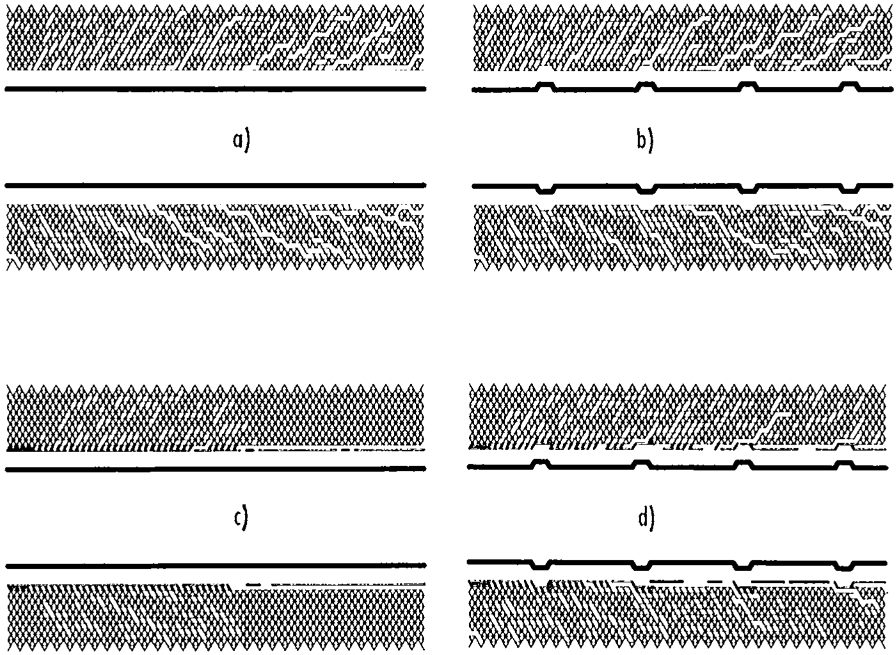

Fig. 13—a), b) Crack patterns for smooth and ribbed rebar where no interfacial strength is specified (i.e., it can vary between 1.25 and 10 MPa); and c), d) For an interfacial strength of 0.5 MPa

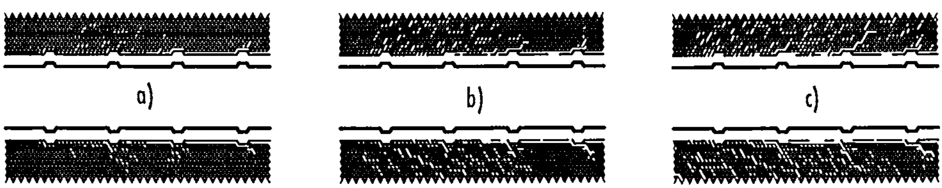

Fig. 14—Crack history for a ribbed rebar with an adhesive strength of 0.5 MPa for beam elements in the interfacial zone. The numbers between brackets indicate number of broken beams

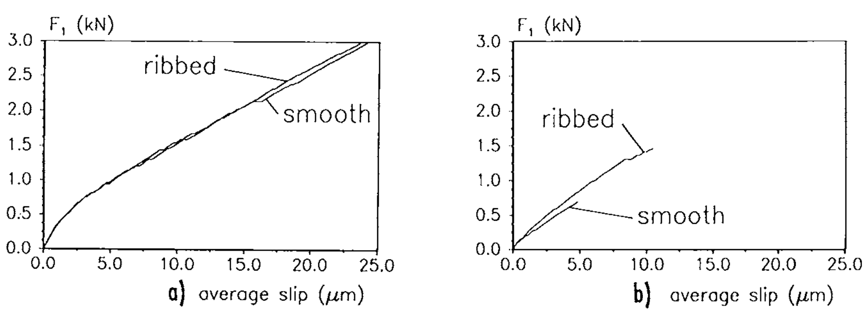

Fig. 15—Load-slip diagrams of local bond simulations. a) With interface strength equal to concrete strength ($1.25 \leq f_t \leq 10$ MPa); and b) Interface strength of 0.5 MPa

