STRUCTURAL DESIGN FOR AIRCRAFT IMPACT LOADING

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SUMMARY

The distribution of military aircraft and proximity to commercial air routes requires the analysis of aircraft impact effect on nuclear power plant facilities in Europe. The typical approach on recent projects has been the hardening of safety-related buildings and/or protection of redundant safety-related equipment through separation. The "hardened-building" approach has led to the consideration of severe shock and vibration caused by the aircraft impact and development of corresponding floor response spectra for component design. Conservatively calculated loads resulting from these are in some cases quite severe.

The reactor auxiliary system building allows a more defensive alternate in the form of a partially softened design. In this approach the equipment layout is arranged such that equipment performing either safety functions or having the potential for significant release of radioactivity (upon destruction) is located in the central area of the plant and is enclosed in thick concrete walls for shielding and protection purposes. The non-safety class equipment is arranged in the area peripheral to the hardened central area and enclosed in thin concrete walls. Since the kinetic energy of the impacting aircraft is absorbed by the collapsed thin walls and ceilings, the vibrational effect on the safety class equipment is drastically reduced.

In order to achieve the objective of absorbing high kinetic energy and yet reduce the shock and vibration effects, the softened exterior walls require low resistance and high ductility. In conventionally reinforced concrete structural design, the allowable deformation is controlled by the compressive strain limitation of 0.003 in the concrete. The ACI 349-76 Code allows a maximum rotation of $0.0065 \cdot (d/c)$ for impact and impulsive load where d is the effective depth of concrete section, and c is the depth of concrete in compression. A ductile reinforced concrete design can be achieved by using heavy shear reinforcement in a laced form. In this type of ductile design, the collapse is controlled by the tensile elongation of the reinforcement; hence, large displacements and high energy absorption capacity is achieved prior to wall rupture. However, this kind of lacing shear reinforcement will increase the construction cost. In order not to increase the construction cost, and yet to assure the safety of the plant, some dynamic tests of conventionally reinforced slabs have to be performed all the way to collapse. The soft peripheral area uses two 0.5 meter thick reinforced concrete walls spaced 8 meters apart. Initial calculations used an energy balance method in combination with plastic impact approach. The results indicated that the two 0.5 meter thick ductile walls have enough capacity to absorb the kinetic energy of a phantom jet impacting at 215 m/s. These calculations have assumptions of achieving the maximum velocity instantaneously after impact, and take into account the kinetic energy in the broken wall. Nonlinear equations of motion are also formulated and solved. The results indicate that the phantom jet would go through the first wall. The second wall would stop the jet, but would sustain some permanent deformation and damage.

Additional analyses are performed to calculate the percentage of energy absorbed by the broken and damaged walls, and percentage of energy absorbed by the rest of the building and transmitted into the hardened central area. Different design concepts which have high effective wall mass during the impact are also considered. This nonconventional design concept of soft outside concrete walls and roofs is believed not only to reduce the overall plant design and construction cost but also to improve the safety of plant operation.

1.0 INTRODUCTION

The Soft Shell-Hardcore approach to nuclear power plant auxiliary structure design was developed to attenuate the crash effects of impacting aircraft. In using this approach, all controls and equipment necessary for the safe shutdown of the plant as well as equipment having potential for releasing unacceptable levels of radioactivity upon destruction are arranged in the central and lower portions of the structure, immediately surrounded by strengthened wall and roof systems. This bunkered area composes the Hardcore portion of the design. Above and around the exterior of the Hardcore are rooms containing controls and equipment not related to the safe shutdown of the plant. These areas form the Soft Shell and are considered expendable for the postulated aircraft impact. A sketch of the Soft Shell-Hardcore concept as used in an auxiliary structure is shown in Figure 1.

The Soft Shell-Hardcore design requires, in part, that the effects of the aircraft impact on the Hardcore are minimized. The crash effects must be investigated from two diverse viewpoints, both of which are dependent upon the design strength of the Soft Shell. Clearly, a Soft Shell design without sufficient strength will allow the major bulk of the aircraft to break through and impact upon the Hardcore with enough force to cause unacceptable damage to the equipment within. Alternately, upon impact, a Soft Shell system which is too strong may generate and transmit an equally unacceptable shock impulse to safety class equipment contained within the Hardcore.

The first comprehensive analytical study on the effect of aircraft input on nuclear power plants was performed by Riera [1]. However, in the Riera study, the objective was to assure that no structural damage whatsoever occurs.

