

High-Mass, Low-Velocity Impacts on Reinforced Concrete Slabs

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Summary:

The behaviour of reinforced concrete in quasi static regimes has been investigated extensively but there have been few investigations into its transient behaviour, especially under low velocity regimes. This paper describes the finite element modelling and analysis of reinforced concrete slabs under drop-weight impact loads using LS-DYNA. The results obtained from the numerical simulations have been compared with tests that were carried out at Heriot-Watt University to generate high quality input data to validate numerical modelling. The experiments were conducted on four 0.76 m and two 2.3 m square slabs under drop-weight loads. A drop-weight system was used to drop a mass of up to 380 kg with velocities of up to 8.7 m/s. The output from the tests included time histories of impact force, acceleration, strains and video footage using a high-speed video camera which recorded the images at the rate of up to 4,500 frames per second. The simulation results show reasonable agreement when compared to the tests and for the overall kinematic response of the slabs.

Keywords:

FEM, impact analysis, falling weights, reinforced concrete, LS-DYNA

1 Introduction

This paper describes investigations into the impact behaviour of reinforced concrete slabs subjected to falling weight loads. While a number of studies have been carried out – both experimental and numerical for ballistic regimes; there is need of more investigations for low velocity situations, which is of most relevance to civil engineering structures [1, 2]. The main objective of the present study is to establish a rational procedure for the dynamic structural analysis of reinforced concrete structures under low velocity impacts. To compare with finite element analysis, the experimental data for the slabs tested at Heriot-Watt University has been used [3]. This data was produced as a result of a series of well monitored tests conducted on reinforced concrete slabs impacted by falling weights. The test programme was specifically designed to produce high quality input data for the validation of computational methods.

The finite element analysis has been carried out using LS-DYNA [4] employing different material models suitable for modelling reinforced concrete.

2 Description of experimental tests

A series of well monitored drop weight tests was performed at Heriot Watt University by May et al. [2, 3, 5, 6] in order to get a sound basis for verification of tools for numerical simulations. These tests have now been simulated numerically using the commercial finite element code LS-DYNA. The purpose of this study is to evaluate the ability of the chosen numerical method and material models to predict the material and structural response.

In the impact tests, four 760 mm square, 76 mm thick and two 2320 mm square, 150 mm thick slabs were tested under a drop weight of up to 380 kg with velocities of up to 8.7 m/s. The slabs are shown in Figure 1. The output from the tests included time histories of impact force, acceleration, strains and a video footage using a high-speed video camera which recorded the images at the rate of up to 4,500 frames per second. Further details of the tests are given in [3].

