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Impact resistance of reinforced concrete columns: experimental studies and design considerations

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Impact resistance of reinforced concrete columns: experimental studies and design considerations

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ABSTRACT: There are instances where reinforced concrete structures designed for static loads are subjected to accidental or deliberate impact or blast loads because of industrial or transportation accidents, military or terrorist activities. Analysis and design of structures for such events require realistic assessment of the ultimate impact resistance and a mode of failure of the structure. In this paper, a series of falling weight impact tests on conventionally designed reinforced concrete columns are described. The behaviour of quarter-scale reinforced concrete columns under static and impact loads is presented. An impact load was applied at the mid-height of the columns by a free-falling 160 kg mass using a drop hammer test rig. The impact force, the peak mid-span deflection, and the reaction forces were recorded using a high-speed digital storage oscilloscope. The aim of the static tests was to compare the load-deflection and cracking response of the columns under static and impact loads and to determine the resistance functions for shear deficient reinforced concrete columns to be used in a single-degree-of-freedom (SDOF) simulation of the response of conventional concrete columns subjected to impact and blast loads.

1 INTRODUCTION

1.1 *Background*

There has been a growing interest in the past few decades among the engineering community to understand the response of reinforced concrete structures subjected to extreme loads due to blast and impact. Although these severe transient dynamic loads are rare in occurrence for most structures, their effect can result in catastrophic and sudden structural failure. Some example of structures and their impact design requirements are:

- Bridge piers must be designed to resist accidental impact by heavy vehicles.
- Nuclear power facilities must be designed to resist aircraft impact.
- Military structures and critical civilian infrastructure must be able to survive impact and blast loads from conventional weapons explosions and debris fragmentation impacts.
- Offshore structures must be designed to sustain repeated impact loads from docking ships.

In the past, design and construction of these structures were based on the empirical data obtained in laboratory testing. Nowadays, with the rising concern for improved protective civilian structures, these design methods are proving uneconomical and require development of the improved procedures and design tools for impact and blast design of conventional structures. There are no generally engineering standards that would guide the design engineers in impact and blast loads determination for various design conditions (Remennikov, 2003; Remennikov and Rose, 2005).

In this paper, the impact behaviour of conventionally designed RC columns is evaluated using the falling-weight impact testing procedure. The impact performance of RC columns was analysed using the following experimental data: (1) failure patterns; (2) time histories of impact loads and mid-span deflections; (3) ratio of absorbed energy by the column to input energy delivered by a falling mass. The resistance functions for a design procedure based on a single-degree-of-freedom (SDOF) model of the column dynamic response have been established.

1.2 *Impact resistance of structures*

There have been a number of studies on impact resistance of reinforced concrete members over the past decades. A majority of those investigations were focused on impact behaviour of structural members failing in flexure. It was found that the economically reinforced beams could fail by yielding of the steel and crushing of the concrete with the form of damage to be roughly the same under either

Table 1. Mechanical properties of materials from tests.

Properties	Concrete (at 28 days)	Steel bars	
		Rebar	Ribbed wire
Young's Modulus: E (MPa)	29,450	200,000	200,000
Compressive Strength: f_c' (MPa)	34.0	-	-
Tensile Strength: f_t (MPa)	-	600	550
Gravitational Mass density: m (kg/m^3)	2,185	7,850	7,850

static loading or impact (Simms, 1945; Bate, 1961). Sukontasukkul et al. (2004) noted that concrete strength under impact loading shows different behaviour from that under static loading. In particular, the concrete material behaves in a more brittle manner, and increases in strength, toughness, and modulus of elasticity were found as the rate of loading increased. This is because the impact-induced cracks tend to propagate through rather than around granular aggregate, resulting in an increase in strength and toughness.

Apart from the impact material property testing, the studies of impact behaviour of concrete members have mostly dealt with flexural members. It was discovered that the response of a structural element to impact depends on an interaction between impacting body and structure described by a number of factors that include relative masses, velocities, contact zone stiffness, frequency of loading, precision of impact, and the area of local energy absorbed (Banthia et al., 1987; Kishi et al., 2002a, 2002b; Hughes and Al-Dafiry, 1995). Recently, Ando et al. (2001) have developed a simple elasto-plastic finite element model of half-columns subjected to lateral impact loading. The numerical results were found in relatively good agreement with the experimental data. The crack patterns of those half-columns were found based on the zero values of the maximum principal stresses. In general, the impact response of columns was not satisfactorily predicted for high-velocity impacts.