This report is an initial investigation into defining the important structural features involved that would allow the Soft Shell-Hardcore design to successfully sustain the postulated aircraft impact. Also specified for purposes of this study are aircraft impact locations and the type and velocity of impacting aircraft.

The purpose of this initial investigation is to determine the feasibility of the two 0.5 m thick walls of the Soft Shell with the simplest possible mathematical model. After feasibility of the wall thickness is determined, a more sophisticated mathematic model can be developed in a followup study to investigate the vibrational effects on the safety class equipment inside the Hardcore area.

2.0 APPROACH AND ASSUMPTIONS

The Soft Shell-Hardcore concept for the design requires an assurance that at no time is the Hardcore unacceptably damaged. Additionally, it must be assured that acceleration and vibrations resulting from the impact do not impair the safe functioning of equipment within the Hardcore.

Such assurances require that rational and conservative procedures be developed incorporating the major structural phenomena which can be expected to occur during such a hypothetical accident. The nature of extreme probability problems, such as this one, inherently include a great number of variables and uncertainties. To assist this initial investigation the uncertainties will be categorized into general areas, described next, each area having several specific simplifying assumptions.

2.1 IMPACTING AIRCRAFT

Regulatory criteria of the Federal Republic of Germany has established that the impacting aircraft is postulated to be a 20 metric ton Phantom RF-4E fighter, having a velocity of 215 meters/second upon impact. Further dynamic and structural characteristics of this aircraft are described in Section 3.2. In this study, the aircraft is postulated to hit perpendicularly upon the structure. The aircraft's frame is assumed to crush progressively from the nose toward the tail as it impacts the wall. Crushing is assumed to occur only at the point of wall contact, and secondary breakup, such as wing separation is not considered. The overall motion of the aircraft will be modelled in two parts, the forward portion of the aircraft that has already impacted and crushed and the rear portion which is still intact and crashing.

2.2 AUXILIARY STRUCTURE BEHAVIOR

The structural behavior of the auxiliary structure, as modeled in this study, is divided into two parts, similar to the modelling of the impacting aircraft. One part represents the structural behavior of the Soft Shell in the area of the crushing and penetrating aircraft. This area is characterized by extreme deformations, yielding, and wall breakup. The actual extent of this area is difficult to define and judgment is required. The second part is that area remote from the impact region and is characterized by a generally elastic, dynamic structural behavior. The structural behavior of this area can be analyzed more accurately, using methods currently available for earthquake analysis. This intact area of the auxiliary structure (including the Hardcore) is very large compared with the area in which the aircraft is crashing. It is this feature of the aircraft impact problem that makes a reasonable analytical investigation feasible.

2.3 LOCATION OF AIRCRAFT IMPACT ON STRUCTURE

In general, the aircraft impact can occur from any direction, on any above ground part of the auxiliary structure not shadowed by an intervening building. Referring to Figure 1, the exposed areas would be the East and North walls, and the roof. Herein, the investigation will be focused on an East wall impact only.

Additionally, the impact response is greatly dependent upon the structural nature of the actual point of impact. Clearly, a direct impact upon the center of a wall panel will produce a response that is different from that of an inplane impact on a floor slab. This report will be restricted to investigating two impact locations midway along the East wall. In one case, the impact will occur midspan of the exterior wall extending from elevation 0.0 m to elevation 5.2 m, as shown in Figure 1. It is also assumed that rupture of this exterior wall would lead to a second impact on the interior wall of the Soft Shell. This impact upon the interior Soft Shell is described in Section 4. The other impact studied is the case where the impact occurs on the floor slab at elevation 5.2 m, also shown in Figure 1. The first case is a "Soft Shell-Soft hit" condition, while the latter is described as a "Soft Shell-Hard hit" condition. In both cases, the aircraft impact is perpendicular to the exterior wall. It will also be assumed that the walls will have a thickness of 50 cm.

Although this investigation is narrowed to the two impact locations described, the analytical procedures developed would be equally applicable for similar investigations of impacts at other locations.

3.0 DESCRIPTION OF ANALYSES

The analytical procedures used in this investigation describe the continual interaction of the aircraft as it crushes, the wall as it deforms, and the elastic part of the Soft Shell. The formulations consist of a series of time dependent ordinary differential equations. The equations representing the crushing aircraft and the yielding wall are non-linear. The following sections describe the model developed, equations, and associated parameters.

