PULL-OUT FAILURE MECHANISMS IN CONCRETE

D.V. Phillips, D.R. Green, B.S. Zhang, C.J. Pearce, and N. Bicanic

Department of Civil Engineering, University of Glasgow, Scotland, UK

Summary

Complex stress states exist in regions adjacent to reinforcing bars in concrete subject to pullout forces. This has been the subject of considerable experimental and numerical research. Design recommendations are normally based on empirical equations or on upper bound plasticity solutions, which usually overestimate pullout forces, leading to conservative design.

Experiments on Bond Behavior in Curved Bars

Bars are often bent through angles of up to 90° to meet geometrical constrains imposed by section depths. In such situations the transverse stress on the concrete, and in the stress concentrations, secondary cracking and concrete damage in the region of the bend, are more complex than that experienced in straight bars. If bent bars are to be properly designed, suitable criteria have to be developed and degradation of ultimate strength and stiffness under cyclic loading should be predictable.

Fundamental experimental data on the pull-out behaviour of curved reinforcing bars subjected to monotonic and cyclic loading regimes, designed to follow a typical earthquake loading history, have been obtained at Glasgow University [1, 2]. These include strain and stress distributions within the reinforcement, and bond stress distributions along the bar/concrete interface. Factors such as the influence of embedded length degree of curvature, bar diameter and bar type have been investigated.

Specimens, illustrated in Fig 1, were tested in a 2000 kN uniaxial servo-controlled loading machine using a ramp generator manually. The blocks were held down onto the base of the machine by using two steel bars of 60 mm connected to a cross frame. Two LVDTs were glued on the top edges of the block and touched a steel arm which was welded on the main bar 100 mm from the top surface of the block (350 mm from the active end) to monitor the total relative movement Δ_T of the bar against the concrete block during testing. The bond slip at the active end, Δ_a, can then be obtained by subtracting the bar elongation, Δ_S, from Δ_T, Δ_S is calculated by multiplying the reinforcement strain outside the bonded length by the non-bonded length of 250 mm. In addition, the load and the displacement of the cross-head were measured. A third LVDT was fixed to the bottom of the block to measure the bond slip, Δ_p at the passive end (the movement of the free end of the bar).

