BEHAVIOR OF REINFORCED CONCRETE BARRIERS SUBJECT TO THE IMPACT OF TURBINE MISSILES

P.M. McMAHON, S. K. SEN, B. L. MEYERS
Bechtel Power Corporation,
15740 Shady Grove Road, Gaithersburg, Maryland 20760, U.S.A.

SUMMARY

The paper presents a methodology for evaluating the local damage (missile penetration and backface barrier damage) of a reinforced concrete barrier impacted by a non-deformable missile. An interface force-time history and barrier failure mechanism are developed, using available experimental data. These methods are extrapolated to the case of turbine missiles which are characterized by large dimensions and high impact velocities outside the range of available data.

The procedure for predicting missile penetration is based on a triangular interface force-time history derived from time history measurements of smaller missile impacts.

Backface barrier damage, including perforation of the missile is predicted using the limiting strength of the failure mechanism developed in the barrier. During impact and penetration, shear cracks propagate through the barrier at an angle extending from the missile impact area to the barrier backface. These cracks form the boundaries of a shear cone. If the shear stress capacity along the shear cone surface is exceeded, concrete failure occurs, and perforation can only be prevented by the backface reinforcing or spall plate. Methodology for dimensioning the cone, it's shear capacity, and the reinforcing capacity are presented.

The penetration and perforation criteria developed here are shown to correlate well with available test data.

The paper also presents a sensitivity study of the key parameters such as equivalent missile diameter, barrier shear strength, "shear cone" dimensions, peak interface force and spall plate thickness. The assumed "shear cone" dimensions and spall plate thickness appear to be the most sensitive and important parameters.

1. Introduction

The present state of the art for evaluating missile impact damage on barriers caused by ruptured turbine discs generally involves the use of empirical equations developed from experimental data for ballistic missiles. While the shape, mass and velocity os such missiles differ significantly from the postulated turbine missiles, nevertheless in the absence of any realistic experimental data, two ballistic based damage criteria (1), e.g., NDRC (proposed by National Defense Research Committee) and BRL (proposed by the Ballistic Research Laboratory) have been frequently used to determine the effectiveness of reinforced concrete barriers in nuclear power plants.

To overcome the apparent shortcoming involved in extrapolating empirical formulas way beyond the parametric range of the test data, a quasi analytical methodology which explicitly considers the mechanics of missile penetration in light of the limiting local capacity of the barrier has been developed and discussed in this paper. Following a brief presentation of the theoretical aspects of the formulation, its applicability to the impact of smaller missiles is demonstrated by comparing the analytical results with the available experimental data. The analysis is then extended to cover the turbine missile impact case and a parametric sensitivity study is performed to identify the critical parameters.

Finally, an estimate of the required barrier thickness for a given turbine missile impact case is presented.

2. Theory

The general interface force-time history for a non deformable missile impacting on a reinforced concrete barrier of infinite thickness may be assumed to be an isosceles triangular pulse. This assumption is in part based on the available experimental data (2) and analytical studies (1) with quasi deformable steel pipe missile. Integrating the triangular force-time curve twice results in the maximum penetration, X_p^*, of

$$X_p^* = F_1 t_1{}^2/M \tag{1}$$

where F_1 is the peak of the triangular shaped interface force, t_1 is one-half of the total duration and M is the mass of the missile. Using Eq. 1 and the impulse-momentum relationship associated with the impact ($F_1 t_1 = M V_o$), the slope of the triangular pulse F/t_1 can be expressed as

$$F_1 t_1 = M V_o{}^3/(X_p^*)^2 \tag{2}$$

where V_o is the impact velocity of the missile.

Based on the available missile test data estimates of the slope F_1/t_1 have been obtained as shown in Table I. While the slope appears to increase with the missile diameter it is essentially independent of the impact velocity, V_o for the velocity range considered. Based on the values of F_1/t_1 given in Table I for different missile diameters, the following empirical equation has been derived.

$$F_1/t_1 \text{ (Kip/Sec)} = 430{,}000\ D^{1.72} - 350{,}000 \tag{3}$$

where D=Missile diameter in inches

The foregoing formulation on the missile penetration is based on a missile impacting an infinite concrete barrier. However, in the practical case of a barrier with limited thickness and capable of developing only finite resistance prior to failing in punching shear, the formulation has been modified to take into account such a phenomena. Neglecting the overall flexural response of the barrier, it is postulated that when the missile barrier interface force during the penetration phase exceeds the punching shear capacity of the barrier, cracks will develop isolating a "shear cone" as shown in Figure 1. The existence of such a failure made has been observed in sections cut through test barriers (2).