3.1 ANALYTICAL MODEL AND EQUATION OF MOTION

Figure 2 shows a schematic of a 3 mass dynamic model and descriptive notations developed for use in this study. Associated with each mass point are the following differential equations representing equilibrium conditions at the mass points.

Using the notations of Figure 2:

$$M_1\ (m,\ d_1)\ \ddot{S}_1 + F_1\ (d_1) = 0 \tag{1}$$

$$M_2\ (m,\ d_1)\ \ddot{S}_2 + F_2\ (d_2) = F_1\ (d_1) + G_1\ (m,\ d_1) \tag{2}$$

$$M_3\ \ddot{S} + K_3\ \ddot{S}_3 = F_2\ (d_2) \tag{3}$$

$$M_1\ (m,\ d_1) = M_1 - \int_o^{d_1} m(\ell)d\ \ell, \text{ and } M_2\ (m,\ d_1) = M_2 + \int_o^{d_1} m(\ell)d\ \ell \tag{4}$$

$$G\ (m,\ d_1) = m(d_1)(\dot{d}_1)^2 \tag{5}$$

Equation (4) represents a mass flow rule which describes, as the aircraft is crushing, the mass of the crushed portion being taken from the original mass of the aircraft and is added to the effective mass of the deformed wall. This requires that the aircraft mass distribution be known (see Figure 3). The force resulting from the continuously crushing mass, as its velocity decreases to that of the deforming wall, is represented by the Equation (5). This expression represents the mass flow effect and is used in the derivations of Riera [1] and Drittler and Gruner [2].

Equation (1) represents the dynamic equilibrium of the uncrushed part of the aircraft. The mass deceleration of the intact portion of the aircraft, M_1, is due to structural crushing resistance of the aircraft frame, indicated by the function F_1 (d_1). The aircraft crushing resistance is described in Section 3.2 and Figure 3. Similarly, Equation (2) represents the equilibrium of the effective mass of the wall. The forces loading the wall, which are determined by the aircraft mass momentum and the aircraft fuselage crushing strength, are balanced by M_2, the effective wall mass inertia, and F_2 (d_2), the wall structural resistance. Finally, Equation (3) represents the elastic response (mass and stiffness) of the Soft Shell. The force in the spring K_3 is representative of the force transmitted into the Hardcore. The maximum force exciting the Soft Shell elastic response areas is limited to the peak of the crushing wall resistance function. The wall resistance functions are described in more detail in Section 3.3.

3.2 AIRCRAFT STRUCTURAL CHARACTERISTICS

As mentioned in Section 2.2, the postulated aircraft impact is that of a Phantom RF-4E fighter, impacting perpendicularly midway along the East Wall at a velocity of 215 meters/second. The RF-4E has a gross weight of 26 and an empty weight of 15 tons metric. This analysis will assume an aircraft weight of 20 tons. This study uses the mass distribution along the length of the aircraft, shown in Figure 3, as used by Drittler and Gruner [3]. Also shown on the same figure is a fuselage crushing force distribution. The crushing force represents the ultimate compression force at each location along the length of the fuselage. As long as this force is exceeded, aircraft crushing will continue to occur. It is assumed that the crushing occurs at the point of wall/airplane contact only. Therefore, a force equal to the crushing force, as taken from the curve in Figure 3, will be applied as an external load on the wall, and equally in the opposite direction, as a deceleration force to the uncrushed part of the airplane. In Equations (1) and (2) of Section 3.1, F_1 (m,d_1) represents the crushing force distribution as shown in Figure 3. The crushing force distribution was obtained by scaling the fuselage crushing load distribution available for a Boeing 720 (Riera [1] using the ratio of the lengths of the two aircraft. The peaks of the curve were then adjusted to coincide with the peaks of the mass distribution curve.

As the aircraft crushes upon the Soft Shell wall, the mass of the crushed front end of the aircraft decelerates from a velocity close to the velocity of the original aircraft to the velocity of the impacted wall (originally at rest). This force is calculated using the mass flow effect wherein $F = m(\dot{d}_1)^2$, m being the mass per unit length at the crushing interface location found by using the mass distribution curve in Figure 3, and $\dot{d}_1$ being the difference in velocity between the uncrushed part of the aircraft, and the velocity of the wall.

