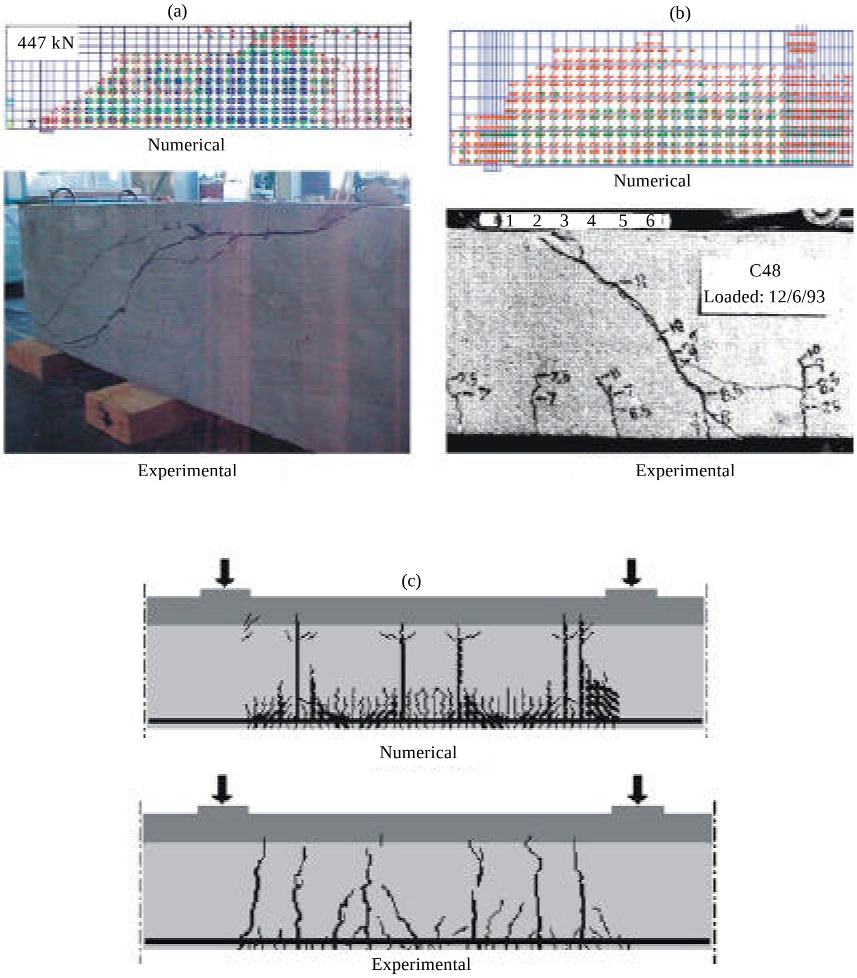

Fig. 1: Numerical and experimental crack pattern obtained by: (a) Chansawat *et al.* (2009), (b) Santhakumar *et al.* (2004) and (c) Cervenka (2001)

- Percentage ratio and yielding strength of the stirrups
- Height of the covered concrete near embedded reinforcement of concrete members

The individual contributions of those factors are difficult to separate or quantify, although shear interlock, the shrinkage confining effect and the quality of the concrete can be considered as major factors. In fact, the mechanism of bond formation between concrete and embedded reinforcement is not clearly known due to difficulties in testing and complicated contributing factors.

The numerical modeling of the bond between concrete and reinforcement is a difficult task in the finite element analysis for the civil engineering structures (Santhakumar *et al*., 2004). Several mathematical models are proposed in the last decade (Chansawat *et al*., 2009; Santhakumar *et al*., 2004; Cervenka, 2001) but the numerical analysis do not provide always satisfactory results.

In all the finite element models the cracks pattern consists of a dense mesh of cracks in those areas in tension, contrary with the tests which show fewer and larger cracks (Fig. 1a-c).

It is well known that the bond between concrete and reinforcement is a complex mechanism which can’t be described with classical finite element equations and the interdependence between bond and cracks affects the pattern of the cracks.

The foregoing mathematical models provide good results in terms of stresses, deformed shape and bearing capacity of the RC members. However, the cracks pattern presented in those models is poor comparative with tests. Therefore, in order to obtain a cracks pattern closer to reality of the tests, new models should be created.

EVALUATION OF THE BOND BETWEEN CONCRETE AND REINFORCEMENT WITH FEM

A regular simply supported girder was considered to evaluate the bond between concrete and reinforcement using the finite element method. The girder is loaded with two concentrated forces to eliminate the shear force effect in the middle part of the element (Fig. 2).

