The R3 Impact Assessment Procedure for Nuclear Power Plant Structures

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ABSTRACT

An assessment procedure, developed in the UK, for impact damage caused to steel and concrete targets is introduced and an appraisal of further research requirements to improve impact understanding is provided.

1 INTRODUCTION

Nuclear Electric, with AEA Technology, have been putting together a comprehensive package of procedures for the assessment of the consequences of pressure boundary failure, dropped loads, aircraft crash and turbine failure. The R3 Impact Assessment Procedure brings together methods which are partly based on an accepted interpretation of experimental data and partly on theoretical and numerical studies. Much of the source material behind the different aspects of assessment has previously appeared in the open literature, in some cases several decades ago. In making use of the source material, the intention has been to make R3 as all-embracing as possible so that it should be possible for an assessor to produce a safety case which is as complete as available information can make it.

This paper details the scope of R3, the procedures incorporated and the status of understanding. Information will be given on factors included to assure conservatism in an assessment and on our most recent research into scaling effects for steel targets. The aspects considered to need further investigation for UK applications will be discussed.

2 SCOPE OF THE R3 PROCEDURE

The modes of failure of plant or other sources explicitly considered in the first issue of R3 are (1) pressure boundary failure giving rise to projectiles, or jets and blast, (2) hot gas or steam release giving rise to global pressure and temperature transients, producing thermal damage, (3) rotating machinery failure giving rise to projectiles, (4) wind borne projectiles and (5) aircraft crash.

The modes of damage considered are (1) whipping pipe impact leading to target pipe local damage or global collapse, (2) impact such that a projectile either completely passes through a steel or concrete target (perforation) or forms an indentation in the impact face of a concrete target (penetration), (3) impact resulting in fragments being ejected from the distal (remote) face of a concrete target without perforation occurring (scabbing), (4) impact resulting in a plug of a concrete target being formed which is capable of being pushed through the target by the projectile (cone cracking) and (5) global distortion of non-pipe targets by impact or overpressure loading.

The above aspects are covered in five volumes of R3: (0): Overview, (1): Specification of Loading, (2): Assessment of Pipewhip, (3): Concrete Target Response and (4): Response of Steel Structures. In addition, consideration is being given to providing a further volume on energy absorption assessment.

3 STATUS OF UNDERSTANDING

Upper limit correlations of experimental data are provided for a wide variety of missile types generated by rupture of gas-pressurised vessels. However, only two missile types are dealt with for vessels containing liquid which undergoes partial flash-evaporation on rupture. There is insufficient information for other vessel contents.

The properties of blast waves from failing gas-pressurised vessels have been correlated in a similar manner to that employed for high explosives, for blasts in the open. Normal reflection at a rigid surface is treated theoretically.

As there is only very limited experience data available for missile generation from rotating machinery failure, the problem is treated theoretically. Wind borne projectiles are also treated theoretically.

For soft missile impacts, including aircraft crash, judgement is needed on the effective impact area to be used in a simplified theoretical method. Test work in the USA indicates that the predicted force-time history is a good representation of actual loading.

Much of the procedure for determining the characteristics of a whipping pipe is theoretically based and has been available since the need to consider whip events emerged during the 1970's. See, for example, Roemer & East, 1980. The approach of Roemer and East makes use of simplifications which have been used in design against pipewhip in the UK and elsewhere, supplemented by the use of non-linear finite element methods where the simplified methods failed to meet a variety of criteria, particularly the angular movement of the whipping pipe. The R3 procedure is largely based on methods used for Heysham II and Torness. The assessment of pipe on pipe impact is based primarily on numerical studies and theoretical concepts of the deformation of a whipping pipe about a target pipe.

The procedures for impact on concrete targets have been derived from the results of extensive series of experiments and analyses carried out by organisations world-wide. The emphasis in R3 is on local damage.

The assessment of steel target distortion under impact can be performed using non-linear finite element codes but perforation assessment employs high velocity empirical correlations which have been used in the nuclear industry for as much as three decades. The correlations were derived using flat targets and flat ended missiles producing a punched hole. A limited amount of information is available for pointed nosed missiles.

4 APPLICATION OF THE R3 PROCEDURE

The various volumes of R3 are intended to be used in combination with one another to permit a comprehensive assessment of the consequences of any failure which results in transient loading of structures. The procedure within each volume consists of a number of well-defined steps and similarly the overall procedure may be defined in terms of the following steps:

(1) Determine loading characteristics (using Volume 1). This covers the identification and characterisation of missiles as well as pressure or thrust and temperature transient specification.

(2) Where the failure is a complete circumferential break of a pipe, use Volume 2 to determine the characteristics of the resulting whipping motion.
(3) If the target structure is concrete, use Volume 3 to investigate the consequential damage.
(4) If the target structure is steel (including pipes), use Volume 4 to investigate the consequential damage.
(5) If failure of an unpressurised target gives rise to secondary missiles or if, after passing through the target, the original projectile possesses residual energy, use Volume 3 or 4 as appropriate for further damage assessment. If the target is pressurised and failure is predicted, commence further assessment from Volume 1.