This expression is identical to the reaction force of a column of fluid impinging on a flat plate ($F=\rho AV^2$), where ρA is equivalent to m and V is the equivalent to $\dot{d}_1$. This assumes that the fluid has no deformation resistance, which is not the case of the impacting aircraft. As shown in Section 6.2.3, a continuum mechanics approach, wherein deformation of the aircraft at the crushing interface is included, yields an impact force of $F=m(\dot{d}_1)^2/2$.

In this analysis, for any time during the crash, the total impact force on the Soft Shell wall caused by the crashing aircraft is the sum of the mass flow impact, $M\,\dot{d}_1{}^2$, and the fuselage crushing force, $F_1(d_1)$.

Drittler and Gruner [2,3] develop an impulse (force vs. time) function, based on an extensive series of parametric analyses, that represents the impact force of the RF-4E striking a rigid wall. The formulation uses a similar approach to that described above, but allows aircraft breakage at places other than the wall/aircraft crushing interface.

The reason that the aircraft is modeled explicitly, rather than represented by the established impulse function of Drittler and Gruner [3], is that it is necessary to have the aircraft velocities after exterior and interior wall failure. With these velocities the overall Hardcore dynamic response can be determined.

3.3 WALL RESISTANCE FUNCTIONS AND EFFECTIVE MASS

A structural element (such as a wall or floor slab), when subjected to an external load, deforms and develops internal forces to resist the external load. The sum of these internal forces is the resistance of the structural element. The resistance-deflection curve, or more simply the resistance function, for a structural element is a plot of the variation of resistance force vs. displacement.

An idealized resistance function for a wall subjected to aircraft impact is shown in Figure 4. The parameters necessary to define the idealized resistance function are the ultimate resistance when the member's response is fully plastic, the deflection at partial failure, the member's resistance after partial failure, and the deflection at complete failure. The ultimate resistance of the wall is dependent upon the distribution of the external loading and the failure mechanism of the wall associated with the external loading.

For an aircraft impact midway between floor slabs, it is assumed the wall will respond as a one-way slab spanning between the floors. The effective length for this slab is assumed to be three times the span length. The force due to the aircraft impact is represented by a uniform line load.

Both concrete and steel reinforcement exhibit higher strengths for rapidly applied loads than for statically applied loads ([4], Ghali, Elmasri, Dilger [5]). To account for the wall's higher dynamic resistance, the static strengths of the materials are increased by Dynamic Increase Factors (DIF). For concrete in compression, the DIF is 1.25 and for steel reinforcement in bending the DIF is 1.20 [4].

The displacements at partial and complete failure are dependent upon the ultimate rotational capacity of the member. The rotational capacity of a reinforced concrete beam has been developed by Mattock [6]. This method is also used to prescribe the rotational limits for reinforced concrete members subjected to impact loads in nuclear power plants (Rice, Bahar [7] and [8]).

The total energy the wall can absorb is dependent upon the ultimate resistance and the deflection of the wall at failure. Both are dependent upon the amount of reinforcement in the wall, but in opposite ways for conventionally reinforced structures. The wall resistance increases but the wall deflection at failure decreases with an increasing amount of reinforcement. In other words, increasing the reinforcement in the wall will increase its resistance, but decreases its ductility. These parameters, presented on Table I, show that no increase in energy absorbing capacity is gained by increasing the reinforcement in the wall unless laced reinforcement is used. In fact, the opposite is the case. However, the member with less reinforcement must experience a larger rotation to achieve the same energy absorption. A maximum allowable rotation of 0.07 radians (4 degrees) has been specified by the ASCE Manual [9]. Therefore, a reinforcement ratio is used which has a maximum rotational capacity of less than 0.07 radians.

The rotational capacity, and consequently the energy absorbing capacity, of a reinforced concrete member can be greatly increased if lacing reinforcement is provided. The rotational capacity is limited by the ultimate compression strain in the concrete. The lacing reinforcement increases the ultimate compression strain by confining the concrete. An ultimate rotation of twelve degrees can be achieved with lacing reinforcement [4]. The shear capacity of the concrete member is also increased assuring that a shear failure will not occur before the ultimate rotational capacity is reached.

The effective mass is equal to one half of the wall mass enclosed within the vertical span and the assumed effective length of three span lengths.

3.4 SOFT SHELL ELASTIC DYNAMIC PROPERTIES

In Section 2.0 it is assumed that the vicinity of the Soft Shell, that is impacted by the crashing aircraft, is small in relation to the size of the remaining elastically behaving structure. In this study, the elastic part of the Soft Shell is modeled as a single degree of freedom spring mass system, which comprises M_3 and K_3 in the three mass dynamic model described in Section 3.1 and Figure 2.