The punching shear capacity of the barrier, V_u, will essentially depend on the ultimate shear stress v_u and the shear cone surface area which is a function of the angle θ. Based on an analysis of the full scale impact test data (2) it has been suggested in Ref. 4 that $v_u \sim 12\sqrt{f'c}$. Experiments with blast loading (5) also indicate that $V_u \sim 9$ to 15 times $\sqrt{f'c}$. The maximum punching shear resistance V_u is offered by the barrier prior to formation of the cracks and isolation of the shear cone is determined by considering Vu acting over an equivalent cylindrical surface of height = $(d-X_p)$ and diameter = $(d_t+d_B)/2$ (see Fig. 1) thus

$$V_u=\frac{\pi}{2}(d_t+d_b)\ (d-X_p)\ v_u \ldots\ldots\ldots\ldots\ldots\ldots (4)$$

The angle θ, which essentially determines the periphery of the shear cone, can be estimated to be around 60° based on the observation from several experimental results (2, 6, 7, 8). It should be noted that the observed failure surface actually curves out toward the backface as shown in Figure 1 and designated angle θ is an average fit of the failure surface.

As indicated before the shear cone isolated only when the interface force F exceeds the punching shear capacity, V_u. Since V_u, F and X_p are interrelated (see Equations 2 & 4), the following equations have to be solved interrelatively in conjunction with Eq. 4

$$F(t=t_1) = Vu(t=t_1) \qquad (5)$$

$$X_p(t=t_1) = \frac{F_1(t_1)^2}{6M}+V_o t_1 \qquad (6)$$

where t represents the time unit at which the shear cone isolates instanteneously.

In evolving a realistic theory of barrier perforation, the basic consideration has been to estimate the various modes of energy dissipation in the barrier. Understandably if the sum total of the energy so dissipated is less than the initial energy at impact, $E_o=\frac{1}{2}MV_o^2$, a missile will perforate the barrier. Designating E_{xp} as the energy absorbed during the penetration sequence,

$$E_{xp}=\int_o^{x_p(t=t_1)} F(t)\ dx_p = \int_o^{x_p(t=t_1)} \frac{F_1 t}{t_1}\ dx_p \qquad (7)$$

If $E_o > E_{xp}$, the shear cone will be formed instantaneously at $t=t_1$ (i.e, $F(t+t_1)=F_1=V_u(t=t_1)$ and a momentum transfer would take place between the missile and the shear cone via a plastic impact. The external energy Em available after the impact is given by

$$E_m=(E_o-E_{xp})M/(M+M_c) \qquad (8)$$

where M_c=Mass of the shear cone

If the energy absorbing capacity of the backface rebar net and the spall plate, if any, designated as E_{rb} and E_{sp} respectively, is greater than E_m, then the missile will not perforate the barrier. Otherwise the barrier will be perforated and the missile will exit with a residual velocity V_R given by

$$V_R = \sqrt{\frac{2(E_m - E_{rb} - E_{sp})}{M + Mc}} \qquad (9)$$

It should be noted that the missile must be sufficiently large to activate the backface rebar. If not, the missile will perforate immediately after the shear stress is exceeded along the shear cone.

The energy absorption in the rebar and the spall plate is achieved through stretching of the members to a strain level corresponding to the ultimate stress, in the vicinity of the impact, specially over an area with diameter = d_B.

It is assumed that the spall plate would be adequately anchored and most probably would be stiffened. Although not considered here, such stiffeners would enhance the energy absorbing capacity of the plate.