In this study, a drop-weight impact hammer was used to apply short-duration high magnitude impact loading to the reinforced concrete column specimens from the certain drop heights. The impact pulses were recorded using high-speed digital storage oscilloscope. The comparative study of both static and impact energy absorption capacities for each concrete column was performed. The damage and failure forms were identified.

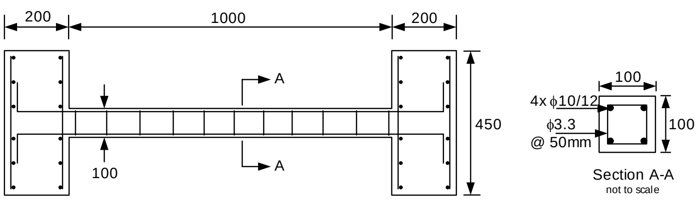


Figure 1 Scaled dimensions and shape of test columns

2 EXPERIMENTAL PROGRAM

2.1 *Test specimens*

The overall size and stiffness of the columns, which were designed in accordance with AS3600, were scaled from the actual beam-column design calculations with a model ratio of 1:4. The original aim was to subject these columns to large axial compressive load simultaneously with accidental extreme loads. All columns were of square cross section with four main rebars. Figure 1 shows the dimensions of the RC columns used. The dimensions of the cross section were 100x100 mm, the column height was 1000 mm. These scaled dimensions were based on a prototype column with the dimensions of 400x400 and 4.0-m high, typically used in ground floors of medium-rise office concrete framed buildings. The normal-weight concrete was used to construct the columns, with the design compressive strength at 28 days of 32 MPa, and the rebars used were Grade 500. Two types of the main reinforcing bars were used: deformed bars and ribbed wire. The stirrups used were 3.0mm plain steel wire with the yield strength of 250 MPa. Summary of the test series and specimens is presented in Table 2.

2.2 *Experimental approach*

In the experiments, the concrete block footings at each end of the column specimens were designed to provide the required boundary conditions. The supports were modeled as fixed-fixed to simulate the column prototype. Load was applied by means of a free falling 160 kg steel impactor.

Based on the relationship for the energy absorbed by the beam in bending (Simms, 1945), the drop height is related to the energy of deformation of the beam as:

$$\alpha WH = E \tag{1}$$

where,

W = the weight of a falling mass onto structural element;
H = the drop height;

Table 2. Summary of the test series and specimens.

Experiment No.	Main Reinforcement	Shear Capacity	Bending Capacity	Shear/Bending Capacity ratio	Type of Loading	Drop Height (mm)
A1-S	4-N12	50 kN	80 kN	0.63	Static	-
A2-I	4-N12	50 kN	80 kN	0.63	Impact	1,200
A3-I	4-N12	50 kN	80 kN	0.63	Impact	1,500
A4-I	4-N12	50 kN	80 kN	0.63	Impact	1,900
B1-S	4-N10	50 kN	54 kN	0.93	Static	-
B2-I	4-N10	50 kN	54 kN	0.93	Impact	1,400
B3-I	4-N10	50 kN	54 kN	0.93	Impact	1,600

Table 3. Impact testing data.

Experiment No.	Energy Absorbed, E_a (kN.mm)	Input Kinetic Energy, E_k (kN.mm)	Drop Mass (kg)	Impact Velocities (m/s)	E_a/E_k
A2-I	780	940	160	3.4	0.83
A3-I	780	1,160	160	3.8	0.68
A4-I	780	1,460	160	4.3	0.54
B2-I	880	1,080	160	3.7	0.82

E = energy absorption capacity of the beam;

α = reduction factor to account for the beam inertia

$$= \frac{1}{1 + \frac{4}{5}\frac{w}{W}}$$

and, w = weight of the falling object.