K_3 is the effective stiffness of the Soft Shell. Many methods are available to calculate the value of K_3, which represents the force required to develop a unit displacement in the Soft Shell at the location and in the direction of the impacting aircraft. By inspection of Figures 1 and 5, which both represent cross-sections of the auxiliary structure showing the relative positions of the Hardcore and Soft Shell, it can be seen that this stiffness (K_3) is directly dependent upon the structural coupling through the corridor separating the two areas.

The stiffness of K_3 was developed assuming that the Soft Shell behaves similarly to a vertical cantilever beam, fixed at its base. This approach assumes that the corridor is effectively uncoupled throughout the height of the auxiliary structure. However, depending upon the degree of coupling at the roof, an approximation using a vertical beam pinned at the roof and fixed at the base could also be used.

In either case, the force developed in the spring K_3 is indicative of the force that will act upon the Hardcore. The spring force is not very dependent upon the stiffness value of the spring K_3 when the ratio of the loading duration time to the structure elastic period is less than 0.3 (Clough, Penzien, [10]). For this study, the stiffness approximation as a cantilever is sufficient. However, when a more detailed analysis is required, for example, when displacements or the frequency content of the force may be needed, the spring stiffness must be determined in a more accurate manner. Also, usually several extra mass and stiffness values would be used to approximate the elastic Soft Shell behavior.

The effective mass of the Soft Shell (M_3) is determined by approximating the deformed shape the Soft Shell would attain when impacted, as shown in Figure 5. The mass of the floors and walls are combined in a weighted fashion according to the relative displacement as shown in the Figure.

When the Soft Shell is modeled as a single degree of freedom spring-mass system, the dynamic characteristics of the force transmitted to the core is limited to a single frequency and amplitude. The magnitude of the force transmitted can be used in estimating the Hardcore structural accelerations. These accelerations are obtained by taking the quotient of the spring force in K_3 and the Hardcore mass. This approximation assumes the Hardcore to be an unrestrained rigid body with spring force in K_3 having a long duration. The actual acceleration of the Hardcore would be distributed throughout its area, and would be dependent upon the location of the aircraft impact and the degree and manner the Soft Shell area is structurally coupled with the Hardcore.

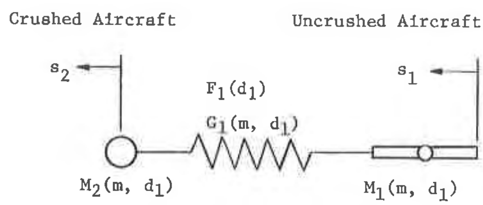
The analysis herein uses the acceleration estimates as a measure for determining the relative effectiveness of the various structural parametric studies made.

4.0 AIRCRAFT IMPACT UPON SOFT SHELL INTERIOR WALL AND HARDCORE

As part of this analysis, the velocities of the crushed aircraft and the uncrushed part are assumed to be unchanged during the unobstructed free flight from the Soft Shell exterior wall to the Soft Shell interior wall. This assumption along with the effects of impact on the Hardcore structure by the crushed aircraft will be further investigated in this chapter.

4.1 AIRCRAFT FREE-FLIGHT THROUGH SOFT SHELL

As an alternative to the approach described in Section 4.0, the following analysis was conducted which considers the difference in velocities between the crushed and uncrushed portions of the aircraft as it heads toward the interior wall. The analysis consists of a two mass model, one mass point, M_1 (m, d_1), representing the uncrushed tail portion of the aircraft, and the other, M_2 (m, d_1), representing the crushed front end. The model, as shown in this sketch, is identical to the 3 mass model of Figure 2 without the auxiliary structure parts included.



where, $d_1 = s_1 - s_2$

The equations governing the free-flight motion are as follows:

$$M_1\ (m,\ d_1)\ \ddot{S}_1 + F_1\ (d_1) = 0 \tag{1}$$

$$M_2\ (m,\ d_1)\ \ddot{S} = F_1\ (d_1) + G_1\ (m,\ d_1) \tag{2}$$

$$M_1\ (m,\ d_1) = M_1 \int_0^{d_1} m\ (\ell) d\ \ell, \text{ and } M_2\ (m,\ d_1) = \int_0^{d_1} m(\ell) d\ \ell \tag{3}$$