3. Evaluation of Experimental Data

The above procedure for determining the perforation characteristics of reinforced concrete barriers when applied to smaller diameter solid missiles yields results which are in good agreement with the available test data as shown in Table II. Listed in the table under the Column[1] perforation thickness, test[1], are the estimated slab thicknesses at the threshold of perforation based on test data. Specifically, the 1" diamater missile (Ref. 8) perforated a 3" thick slab but failed to go through a 6" slab. Similarly the 8" diameter missile (Ref. 6) perforated a 12" thick slab but did not exit through a 18" slab. The predicted and the measured residual velocities reveal excellent agreement.

The effect of rebar has been considered for the 8"Ø missile case only since the shear cone diameter d_B for the 1"Ø missile is smaller than the rebar spacing.

4. Turbine Missile Impact

In extending the proposed methodology to the turbine missile impact case, it is recognized that there are several key parameters which due to their random nature of occurence and/or lack of any specific test data, could vary and affect the results of the analysis. These parameters are: (a) the area of the impact; (b) the force-time history slope F_1/t_1; (c) the angle θ defining the shear cone; (d) the ultimate punching shear stress capacity Vu. Using the 43" last stage wheel missile (Type IIIa) as an example, the missile being the most destructive one postulated for a General Electric Turbine (3), parametric studies have veen conducted to determine how the relationship between the residual velocity V_R and the barrier thickness is affected by the aforementioned parameters. The missile, assumed to be nondeformable, weighs 8200 lbs. and the maximum postulated velocity of ejection is 650 ft./sec. (3). The missile assumed to impact normally to the barrier to produce the worst effect, usually produces an irregular area of impact which is converted to an equivalent circular area for the analysis purposes. Based on the configuration of the missile, a maximum and a maximum area of impact have been identified.

Consider first the ultimate punching shear stress Vu. When, for reasons indicated earlier, Vu was varied between $9\sqrt{f^1c}$ and $15\sqrt{f^1c}$, it had negligible effect on the V_R vs. barrier thickness curve. This is because the energy absorbed during penetration E_{xp} (see Eq. 7) is small compared to Eo even with a high value of Vu.

The effect of the shear cone angle θ is shown in Figures 2(a) and (b) and can be seen to be significant. The reason behind this significance is that the angle θ determines the mass of the shear cone M_c which is inversely related to E_m, the portion of the initial kinetic energy left in the system after the plastic impact and the resultant momentum transfer (see Equation 8).

Based on the analysis presented in Section 2, $\theta=60^{o}$ appears to be a reasonable assumption with the present state of information in this respect.

The graphs presented in Figure 2(a) and (b) essentially differ in the way the residual velocity has been calculated from Equation 9. While in Figure 2(a) V_R has been calculated using Eq. 9 as given, in Figure 2(b) M_c has been neglected (i.e., $M_c=0$) to provide an upperbound estimate of the V_R curves. In either case, the computed barrier thickness at the threshold of perforation ($V_R=0$) did not change as expected. For the sake of brevity, however, the results of other parametric studies which have been presented here were derived using Equation 9 with $M_c=0$.

Figure 3 illustrates the effect that variations in the force-time history slope and the impact area (reckoned here with the equivalent diameter D) have on the residual velocity V_R. The missile diameters considered correspond to the maximum, minimum impact area as well as an average value. Based on the available experimental results which have indicated that the slope F_1/t_1 increases with the missile diameter (see Equation 3), the slope for the turbine missile impact has been varied from a minimum of $15x10^6$K/Sec. (corresponding to a 8" diameter missile) to a maximum of infinity. The close clustering of the curves in Figure 3 indicates that the results are not sensitive to the aforementioned variations; the reason being that the impact diameter and the slope primarily affects the magnitude of the energy E_{xp} absorbed during the penetration phase. However, with the bulk of the energy dissipation occuring during the plastic impact and little during the penetration even a significant variation in E_{xp} affects the results only marginally.

The effect of adding a spall plate on the backward face of a reinforced concrete barrier is exhibited in Figure 4. The plate, when not perforated, will not only contain spalling but will also absorb energy primarily by membrane action. For the plate to behave in such a fashion, the isolated concrete shear cone has been assumed to act as a buffer to prevent a direct and premature missile perforation of the plate.

It should be noted that the backface reinforcing (#11 @ 12 for all barrier thicknesses) and the spall plate absorb only a small percentage of the total impact energy, approximately 5%. However, since they are activated after the plastic impact and after the dissipation of the bulk of the energy, they effect the results significantly.

