Development of design guidance for low velocity impacts on concrete

K.Fullard
CEGB Berkeley Nuclear Laboratories, Gloucestershire, UK
P.Barr
UKAEA, Safety and Reliability Directorate, Culcheth, Warrington, Cheshire, UK

1 INTRODUCTION

It has been recognised in the UK, and presumably elsewhere, that when designers or safety assessors have to consider the consequence of crane failure on potentially vulnerable targets, there is uncertainty associated with the fact that these are low velocity impacts. The major uncertainty for dropped load assessments lies in the fact that, in general, the particular parameters of the event are clearly outside existing ranges of test data, whether geometrical or in respect of velocity. Nevertheless, in this situation it is quite usual to make use of empirical formulae which are intended for high velocity missiles. Confidence in the use of the empirical formulae at low velocities can obviously be improved if the data base is extended to cover drop events and shown not to affect those formulae. If it is the case that the present formulae are not adequate, it is only with the aid of relevant data that the appropriate changes can be proposed. For this reason, a programme of drop test experiments has been planned in the United Kingdom, making use of facilities at the CEGB's Structural Test Centre in Cheddar, Somerset and at the UKAEA's Atomic Energy Establishment at Winfrith, Dorset. At Cheddar masses weighing several tonnes can be dropped on to relatively large targets, while at Winfrith the economies achievable with smaller scale tests using masses in the hundreds of kilogrammes range, and with suitably smaller targets, are exploited to obtain a rapid testing rate.

There is interest in a variety of load-target combinations, but in this paper we deal only with the effects of heavy, rigid loads impacting reinforced concrete floor targets. As well as indicating the range of events that need to be considered, a method of assessing the likely consequences of a postulated dropped load accident, which is presently used, will be described. The limits of applicability of the available empirical methods and the quality and quantity of the relevant, available data base will also be addressed. Finally, the experimental programme now in progress in the UK will be outlined. This programme has been developed in response to an identified research and development requirement in UK Nuclear Power Stations, taking into account internationally available information. The programme of research is monitored by representatives of the CEGB, the UKAEA, the National Nuclear Corporation and the South of Scotland Electricity Board, and has the objective of improving the guidance which can be given to designers.

Other papers in this Conference (Wicks, J3/2 and Sinclair, J3/7)

will describe the progress which has been made, and indicate the interim conclusions which can be drawn from the test work.

2 DROPPED LOADS AND TARGETS

In an assessment of dropped load events, the range of mass considered can be from as little as a few kilogrammes (for example, hand tools), tens to hundreds of kilogrammes (scaffolding, plate sections of structural steelwork, refuelling equipment), through thousands of kilogrammes (refuelling equipment, floor slabs, boiler or steam/feed components) to tens and more of tonnes (circulators, spent fuel flasks, charge machines). The significance of any of these events is clearly associated with the height through which they are dropped, the area of contact and the nature of the impacted target. Some of the heaviest items are normally moved at heights which are no more than a metre or thereabouts, while others are invevitably up to as much as 40 metres above a floor at some sections of the transfer route.

Such drop heights could, of course, be postulated in the case of a spent fuel container. However, it should be borne in mind that for a fuel flask a concrete floor is not equivalent to the essentially rigid target used in the 9 metre drop tests of flasks under International Atomic Energy Agency regulations. The test programmes of the CEGB have demonstrated the integrity of their fuel flasks under realistic accident conditions, and we emphasise that it is the target which is vulnerable here, not the dropped load.

The floors which we are considering in this paper are reinforced concrete with the reinforcement either in both top and bottom surfaces or only in the bottom surface. It is often the case that the quantity of reinforcement varies in both directions as well as in both surfaces. However, our studies to date have not included directional variation. Typical power station floor thicknesses vary from about 200 mm through to about 2 metres while minimum span to thickness ratios range from 2:1 up to 30:1. (Gas cooled reactor pile caps are not included in the range of floors being considered). The floors are often irregular in plan but in our research programme we have restricted ourselves to square targets. Furthermore, there is a wide range of boundary conditions which could be investigated, associated with the different floor support requirements in different parts of the power station. We chose to have integral side walls for our large scale targets and simple edge supports for the small scale targets. The effect on local damage of the difference between the boundary conditions of the two scales of target may not be very significant but it is intended to confirm this by replicating the full geometry of the large scale target, at small scale, later in the programme. The span to thickness ratio has already been replicated.