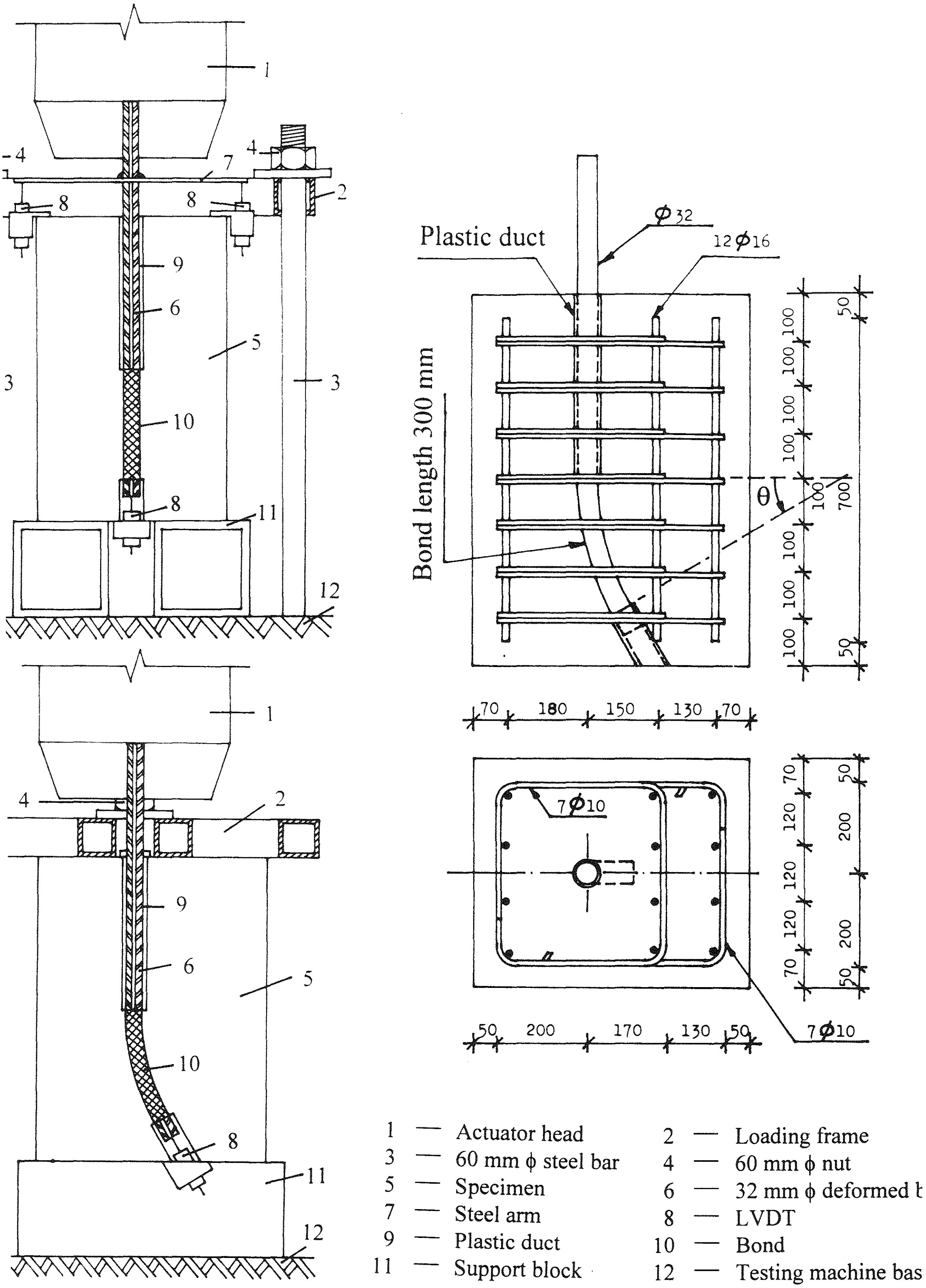


Fig 1 - Test Layout for Glasgow University Experiments of Bond Behaviour in Curved Bars

Preliminary analysis of experimental results for both monotonic and cyclic tests indicate th existense of an envelope of the softening bond-slip curve. An increase of the bond strength i indicated for curved bars, however for bending angles greater than 45 degrees, no signifaca increase is noted, Fig 2.

