Low-Velocity Impact Behaviour of Plain Concrete Beams

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Abstract

Concrete structures are designed and constructed to serve their anticipated service life, generally with minimal consideration of accidental loads such as impact or explosion. The behaviour of reinforced concrete structures under impact loads has been widely discussed in the last decades, however, there are few studies on the behaviour of plain concrete under impact loading. This paper presents a finite element model of plain concrete beams using nonlinear finite element analysis. The numerical results are compared to experimental data taken from an existing study. The experiments consist of drop-weight tests with varying drop-heights. A parametric study is conducted with respect to the concrete material model and mesh size of elements in order to fine-tune the model and to understand the dynamic response of the beam under low-velocity impact load.

Keywords: FEM, impact analysis, plain concrete, LS-DYNA

1 Introduction

Plain concrete is a relatively brittle material and might not always be capable to sustain the rapid rise of the energy from impact loads. Nevertheless, they are sometimes used as impact-resistant materials e.g. for barricades to protect sensitive instalments, for breakwater structures to reduce wave impact on marine structures and in industries to protect from accidental explosions. Limited studies are available on the behaviour of plain concrete under impact, whereas studies on the impact behaviour of reinforced concrete are more common. This paper discusses the finite element (FE) modelling of the impact behaviour of plain concrete without internal reinforcement. The study is conducted based on LS-DYNA software using three available concrete models i.e. Winfrith Concrete model (MAT_084), Concrete Damage Release 3 model (MAT_072R3) and Continuous Surface Cap model (MAT_159). The experimental data of control specimens is taken from an existing study [1]. The primary objective of this paper is to present and validate the material and structural response of small scale plain concrete beams under impact loading by using finite element (FE) modelling.

2 Description of experimental tests

The experimental data have been taken from an existing study [1] in view of validation of the FE model. The specimens consist of plain concrete prisms of size 710 mm x 150 mm x 150 mm, with compressive strength 25 MPa and coarse aggregate size of 15 mm. The impact load machine which is used in the experimental study consists of a drop-weight hammer of 5.25 kg with variable drop-height capacity. The conducted FE modelling focuses on the behaviour of concrete specimens tested at 300 mm up to 450 mm drop-height. The behaviour after one impact on the specimen is examined in the FE model. Generally, specimens are fixed on both ends to avoid the recoil of the specimen but no such arrangement was followed in [1]. Accelerations were recorded by using two integrated circuit piezoelectric (ICP) accelerometers and were fixed on the compression zone of the concrete specimen (top face of the beam) at a distance of 150 mm on both sides from the centre. A data acquisition system was connected to the accelerometers to store and process the data. A summary of the main experimental results is given in Table 1. Note that the observed maximum vertical acceleration at the measurement point is both dependent on the drop-height and damage level generated by the impact.

Drop-height (mm)	Maximum acceleration (m/s^2)		Damage
	(-) Peak value of the inbound stage	(+)Peak value of the outbound stage	
300	-2677	2555	Failed
400	-1515	1544	Failed
450	-2088	1844	Failed

Table 1: Summary of experimental results

3 Finite element modelling

The validation is carried out using FE code LS-DYNA with following computer specifications and credentials of software as indicated in Table 2.

Processor	Intel Core i7 (2.27 GHz)
Main memory	3 GB
Operating system	Windows 7 Professional (64-bit)
Finite element analysis software	LS-DYNA version R10
Post-processor software	LS-PrePost 4.5

Table 2: System specifications

3.1 Element generation

The model of the beam, the reaction supports, the surcharge of the impactor and the impactor are created as shown in Figure 1. By using the energy conservation law, velocities for the impactor are calculated. The velocity of the impactor is taken as 2.42 m/s, 2.8 m/s and 2.96 m/s to represent a drop-height of 300 mm, 400 mm and 450 mm, respectively. The respective velocity is assigned to the impactor and weight of the impactor which allows to take the starting position of the impactor a few millimetres above to the steel contact plate. This technique helps to reduce the processing time.