A series of experimental girders was tested to validate the results obtained with the finite element method (Fig. 3).

The initial results obtained were not satisfactory and important differences appear between numerical and experimental results:

- In the numerical results, the number of cracks is too large and cracks are present in all tensioned nodes (Fig. 4a); if the model contains finite elements of 100-200 mm each, the results appear to match the real values, but if the mesh is refined to 15 mm for each finite element, cracks in the FEM model appear at 15 mm and the results do not compare well with experiments (Fig. 4b)
- In the numerical results, the stresses in the reinforced concrete appear as in a simple concrete element without reinforcement (Fig. 4a); in the cracked area, stresses in the concrete have the same distribution as in the non-cracked areas. In the real case (as demonstrated by experiments), the stresses in the concrete in the cracked areas are very small compared with the stresses in the concrete located in zones between the cracks (Fig. 6)
- Numerical results show that the stresses in the reinforcement appear as a smooth parabolic variation without local extremes. In the real cases, when cracks appear, the stress in the reinforcement increases directly at the crack area and there exist points with local extremes (Fig. 6), so that the real variation of the stresses in the reinforcement is not smooth (Dahou *et al*., 2009)

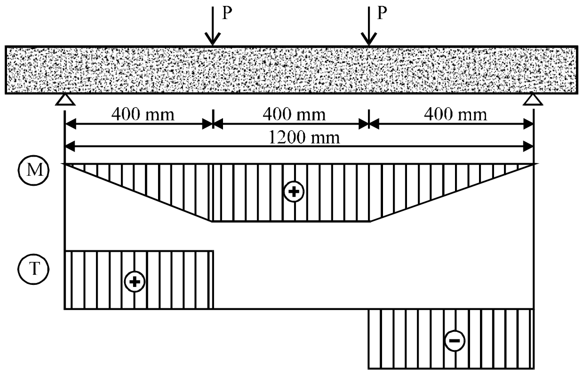

Fig. 2: Simply supported girder used in the study

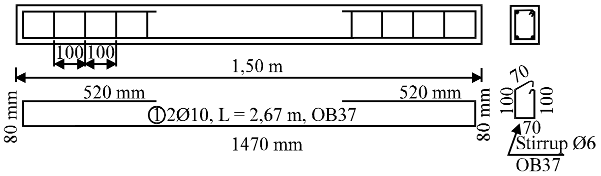

Fig. 3: Reinforcements of experimental girders

The FEM algorithm produces a new crack when the stresses on the bottom side exceed the concrete tensile strength. Because the connection between concrete and reinforcement is fixed, the bond is affected only at the node (Fig. 5a) and the tensile stress is transferred from the reinforcement to all nearby concrete finite elements. In this manner, the concrete tensile strength is exceeded and cracks are present in each concrete finite element located on the bottom side (Yankelevsky *et al*., 2008).

