

Reinforcement bond is an extremely important factor in the performance of reinforced concrete. Knowledge of the bond strength of reinforcement is therefore essential in both the design and assessment of reinforced structures. Design codes, such as BS 8110<sup>1</sup>, and current assessment codes<sup>2</sup> treat bond in a very simple manner, which is solely in terms of average bond stress. When assessing structures with inadequately anchored reinforcement, such a simplification is inappropriate and an understanding of the bond slip behaviour, including residual bond strength, is necessary. It has been reported that for both types of plain and deformed bars, residual bond strength is 15-27% of the ultimate strength<sup>3</sup>.

Over the past several years an extensive program of research investigating bond has been carried out at the University of Birmingham with a view to improving assessment criteria for concrete structures. The aim of this work is to understand the bond behaviour of groups of reinforcing bars with a mix of fully and inadequately anchored reinforcement as the first step towards understanding the flexural strength and ductility of reinforced concrete sections with similar reinforcement.

The motivation<sup>4</sup> for the research arose as a result of the assessment of a number of three-span continuous beams acting as primary load carrying members of a reinforced concrete frame. At internal supports, the reinforcement bars in the tension zone were found to be inadequately anchored according to current standards. Consequently, the beams were assessed as having inadequate hogging bending resistance at the supports. The moment-rotation response of a beam with inadequately anchored reinforcement at ultimate limit state is highly non-linear because a combination of slip and yield can occur and is therefore difficult to model. It is not covered by the codes and there exists no established method to calculate either the flexural capacity of such a hinge or its rotation capacity. Hence, when faced

## Flexural strength and ductility of concrete sections with inadequately anchored reinforcement

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with this type of assessment, a structural engineer would perform a non-code assessment using engineering judgment, based upon knowledge of materials properties, reinforcement properties at the time of construction, yield strength, ductility and bond strength.

The major output of the work will be a model for the prediction of bond behaviour of groups of bars with mixed anchorages. This model is now in the final stage of development and has been developed as follows.

Initially experimental data relating to single bar pull-out tests were analysed using multiple linear regression to produce equations relating each peak and residual bond stress and slip

to bar properties.

Then the equations were used to predict the force-slip response of each individual bar in a group, taking account of the bar characteristics, including bar type, diameter, cover and embedment length. Residual reinforcement forces after slip of the reinforcement were estimated using a simplified bond-slip model<sup>5</sup> on the basis of published test data<sup>3</sup>, which are currently available only for pull-out tests of single bars.

Due to a lack of available test data for pull-out tests performed on groups of bars, the forces were estimated based on the assumption that the residual strength of each bar in a group of bars is identical to that of a single bar.

Finally the individual force-slip curves were combined, taking into account the elasto-plastic behaviour of any fully anchored reinforcement in the group to produce a force-slip curve for the bar group (see Fig 1).

A programme of multiple bar bond tests is under way, the results of which will be used to verify and adapt the prediction model. The experimental work consists of a series of multi-bar semi-beam pull-out tests and beam tests. A test rig has been developed to allow three bars to be pulled simultaneously from a concrete block, which is arranged to replicate the forces at a section of a beam subject to bending (see Fig 2).

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The experimental programme enables realistic modelling of bond behaviour of different arrangements of reinforcing bars with a mix of full and inadequate anchorages. The rig is being used to test groups of bars with a number of arrangements of full and inadequately anchored bars.

To date, the first series of pull-out tests on plain and deformed bar specimens with various bar arrangements, combining fully anchored and inadequately anchored bars with fixed bond length at constant concrete cover and strength, have been completed.