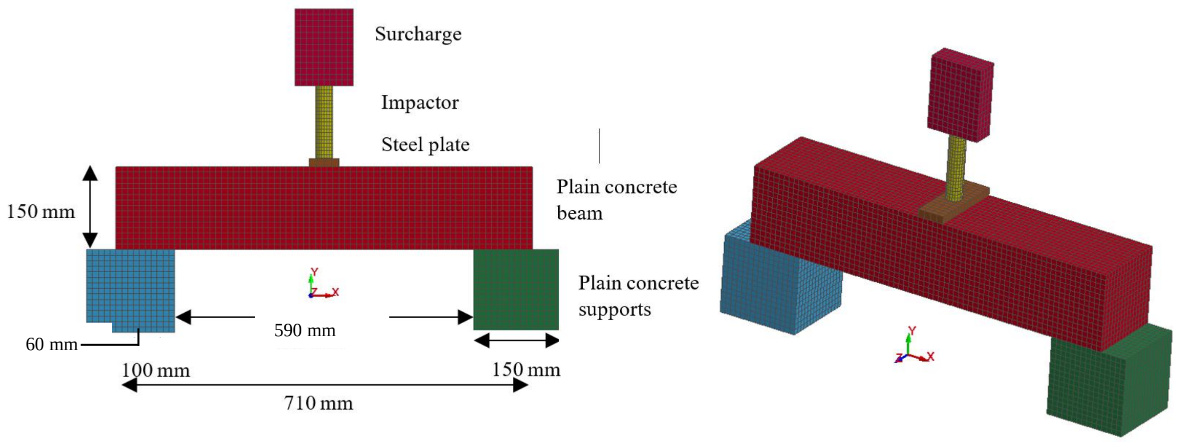


Fig.1: A schematic representation of the numerical model

3.2 Material models for the concrete

In LS-DYNA there are mainly three material models for the representation of the concrete.

a) Winfrith concrete model (WIN model) “MAT_84”
b) Concrete Damage Release 3 model (CDR3 model) “MAT072R3”
c) Continuous Surface Cap model (CSC model) “MAT_159”

The working mechanism and a general discussion on concrete models in LS-DYNA under impact loading can be found in [2]. Some main features of the concrete models are described in Table 3. This study has used the three available models and a comparison is made. Though any of the concrete models can be used, the WIN model is often used for impact loading responses [3, 4] because the dynamic response of the WIN model is somewhat better compared to the CDR3 model [5]. At the other hand, Youcai [2] states that the CDR3 model is suitable for quasi-static, blast and impact loading. In the FE model, the beam and supports are assigned concrete properties which are described in Table 4.

Material ID	Material name	Strain-rate effects	Failure criteria	Damage effects	Tension handled differently than compression	Application
84	WIN model	✓	✗	✗	✓	Soil, concrete, rock and foam.
72	CDR3 model	✓	✓	✓	✓	Soil, concrete and rock.
159	CSC model	✓	✓	✓	✓	Soil, concrete and rock.

Table 3: Properties of concrete material models

Density	2400 kg/m^3
Compression Strength	25 MPa
Tensile Strength	2.9 MPa
Aggregate Size	15 mm
Poisson's Ratio	0.19

Table 4: Properties of concrete

3.3 Material model for the impactor

The details of the impactor used in the experiments are not fully defined [1]. In this respect, some assumptions are taken into consideration. The impactor has a weight of 5.25 kg and exists of two parts i.e. the impactor surcharge and the impactor rod. For the radius of the impactor rod, 15 mm is assumed. A steel plate of size 50 mm x 150 mm x 15 mm was used to distribute the load. The material properties are given in Table 5. The steel material model used is PLASTIC_KINEMATICS (MAT_003), which assumes a bilinear stress-strain relationship and has the ability to incorporate the strain-rate effects [6]. To create a contact between the steel impactor, the steel plate and the concrete specimen, AUTOMATIC_SURFACE_TO_SURFACE contact model is used. During impact load, deformation may take place in any direction and this command is used to predetermine the penetration from all sides. Both impactor parts (surcharge and rod) are connected together using contact model AUTOMATIC_SURFACE_TO_SURFACE_TIEBREAK, which states that both the elements are tied together and allows the modelling of connections which transmits both compressive and tensile forces.