The drop height in the series of experiments was determined initially assuming a flexural mode of response of the RC columns using Equation 1. The details of the first series of tests can be found in Table 2. Columns in each series of tests were subjected to static loads in the transverse and axial directions. The transverse load was increased from zero to the point of complete failure of the column whilst the axial load was kept constant at about 60 kN to simulate the existing compressive stresses in columns due to dead and live loads. This allowed establishing the transverse load-deformation characteristics for the columns. For the first series, the columns were designed to withstand over 900 kN; therefore the scaled axial load was assumed be 60 kN. To maintain the required boundary conditions, the columns were attached to a strong floor using a special frame in the laboratory. Loading frame was also used to transfer the axial load and apply constraints to the specimens (see Fig.2). A load cell was used to measure the axial load in the column in order to keep axial loading consistent, while LVDT mounted at the mid-span was used to measure the corresponding deflection.

To perform impact tests, the loading frame in static tests was employed again to provide identical loading and boundary conditions. The drop hammer included a steel container filled with lead shot as an impactor. At the base of the container, there was a high-strength impact plate to transfer the load to the specimens. The falling mass was attached to a steel tower through the linear bearings guiding the descent of the drop-weight hammer. The hammer was hoisted mechanically to the required drop height and released by a quick release latch. The impact load was monitored and recorded by the dynamic load cell. The velocity of the drop weight hammer was obtained using a proximity switch at the base of the guiding column. All measured signals were sent to the digital high-speed oscilloscope. A device to measure peak impact deflections was devised for these tests. The impact testing setup and instrumentation are illustrated in Figure 3. The drop weight impact machine was tested to evaluate its efficiency. It was found that due to friction in the bearings the hammer's experimental velocity was about 70% of the theoretical velocity. Therefore, the required drop height based on the energy conservation equation was revised taking the test rig efficiency into account. The adjusted required drop height (h) was

$$h = \frac{h_T}{0.49} \tag{2}$$

Figure 2. Static testing setup

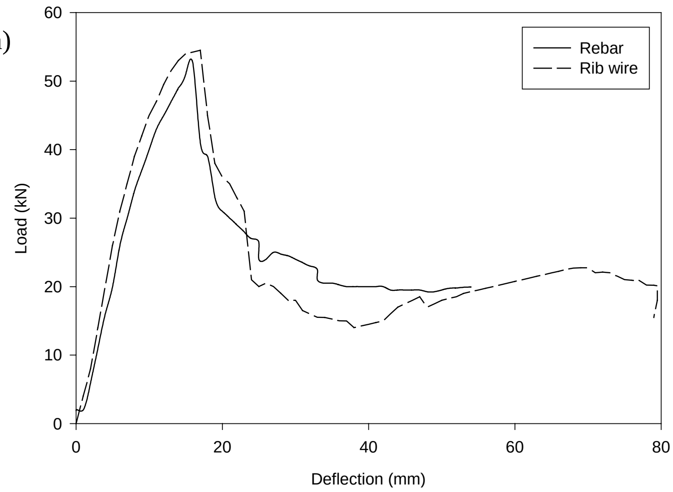
Figure 3. Impact testing setup

a)

b)

Figure 4. Static failure of test specimens

a)



b)