$$G\ (m,\ d_1) = m(d_1)(\dot{d}_1)^2 \tag{4}$$

$$F_1\ (d_1) = \text{Fuselage crushing function as in Figure 3.2} \tag{5}$$

The model is set into motion by prescribing four initial conditions to the mass points M_1 and M_2. The four initial conditions prescribed consist of the crushed aircraft mass and velocity and the uncrushed aircarft mass and velocity occurring at the time of the exterior wall failure. During the free-flight, the faster tail section, M_1, will continue to crush into and accelerate the crushed front end, M_2. When the Soft Shell distance of 8 meters has been traveled, the analysis is stopped. The aircraft mass and velocity conditions at this point become the new initial conditions used for the interior wall impact analysis.

5.0 COMPUTER ANALYSES AND RESULTS

5.1 DESCRIPTION OF COMPUTER RUNS

The computer runs conducted for this study represent a series of parametric studies in two general areas described next.

1. Aircraft impact at midspan of the Soft Shell exterior wall between elevations 0.0 m and 5.2 m with parametric studies on the wall effective mass and resistance. Both conventional reinforced and shear reinforced (lacing) conditions are investigated. The breaking mechanism and structural parameters are described in Section 3.3.
2. Aircraft impact at midspan of the Soft Shell interior wall between elevations 0.0 m and 5.2 m. No parametric studies are conducted on the interior wall structural characteristics (mass, resistance, e.g.). The Soft Shell interior wall has doorways and other penetrations at various locations which make definition of structural behavior difficult. The interior wall was given one half the strength of a normally reinforced wall (chosen to be D25 @ 15 cm spacing) to account for the openings. The behavior of the interior wall, if parametric studies were made, would be similar to the results of parametric studies on the exterior wall. Therefore, the effects of structural changes on the Soft Shell interior can be deduced from the exterior wall behavior. Impact on the interior wall results from a partially destroyed aircraft which has broken through the exterior wall. The aircraft conditions (velocities of crushed and uncrushed portions) are applied to the interior wall. In one case, conditions at the time of rupture of the exterior wall are used. Another set of aircraft conditions, wherein an intermediate analysis is conducted to monitor the aircraft free-flight through the 8 meters distance between the exterior and interior walls is also used. The intermediate analysis considers the difference in velocities of the crushed and uncrushed aircraft parts which are assumed to remain together, and, using momentum conservation, calculates a new set of aircraft impact conditions on the interior wall. The details of the free-flight analyses are presented in Section 4.1.

5.2 ANALYTICAL RESULTS

The computer run results are presented in Tables II through V and Figures 6 and 7. The results are generalized as follows:

1. In all cases, for aircraft impact on the exterior wall, the wall ruptures, allowing the aircraft to penetrate the Soft Shell.
2. In all cases, for secondary impact on the Soft Shell interior wall, the wall also ruptures. However, for 1/2 of these runs, the aircraft is 94 percent to 100 percent destroyed during impact and it is the momentum of the interior wall inertia that carries it to final failure.

5.2.1 Results of Aircraft Exterior Wall Impact

The computer runs, numbered 1 through 14 as shown in Table II represent the parametric studies conducted with the aircraft impacting on the exterior wall. Runs 1 through 7 model the exterior wall as conventionally reinforced, and 8 through 14 utilize the extra ductility that lacing provides. The structural parameters (effective wall mass, wall plastic resistance) are tabularized for each run. The last 4 columns of the table provide the measures by which the effectiveness of the wall system to attenuate the aircraft impact can be judged when the wall fails. These columns include the percentage of the aircraft destroyed (on weight basis) and the aircraft kinetic energy when the exterior wall fails. These parameters are important, since they are used not only to evaluate the wall effectiveness, but also to determine what impact conditions will occur on the Soft Shell interior wall.

The last two columns of Table II indicate the Hardcore response to the aircraft breaking through the exterior wall. The same resistance that attenuates the aircraft motion during the impact also develops a dynamic force in the elastic portion of the Soft Shell which is transmitted to the Hardcore.

It is seen that the structural acceleration of the Hardcore is directly related to the strength (resistance) of the impacted wall. Clearly, a weak wall cannot transmit a high structural force, but neither does it do much to slow down the aircraft.

The estimated Hardcore structural accelerations have an elastic dynamic nature, and will continue in a vibratory fashion after the aircraft is completely stopped until they die out because of structural damping. Therefore, equipment contained within the Hardcore may experience an amplification of the structural acceleration as is the manner of acceleration response spectra.