SP 156-7

Fracture Mechanics Analysis of Bond Behaviour under Dynamic Loading

by C. Yan and S. Mindess

Synopsis; The bond between reinforcing bars and concrete under impact loading was studied both experimentally and by the finite element method. The experiments consisted of pull-out tests and push-in tests, under three different types of loading: static, medium rate, and impact. Different concrete strengths (normal and high), types of fibres (polypropylene and steel), and fibre contents were considered. The study focused on the bond-slip relationships, and the fracture energy in bond failure. The experimental results were compared with those obtained by the finite element method, in which a special "bond-link element" that was able to transmit both shear and normal forces was adopted to model the connection between the rebar and concrete. It was found that higher loading rates, higher concrete compressive strengths, and the addition of steel fibres had significant effects on the bond resistance, the fracture energy and the bond stress-slip relationship, especially for the push-in case. Reasonably good correspondence in the results between the two methods was also found, and a bond-stress-slip relationship under high rate loading could be established analytically.

Keywords: Bond (concrete to reinforcement); fiber reinforced concretes; finite element method; fracture mechanics; fracture properties; impact; loads (forces)

Dr. Cheng Yan is a Research Associate in the Department of Civil Engineering, University of British Columbia, where he received his Ph.D. in 1993. His research has dealt primarily with the behaviour of concrete under impact loading.

ACI Fellow Sidney Mindess is a Professor of Civil Engineering at the University of British Columbia, where he has taught since 1969. He is a member of the ACI Committees 370 and 446. He is also a member of the Co-ordinating Committee of RILEM.

INTRODUCTION

The behaviour of a reinforced concrete structure is strongly dependent upon the bond between the concrete and the reinforcing bars. The prediction of the linear or nonlinear response of reinforced concrete structures subjected to static or dynamic loads, regardless of the method of analysis, is based upon our knowledge about the local bond stress vs. slip relationship governing the behaviour at the steel-concrete interface.

While there is extensive literature on static bond tests, there is little experimental work on the bond between concrete and steel reinforcement under dynamic loading (Isenberg et al. [1]). The bond behaviour under dynamic loading is quite different from that under static loading, and involves more complex mechanisms. Most of the reported experimental results for impact loading [2-6] show that the shearing mechanism (rib bearing against the concrete) is the main mechanism for the bond between deformed bars and concrete, and that the concrete strength, the loading rate, and the presence of reinforcement (either in the form of fibres or of continuous bars) have a great effect on the bond behaviour. These effects may result from the strengthening of the material surrounding the rebar, the increasing crack resistance, the strain rate sensitivity of the materials, the non-uniform strain distribution along the reinforcing bar, or other energy absorbing mechanisms.

Previous studies regarding the application of the finite element method to the bond problem simply introduced the load bond stress-slip relationships which were obtained from tests. Theoretically, there is a unique relationship between bond stress and slip at the interface between a steel bar and concrete for which the geometric and mechanical properties are known. The problem can be solved by reasonably modelling the mechanical properties at the interface between the rebar and the concrete, as well as the constitutive laws for both materials and appropriate cracking and crushing criteria.

The present paper describes the results of both an experimental study and a finite element technique in which the bond behaviour between rebars and concrete under impact loading was studied.

EXPERIMENTAL PROCEDURES

Specimens

The test specimens were concrete prisms 152.4×152.4×63.5 mm, containing a centrally loaded 11.3 mm diameter (No. 10) deformed reinforcing bar. Two concentric 6.35 mm steel spirals, 63.5 mm and 127.0 mm in diameter, were also cast in the prisms (Fig. 1). Their purpose was to prevent splitting of the concrete, and thus a pure pull-out or push-in bond failure could be achieved. Three types of concrete were tested: plain concrete, polypropylene fibre reinforced concrete (with fibre contents of 0.1% and 0.5% by volume) and steel fibre reinforced concrete (with fibre contents of 0.5% and 1.0% by volume). The polypropylene fibres were fibrillated fibres (40.0 mm long, 0.05 mm diameter)[1]. The steel fibres had hooked ends (30.0 mm long, 0.5 mm diameter)[2]. The basic mix designs are given in Table 1 for low compressive strength concrete (about 40 MPa) and high compressive strength concrete (about 75 MPa). The maximum aggregate size was 10 mm.