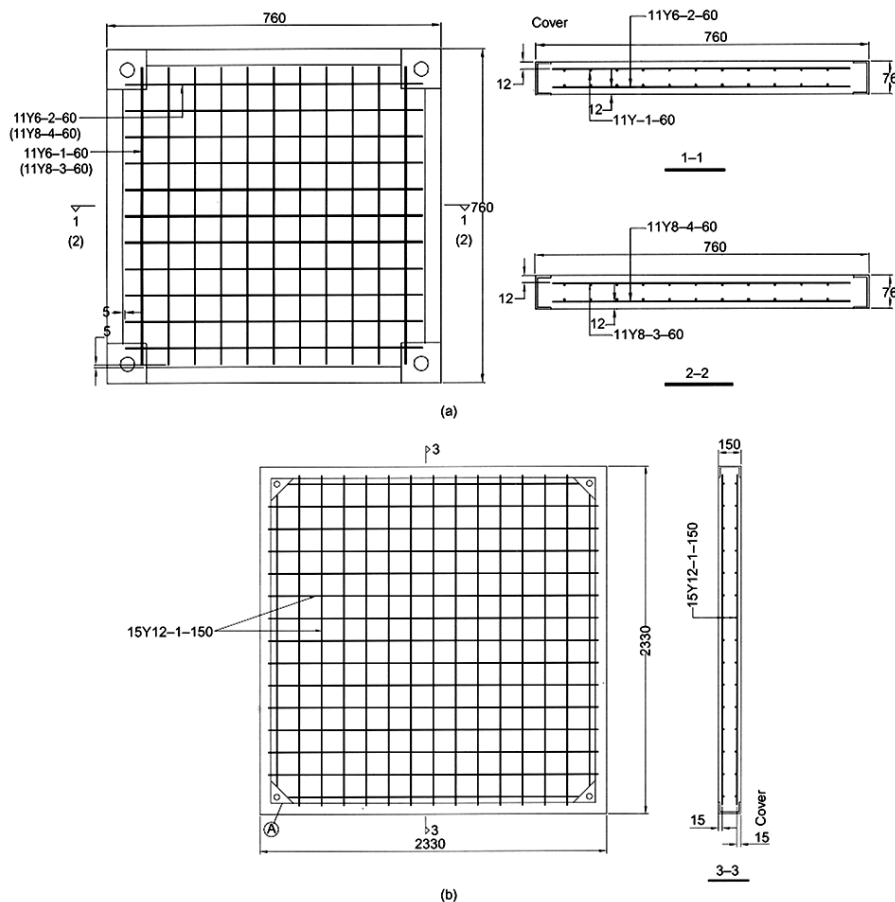


Figure 1: Details of the slabs: (a) 0.76 m square slabs; (b) 2.3 m square slabs (dimensions in mm)

3 Finite element modelling

The tests have been numerically analysed using the finite element code LS-DYNA version 971.7600. The computer system used for these simulations is specified in Table 1.

Table 1: System specifications

Computer	Dell Precision 690
Processor	2.33 GHz Dual Intel Xeon
Main memory	4 GB
Operating system	Windows XP Pro-SP2
Pre-processor software	HyperMesh version 8.0
Finite element analysis software	LS-DYNA version 971.7600
Post-processor software	LS-PREPOST version 2.1

3.1 Spatial discretization

A material, or Lagrangian, description of the motion has been used for the whole model. The concrete slab and drop weight were discretized in space with eight-node hexahedron elements. The elements for the concrete slab have an aspect ratio of 1. One-point Gauss integration and viscous hourglass control were used for the elements in the slab and impactor. The reinforcement bars were spatially discretized with beam elements. The supports have not been modelled explicitly; only restraints to vertical and horizontal movements have been applied along the edges of the slab. The model has been created for the whole problem. The concrete solid elements and reinforcement beam elements share the common nodes. In some of the models, keyword *CONSTRAINED_LAGRANGE_IN_SOLID was used to couple the beam elements with the solid elements. The finite element model for the slab is shown in Figure 2.

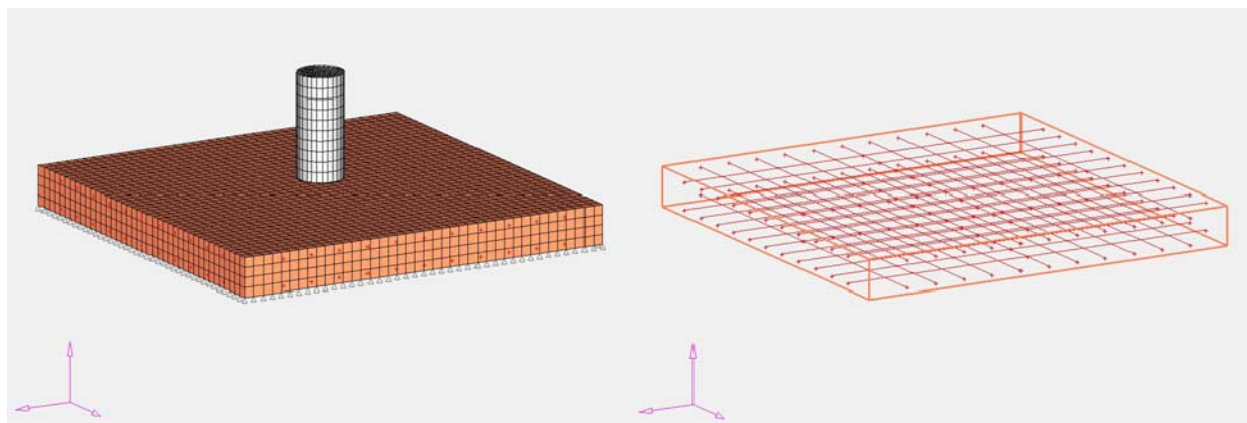


Figure 2: Finite Element model of slab S3

In a typical model of a small slab, there are about 50,000 elements for a mesh size of 10 mm. A coarser mesh of 19 mm contains about 10,000 elements. Further detail of the mesh data for the two mesh sizes is shown in Table 2, below.