5 CONSERVATISM

Those parts of R3 which are based on interpretation of experimental data, in particular for assessment of perforation of steel or concrete targets, include statistical information about the data bases. The experimental perforation data for mild steel plates were compared with predictions of perforation given by several empirical formulae, assuming the data to have a log normal distribution around a calculated mean value. Values by which the formulae had to be multiplied in order to give a lower bound to various percentages of the data were calculated. R3 states the mean of the data and, to give a conservative estimate of perforation energy, a multiplying factor for each formula corresponding to the level above which 95% of results are expected to lie.

In considering the various empirical formulae for steel target perforation, missile impacts were classified depending on the ratio of missile length to missile diameter, ℓ/d. If $\ell/d \geq 13$, the missile is considered "long", while if $\ell/d < 13$, the missile is considered "short". R3 currently gives two formulae to predict whether long missiles will perforate a mild steel panel. These are the SRI formula (Zabel, 1958) and Neilson's formula (1985). Three formulae are available to predict whether a short missile will perforate a mild steel panel, these being the BRL formula (Gwaltney, 1968) and two formulae by Jowett (1986).

A sample size of 32 was used for the short missile analysis. The ranges of the data on which the statistical analysis was carried out were: $0.07 < t/d < 0.99$, $2.00 < \ell/d < 8.18$, $8.03 < w/d < 34.88$, $12.01 < w/t < 255.2$ and $57 < v_p < 270$.

A sample size of 42 for long missile impacts is available, coming mostly from the SRI experiments. The ranges of data for the long missile experiments were: $0.12 < t/d < 0.58$, $13 < \ell/d < 223$, $4.5 < w/d < 32.26$, $7.8 < w/t < 138$ and $23 < v_p < 107$.

For each experimental result, R is the ratio between the actual perforation energy and the predicted perforation energy and $L = \ln(R)$. The sample mean of L is $\bar{L}$. The scatter of the data around this average value gives a value for the estimate of the standard deviation of L, s_L. ;.br

The log mean ($\bar{L}$), log standard deviation (s_L) and best estimate lower bound tolerance limits to 95% of the data for short missiles were respectively -0.1115, 0.2956 and 0.538 for BRL, 0.0135, 0.2457 and 0.664 for Jowett, -0.5336, 0.3718 and 0.309 for SRI and -0.5731, 0.4657 and 0.253 for Neilson's correlation. For long missiles, the corresponding results were 0.0903, 0.2352 and 0.733 for BRL, 0.2528, 0.2376 and 0.859 for Jowett, -0.0390, 0.1460 and 0.750 for SRI and -0.0620, 0.1682 and 0.706 for Neilson's correlation.

If the formulae perfectly predicted the perforation energies, both $\bar{L}$ and s_L would equal zero (and the mean value of R would equal unity). Therefore, an indication of a good fit to the data is given if $\bar{L}$ and s_L are close to zero.

If $\bar{L}$ is negative, the formula on average overpredicts the perforation energy and if $\bar{L}$ is positive, it underpredicts the perforation energy.

It is obvious from the results that only the BRL formula and Jowett's formulae are applicable to short missile impacts with Jowett's formulae giving a value of $\bar{L}$ close to zero and the tightest grouping of data around this mean value. A scatter plot showing the experimental data compared against Jowett's formulae is shown in Figure (1). Both the SRI formula and Neilson's formula greatly overpredict the perforation energies for short missile impacts.

For long missiles, both the SRI and Neilson's formulae give good estimates of the perforation energy and give the tightest grouping of data around the mean values. Although both the BRL and Jowett's formulae give conservative estimates on average, the scatter of data is much greater than with the SRI and Neilson formulae. A scatter plot of the long data compared with Neilson's formula is shown in Figure (2).

The same approach has been used for reinforced concrete perforation data. Against the formula given in R3, it was found that 95% of the results lie above 0.79 times the formula prediction.

6 SCALING STUDIES

The R3 perforation formulae are apparently applicable to any size of target and missile, provided the various ranges of parameter ratios apply. However, the bulk of the data on short missiles involves plates of less than 7mm thickness and few that are intended to be complete scales of one another. Fully scaled tests have been carried out in the UK with 3mm and 30mm mild steel plates for missiles of ℓ/d of 4.00, flat nosed and 90° coned. The flat nosed missiles perforated the 3mm targets at 95m/s while the 30mm targets were perforated at 85 $\pm$ 2.4m/s. A Jowett (unfactored) prediction of the perforation velocity would have been between 12 and 17% below those observed, so the assessment would have been safe.

With cone-nosed missiles, the observed perforation velocity was between 100 and 106m/s for the thin plate. The perforation velocity for the thick plates was about 55m/s. In energy terms, instead of 1000 times as much energy for perforating the thick plate as the thin, only about 300 times as much was needed. A major difference between the two sizes was seen to be the greater relative thickness of plane strain in the 30mm plate, along the fracture surfaces. A skin of approximately 1mm thick on each face appeared to have failed under plane stress. Fracturing producing petals is apparent with cone nosed missiles and clearly absorbs a significant proportion of the impact energy. Fracture is a recognised non-scaling phenomenon but the extent to which it will affect perforation is still unknown. We have some evidence that room temperature laboratory tests could give unrepresentative, brittle failure results which would not be observed with high temperature plant targets.