About one-quarter of the reinforcing bars were instrumented with five pairs of electric resistance strain gauges to measure the strain distribution along the rebar. These pairs of strain gauges were mounted on diametrically opposite sides of each test bar at a spacing of 15.9 mm (centre to centre) to take care of the bending effect, if any, in the test bar during loading.

Impact Tests

The impact tests were carried out using a large, instrumented drop weight impact machine, which was designed and constructed at the University of British Columbia. The details of this machine have been presented elsewhere [7,8]. Briefly, it is capable of dropping a mass of 345 kg[3] from

[1] Produced by Fibermesh Corporation, Chattanooga, Tennessee, U.S.A.
[2] Produced by Bekaert Corporation.
[3] It has since been modified to provide a capacity of 505.0 kg.

heights of up to 2.5 m on the target specimen, giving a kinetic energy of up to 8450 Nm. Two accelerometers mounted on the falling mass and the rebar, respectively, monitored their accelerations; a strain-gauged bolt load cell monitored the load on the specimen. The static and medium rate tests were carried out in an Instron universal testing machine. By appropriately setting the crosshead speed of the universal testing machine, or altering the drop height of the hammer of the impact machine, three different ranges of loading rates could be achieved to induce a wide range of bond stress rates. They were: static, medium, and impact rates. The equivalent ranges of the bond stress rates are listed in Table 2.

The specimens were supported by a steel base (200 mm in diameter and 100 mm in height) with a 35 mm diameter hole in its centre. They were pushed (for static and medium rate loading) or struck (for impact loading) at the top of the rebar. In the case of pull-out tests a solid steel frame with a stiffness of 15 times that of the reinforcing bar was used to apply a pull-out force.

The load, acceleration and strain data were recorded at 200 μs intervals by a PC-based, 16-channel high speed data acquisition system. A high speed video camera (EKTAPRO 1000 Motion Analyzer)[4], which can take 1000 to 6000 frames per second, was also used to take a video of the specimen during the impact event. By analyzing the videos frame by frame, the calculated displacements could be verified. Figure 2 shows a schematic of the set-up for the experiments. The details can be found in reference [9].

REDUCTION OF TEST DATA

After signal processing, the applied load, the accelerations of both the hammer and the reinforcing bar, and the strains along the rebar could be calculated from the data acquired, using linear calibration curves. These data were all obtained as a function of time.

The displacements of the hammer and the rebar were found by integrating the recorded accelerations over time. The axial stresses in the rebar and in the concrete were calculated from the recorded strain data. Using the dynamic equilibrium condition, the local average bond stresses and slips along the rebar were calculated; the fracture energy in the entire bond-slip

[4] Manufactured by Eastman Kodak Company, U.S.A.

process was calculated as the work done by the bond stress during slip. Detailed equations for the above calculations can be found in reference [9].

RESULTS AND DISCUSSIONS

Bond Stress-Slip Relationship by Experiments

It is clear that for all of the bond tests, the bond stress-slip relationships kept changing with time under dynamic loading; in other words, there were different relationships between the bond stress and the slip at different stages of loading. For simplicity, all of the bond stress-slip relationships were referred to the moment at which the bond stress reached the peak value, and these relationships were then averaged over the embedment length, unless otherwise specified.

Figures 3 to 5 show several bond stress-slip relationships obtained by experiments. It can be seen from these figures that there were always a greater bond stress for the high strength concrete, especially under higher rate or push-in loading (impact), or for specimens with steel fibres). The polypropylene fibres seemed to have much less effect in this regard than the steel fibres.

The shear mechanism is the main mechanism for the bond resistance of deformed bars, under either static or dynamic loading [9,10]. The force transferred by the concrete surrounding the rebar increased with an increase in the shear strength of the concrete, which is, to some extent, proportional to the compressive strength. The stress rate sensitivity of concrete has been reported by numerous investigators (e.g. [11, 12, 13]), and explained on the basis of fracture mechanics [14]. Steel fibres increased the load carrying capacity in the area surrounding the rebar, especially in the post-cracking region [15,16].