Table 2: Mesh data for Slab S3

Mesh data	Mesh 1	Mesh 2
Nodes	56,247	11,051
8-node hexahedron elements	48,482	8,566
Beam elements	3,400	1760
Element sizes	10 x 10 x 10 for solid elements, 10 mm for beam elements	19 x 19 x 19 for solid elements, 19 mm for beam elements

3.2 Constitutive modelling

LS-DYNA offers a number of material models for both concrete and reinforcement. The majority of these concrete models require multiple and complex parameters, which are not readily available without performing multiple material tests. The description for some of the parameters is also poorly documented in both the theoretical and keyword manuals. However, recent versions of a few models have incorporated a capability to generate default parameters requiring only basic material properties like unconfined compression strength, Poisson's ratio and aggregate size [7]. Pseudo-Tensor (Material 16), Concrete Damage Rel. 3 (Material 72R3) and CSCM concrete (Material 159) possess such a capability. The input parameters for Winfrith concrete (Material 84) can also be determined with relative ease. The evaluation of the most commonly used concrete material models in LS-DYNA is described by Yonten et al.[8]. In the present study, Concrete Damage Rel.3 [9] and Winfrith concrete [10-12] have been used for the concrete slabs. The material properties for concrete used in the simulations are given in Table 3. The material model used for reinforcement is *MAT_PLASTIC_KINEMATIC with the properties as shown in Table 4. The impactor was modelled as rigid with a density of 7800 kg/m³ with an elastic modulus of 210 GPa, and a Poisson's ratio of 0.30. A layer of elements 5 mm thick and with an elastic modulus of 1500 MPa was placed between the impactor and the slabs to simulate the interface.

A surface to surface contact was defined between the impactor, interface and the target slab.

Table 3: Material properties of concrete

Density (kg/m ³)	2400.0
Compression strength, f_c' (MPa)	48.0
Tensile strength, f_t (MPa)	4.06
Poisson's ratio	0.19

Table 4: Material properties of steel reinforcement

Density (kg/m ³)	7800.0
Yield Strength (MPa)	560.0
Elastic modulus (MPa)	210000.0
Poisson's ratio	0.19
Tangent modulus (MPa)	2100.0

4 Results and comparison with tests for slab S3

A number of models were created with varying mesh sizes using two different material models for concrete slabs. In this paper, only the results of two simulations performed for slab S3 (760 mm square, 76 mm thick) using Concrete Damage Rel. 3 and Winfrith Concrete are described. The slab was impacted by a falling mass of 98.7 kg with an impact velocity of 6.5 m/s. There was local damage on the top and bottom faces of the slab, while no perforation of the slab occurred.

Figure 3 and 4 compare the simulation results using Winfrith concrete model for slab S3 with the tests. The comparison of damage for both top and bottom faces of the slab is given in Figure 3. As shown in Figure 3(a), the local damage on the top face of the slab is in close agreement with the experiment. There is some penetration of the impactor. In Figure 3(b), the damage on the bottom face of the slab is compared. The diameter of the damage zone in the experiment is similar to the simulations. Closer examination of results for the two mesh sizes, shows a small variation in the damage zones. The finer mesh size of 10 mm seems to show more accurate size and pattern of the damage zone at the top and bottom of the slab, as compared to the coarse mesh of 19 mm.

In Figure 4, the transient impact force histories are compared for two mesh sizes of 10 mm and 19 mm. As shown in figure 4, there is no significant difference between the impact force histories for the two mesh sizes.