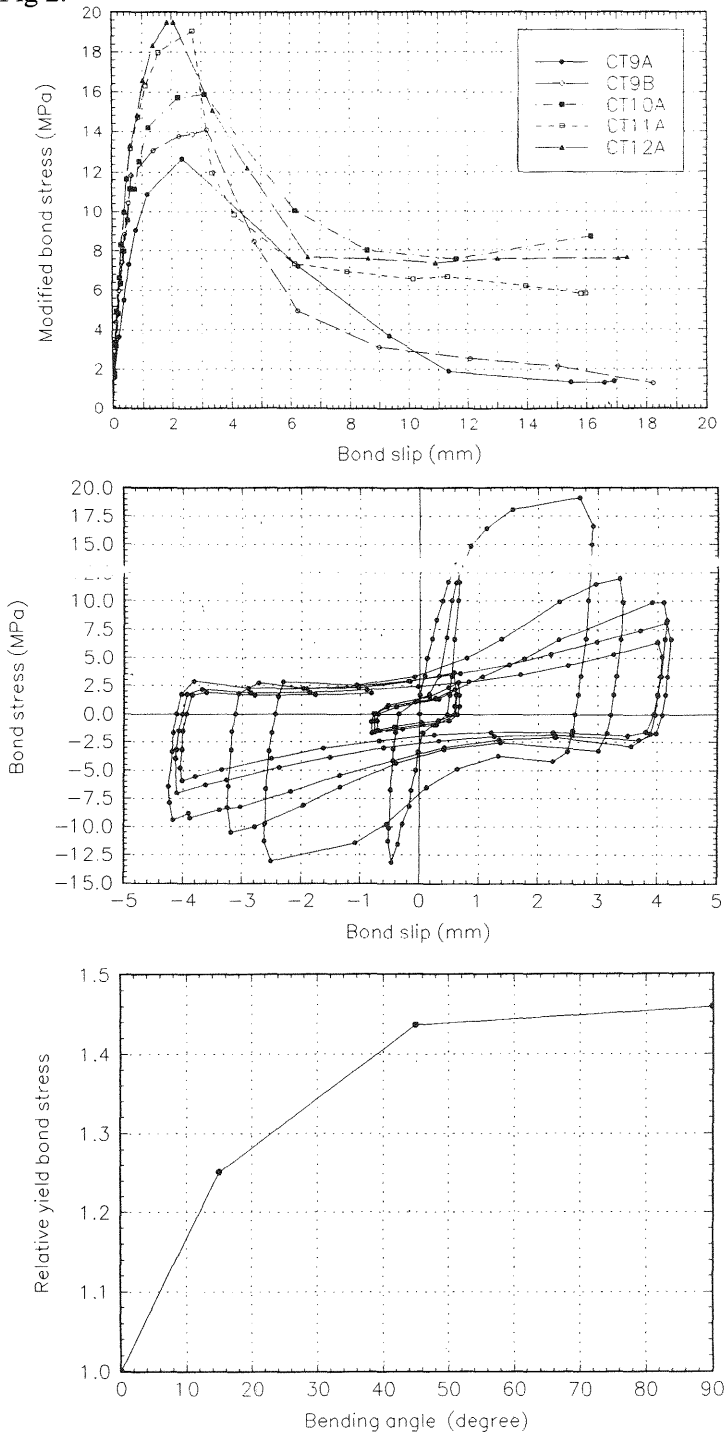


Figure 2 - Bond Slip Envelope for Monotonic and Cyclic Pullout Tests (45 degrees bend) and the Relative Bond Strength Increase as a Function of Bending Angle

Computational Modelling

Numerical predictions were conducted using a smeared failure analysis employing a fracture energy based tensile softening five parameter model, Fig 3. The five parameter model, originally proposed by Willam and Warnke, has been implemented with modified meridians and the failure surface evolution during softening is controlled by the fracture energy, which affects the reduction of tensile strength only. Such softening format implies failure surface softening in tensile regime with slight hardening for the high confinement regime. Consistent tangent formulation and the use of improved predictors [3] within the stress return algorithm have ensured an efficient and robust algorithm. The characteristic length is assumed to be equal to the diameter of a circle with an area equal to the tributory volume corresponding to a particular integration point.

The results of simulation analyses for the model pullout problem of anchor bolts, formulated by RILEM TC90-FMA [4] , have indicated reasonable mesh insensitivity the for two very different finite element meshes, with no mesh bias - one with an unstructured mesh of triangles and the other with a regular mesh of four noded elements. The orientation of discontinuity surfaces is determined on the basis of acoustic tensor analyses at element integration points. The failure mechanism near the anchor bolt appears to be of a mixed mode type, as the eigenvectors **m** of the acoustic tensor form an acute angle with the normals **n** to the discontinuity surface, Fig 4.