In the case of pull-out tests, when the bond stress reached the critical value, a longitudinal tensile stress and a radial tensile stress (tending to cause separation), combined to produce the first internal cracks from the tops of the ribs, because of the stress concentrations at these locations. With a further increase in external loading, the Poisson effect in the steel resulted in a decrease in the bar diameter, and the contact area between the concrete and the ribs of the deformed bar was reduced. This would increase the bearing stress between the concrete and the ribs, and enhance crack development around the tip of each rib. Generally speaking, the combination of the above-mentioned longitudinal and radial tensile stresses was quite large so that the high strength concrete was not much better than the normal strength concrete in inhibiting first cracking.

For the push-in tests, the stress transfer mechanism involved was quite different from that in the pull-out tests. The force in the rebar deformed the concrete inwards (in the direction of the force). This served to tighten the concrete around the bar and increased the frictional resistance between the concrete and the rebar. The slight increase in the diameter of the rebar due to the Poisson effect also improved the frictional resistance [17]. The stresses in the concrete, thus, were generally less for pull-out tests than for push-in tests. A small zone of concrete was subjected to compression-tension-tension in the radial, longitudinal and circumferential directions, respectively. However, few cracks were found after slicing the specimens. The inward deformation of the concrete provided some lateral compression in the concrete surrounding the bar, and thus reduced the radial component of the wedging force. All of this contributed to the great influence of concrete strengths, high loading rates, push-in loading, and steel fibre additions on the bond strength.

Fracture Energy

The fracture energy results for different types of specimens are presented in Table 3. It can be seen that specimens made of high strength concrete, or steel fibre reinforced concrete and specimens under high rate loadings, or push-in loading always absorbed more fracture energy (about 2.5% to 6.7%). For reinforced concrete structures it is essential that the bond between the reinforcing bar an the concrete exhibit a certain "ductility" during dynamic loading. That is, the bond resistance in the member should decrease gradually instead of suddenly failing, so that the dynamic energy can largely be transferred, absorbed and dissipated to the entire structural member over a relatively long time period. This bond ductility may be represented by the fracture energy, which is calculated as the work done by the bond stress. A larger value of fracture energy means a more "ductile" bond.

Comparison with Dynamic Finite Element Method

In the finite element analysis, using fracture mechanics concepts, the chemical adhesion, frictional resistance and the shear mechanism were all taken into account. Twenty node quadratic solid isoparametric elements were employed for both steel and concrete before cracking. After cracking the concrete elements were replaced by quadratic singularity elements capable of modelling curved crack fronts. A special "bond-link element", which was able to transmit both shear and normal forces, was adopted to model the connection between the rebar and concrete. A new approach was proposed for the establishment of the stiffness matrix of the "bond-link element". The dynamic constitutive laws of both steel and concrete, the criteria for crack formation and propagation in concrete, based on the energy release rate theorem, and the criterion for concrete crushing were used in the finite element process. Details can be found in reference [9].

The calculated results showed that at very low levels of the steel stress (about 30-40 MPa) the chemical adhesion between the rebar and the concrete was destroyed, and for the case of pull-out loading the frictional resistance reduced rapidly with the separation between the rebar and the concrete when the steel stress increased. At that point, the rib bearing became the main factor providing resistance in the bond process. These calculations seem to agree well with the experimental results.

It was found from the finite element analysis that at a relatively low level of applied load, the distribution of the stress in the rebar was not much different from that obtained by the experimental method. With further increases in the applied load, however, the differences in the distributions between the two methods increased. That is, the finite element analysis became increasingly sensitive to the various parameters adopted in the analysis, mainly the nonlinear dynamic constitutive relation of the concrete and the damage mechanism. The results of the experimental method were obtained directly from the strain gauge measurements and are considered to be more reliable. Using more accurate parameters in the finite element analysis would result in very good prediction for the bond behaviour at the interface between rebar and concrete.

It was also found that relatively high values of principal tensile stresses developed in the concrete in the vicinity of the tips of the ribs, especially for the pull-out case, which indicated that the secondary cracks would form first. For the plain concrete and the polypropylene fibre concrete, some crushing of the concrete also took placed at the tips of the ribs. This resulted in a great decrease in the bond strength, or, from the viewpoint of energy, in the capacity of energy transfer. On the other hand, there was seldom crushing in the concrete for the steel fibre concrete. This may help to explain why the specimens made of plain concrete and polypropylene fibre concrete consumed much less fracture energy during the entire bond-slip process.