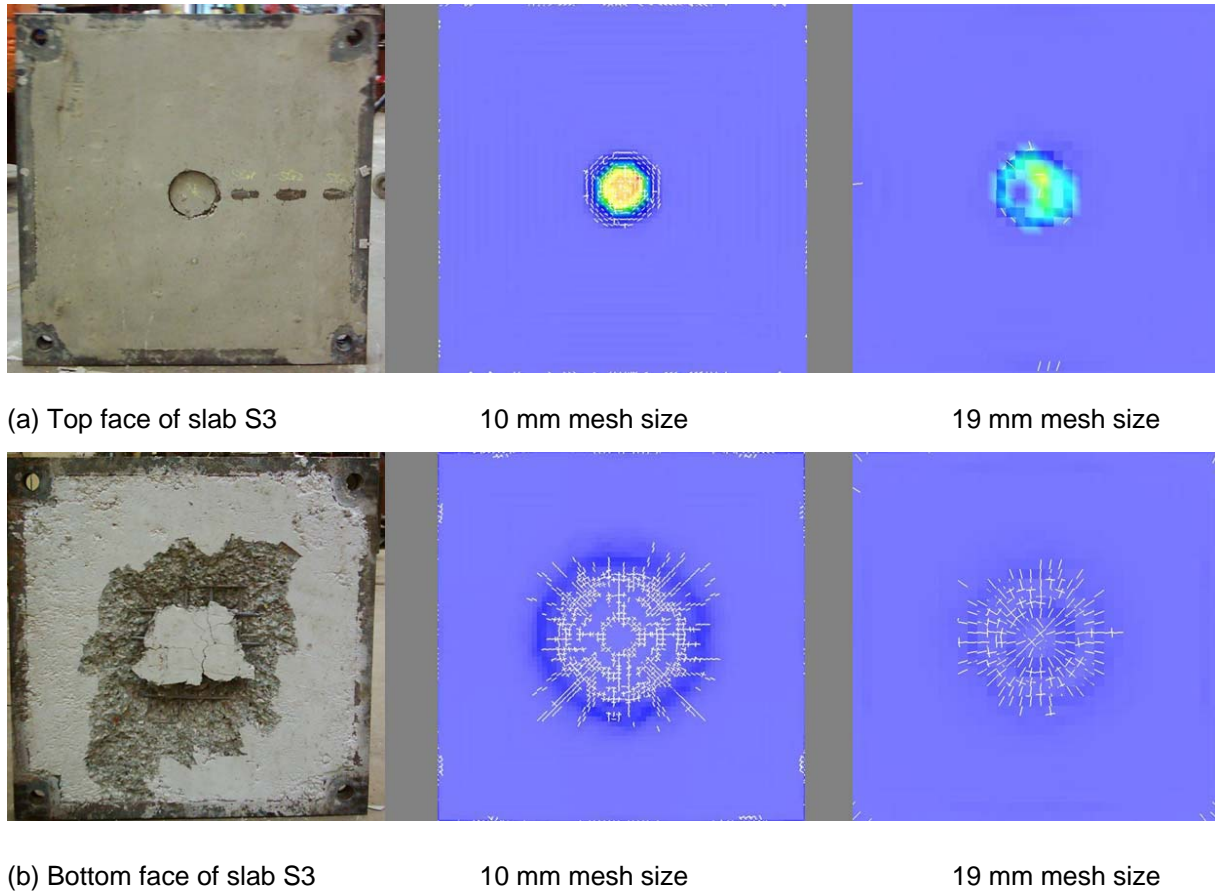


Figure 3: Comparison of simulation damage and cracking for slab S3 (Winfrith concrete model)

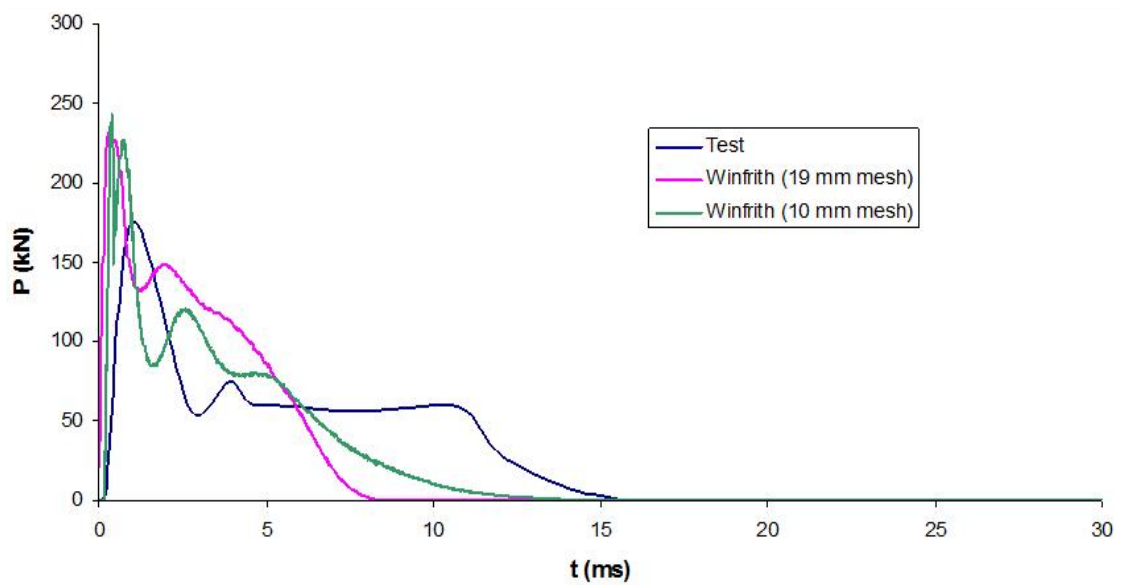
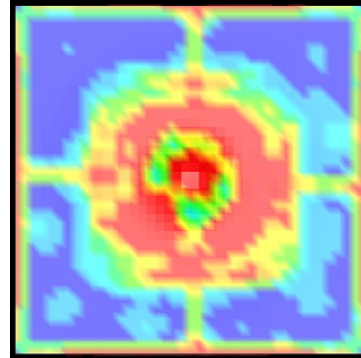
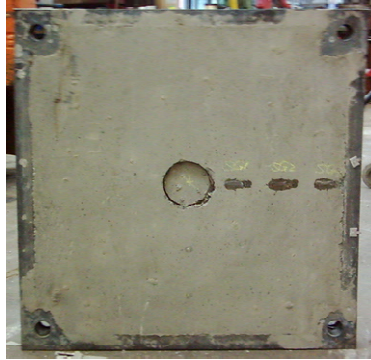
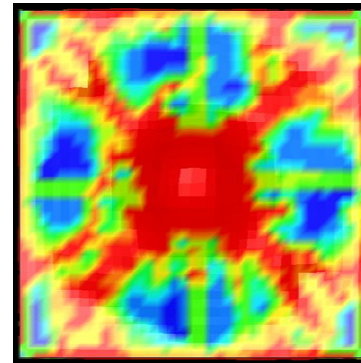