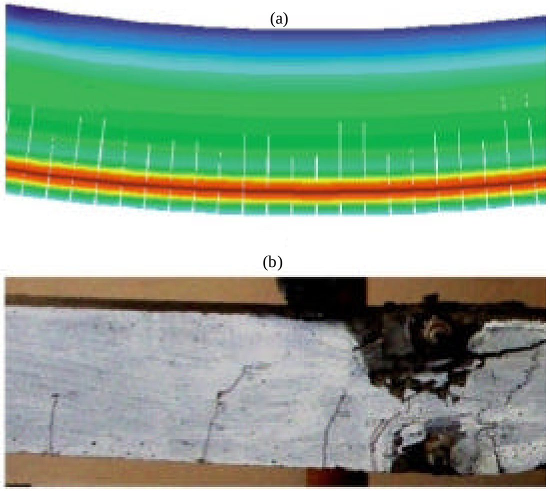

Fig. 4: Crack appearance in: (a) FEM analysis and (b) experiments

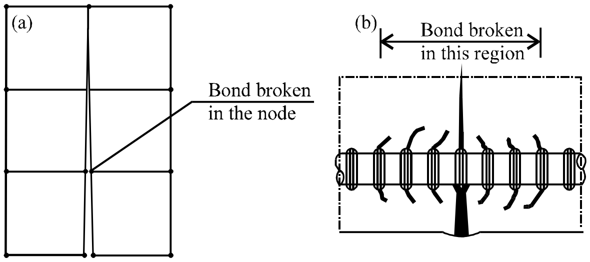

Fig. 5: Broken bond obtained with: (a) FEM method and (b) experimental results

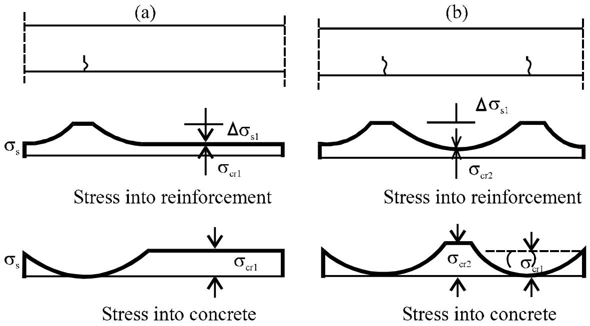

Fig. 6: Stresses on cracked areas: (a) one crack and (b) two cracks (σ_{cr1}: Tensile stress into concrete in non-cracked area; σ_{cr2}: Tensile stress into concrete between cracks; $\Delta\sigma_{s1}$: Supplementary stress into reinforcement on first crack; $\Delta\sigma_{s2}$: Supplementary stress into reinforcement on second crack)

In the real case, bonding behavior is affected over a larger region (Fig. 5b) and the tensile stress from reinforcement is not transferred entirely to the nearby concrete (Wang and Liu, 2003).

A complete transfer of load (Fig. 6a) from the tensioned concrete (tensile stress σ_{cr1}) to the reinforcement (supplementary stress $\Delta\sigma_{s1}$) accompanies the formation of the first crack, with a consequent loss of bond. There is a transitional region located on either side of the crack within which the original stress regime is gradually re-established by virtue of the bond. The bond characteristics of the materials determine the position of subsequent cracks relative to the first. The second crack is unlikely to form within the transitional region because of the lower concrete stresses applied there (Malecki *et al*., 2007). The new crack will form at a slightly increased load and will give rise to stress distributions of the type shown in Fig. 6b.

Because the finite element method does not offer accurate results that agree with experimental data, a new solution must be proposed. To avoid cracks in every concrete finite element, the firm bond between concrete and reinforcement was re-evaluated (Wang, 2009). The algorithm was changed to accept the two-bond hypothesis:

- In non-cracked areas, the bond connects concrete firmly with reinforcement
- In cracked areas, the bond is entirely eliminated (broken bond from Fig. 5b) and the entire tensile stress is transferred to the reinforcement

The new results partially solve the problem and the resulting distribution of cracks appears to be more rational (cracks appear at longer distances) but certain problems still remain (Fig. 7). Crack development was observed to stop very quickly and the length of the cracks was small.

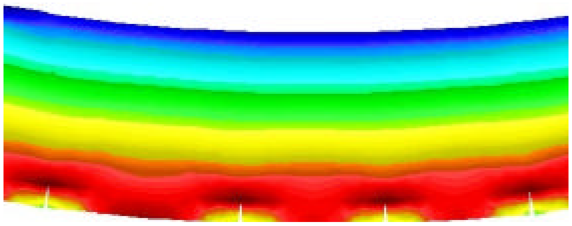

Fig. 7: Cracks and stresses in the two bond hypothesis in FEM

Because the reinforcement takes over the tensile stress in broken bond areas, the stresses in the concrete remain constant even as the external force increases. For this reason, the crack length will be the same and the development of cracks is stopped.

In conclusion, the two-bond hypothesis does not meet the requirements and a new approach is necessary.

CORRECTION OF THE FEM MODEL

To better calibrate the finite element method, experimental tests must be conducted to establish the size of the broken bond area around the crack and the parabolic functions from Fig. 6b.

A set of experimental cylinders was prepared to obtain the experimental results. Cylinders were made from the same class of concrete used in girders (C16/20) and a reinforcement bar was placed in the middle of each sample (Fig. 8).

The concrete cylinders are fixed and a pullout force is progressively applied to the reinforcement. To measure the stress in the reinforcement, a strain gauge was placed on the top side of the bar. Two displacement transducers were mounted to monitor the reinforcement slip, one on the top side and one on the bottom side (Fig. 8).

The correspondence between tensile stress and the reinforcement is presented in Fig. 9. The slip on the free side of the bar is very small initially (almost zero), but after a certain amount of tensile stress is exceeded, the development of the slip is accelerated (Oh and Kim, 2007).