5. Conclusion

Based on the methodology presented here it is found that a 5'-6" thick reinforced concrete barrier would be required to prevent the selected missile from perforating the barrier. Adding a 1/4" steel spall plate would reduce the barrier thickness to 4'-6". These computed barrier thicknesses which are considerably smaller than that predicted by the NDRC formula, will, of course, vary with the missile characteristics and would have to be determined on a case by case basis.

References

(1) Kennedy, R. P., A Review of Procedures for the Analysis and Design of Concrete Structures to Resist Missile Impact Effects, Holmes and Narver Corp., Anaheim, Sept. 1975.

(2) Stephenson, A. E. "Full-scale Tornado Missile Impact Tests", Electric Power Research Institute Report No. NP-440, July 1977.

(3) Downs, J. E., Memo Report: Hypothetical Turbine Missile Data, 43-inch Last State Bucket Units, General Electric Co., March 1973.

(4) McMahon, P. M.; Sen, S. K.; Meyers, B. L.; Buchert, K. P., "Response of R/C Slabs Impacted by Tornado Missiles", ASCE, J. Structural Division, March 1979.

(5) Albritton, G. E. "Deep Slabs Subjected to Static and Blast Loading", ASCE, J. Structural Division, Nov. 1969.

(6) Vassalo, F. A., Missile Impact Testing of Reinforced Concrete Panels, Calspan Corp., HC-5609-D-1, Buffalo, NY, Jan. 1975.

(7) Jankov, Z. D.; Shanahan, J. A.; White, M. P., "Missile Tests of Quarter Scale Reinforced Concrete Barriers", A Symposium on Tornadoes, Texas Tech. Univ. Lubbock, TX, June 1976.

(8) Barber, R. B., "Steel Rod/Concrete Slab Impact Test", Bechtel Corp., Oct. 1973.

TABLE I - COMPARISON OF PENETRATION TEST DATA (TORNADO MISSILES) VS. VALUES PREDICTED BY TRAINGULAR TIME HISTORY

REF.	SLOPE (K/Sec.)	MISSILE DIAM. (In.)	MISSILE WGT. (#)	INITIAL VEL. (fps.)	PENETRATION, TEST (In.)	PENETRATION, CALC. (In.)
8	80,000	1	8	213	2.1	1.7
8	"	1	8	150	1.2	1.2
2	"	1	8	435	6.1	5.8
2	"	1	8	303	3.5	3.6
7	$2.5x10^6$	3	12.7	101	0.15	0.15
7	"	3	23.5	95	0.19	0.19
6	$15.3x10^6$	8	215	122	0.34	0.4
6	"	8	215	161	0.50	0.3
6	"	8	215	295	1.25	1.25
6	"	8	215	377	1.81	2.0

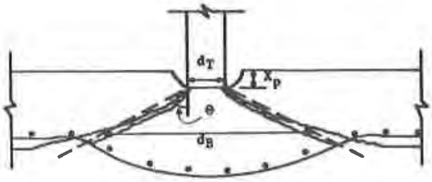

FIGURE 1 - SHEAR CONE MECHANISM

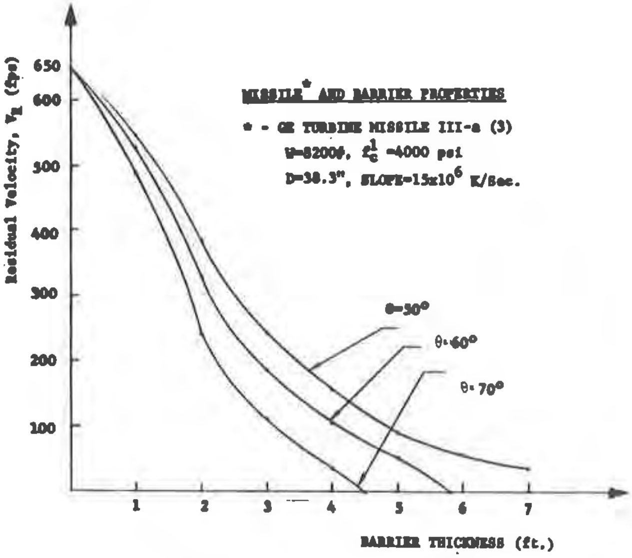

FIGURE 2a - RESIDUAL VELOCITY VS. BARRIER THICKNESS FOR DIFFERENT SHEAR CONE ANGLE, θ (PER EQ. (8))