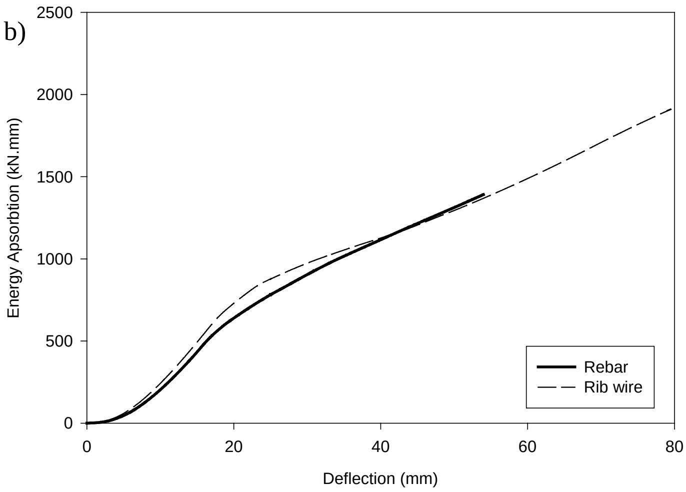


Figure 5. Load-deflection curve and energy absorptions

3 EXPERIMENTAL RESULTS

3.1 *Results of static tests on columns*

The static tests in the first series of experiments were conducted using two reinforced concrete columns using different types of steel reinforcements. Failure mode for the column reinforced with N10 deformed bars is shown in Figure 4a. It is seen that the specimens did not fail in a ductile manner as was assumed initially. Although the first cracks were flexural cracks, the column failed suddenly in a brittle mode. Figure 5a shows the load-deflection curve from the test. The initial part of the curve exhibits almost linear behavior, followed by a sudden loss of stiffness and strength, which is indicative of a shear failure in concrete members. Sectional analysis yields the ultimate shear strength of the column to be about 50kN under the test conditions. The flexural strength of the column specimens was predicted to be slightly higher, about 54 kN. It could be seen that the column is weaker in shear than in flexure, which limits the its capacity to absorb energy imparted by the impacting body. These results demonstrate that a typical column designed according to the code requirements could be shear deficient in the transverse load scenario.

The concrete column reinforced with ribbed wire reinforcement failed in a very similar way demonstrating shear failure mode. Flexural cracks at supports were followed by a rapid disintegration of the column. The load-deflection curve (in Fig. 5a) demonstrates a brittle failure at approximately the same load and deflection position as the rebar type specimens do. Clearly, the ultimate strength of the columns is limited by their shear strength. Fig. 5b presents energy of deformation for the tested columns.

3.2 *Impact Behaviour of Columns*

Examples of time histories of impact forces recorded by the digital oscilloscope are given in Figure 6. The comparison between theoretical and measured velocities of the falling hammer confirmed the efficiency of the test rig to be around 70 percent due to losses in linear bearings. Figure 7 gives a comparative chart of the predicted and measured deflections in the tests. It was found that the test results yield larger deformations than initially expected. This implies that the energy conservation equation (Simms, 1945) that works satisfactory for the members failing in bending under impact could not properly describe the impact behaviour of shear-failure-type reinforced concrete columns under impact loading.

Crack patterns for tested specimens are illustrated in Figure 8. The reinforced concrete columns have obviously collapsed in a shear failure mode due to the development and widening of a severe diagonal crack. These results correlate with the findings by Kishi et al. (2002) that if the static shear-bending capacity ratio is less than unity, the RC shear-deficient beams collapse in a shear-failure mode under impact loading. It should be noted that even if the static shear-bending capacity ratio is greater than unity, the RC columns might still collapse in a shear-failure mode. This occurs under high-velocity impact loading and can be attributed to the significant amplification of the peak reaction force by a factor between 1.5 and 2.5 compared to the static shear capacity of the column.

In all impact load tests in this study, the columns fail almost without bending cracks. Shear failure occurred near the middle of the columns under impact before significant bending occurred. This phenomenon may be attributed to the contribution of the inertial forces carrying a certain percentage of the external load and thus reducing the bending moments.

