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Experiments to Validate Computer Codes Used in the Safety Assessment of Concrete Containments

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1 INTRODUCTION

Safety analyses for hazardous plant with reinforced/pre-stressed concrete containments include an assessment of containment performance under severe accident loadings. Such an assessment is normally based on the predictions of computer codes, supported by measured evidence from small-scale experiments.

Experiments are performed for two purposes, to demonstrate the response of the containment to accident loadings and to provide data for the validation of the codes. A programme of small-scale experiments is in progress at AEE Winfrith.

A first series included five tests on simple concrete "frame" specimens; this series was designed to provide basic response data for a structure with a re-entrant corner under static loading conditions and for a range of typical reinforcement/pre-stress levels.

A second series included tests on reinforced concrete "slab" specimens which have geometries representative of an element of a steel-lined containment wall. This series is designed to investigate the response of the steel-liner when a steel-lined concrete containment is subjected to severe bi-axial (quasi-static) accident loadings.

The experiments and measurements are described; a selection of measured results are presented. Progress with the validation of the finite-element computer codes ABAQUS and DYNA3D against the measured results is commented upon.

2 EXPERIMENTS WITH FRAME SPECIMENS

2.1 Description

A shematic of a frame specimen is shown in Fig. 1. The overall dimensions of the frame in the vertical ("wall") and horizontal ("floor") directions were 2.5m and 1.904m respectively, the depth (orthogonal to these directions) was 0.25m. The wall and floor thicknesses were 0.26m and 0.5m respectively, so that the floor was relatively "overstrong" compared with the wall.

The specimens were loaded symmetrically, at positions on each floor and each wall, using hydraulic jacks reacting across the spans of the specimen,

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Fig. 1. The jacks were coupled to a common hydraulic system with a single hand-pump. The loading configurations allowed quadrant symmetry repeat measurements.

The levels of reinforcement in the wall ranged from 1.0% to 4.5% and the specimens for two tests incorporated pre-stress.

The jack assemblies were mounted in square steel conduits and the loading was applied to the specimen via steel platens, Fig. 1. A load cell was located in-line with each jack to measure the applied load. The specimens were loaded in two phases: firstly to an intermediate level, followed by unloading, and secondly to a maximum loading (at which significant creep occurred), followed by unloading.

2.2 Material properties

The concrete used had 10mm maximum flint aggregate and had a nominal compressive strength of about 45MPa; its properties were measured using cylinders, cubes and beams, cast at the same time as the specimen and from the same mix. The tests were performed and the material properties measured on day thirty after the day of casting.

Mechanical properties in the form of stress-strain curves were measured for the reinforcement bars using samples of the actual bar used.

2.3 Measurements

The displacements of the specimens were measured at sixteen positions (Fig. 1) using displacement gauges mounted on a rigid scaffold system. The positions provided sets of two or four repeat symmetry measurements. In addition, mechanical strain gauge points were fixed to the concrete surface at the four re-entrant corners, providing five measuring spans at each corner, located to capture crack-opening. Straining of the reinforcement bars, within a wall, was measured using strain gauges installed on the bars.

The loading was adjusted in increments or decrements. At each loading step, measurements of the applied loads, displacements and strains were recorded on a computer controlled data logger. The formation of cracks was observed at each loading step and crack locations at the surface were marked for clarity.

In general, the global cracking behaviour for the five tests was similar and progressive. Initial cracking propagated outwards across the floor from the re-entrant corners accompanied by cracking inwards from their outer surface, Fig. 2. Subsequently, flexural cracking of the walls and further cracking of floors occurred. Finally, some diagonal "shear" cracking formed across the walls near the re-entrant corners. A typical load-displacement curve for the wall at mid-height is shown in Fig. 3.

Differences in the measured results between tests were obtained according to the loading configuration and levels of reinforcement and pre-stress. Consequently, the tests provided a set of scoping experiments for code validation, with respect to dominant cracking mode, displacements and maximum loadings attained for a structure with a re-entrant corner.

3 EXPERIMENTS WITH SLAB SPECIMENS

3.1 Description

Outlines of the slab specimens are shown in Fig. 4. The specimens were 2.4m square and 0.13m thick, about 1/10th scale of a typical containment wall thickness. The liner thickness was 0.7mm.