Figure 10 shows the relation between tensile stress and shear stress. Three values of shear stress are important:

- Shear stress at the start, when the loaded top side of the bar starts to slip. This shear stress is measured for a displacement of 0.01 mm measured at Transducer 1

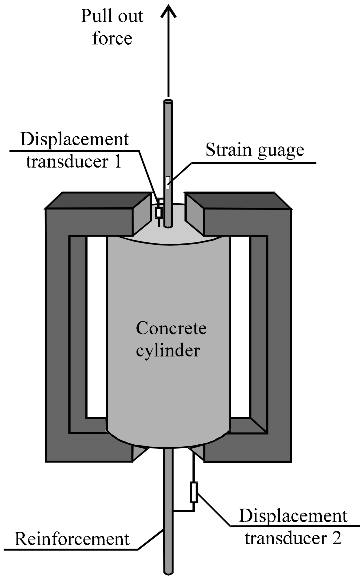

Fig. 8: Test bond in concrete cylinders

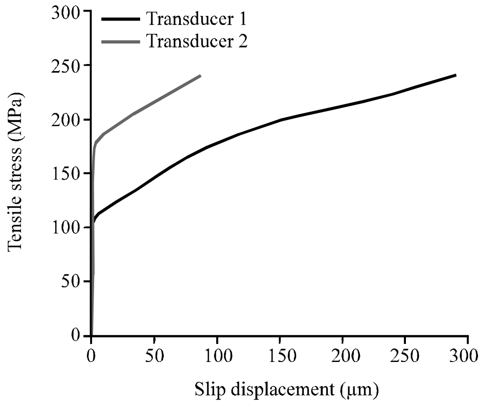

Fig. 9: Slip of the reinforcement according to the tensile stress

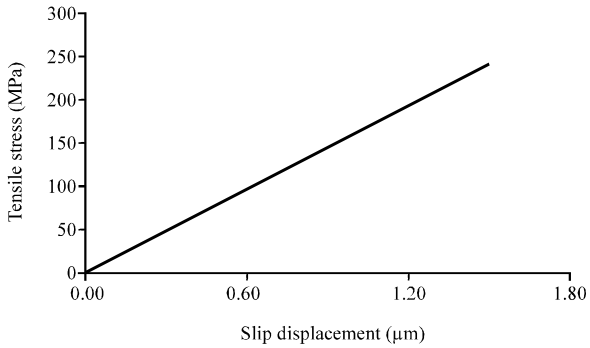

Fig. 10: Variation of slip stress according to the tensile stress in the reinforcement

- Shear stress when the free end of the bar starts to slip. In most cases, when the free end starts to slip and the loaded end has a slip around 0.1-0.15 mm
- Final shear stress when the reinforcement is pulled out from the concrete

The bonding mechanism may be described by the relation between shear stress τ and the relative displacement between the reinforcement bar and concrete. The maximum shear stress τ_{max} depends on the concrete tensile strength and this value is computed with the following relations:

$\tau_{max} = 1.5\cdot f_{ct}$ for round reinforcement bars (without ribs)
$\tau_{max} = 2.4\cdot f_{ct}$ for reinforcement bars with ribs

The maximum shear stress can increase if a supplementary pressure is present in the concrete, but this pressure must be located perpendicularly on the splitting plane. The increase of shear stress is according with Eq. 1:

$$\tau^f_{max} = \tau_{max}\frac{1}{1-0,04\cdot p_s} \le 1,4\cdot\tau_{max} \qquad (1)$$

where, τ^f_{max} is the final maximum shear stress and p_s is the supplementary pressure. If no supplementary pressure is present in the concrete, then $\tau^f_{max} = \tau_{max}$.

A very important factor is the length of the broken bond according to Fig. 5b. To establish this length, an equilibrium relation can be written as Eq. 2:

$$\frac{\pi\cdot\phi_s^2}{4}\sigma_s = \pi\cdot\phi_s\cdot l_b\cdot\tau^f_{max} \qquad (2)$$

Where:

ϕ_s = The diameter of the reinforcement
σ_s = The tensile stress in the reinforcement
l_b = The length of the broken bond area
τ^f_{max} = The maximum shear stress

The length of the broken bond area can be obtained with the relation Eq. 3:

$$l_b = \frac{\phi_s\cdot\sigma_s}{4\cdot\tau^f_{max}} \qquad (3)$$

In the finite element method, the bond between concrete and reinforcement must be affected along the l_b length. To do this, certain supplementary steps must be added in the finite element method.