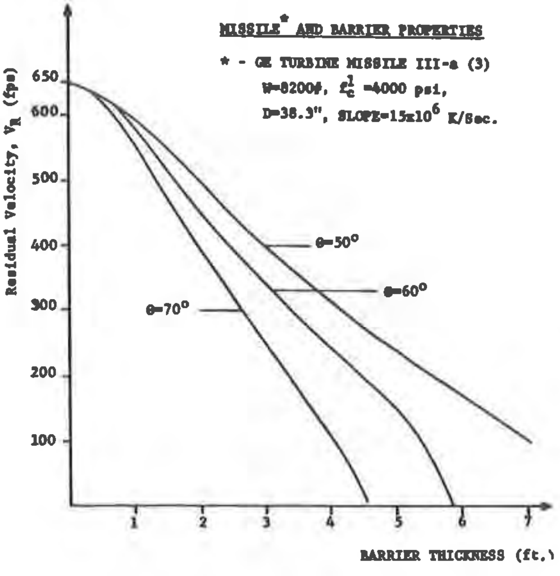

FIGURE 2b - RESIDUAL VELOCITY VS. BARRIER THICKNESS FOR DIFFERENT SHEAR CONE ANGLE, θ (PER EQ. (8), M_c=0)

TABLE II- COMPARISON OF TEST DATA VS. PENETRATION THICKNESS USING "SHEAR CONE" METHOD

REF.	MISSILE DIAM. (In.)	MISSILE WGT. (#)	INITIAL VEL. (fps)	PERFORATION THICKNESS TEST	PERFORATION THK. CALC.
8*	1	8	218	5	5.3
6**	8	215	340	16	15.2

* - Predicted Residual Velocity thru 3" Wall=183 fps, Measured=180 fps

** - Predicted Residual Velocity thru 12" Wall=173 fps, Measured-170 fps

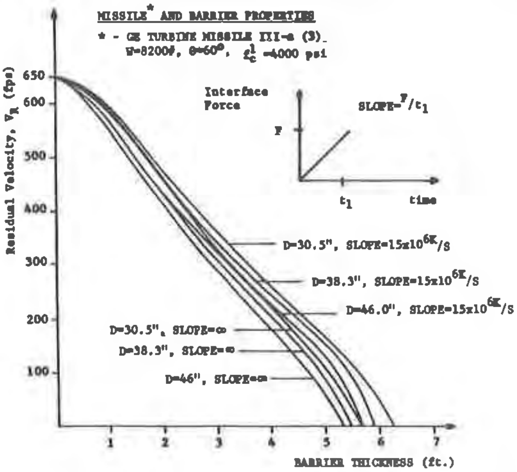

FIGURE 3 - RESIDUAL VELOCITY VS. BARRIER THICKNESS FOR DIFFERENT EQUIVALENT TURBINE MISSILE DIAMETER AND INTERFACE SLOPE (PER EQ. (8), M_C=0)

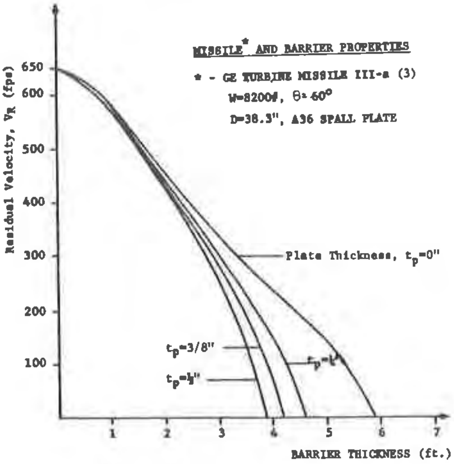

FIGURE 4 - RESIDUAL VELOCITY VS. BARRIER THICKNESS FOR DIFFERENT SPALL PLATE SIZES (PER EQ. (8), M_C=0)