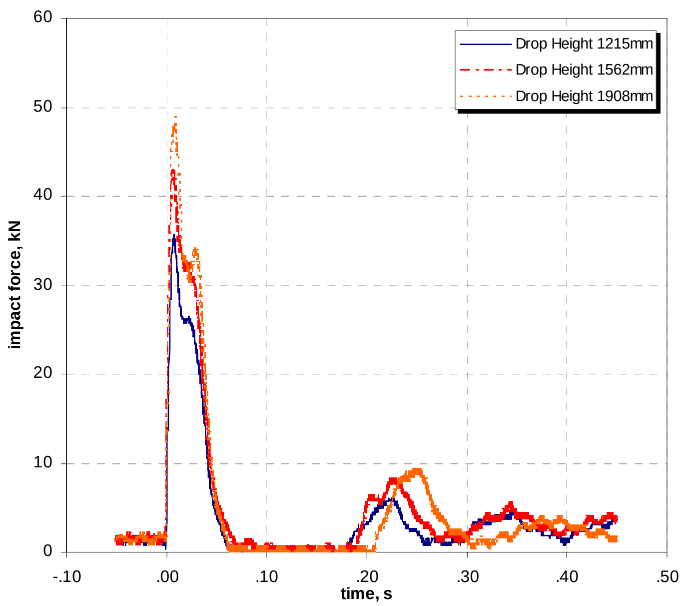


Figure 6. Example of impact forces measured

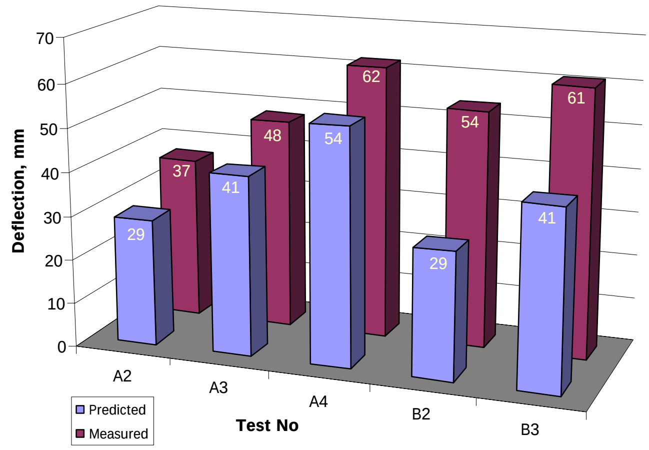


Figure 7. Dynamic impact deflections

Figure 8. Impact failure of rebar type specimen.

Figure 9. Impact failure of ribbed wire type specimen.

4 RESISTANCE FUNCTIONS

For the design procedure, a single-degree-of-freedom (SDOF) model can be used to predict the column's response, to determine the need for retrofits and to design them. The SDOF methodology requires the resistance functions to be known prior to the dynamic analysis of a structural component under impact or blast loads. The existing resistance functions represent the flexural resistance for typical structural elements. As this study has indicated, for the columns under impact load there is the need to develop the resistance functions considering the predominant shear-failure mode in order to predict their response realistically. Figure 10 presents a theoretical flexural resistance function that includes tension membrane behaviour. This flexural behaviour can only be developed if the shear capacity significantly exceeds the bending resistance capacity. Columns with poorly confined concrete require enhancement to their ductility capacity.

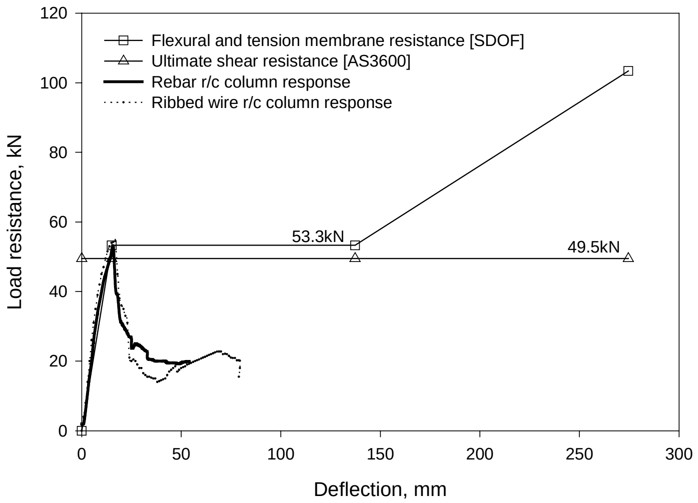


Figure 10. Column test specimen resistance functions

5 CONCLUDING REMARKS

This investigation contributes to the development of an approach for designing concrete structural members to resist accidental loads due to impact or blast events. In order to establish a rational analysis and design procedure, falling weight impact tests were conducted on a number of scaled reinforced concrete column models. The concrete columns were designed in accordance with Australian Standard AS3600 (2001). These column designs were then scaled down by a factor of four using the similitude requirements. Several laboratory tests were conducted on columns under falling weight impact loads using a drop hammer test rig. It was established that conventional reinforced concrete columns are likely to experience shear failure under transverse impact loads. When the static shear/bending capacity ration is less than unity, concrete columns collapse due to severe diagonal cracks developing from the loading point to the support point. It should also be noted that the dynamic reaction force in columns could be enhanced by a factor up to 2.0 under high-velocity impacts with the input energy-absorbed deformation energy factor of about 0.6 for high-velocity impacts.

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