3 PRINCIPLES OF THE ASSESSMENT

For floors, as well as for the case of missiles impacting reinforced concrete structures at velocities from aout 30 m/s upwards, the design or assessment procedure usually followed involves using the available empirical formulae, not only for estimating the local damage which they are intended to address, but also to define a load-time history or impulse for the purposes of determining slab response. The alternative approach of using computer codes is not normally employed, partly on the

grounds of cost and time but also because there may be doubts over the material models available, in the codes themselves and over the validation of the codes for the specific application.

Whilst there are many alternative empirical formulae available (see Adeli and Amin (1985) for a recent review) for the various levels of local damage, the authors, on the basis of presently available experimental evidence and until our current testing is completed and assessed, would normally recommend the use of the CEA/EDF/AEEW formula for perforation and the NDRC (1979) formulae for sub-perforation damage assessments (Gittus 1982). A data base is being assembled to permit statistical assessments in support of our eventual recommendations. The suggested stages in making an assessment of the effect of impact on a floor have been based on high velocity impact behaviour, as stated above. While we expect to amend the procedure, at present it is as follows:

1. Treating the dropped load as a rigid missile (since most heavy loads are unlikely to be significantly deformed by the impact), use the CEA/EDF/AEWW formula to predict whether perforation of the floor will occur. (See Appendix 1).
2. If floor perforation is not predicted, the NDRC formula can be used to make an assessment of the possibility of scabbing occurring. (We interpret this as being equivalent to the development of a conical failure surface through the floor.) (See Appendix 2).
3. Also, if floor perforation is not predicted and in order to assess global response, derive an impact force time history using the known mass (m) and impact velocity (V), together with a prediction of penetration depth (x) (into a semi-infinite target) obtained from the NDRC formula. (See Appendix 2). This loading history consists of the duration of the impact, $t = 2x/V$, the average magnitude of the impact force, $F = mV/t$, as well as the known impulse of the impact, $I = mV$. Assuming the force remains constant gives acceptable response (within 20%) for floor natural periods above about twice the impact duration. The floor itself is idealised as a single degree of freedom system with linear or non-linear stiffness depending on its ultimate load capacity relative to the applied load, and taking membrane compression forces into account. A non-linear analysis would follow any elastic analysis which indicated response beyond the elastic load capacity of the floor.

4 THE DATA BASE AND VALIDITY RANGES OF EMPIRICAL FORMULAE

The empirical formulae which we have recommended are not as relevant as we would wish to the practical situations in which they must be applied. For example the parameter ranges for the existing empirical formulae do not include applications involving masses up to 50 tonnes or more and drop heights as low as 1 metre on to targets up to approximately 2 metres thick. In general, much lighter masses impacting thinner targets at higher velocities have been used to establish the experimental data base. This is apart from considerations of dropped load geometry (nose shape, cross section shape, aspect ratio) and target span to thickness ratios. Nor is the effect of the reinforcement taken into account in sub-perforation correlations typically available, and reinforcement appears in few perforation formulae.

It will be seen from Appendix 1 that we have accounted for cross section variation by taking perimeter divided by π as being equivalent to the diameter, d, of the published version of the perforation formula.

This modification is based on high velocity tests using missiles having a variety of cross section shapes.

The validity ranges of the empirical formulae, where quoted, are generally more relevant to high velocity missiles than those impacting at speeds below 30 m/s. Of course, some low velocity tests have been carried out and included in the data base of some formulae. However, the missile masses (m) which have been used in the data base are generally less than 350 kg (Adeli and Amin), missile diameters (d) less than 300 mm and target thicknesses (t) below 600 mm.

In practice, the formulae group quantities together (not necessarily non-dimensionally) so that even when particular parameters (for example, mass) are outside these absolute ranges the event can be within the group range The ranges themselves do need careful examination. For example, taking the two groups m/d^2t (kg/m^3) and d/t, the field $1.500 < m/d^2t < 15{,}000$, $0.2 < d/t < 1.5$ is reasonably well covered with perforation data points. However, although there are few data points outside this field, the group range can be stated, legitimately, to be up to m/d^2t of 100,000 and d/t of 3.0. As far as scabbing is concerned, while we find data points for m/d^2t in the range 1500 to 40,000 and d/t in the range 0.18 to 1.5, little data appears to be available for the combination of $m/d^2t > 8000$ with $d/t > 0.5$. It will also be noted from Appendix 2 that the accuracy of the scabbing formula has not been assessed for $d/t > 0.5$.