Figure 4: Recorded and simulation impact force histories for slab S3 (Winfrith model)

Figure 5 and 6 show the simulation results using Concrete damage rel.III model for concrete. Failure of the concrete was defined using erosion of the material. In figure 5, the comparison of test and simulation damage for slab S3 is shown. The damage patterns at the top and bottom faces of the slab are similar to the tests. The diameter of the damage zone at the top face is in very good agreement, as in the tests there is no perforation of the slab. Figure 6 compares the impact force histories for the slab.



(a) Top face of slab S3



(b) Bottom face of slab S3

Figure 5: Comparison of simulation and test damage (Concrete damage rel. III model)

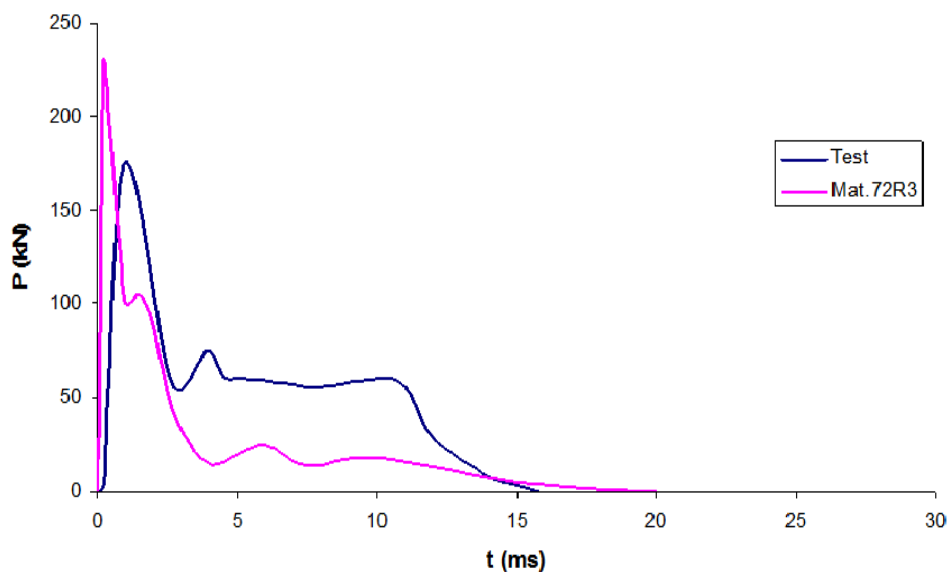


Figure 6: Comparison of simulation and test impact force histories (Concrete damage rel. III)

5 Discussion & Conclusions

The comparison of crack patterns obtained using Winfrith concrete model with the test shows close agreement. The diameter of the scabbing zone is captured well by the simulation. The impact force histories obtained from simulation using both Winfrith concrete model and Concrete damage rel.III model, with the tests show good agreement. No perforations were obtained in finite element analysis which confirms to the experimental tests. The numerical analyses indicated that the overall kinematic response is captured very well. The impact behaviour of reinforced concrete slabs subjected to drop-weight loads can be determined using the finite element procedure described.

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