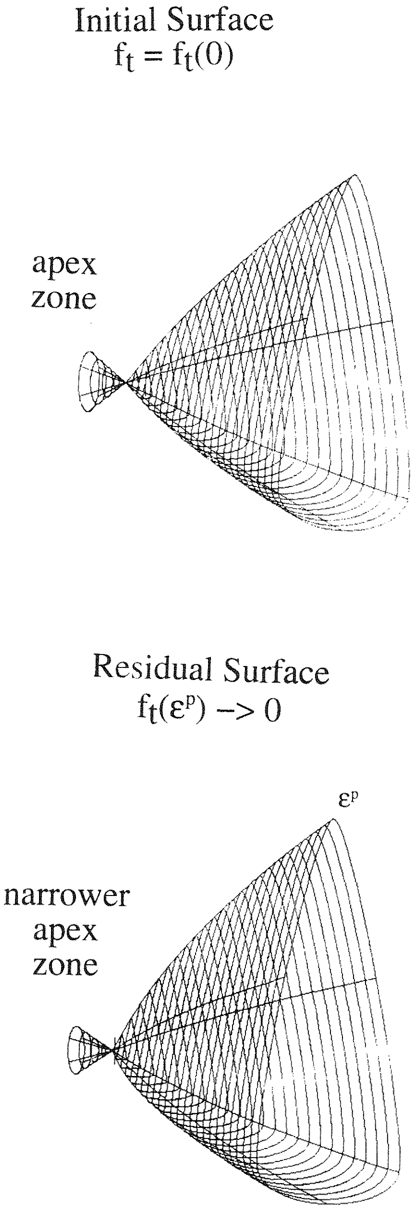


Fig 3 - Tension Softening Five Parameter Model

The level of the reduced tensile strength ft(εp) illustrates the appearence of damage zones and bondslip in the preliminary numerical analyses of bond slip in curved bars, Fig 5.

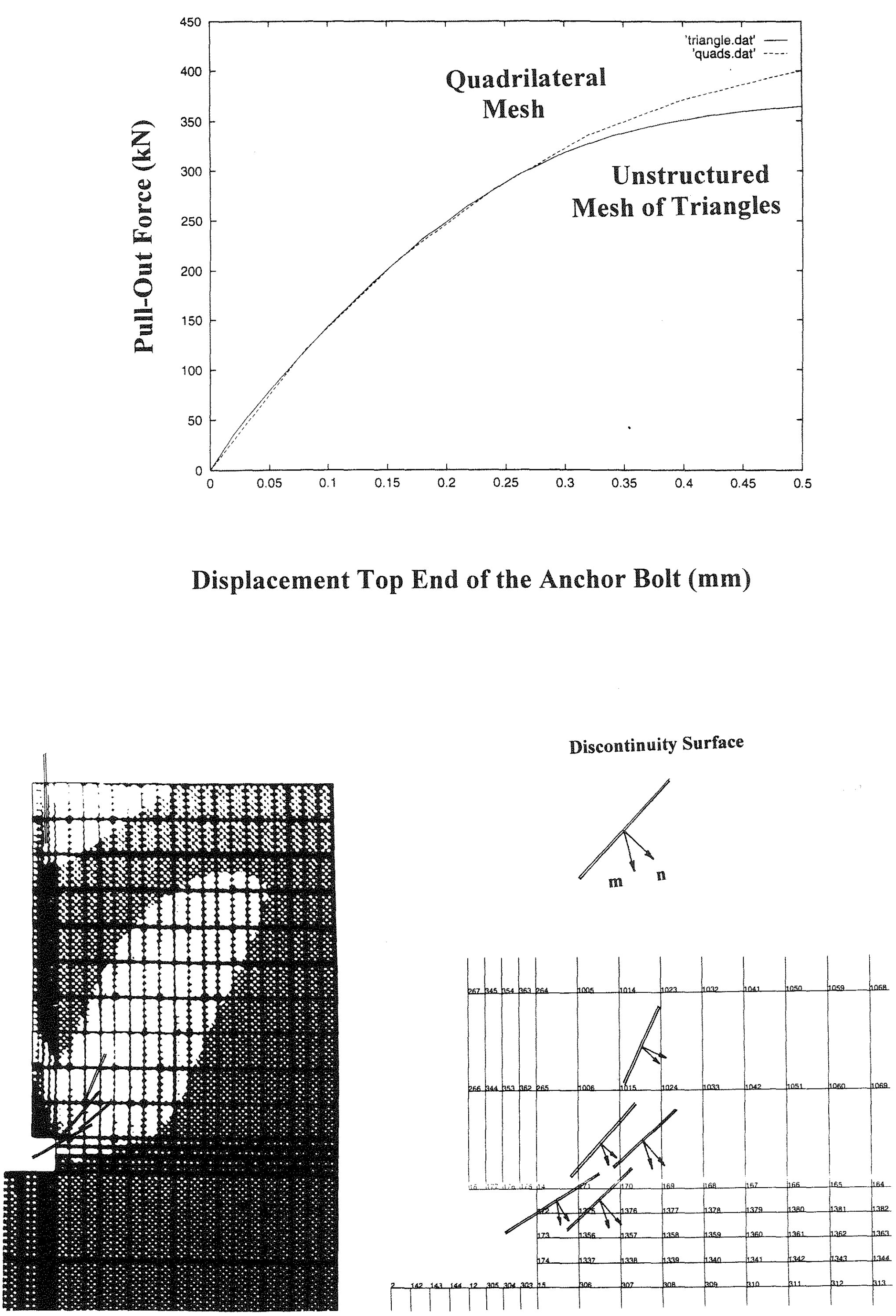
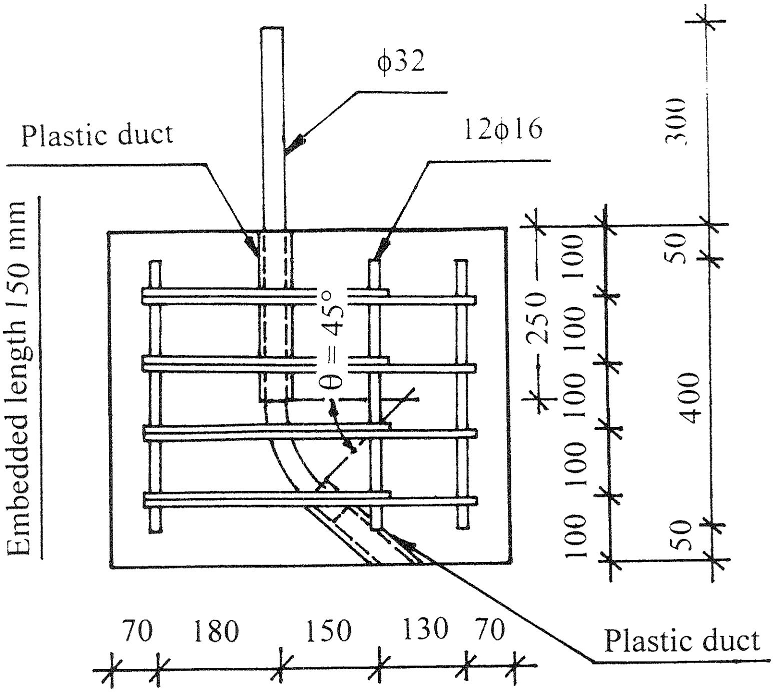