Results obtained so far indicate that the prediction model works well with all cases of plain bars and deformed bars with not more than one inadequately anchored bar. However, in cases of two or more inadequately anchored deformed bars, concrete

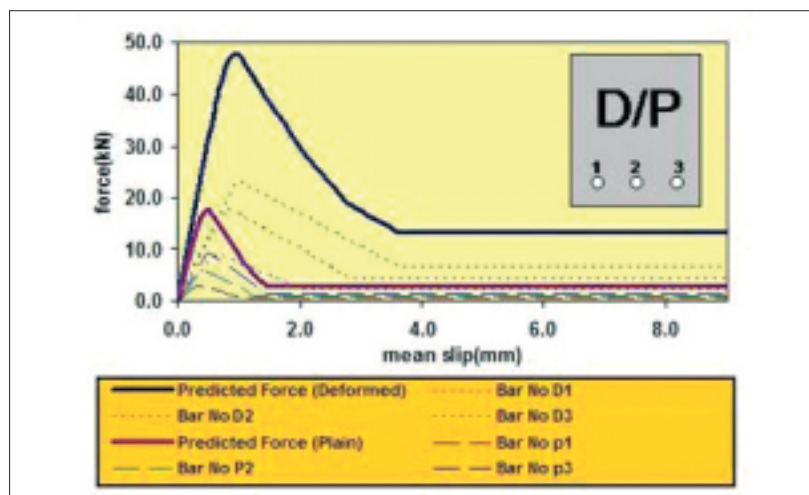


Fig 1. Predicted force-slip relationship of three 8mm deformed (D) and plain bars (P) with bond length of 10d, 20d, 30d, with concrete cover,  $c/d=2$

tensile strength governs.

In specimens with two inadequately anchored bars and one fully anchored bar, it was observed that when the tensile stress exceeded concrete tensile strength, a horizontal crack formed perpendicular to the bar at the end of each inadequately anchored bar. If a bar has slipped significantly, a longitudinal surface crack along the bond length should be present. This crack is due to the failure of concrete in tension as the wedging action of the ribs creates a circumferential tension.

As no such longitudinal surface crack was observed in these specimens, it is assumed that no significant slip occurred. Once the horizontal crack formed and widened, force carried by

the inadequately anchored bars was transferred to the remaining bar with a reduced bond length as a result of the crack. The reduced bond length was found to be less than that required to yield the bar hence slip of the remaining bar occurred.

In addition to the main programme of pull-out bond tests, a small series of beam tests is being carried out to investigate the flexural and ductile behaviour of a concrete section with a mix of fully and inadequately anchored reinforcement.

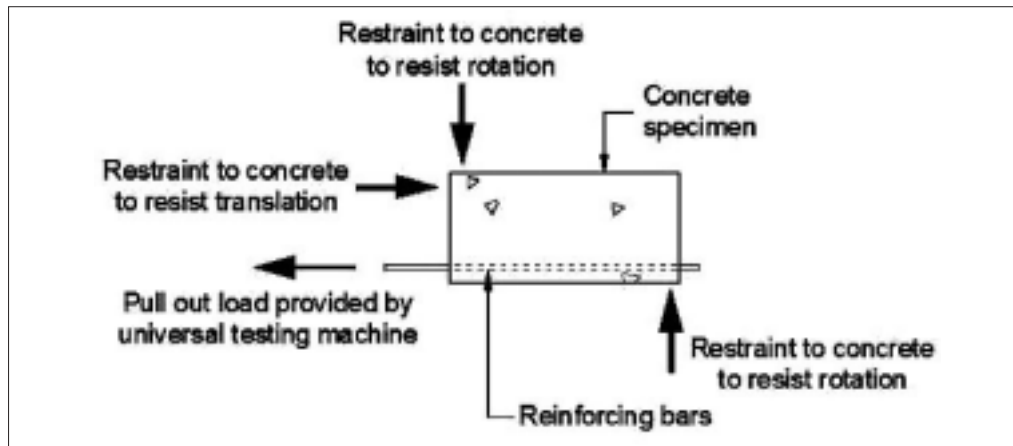
In conclusion, preliminary experimental results confirm the limitation of the initial assumption that residual strength of a group of bars is identical to the sum of that of the individual

bars. This effect is currently being incorporated into the prediction model.

#### Acknowledgment

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Fig 2. Schematic of pull-out test



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