The series consisted of six tests. Three geometry discontinuities were included, Fig. 4, (i) a thickened liner insert, (ii) a group of four "small" penetrations and (iii) a single "large" penetration. For each geometry two types of liner-concrete anchors were studied, headed-stud and continuous-angle. The thickness of the liner insert and the liner around the penetrations was 2.5mm.

A loading frame, Fig. 5, was used to load the specimens bi-axially; it comprised four struts in each direction, interlinked with cross-beams. Hydraulic jacks were used to load the specimens.

A typical specimen under construction (with continuous-angle anchors) is shown in Fig. 6. Integral beams, each containing four steel "loading-plates", were cast at each edge of a specimen. The specimens were loaded via bars acting on the loading-plates, Fig 6. Reinforcement along the longitudinal direction of the beams was limited to short lengths of bar so that the load transmission between loading plates, along a beam, was limited to the tensile strength of the concrete.

A bi-axial loading was applied in the ratio 2:1 to simulate the loading on an element of the wall of a cylindrical containment under severe accident loadings. A load cell was located adjacent to each jack to measure the applied loadings. Similarly to the frame experiments, the specimens were loaded and unloaded in two phases, by small increments or decrements.

3.2 Material properties

The concrete used had 5mm maximum flint aggregate and had a nominal compressive strength of about 40MPa; its properties were measured by the same method adopted for the frame experiments.

Mechanical properties in the form of stress-strain curves were measured for the reinforcement bars and liner steels, using samples cut from the actual materials used.

3.3 Measurements

The measurements focussed on investigating the response of the liner at the geometry discontinuity (ie the thin-to-thick transition in the liner) with respect to the deformation of the specimen. For this purpose, straining of the liner was measured using strain gauges adhered to the liner surface, at and near the thin-to-thick transition, and displacement gauges were positioned at each edge of the specimens to measure the specimen displacement. Straining of the reinforcement bars was also measured using gauges mounted on the bars. A total of 100 instrumentation channels was used.

At each loading step, measurements of the applied loads in the two directions, displacements and strains were recorded on a computer controlled data logger. The formation of cracks was observed and marked as described for the frame experiments.

The three geometry discontinuities provided differences in the cracking patterns, Fig. 7. As expected, cracks formed preferentially in the direction orthogonal to the direction of the greater loading and diagonal cracks formed at the corners due to the bi-axial loading. The presence of a penetration invoked perturbations in the general crack pattern in the vicinity of the penetration.

Straining of the liner was measured along the centre lines in the two loading directions. Fig. 8 shows the peak-strain spatial distribution, along the centre line in the greater loading direction, for a specimen with four penetrations. Straining of the thick liner insert was negligible; at positions on the thin liner, near to the thickness transition, a stress concentration occurred and strains peaking to about 5.5% were measured.

These experiments provide measured data, representative of the local straining of a containment liner at typical geometric discontinuities, for the validation of computer codes.

4 CALCULATIONS

The validation of computer codes against the experiments is ongoing.

The ABAQUS Version 4.8 code (Hibbitt et al. 1989) is being applied to the first frame experiment. This version of the code includes a concrete model with a strain dependent "tension stiffening" relaxation curve. Fig. 3 shows a comparison of the calculated and measured displacements at the mid-wall height. Using measured material data for the concrete and steel reinforcement, the code predicts the frame to be more stiff than the measurements indicated. Scoping calculations performed with changes in material data and in the tension stiffening parameter show that the discrepancy is not attributable to uncertainties in these parameters.

The DYNA3D code (Hallquist 1988) is being applied to the slab experiment with a simple liner insert. The quarter symmetry mesh structure for a first calculation is shown in Fig. 9 and was chosen so that the positions of the headed-stud anchors coincided with nodes. The attachment of the liner and concrete by the anchors was modelled by using appropriate shared nodes between the liner shell-elements and the concrete continuum-elements. Point loadings were applied at the appropriate nodes. The calculated and measured liner strains are compared in Fig. 10; with the model used, the code tends to underestimate the peak straining.

5 CONCLUSION

Two aspects of safety analyses for concrete containments under severe accident loadings are the need for computer codes to predict accurately (i) the structural response at a re-entrant corner (eg at the base-mat junction with the wall) and (ii) the integrity of the liner (with respect to leakage criteria). The Winfrith containment experiments provide data for the validation of computer codes used for such analyses. The experiments have been successfully completed and application of the codes to the experiments is continuing.