As examples of some of the events of interest to us, we quote the following m/d^2t and d/t pairs: 17,000 and 3.4; 32,000 and 2.5; 37,000 and 2.9; 32,000 and 3.2 and 53,000 and 4.2 Several of our drop events are therefore not covered by existing parameter group ranges, even disregarding the fact that the data is not for the low velocity regime.

5 THE UK PROGRAMME OF DROP TESTING

Bearing in mind the comments made earlier concerning validity of existing hard missile empirical formulae, the objectives of the UK programme have been to investigate this issue of validity and to improve understanding of low velocity impacts in the process. The subject of sub-perforation modes of damage has been one which we have wished to address for some time, although the need to increase the information on which predictions of perforation could be based has influenced the UK programme during the last decade. For dropped loads, we wished to develop the prediction of scabbing, wide crack formation and penetration in the local impact zone as well as investigating the conditions which might lead to global failure of the floor. We were aware that span to thickness ratios were not included in the empirical formulae in use in the UK and we considered this should be investigated. Finally, the effects of various reinforcement geometries deserves study since there is an implicit assumption in the factor accounting for reinforcement in the CEA/EDF/AEEW perforation formula that this is equally placed in both surfaces and in both orthogonal directions.

In the early stages of planning it was decided to size both missiles and targets such that standard concrete aggregate and normal rebars could be used. This decision was later modified so that information at small scale could be obtained quickly, and also confirm the validity of replica scaling for low speed impact events. Thus both facilities at our disposal came to be used in the overall programme of studying dropped load events.

The large scale part of the programme carried out at Cheddar makes use of square targets with span to thickness ratios of 5 to 1. This is, therefore, less than had been used for much of the Winfrith high velocity tests which had been carried out with ratios of about 8 to 1, but greater than the smallest span to thickness ratio existing in a CEGB power station. The missiles used in our tests have interchangeable nose pieces, allowing the impact area to be changed and the nose to be flat or otherwise. Again, nose shape effects are an aspect of localised damage which we considered needed attention for finite thickness targets. The overall masses of the missiles used have been 2500 kg, and the target thicknesses have been 300 mm. The majority of tests carried out up to the present time have used flat nose pieces of 300 or 600 mm in diameter. There have also been tests with conical noses having 90° or 176° included angle. In many of the targets the reinforcement has been placed only in the rear face, but both rebar size and spacing, as well as front face reinforcing, have been studied in some of the tests.

The small scale tests at Winfrith have been based on micro concrete targets of 83 mm thickness. A variety of flat faced, circular cross-section missiles have been used with masses from 52 kg to 310 kg and diameters from 83 mm to 150 mm. Target parameters studied have included bending reinforcement on the target rear face only as well as symmetrical reinforcement, rebar diameter and pitch, and span to thickness effects.

6 CONCLUDING REMARKS

The first large scale drop test was carried out at Cheddar in the Autumn of 1985, and tests have continued at approximately two week intervals for most of the ensuing period., The body of data from large scale tests has thus been substantially increased over what it was prior to this programme and includes both perforation and sub-perforation results. We are seeing sub-perforation damage which is clearly different from that due to high velocity impact and which will eventually be reflected in amended assessment procedures.

The small scale tests have also continued over a similar period and have allowed a number of interesting phenomena to be studied, as well as showing the validity of replica scaling to low speed impact events, and they have indicated the expected uncertainties in results from repeated nominally identical experiments. More details of the tests and discussion of the results appear in other papers at this Conference Wicks, J3/2 and Sinclair, J3/7). The limitations of the existing empirical formulae are becoming clearer from our results, but it will be necessary to continue with the research programme for some time yet before firm amendments can be proposed.

7 ACKNOWEDGEMENT

This paper is published with permission of the Central Electricity Generating Board and the United Kingdom Atomic Energy Authority.

REFERENCES

Adeli,H. and A.M. Amin 1985. Local effects of impactors on concrete structures. Nucl.Engrg.Des.88:301-317.