Mass density	8050 kg/m^3
Young's modulus	200000 MPa
Poisson's ratio	0.27
Yield stress	415 MPa

Table 5: Properties of steel

4 Parametric studies

4.1 Mesh size sensitivity

The validation of the FE model for the behaviour of the plain concrete beam was conducted using available experimental results at three drop-height positions i.e. 300 mm, 400 mm and 450 mm at a constant drop-weight of 5.25 kg. A mesh convergence study was carried to detect an optimum mesh size for the FE model. The denser the mesh the higher the required computation effort yet targeting a good accuracy of predicting the values, whereas, a coarser mesh would process the model faster but results may not corresponds with the actual experimental values. The optimum number can be assumed when further mesh refinement is no longer significantly contributing to the accuracy of the predicted values. To conduct the mesh sensitivity study the WIN model was selected for the concrete. The obtained calculation time versus mesh size is given in Figure 2. The prediction of maximum negative acceleration of the FE model at 10 mm mesh size is consistent with the experimental values as shown in Figure 3, whereas, there was minor depletion due to cubic mesh elements whereas the accelerometer used in the experimental study is circular in shape.

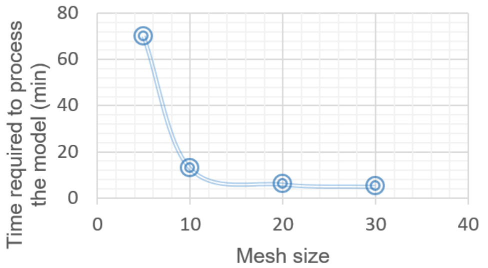


Fig.2: Time required for the respective mesh size for processing of the model.

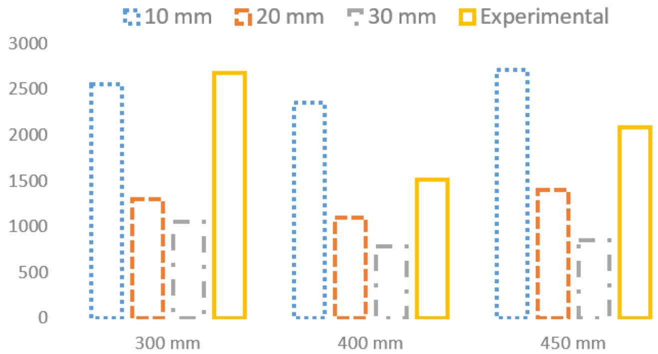


Fig.3: Comparison of mesh sizes at different drop-heights

4.2 Effect of material model on acceleration

4.2.1 Maximum acceleration

The impact load behaviour can be expressed in terms of deflection of the specimen, velocity and acceleration of the specimen, velocity of the impactor and reaction forces at the supports. In this study, the acceleration measured by the ICP accelerometers is compared with acceleration obtained in the simulation at the corresponding location. The maximum value of the outbound and inbound accelerations measured by both systems for the different concrete models at the specified point are reported in Table 6 and Table 7. A significant scatter between experimental and numerical values can be observed and none of the three concrete models sticks out in providing the best prediction.

Drop-height (mm)	Positive maximum vertical acceleration at 150 mm from the centre (m/s^2)						
	Experimental (1)	WIN model (2)	Exp/FEM (1)/(2)	CDR3 model (3)	Exp/FEM (1)/(3)	CSC model (4)	Exp/FEM (1)/(4)
300	2555	1560	1.63	2320	1.01	1830	1.39
400	1544	1890	0.81	2540	0.86	1990	0.77
450	1864	1620	1.15	2510	0.74	2010	0.92

Table 6: Maximum vertical acceleration at different drop-heights

Drop-height (mm)	Negative maximum vertical acceleration at 150 mm from the centre (m/s²)						
	Experimental (1)	WIN model (2)	Exp/FEM (1)/(2)	CDR3 model (3)	Exp/FEM (1)/(3)	CSC model (4)	Exp/FEM (1)/(4)
300	-2677	-2560	1.04	-2760	0.96	-2440	1.09
400	-1515	-2360	0.64	-3150	0.48	-2600	0.58
450	-2088	-2720	0.76	-3530	0.59	-2630	0.79