5.2.2 Aircraft Conditions After Exterior Wall Failure

In this study it is assumed that the aircraft (upon exterior wall failure) will carry across the Soft Shell in an unobstructed manner and impact upon the interior wall of the Soft Shell.

The analyses of the aircraft impact upon the interior wall follows the approach used on the exterior wall, with the exception that the impacting aircraft initial conditions involved now have two distinct parts; a crushed mass part followed by an intact aircraft portion.

Table II lists the interior wall impact initial aircraft conditions. The runs labeled 1FF, 3FF, etc., represent the situations corresponding to conditions occurring during exterior wall rupture described in computer runs 1, 3, etc. The FF designation refers to the results of the "free-flight" analysis described in Section 4.1. This intermediate analysis preserves the aircraft momentum considering the different velocities of the crushed and uncrushed aircraft portions, as the aircraft crosses the 8 meter distance between the Soft Shell exterior and interior walls.

5.2.3 Results of Aircraft Interior Wall Impact

Table IV presents the results of the partially destroyed aircraft impacting on the Soft Shell interior wall, in the same manner as presented for the exterior wall in Table I.

Two sets of aircraft conditions were assumed. The first condition, designated as Run Nos. 1, 3, 4, etc., use the aircraft velocity and mass conditions as obtained directly after exterior wall failure. This is a conservative inconsistency, in that it assumes the aircraft can maintain two different constant velocities without separation as it travels toward the interior wall. The results of this assumption is presented in the first 5 columns of the table.

The intermediate "free-flight" analyses account for energy lost and momentum conservation of the crushed and uncrushed aircraft parts and resolves the above inconsistency. The results of the interior wall impact when using aircraft initial conditions as obtained from the free flight analyses are listed in the last 5 columns of Table IV and are designated as run nos. 1FF, 3FF, etc.

The interior wall strength was reduced by half to account for doorways and other openings. The wall fails in all cases, even though for some cases the aircraft is completely destroyed. Since the interior wall is weak, very little structural force is transmitted to the Hardcore. However, it is assumed that, since the wall is broken, the entire aircraft (crushed and uncrushed parts) will impact directly upon the Hardcore.

5.3 HARDCORE STRUCTURAL RESPONSE

The Hardcore response is generated by two mechanisms. The first mechanism is the force transmitted due to the aircraft impact upon the Soft Shell. The dominant feature which governs the magnitude of the force is the element structural resistance. The second mechanism is the velocity of the aircraft after it crashes through both Soft Shell walls and impacts directly upon the Hardcore as shown in Table V. In this case the dominant feature which governs the magnitude of the aircraft velocity is the effective mass of the impacted walls. The structural resistance (or lack of it) influences the velocity to a somewhat lesser degree. The explanation is that most of the aircraft energy is used in overcoming the wall inertia. As seen in Table I, the energy capacity of the different wall configurations is not very large.

With this in mind, the major structural parameters, effective mass and resistance, are plotted along with their effect on the Hardcore response in Figure 6. Figure 6-a clearly shows the effect of element (wall of slab) resistance to the force transmitted into the Hardcore. For the case of wall impact, where both Soft Shell walls are ruptured, Figure 6-b shows the relationship of wall effective mass, resistance, and the use of shear reinforcement (lacing) to the Hardcore aircraft impact velocity.

5.4 WALL IMPACT TIME HISTORIES

The structural parameters described in this report form an intricate interrelationship when used in a dynamic analysis. Figure 7 shows this relationship on a time basis by plotting the parameter time histories representative of the initial aircraft impact on the wall to the time of wall failure. The figure represents the aircraft impact on the exterior wall and the corresponding subsequent impact on the interior wall (free-flight conditions not used). The parameters printed out on a time history basis in the Figure are: wall resistance, aircraft kinetic energy, aircraft impact force on the wall, crushed aircraft mass and the force transmitted to the Hardcore.

6.0 DISCUSSION

6.1 DISCUSSION OF AIRCRAFT IMPACT MODE

The dynamic response of a reinforced concrete structure under impact loading in the large deformation range is an extremely complicated subject. Depending on the relative mass and stiffness of impacting missile and the impacted target, and the impacting velocity of the missile, the failure modes of the target varies from local penetration effect to overall collapse phenomenon. When the missile is rigid and impacts with extremely high velocity into a massive target, the primary response is local penetration (Kennedy [11]) as shown in Figure 8-a. On the other hand, when the missile is rigid and impacts with relatively high velocity into a flexible target, the primary response is the traveling hinge phenomenon (Symonds [12]) as shown in Figure 8-b. However, when the missile is deformable and impacts with moderate velocity, the target is responding in the stationary hinge mechanism with progressive rotations as shown in Figure 8-c. Most likely, the real response of target is a combination of all three phenomena.