The calculated results also indicated that there were more cracking elements for the steel fibre concrete than for the plain and polypropylene fibre concrete. Because of this, the bond slips in the former case were always found to be larger than in the latter cases in the calculations, which, in turn, made the fracture energy for the steel fibre concrete much larger than for the other types of concrete. This is also in agreement with the experimental results.

As expected, the bond strength and the fracture energy for push-in loading were found to be greater than for pull-out loading. This indicates that by adopting the 3-dimensional elastic matrix in the constitutional law, the Poisson effect was properly considered, and that the modelling of the frictional resistance at the contact surface between the rebar and the concrete by the "bond-link element" was reasonable.

Two examples of the bond stress-slip relationships determined by the finite element method are given in Figures 6 and 7, which represent the cases of polypropylene fibre reinforced concrete under medium rate loading (bond stress rate = $0.5\times10^{-5} \sim 0.5\times10^{-4}$ MPa/s) and steel fibre reinforced concrete under impact loading (bond stress rate = 0.5×10^{-2} MPa/s), respectively. In these figures the curves from experiments are also given for comparison.

The shapes of the curves obtained by the finite element method are different from those from the experimental measurements. There is only a very small linear portion from the beginning of the loading in those curves obtained by the finite element method. This may be because for the finite element models the chemical adhesion is destroyed at a very low level of loading, and the contribution of the frictional resistance to the bond strength depends on the calculated stress state at the interface to a great extent. Both the peak and average bond stress are larger for the analytical than for the experimental results. From the viewpoint of mechanics, the models of the finite elements make the specimen more "rigid", i.e. its stiffness becomes larger even though the modelling of the chemical adhesion and the frictional force may lessen the stiffness of the interface between the rebar and the concrete to some extent. The increase in the bond resistance and the relatively smaller local slip corresponding to the same bond stress may also attribute to this.

CONCLUSIONS

1. High loading rates increase the bond strength and fracture energy during bond failure, especially for the push-in loading case. The bond stress-slip relationships under impact loading is quite different from that under static loading.

2. The high strength concrete, or steel fibre reinforced concrete exhibit higher bond strength and absorbs more fracture energy in the bond

process under impact loading. Their bond stress-slip relationships are also quite different from those for normal strength concrete, or plain concrete.

3. A finite element method based on fracture mechanics with appropriate interface modelling can be used to solve the bond problem. The bond stress slip relationship can be established analytically.

ACKNOWLEDGEMENTS

This work was funded by the Natural Sciences and Engineering Research Council of Canada, through the Network of Centres of Excellence on High Performance Concrete.

REFERENCES

1. Isenberg, J., Bazant, Z.P., Mindess, S., Suaris, W., and Reinhardt, H.W., "Dynamic Fracture," in Bazant, Z.P. (ed.) "Fracture Mechanics of Concrete Structures," Elsevier Applied Science, 1992, pp. 601-609.

2. Hansen, R.J. and Liepins, A.A., "Behaviour of Bond Under Dynamic Loading," ACI Journal, Proceedings, V. 59, No. 4, April 1962, pp. 563-582.

3. Hjorth, O., "Ein Beitrag zue Frage der Festigkeiten und des Verbundverhaltens von Stahl und Beton bei Hohen Beanspruchungsgeschwindigkeiten," Dissertation, Tehcnische Universitat Braunschweig, 1976.

4. Vos, I.E. and Reinhardt, H.W., "Influence of Loading Rate on Bond Behaviour of Reinforcing Steel and Prestressing Strands," Materiaux et Constructions, V. 15, No. 85, 1982, pp. 3-10.

5. Takeda, J.-I., "Strain Rate Effects on Concrete and Reinforcements and Their Contributions to Structures," in Mindess, S. and Shah, S.P. (eds.), Cement- Based Composites: Strain-Rate Effects on Fracture, V. 64, 1986, pp. 15-20.