Table 7: Minimum vertical acceleration at different drop-heights

4.2.2 Acceleration-time histories

The acceleration pattern at 400 mm drop-height was measured in the experimental study and is compared with all three FE concrete models, as shown in Figure 4. It is observed that the WIN model and the CSC model represent a consistent response, whereas the acceleration produced by the CDR3 model exhibited a somewhat higher response than the other concrete models. Nevertheless, the peak value of the acceleration in the inbound stage is overestimated by the three models.

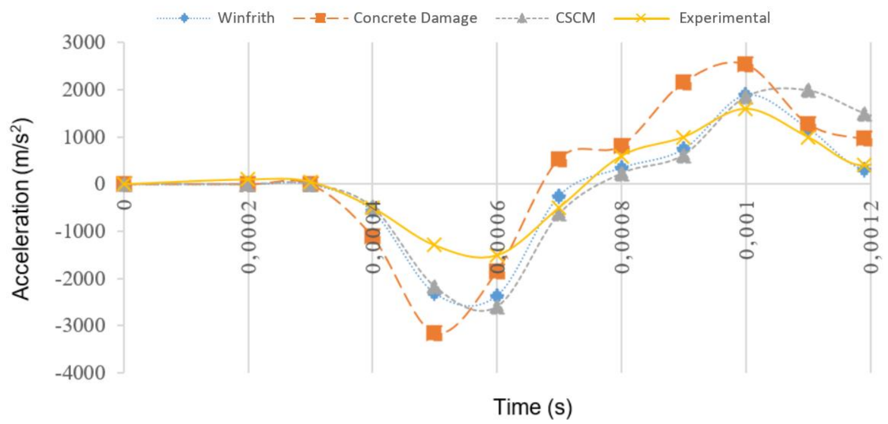


Fig.4: Acceleration-time history generated at 400 mm drop-height for different concrete models

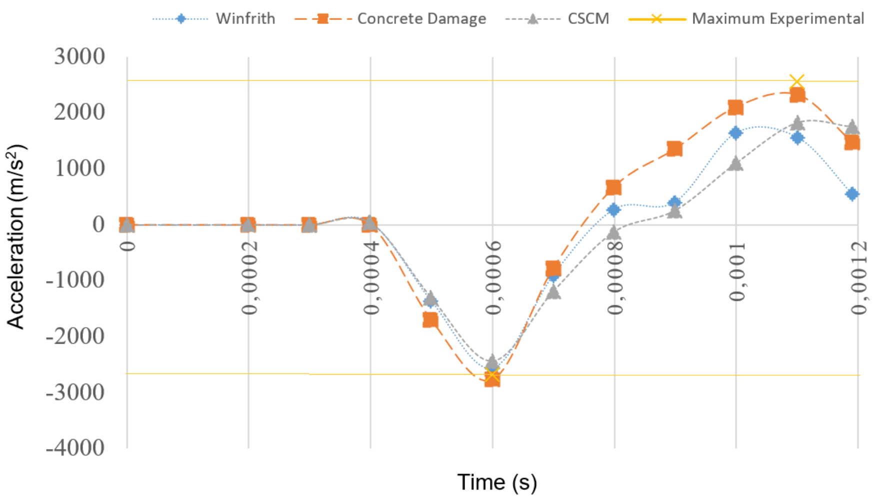


Fig.5: Acceleration-time history generated at 300 mm drop-height for different concrete models

Additional graphs of the FE model at 300 mm and 450 mm are shown in Figure 5 and Figure 6, respectively. In these figures also the peak value of acceleration, as experimentally recorded, are given. It is observed that the CDR3 model shows more pronounced acceleration than the other concrete models.