7 FURTHER NEEDS

The theoretical threatment of jet thrust has been validated against experiment for simple geometries but as there is no satisfactory theoretical description of the pressure distribution within the jet impingement zone and only very limited experimental data, no recommendations have been made for impingement pressures within the jet envelope.

Data on the interaction of blast waves with walls at oblique angles or within a closed compartment, where multiple reflections occur, are scarce and procedures to deal with these situations have not been developed. Research is underway.

Computer programs for determining the global effects of hot gas or steam release have only been validated by data from small scale tests.

Wind borne projectiles are treated theoretically and demonstration is required that the assessment method is pessimistic.

The procedure for determining the characteristics of a whipping pipe is theoretically based and makes use of simplifications which lack experimental validation and have therefore to be treated with caution. Whilst finite element methods have been widely used in design, there is only limited validation against experiment of the finite element modelling of whipping pipelines and this limits confidence in any model used for assessment.

In on-going work on pipewhip effects have been observed which are not yet included in either simplified or more sophisticated methods. An example is the stiffening under centrifugal forces which affects the extent of the plastic material behaviour.

The assessment of pipe on pipe impact lacks experimental validation.

For impact on concrete targets, research has been concentrated on local damage and few experimental data are available to validate global response predictions. There is a gap between methods for low velocity and high velocity non-perforating damage, that is, impacts in the range 5 to 25 m/s. Finite element codes are still being developed and need to be validated over a wide range of applications.

The response of steel targets under impact by a pointed nosed missile, for example, involves a petalling of the target plate not seen with a flat ended missile. This fracturing process is not scalable and thick targets will be fully perforated at lower scaled energies than thin targets. It follows that it is not easy to quantify the effect of nose shape. Work is on-going on these aspects of target response. For the general target, the effect of curvature or radius to thickness ratio on perforation resistance has not been quantified and there is no reported information on the effect of asymmetric impact. The application of empirical correlations at low velocity is in question, particularly for non-circular missiles whose corners can initiate plate failure.

ACKNOWLEDGEMENT

This paper is published with the permission of Nuclear Electric plc and AEA Technology.

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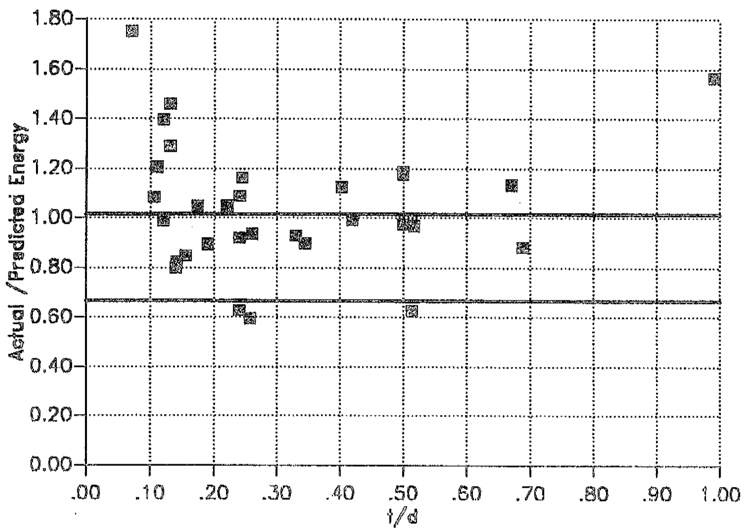

Fig. 1 Jowett Prediction For Short Data

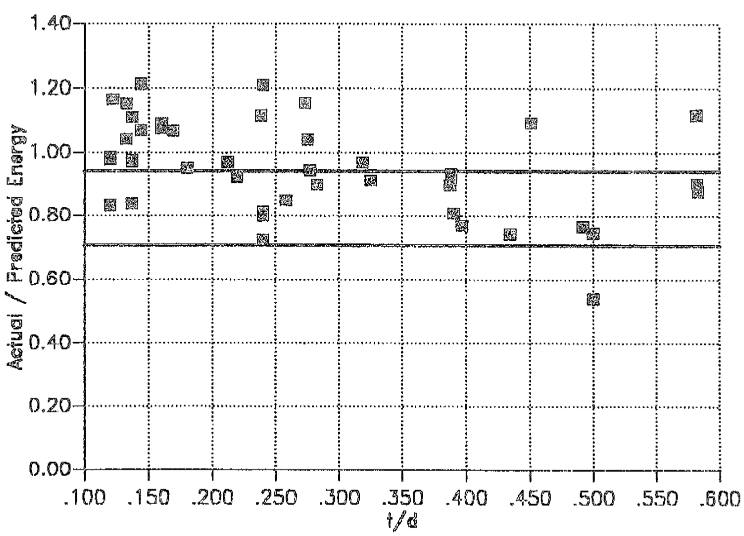

Fig. 2 Neilson Prediction For Long Data