Fig 4 - P-δ response for the Axisymmetric Model and the Orientation of Discontinuty Surfaces based on Acoustic Tensor Analysis for the Anchor Bolt Problem for to Finite Element Meshes

Glasgow University45 Degrees Curved Bar
Pull-Out Specimen CT11



Tensile Softening Five Parameter Model
Reduction of Tensile Strength as Damage Indicator

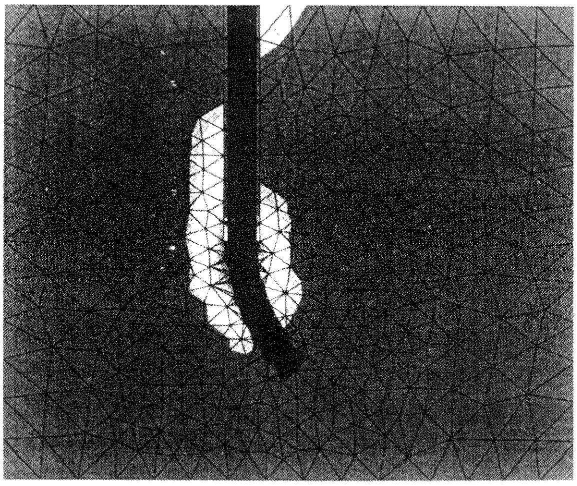


Fig 5 - Reduction of Tensile Strength as Damage Indicator
for the Pullout Test of the 45 Degrees Curved Bar

Research into Anchorage Zones

A similar theme followed at Glasgow University has been the study of anchorage zones for post-tensioned concrete. Extensive experimental tests have monitored the load transfer behaviour in such zones, including reinforcement and concrete strains, redistribution of reinforcement stress, cracking patterns in the surrounding concrete, and anchor strains. The influence of surface and embedded flanges, inclines barrel geometries, single step and multiple step embedded anchors of varying step size and axial spacing and different reinforcement profiles have been studied. Failure mechanisms and load transfer mechanisms have been idealised and isolated. Numerical predictions of this problem is also being undertaken using similar procedures to that the pull-out problem. This work is leading to a logical process of design of post tensioned prestressed concrete anchors.

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