REFERENCES

Hibbitt, Karlsson and Sorenson (1989) ABAQUS User's Manual VERSION 4.8.

Hallquist, J.O. (1988) DYNA3D User's Manual.

ACKNOWLEDGEMENT

This work has been supported by the Health and Safety Executive through its Nuclear Safety Research Programme.

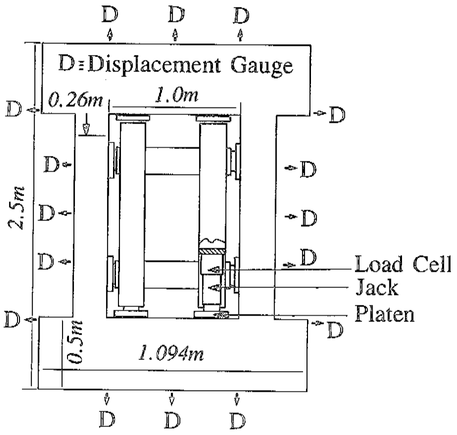


Figure 1 Frame Specimen

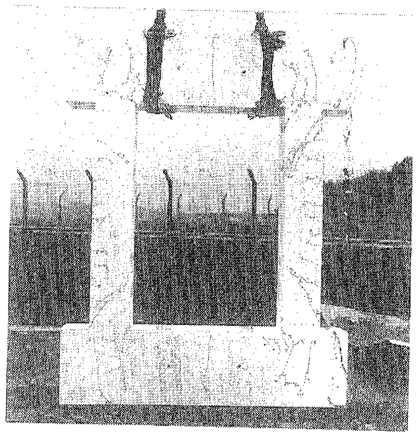


Figure 2 Post-Test Frame Specimen

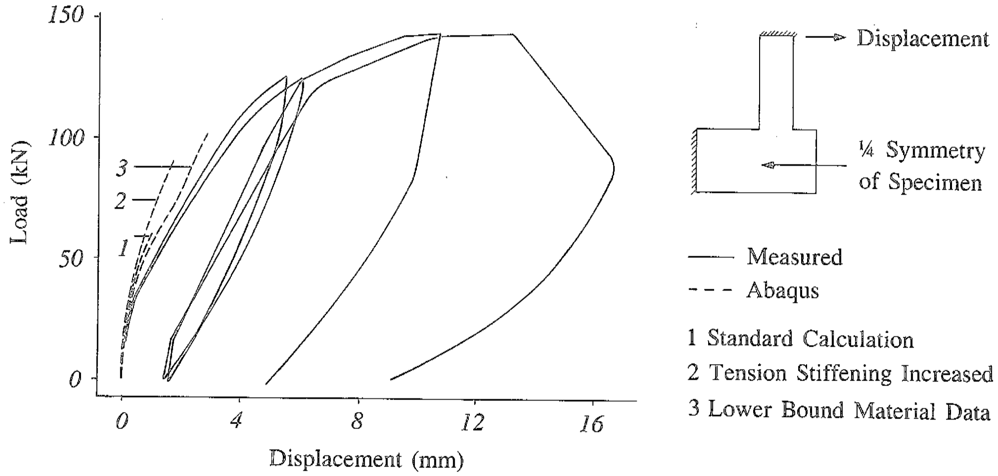
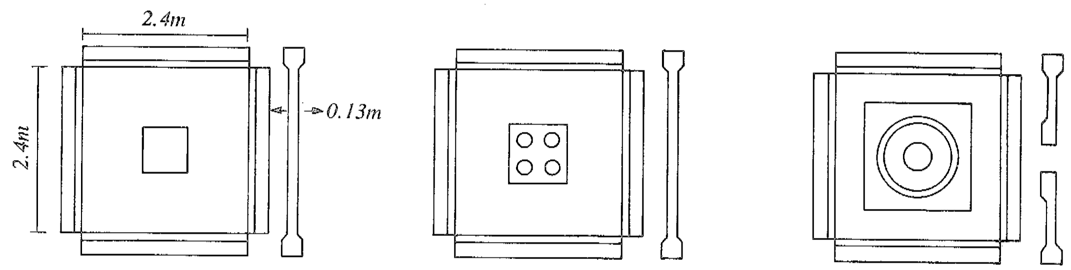