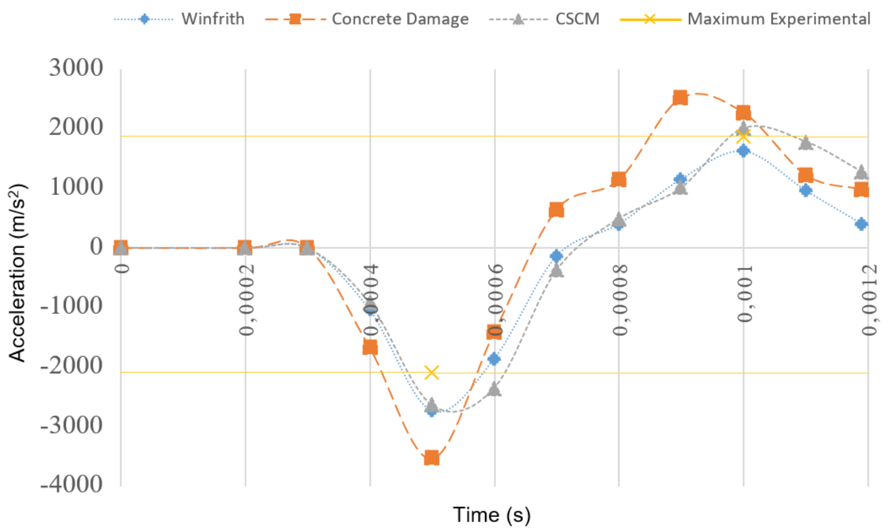
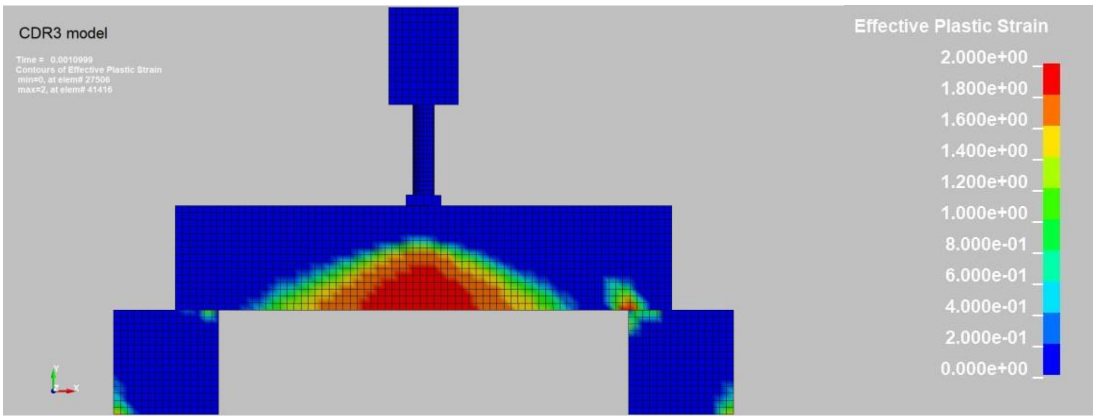


Fig.6: Acceleration-time history generated at 450 mm drop-height for different concrete models

4.3 Failure pattern

In the actual experimental test, all specimens failed by flexural cracking at mid-span. The same overall damage behaviour is observed in the numerical models. This is illustrated further for the case of 450 mm drop-height. To understand the failure pattern, the effective plastic strain over a period up to 0.001s is given in Figure 7 for 450 mm drop-height. Effective plastic strain is often said to be an internal damage parameter which characterizes the nonlinear damage behaviour and highlights the elements which are actively yielding (meaning beyond elastic strain and when concrete damage starts to occur). The effective plastic strain can only be examined for the CDR3 and CSC models, as it relates to the underlying constitutive model with damage effects, and which follows a different approach than the WIN model. Both the CDR3 and CSC model predict a large damaged zone in the tensile region of the beams, that is where the tensile capacity of the plain concrete has been exceeded. The magnitude of damage (effective plastic strain of 2 for CDR3, versus 0.4 for CSC) and the extent of the damaged zone are larger for the CDR3 model compared to the CSC model. The WIN model does not show a separate failure criteria, as the model is not equipped to detect failure and damage effects, but has the capability to predict the cracking as shown in Figure 8 by linking to a fracture energy versus crack width relationship (BINARY_D3CRACK). In line with the damaged zone predicted in Figure 7, the WIN model predicts a flexural crack at mid-span. A single crack is predicted as would be typically the case for plain concrete, whereby no further tensile forces can be distributed after the formation of a tensile crack which is not arrested by tensile reinforcement.