Initially, a loading step will determine the stresses and displacement for elastic stage with the finite element (Eq. 4) (Danesh *et al*., 2008):

$$\{F(t)\} = [k]^e \cdot \{u(t)\} \qquad (4)$$

Where:

$\{F(t)\}$ = The vector of external forces from the finite element nodes

$[k]^e$ = The stiffness matrix for the elastic stage

$\{u(t)\}$ = The nodal displacement vector

Every finite element is checked for cracks with the stress values. If a crack appears, the bond between concrete and reinforcement must be re-evaluated around the crack area and the length of broken bond l_b must be established to delimit the crack area. After that, the stiffness matrix for all of the concrete elements near the crack will be modified with the relation Eq. 5:

$$[k] = [k]^e - [k]^d \qquad (5)$$

where, $[k]$ is the revised stiffness matrix and $[k]^d$ is a damage stiffness matrix. In the $[k]^d$ matrix, all of the concrete elements situated inside the broken bond area will have a reduced stiffness value. The reduction level is established according to the experimental results from Fig. 9 and 10.

All of the concrete finite elements unaffected by cracks have a zero value in the $[k]^d$ matrix.

Next, the new stresses and displacements are established with the relation Eq. 6:

$$\{F(t)\} = [k] \cdot \{u(t)\} \qquad (6)$$

If new cracks appear in this stage, the stiffness matrix will be revised again and the process will be repeated until no new cracks appear. Finally, if failure does not occur, then external loads can be increased with one step.

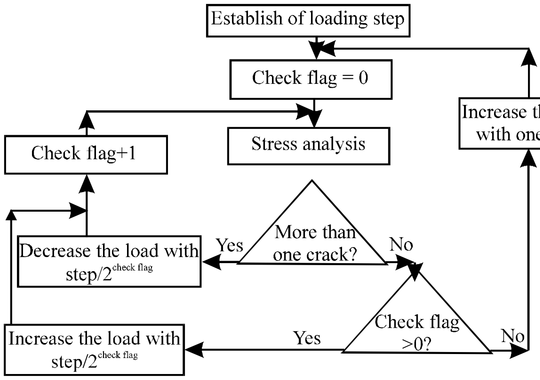

Fig. 11: New proposed algorithm to correct the loading step

The last problem of the proposed algorithm is that of the increase in the loading step. If the loading step is very large, too many cracks appear at the same time and the results will be adversely affected by errors.

To avoid this situation, a good solution is to diminish the loading step. In this case, the results will be satisfactory, but the computation time will increase substantially and many small useless steps will be processed.

The bisection algorithm can be used to avoid this situation, but the convergence of the solution is quite slow. A faster method that establishes the right loading step and obtains good results is proposed in Fig. 11.

The main advantage of the proposed algorithm is speed. The convergence of the solution is much faster than that of the bisection method because the changes in loading step are exponential.

RESULTS AND DISCUSSION

The modified FEM method was applied to the experimental girders and the results are shown in Fig. 12 and 13.

In the initial FEM study, the stresses in the concrete in the tensile area are the same in the cracks and between the cracks (Fig. 4a). In the proposed model, the results are correctly shown and the stresses in the tensioned concrete in the crack area are small compared with the stresses in the concrete between crack areas (Fig. 12).

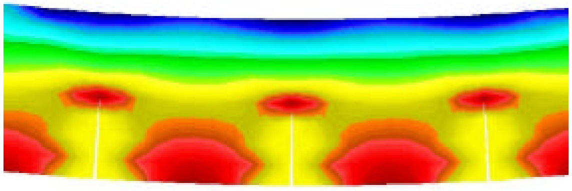

Fig. 12: Stress distribution in concrete for modified FEM

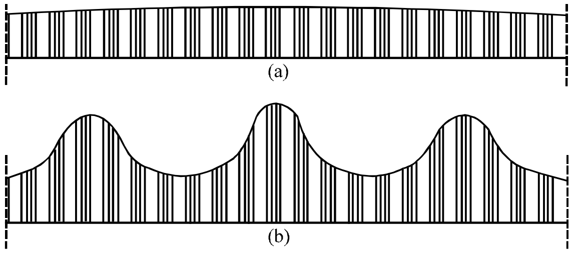

Fig. 13: Stresses in reinforcement: (a) with initial FEM and (b) with modified FEM

When a crack appears, the stress in the reinforcement is increased and a local maximum stress appears. In the initial finite element method, the stresses in the reinforcement have a smooth variation, as in Fig. 13a, but with the proposed modifications, the resulting stress diagram is in accord with stresses obtain in experiments (Fig. 13b).