Gittus, J.H. 1982, PWR degraded core analysis. A report by a committee chaired by Dr. J.H. Gittus, UKAEA Northern Division Report ND-R-610(S). Issued by RNPDE. HMSO ISBN 0-85-356-46

Sinclair, A.C.E. and Baker, D., 1987, The impact resistancke of concrete slabs under heavy dropped loads. SMiRT 9, J3/7.

APPENDIX 1 : CEA/EDF/AEEW Perforation Formula

For targets with symmetrical bending reinforcement meshes close to the face of a slab, and for missiles of circular, rectangular (1 < "face thickness/face length" < 10), triangular, and semi-circular cross-section, the equation relating the pertinent parameters of missile and target is

$$V_c = 1.3\rho^{1/6} f_{cy}^{1/2}\left[\frac{pt^2}{\pi m}\right]^{2/3} (r + 0.3)^{1/2}$$

The range of variables over which the formula has been found to hold (by direct experiment) are:-

45	<	V_c	<	300	m/s
15×10^6	<	f_{cy}	<	37×10^6	Pa
18×10^6	<	f_{cu}	<	46×10^6	Pa
0	<	r	<	0.75	% ewef (each way each face)
0.2	<	$\frac{p}{\pi t}$	<	3	
150	<	$\frac{m}{p^2 t}$	<	10^4	kg/m^3
(OR 1500	<	$\frac{m}{d^2 t}$	<	10^5	kg/m^3)

where

ρ	=	density of concrete	kg/m^3
f_{cy}	=	characteristic compressive strength of concrete measured on cylinders 150ϕ x 300mm	Pa
f_{cu}	=	compressive strength measured on cubes 150mm	Pa
p	=	perimeter of missile impact face	m
d	=	missile (equivalent) diameter	m
t	=	thickness of concrete	m
m	=	mass of missile	kg
r	=	reinforcement quantity	% ewef

With composite targets, where the concrete target is backed by a steel plate, it has been found that the reinforcement term (r+0.3) could be replaced by (B+0.3) where B is the sum of the rear face reinforcement and steel plate area as a percentage of target cross section.

APPENDIX 2 : NDRC Formula

Scabbing

For solid missiles impacting a concrete barrier, the minimum barrier thickness, t_s, required to prevent scabbing from the rear surface can be estimated from the formula:-

$$t_s/d = 5.3\ (G)^{1/3} \qquad 2.1$$

where G is calculated from equation 2.2 below. A simple rearrangement of this formula yields the critical velocity to generate scabbing from the barrier.

The accuracy of this formula to predict the critical scabbing velocity within the parameter ranges:-

26×10^6	$<$	f_{cy}	$< 44\times10^6$	Pa
1500	$<$	$m/(d^2 t_s)$	$< 40{,}000$	kg/m^3
29	$<$	V_i	< 238	m/s

has been assessed as:-

$\pm 40\%$ for $0.18 < d/t_s < 0.5$

Penetration

The normalised depth of penetration, z, of a solid missile into a reinforced concrete barrier can be estimated from the formulae:-

$$G = 3.8 \times 10^{-5}\ Nm\ V_i^{1.8}/(f_{cy}^{0.5}\ d^{2.8}) \qquad 2.2$$

with $G = 0.55z - z^2$ for $z = x/d < 0.22$

$G = (z/2)^2 + 0.0605$ for $0.22 < z < 2$

where x = penetration depth (m) $z = \frac{x}{d}$

d = missile diameter (m)

N = a nose shape factor

G = penetration function

V_i = impact velocity (m/s)

m = missile mass (kg)

f_{cy} = concrete characteristic strength (Pa)

The nose shape factor, N, has the value 0.72 for a flat ended missile, 0.84 for a spherical-nosed missile, 1.0 for a bullet-nosed missile and 1.14 for a sharp-nosed missile.

The parameter ranges of this formula for which the accuracy of the penetration prediction has been assessed are:-

$25 < V_i < 300$ m/s

$22 \times 10^6 < f_{cy} < 44 \times 20^6$ Pa

$5{,}000 < m/d^3 < 200{,}000$ kg/m^3

Within these ranges the accuracy is:-

±20% for $z > 0.75$

+100% to -50% for $z < 0.75$