Figure 3 Load vs Displacement, Frame Specimen



TESTS 1 AND 2
Thickened Liner Insert

TESTS 3 AND 4
Group of Four Penetrations

TESTS 5 AND 6
Single Large Penetration

Figure 4 Slab Specimens

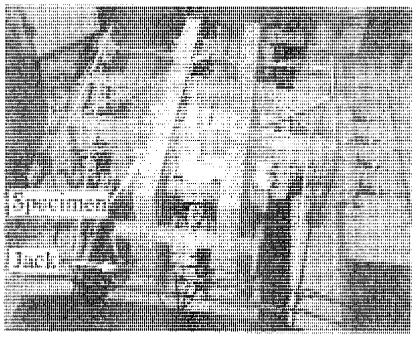


Figure 5 Loading Frame

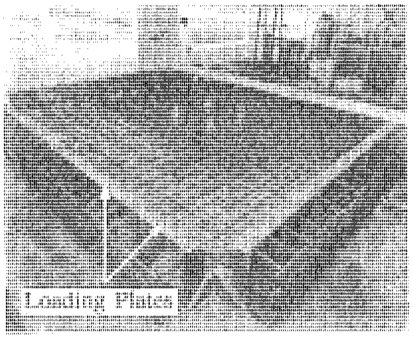


Figure 6 Slab under Construction

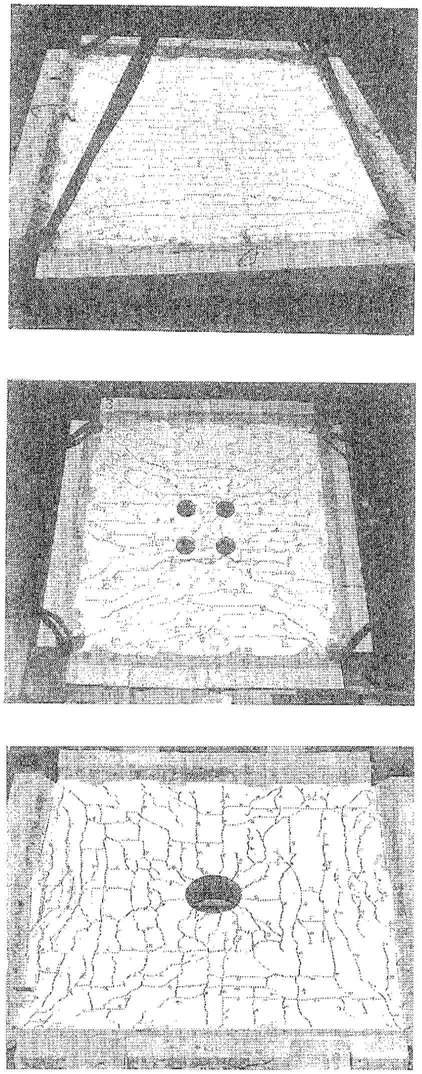


Figure 7 Post-Test Slab Specimens

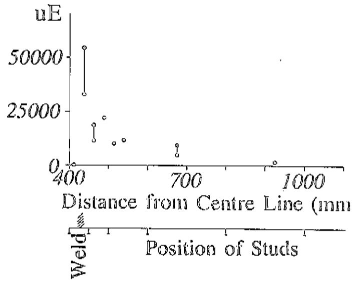


Figure 8 Liner Strains (Test 3)

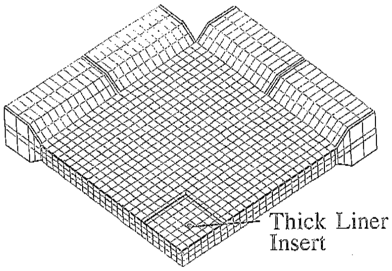


Figure 9 DYNA3D Quarter Model

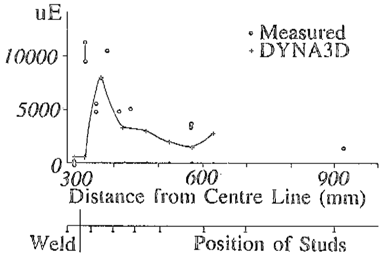


Figure 10 Liner Strains (Test 2)