CONCLUSIONS

Based on FE formulation a computer model was developed for the mechanical analysis of bonding between concrete and reinforcement.

The computer model includes routines that are capable of identifying the crack appearance and to keep track of changes into the pattern crack during the analysis, without user's intervention. Within this computer model the behavior in flexure for reinforced concrete member is achieved.

The final crack pattern obtained in the numerical analysis indicates a satisfactory agreement with the experimental cracks.

The stresses provided by computer model for concrete and steel reinforcing have been agreed with those developed in the experimental test. Particularly, the stress in concrete is very small around the crack and increases between two consecutive cracks. Also, the stress in reinforcement shifts in that section where the crack arises.

These advantages brought by this computer model come with some inherent shortcomings that need to be pointed out.

In order to model with accuracy the bond mechanism the computer model requires a fine mesh (Mihai *et al*., 2006). Time consuming computation is required even for a small member. A coarse mesh may be involved into computer model, but the accuracy of results decrease (Hamidi *et al*., 2009).

It was shown that the computer model is able to provide an important insight into bond mechanism between steel reinforcing and concrete. The reliability of the computer model is mainly based on the developed crack pattern. Therefore, further comparisons of results obtained in future applications will prove useful.

REFERENCES

Barnes, R.A. and G.C. Mays, 2001. The transfer of stress through a steel to concrete adhesive bond. Int. J. Adhesion Adhesives, 21: 495-502.

Cervenka, V., 2001. Computer simulation of failure of concrete structures for practice. Proceedings of the 4th International Conference on Analysis of Discontinuous Deformation in Glasgow, June 6-8, Scotland UK., pp: 1-8.

Chansawat, K., T. Potisuk, T.H. Miller, S.C. Yim and D.I. Kachlakev, 2009. FE models of GFRP and CFRP strengthening of reinforced concrete beams. Adv. Civil Eng., 2009: 13-13.

Dahou, Z., Z.M. Sbartaï, A. Castel and F. Ghomari, 2009. Artificial neural network model for steel-concrete bond prediction. Eng. Struct., 31: 1724-1733.

Danesh, F., E. Esmaeeli and M. Farid Alam, 2008. Shear strengthening of 3d rc beam-column connection using GFRP: FEM study. Asian J. Applied Sci., 1: 217-227.

Hamidi, H., A. Vafaei and A.H. Monadjemi, 2009. Algorithm based fault tolerant and check pointing for high performance computing systems. J. Applied Sci., 9: 3947-3956.

Kovacevic, D., 2006. Nonlinear model for reinforced concrete frames loaded by seismic forces. Proceedings of the 16th European Conference of Fracture, July 3-7, Alexandroupolis, Greece, pp: 779-780.

Malecki, T., I. Marzec, J. Bobiński and J. Tejchman, 2007. Effect of a characteristic length on crack spacing in a reinforced concrete bar under tension. Mech. Res, Commun., 34: 460-465.

Mihai, P., V. Corobceanu and R. Giuşcă, 2006. Study of residual mechanical characteristics to reinforced concrete. IABSE Reports, 92: 216-219.

Nawy, E.G., 2008. Reinforced Concrete: A Fundamental Approach. 6th Edn., Prentice Hall, New York, ISBN-13: 9780132417037.

Oh, H.B. and S.H. Kim, 2007. Realistic models for local bond stress-slip of reinforced concrete under repeated loading. J. Struct. Eng., 133: 216-224.

Santhakumar, R., E. Chandrasekaran and R. Dhanaraj, 2004. Analysis of retrofitted reinforced concrete shear beams using carbon fiber composites. Electr. J. Struct. Eng., 4: 66-74.

Vandewalle, L., 2004. Bond between a reinforcement bar and concrete at normal and cryogenic temperatures. J. Mater. Sci. Lett., 8: 147-149.

Wang, X. and X. Liu, 2003. A strain-softening model for steel-concrete bond. Cement Concrete Res., 33: 1669-1673.

Wang, H., 2009. An analytical study of bond strength associated with splitting of concrete cover. Eng. Struct., 31: 968-975.

Weibe, D. and K. Holschemacher, 2003. Some aspects about the bond of reinforcement in ultra high strength concrete. Leipzig Ann. Civil Eng. Report, 8: 251-263.

Yankelevsky, D.Z., M. Jabareen and A.D. Abutbul, 2008. One-dimensional analysis of tension stiffening in reinforced concrete with discrete cracks. Eng. Struct., 30: 206-217.