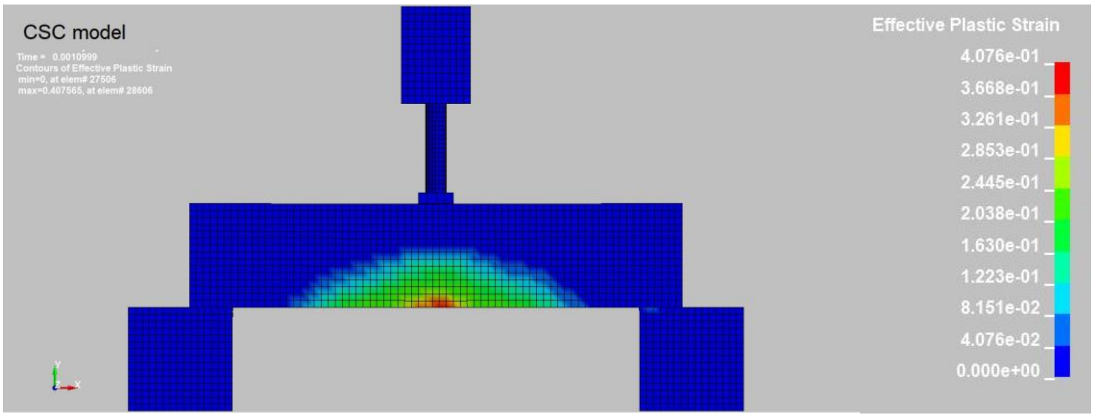


Fig.7: Effective plastic strain at 0.001 s at 450 mm drop-height for different concrete models

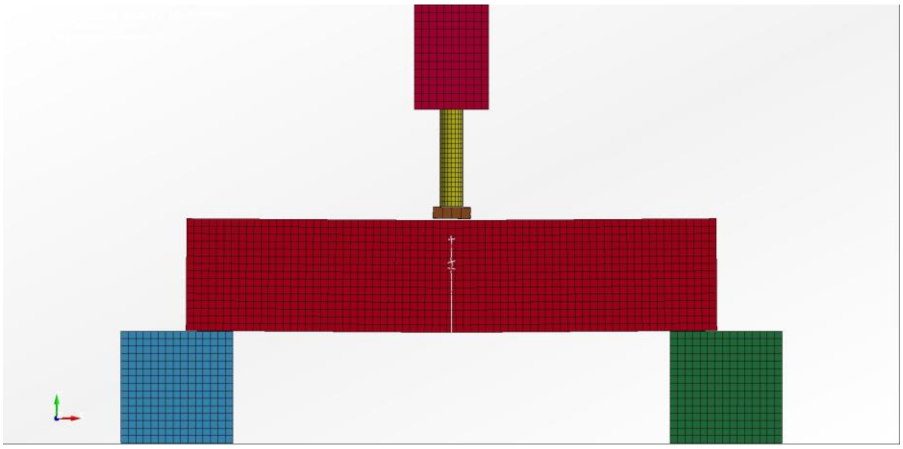


Fig.8: Crack propagation by WIN model at 450 mm drop-height

5 Conclusion

The analyses of results demonstrates the applicability of the FE model to study the impact response of plain concrete. The prediction of vertical acceleration by the FE model showed approximate values with the experimental results. On overall, it was found that the WIN concrete model showed the most consistent behaviour for low-velocity impact testing. Multiple concrete models can be used to compare results e.g. in terms of damage level. The response of the concrete models CDR3 and CSC showed the expected tensile damage zone, whereas the WIN model can be used as a supplement to detect cracks. Further experiments are suggested to understand more about the performance of concrete models under low-velocity or high-velocity impact behaviour of plain concrete.

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