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EXPERIMENTAL TESTING AND FINITE ELEMENT SIMULATION OF THE BEHAVIOUR OF REINFORCED CONCRETE BEAMS UNDER IMPACT LOADING

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EXPERIMENTAL DETAILS

The test facility, which has been used to investigate high mass low velocity impacts, comprises of a drop weight system that has been used to allow weights of up to 200 kg to fall through heights of up to 4 m. Specimens tested to date have been beams with a maximum span of 3.0 m and slabs of 2.3 m square. A general view of the test facility is shown in Fig. 1.

The instrumentation comprises of a load cell placed at the level of the impactor, to obtain load-time histories and accelerometers – the output of which is fed into a data logger which can operate at rates of up to 0.5 MHz. The reinforcement has strain gauges placed inside the bars, using a technique developed by Scott[1] so that the strains in the reinforcement can be recorded without affecting the bond between the concrete and the reinforcement. A high speed video has also been used to record the impacts at a rate of 4500 frames per second. This enables an accurate record of crack formation, propagation, etc to be obtained. Typical output can be viewed at http://www.sbe.hw.ac.uk/research/structural/impact_test/index.htm.

In the beam tests the aspects of particular interest are the global behaviour of the beams, the order of crack formation and spallation and the local fracture behaviour in the vicinity of the impact.

Of particular interest in the slab tests is the mode of failure that includes scabbing, where scabbing is defined as the ejection of material from the back face of the impacted structural element opposite to the face of impact. Also of importance is ascertaining the size and velocities of the elements leaving the scabbed zone. It has been possible using the high speed camera to estimate both these parameters.

Fig 1 View of impact test rig

COMPUTATIONAL PROCEDURES

From a computational viewpoint, constitutive models are almost invariably based on a continuum formulation, which although permitting the development of crack fields to be simulated in a smeared sense, does not allow discrete fracture paths to be traced and hence precludes the simulation of phenomena such as scabbing and spallation. To capture this behaviour a combined continuum/discrete approach has been used[2].

The concrete, as a brittle material, is initially represented as a continuum into which cracking is introduced in a smeared sense as the deformation progresses. The onset of fracturing is based on damage mechanics considerations that account for complex stress/strain fields; particularly those involving combinations of compressive and tensile regimes. The approach permits multi-fracturing to occur in the concrete. Key computational issues requiring attention include the fundamental modelling of damage and failure processes through a rigorous continuum description, the treatment of subsequent softening behaviour and the need for mesh objective solutions.

The generally accepted "rotating crack model" is used to simulate crack formation within a continuum description under tensile conditions. In this approach, cracks (in a smeared sense) are initiated in the three directions normal to the principal strains and are presumed to rotate to maintain this orthogonality condition upon further loading. Cracks are initiated when a limiting tensile stress is reached, after which the material follows a softening/damaging response governed by an appropriate relation. Damage models monitor the accumulated damage incurred during the softening process and permit unloading/reloading with a reduced elastic modulus for partially softened material points. It is found to be critical that during the softening process associated with strain localisation during crack formation discretisation objectivity be maintained, in a continuum sense, prior to discrete fracture insertion.

Several options exist to ensure this, recognising that both shear and opening modes of crack extension must be accounted for. Two approaches are investigated, including: 1) An energetic formulation in which the softening slope is related to the fracture energy release rate, G_f, to ensure mesh independent energy dissipation at the local level; and 2) A non-local approach in which averaging of the damage measure in each orthogonal direction is employed to ensure global mesh objectivity. The introduction of rate dependency is also considered as the impact induced strain rate is found to be sufficiently high.

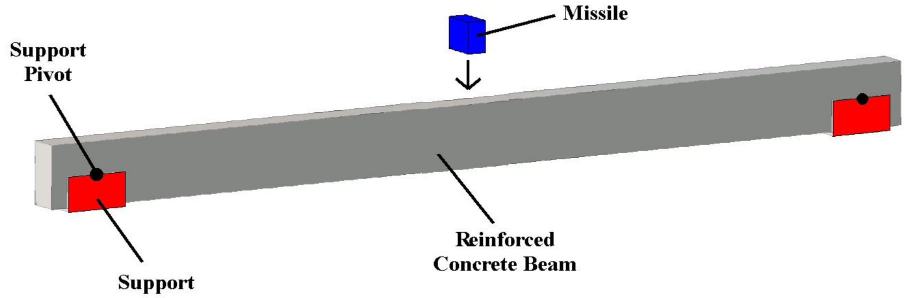
For combined tension/compression regimes, the above model is complemented by a constitutive description based on a Mohr-Coulomb type material model with a limiting compressive cap. The compressive behaviour post-failure is coupled to the tensile softening response and a feature of the model is the ability of the material to independently soften in the three principal stress directions. This constitutive algorithm is capable of predicting fracture for arbitrary tensile/tensile or tensile/compressive stress states.

Following completion of the softening process for an individual smeared crack, a discrete fracture is inserted through the introduction of discrete element concepts. A discrete region is formed from the deformable finite elements describing the original continuum and the constitutive modelling which monitors the onset of fracture as described above. One practical and efficient option is to insert discrete cracks into the continuum on a nodal basis according to a weighted value of a fracture indicator that monitors the damage state of each surrounding element, followed by local element remeshing to provide an adequate element topology. After the insertion of a discrete fracture, the crack surfaces assume a frictional contact response governed by Coulombic representations which will be handled within the combined finite/discrete element environment. A crucial requirement is the maintenance of energy balance during this continuous/discrete transition process.

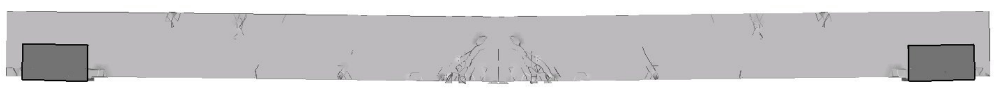
By modelling the creation of discrete cracks within the original continuum a more realistic representation of this class of problems is obtained, which has the added advantage that the constitutive modelling of the concrete material under non-linear conditions becomes much more tractable.

The reinforcement bars are modelled as beams with an elasto-plastic material property and a perfect bond condition is assumed between the beams and the concrete. The governing dynamic equations of the impact system are numerically solved by employing a central difference based explicit time integration scheme and the time step is selected automatically to ensure the numerical stability of the scheme.

Some of the beams tested have been analysed using ELFEN[3] by Bere[4] and the Authors and good agreement has been obtained for both the load-time histories and the crack patterns, Fig. 2. Currently ELFEN is being used to predict the results obtained from the slab tests.



(a) Model



(b) Numerical prediction of crack pattern

(c) Experimental crack pattern at end of test

Fig 2 Comparison of tests and numerical model

The results from the tests are being used to validate and further refine the computational methodology.

REFERENCES

[1] Scott R H and Marchand K A, Measurement of reinforcement strains caused by blast loading, Strain, 36, No4, (2000), 161-164.
[2] Owen DRJ, Feng YT, de Souza Neto EA, Cottrell MG, Wang F, Andrade Pires FM, Yu J, The modelling of multi-fracturing solids and particulate media, Int. J. Numer. Meth. Engng. 60, No.1, (2004), 317-340.
[3] ELFEN 2.8, Rockfield Software Ltd., Swansea, U.K., (2004).
[4] Bere AT, Computational modelling of large-scale reinforced concrete structures subject to dynamic loading. PhD Thesis, University of Wales Swansea, U.K. (2004).