The full scale test of deformable missiles, i.e., utility poles, indicated no penetration into the reinforced concrete structure [13]. The full scale test of a C-119 aircraft indicated negligible local damage on the concrete occurs when compared with the deformation of the aircraft fuselage (Haley, Turnbow [14]. Hence, for analytical purposes, it is assumed herein that the wall behaves as shown in Figure 8-c as a stationary hinge mechanism. In other words, neither penetration nor perforation is the mode of failure.

6.2 DISCUSSION OF APPROXIMATIONS

6.2.1 Inertial Effects of Equipment and Live Load

The equipment load and live load inertial effects are not considered in this study. The equipment inertial effects are expected to be small when compared with that of the concrete structure. However, any significant equipment inertia, would attenuate the aircraft crash effects to a greater degree by increasing the effective mass of the Soft Shell.

Perhaps the most important feature of equipment inertia, that is not considered in this study, is the inertia of any equipment that would block the path of the aircraft after the Soft Shell exterior wall is ruptured. This study conservatively assumes the aircraft will proceed toward the interior wall unimpeded. Clearly, any sizeable intervening equipment would reduce the aircraft velocity and perhaps redirect the flight so that the aircraft would strike the interior wall in a glancing fashion, rather than the direct perpendicular manner that is assumed for this study.

6.2.2 Effect of Broken and Separated Aircraft

This analysis assumes that the aircraft, although crushed and deformed, remains together and maintains its original mass as it passes through the Soft Shell. This too, is very conservative, since the aircraft kinetic energy at any time is in direct proportion to its mass. It is expected that under actual crash conditions, the wing sections and part of the tail section would be broken off and not continue along with the aircraft. This would represent a reduction of aircraft mass and kinetic energy in the order of 20-30 percent as the aircraft strikes the interior wall or the Hardcore.

6.2.3 Effect of Infinitesimal Crushing Region of Aircraft

As used in this report, the reaction force applied on the wall is:

$$F = F_1 + m(\dot{d}_1)^2$$

where F_1 is the buckling strength of fuselage, and m is the linear mass distribution of fuselage. The second term, or the mass flow effect, dominates the response at the impact velocity conditions of 215 m/s. The above equation is based on the assumption that the fuselage velocity drops to the velocity of the wall abruptly like a water column. However, by using a continuum mechanics approach, one can assume infinitesimal crushing region within which the fuselage velocity drops gradually to the velocity of the wall. In this case the impact force will be (Rice, Bahar [7]):

$$F = F_1 + m(\dot{d}_1)^2/2$$

This second equation represents a significant reduction in structure response. However, the applicability of this equation is not certain at this time, and to be conservative, the first equation is used.

6.2.4 In-Situ Strength of Steel and Concrete

The design strength of steel and concrete is used in the analysis. However, for an extreme load of this nature, it is appropriate to use the in-situ strength of concrete at the actual age (usually more than 3 to 4 years) and the actual mill test strength of the rebars.

6.2.5 Effect of Fuselage Strength

Since the buckling strength of the Boeing 720 (Riera [1]) is extrapolated from the testing of a C-119 aircraft (Haley, Turnbow [14]), parametric studies were conducted in which the buckling strength is varied. The results indicate that the response is not sensitive to the buckling strength variation. This agrees with the work performed by Instute für Reaktorsicherheit (Drittler, Gruner [2,3]). The reason for this phenomenon is that the response is dominated by the mass flow term as described in Section 6.2.3.

6.2.6 Rotational Capacity of Slab Without Lacing Reinforcement

The maximum rotational capacity of the slab in this study is based on test results as described in Reference (Mattock [6]). The equation derived in this reference is based on the incipience of failure.

However, there is some additional energy adsorption capacity, along with rotation, between incipience of failure and total collapse of the slab. This additional energy absorption capacity, which is not considered in this study, would need to be evaluated by further testing.

7.0 CONCLUSIONS

The results obtained in this study clearly demonstrate the practical feasibility of the Soft Shell Hardcore design concept. In all the case studies, the results show the kinetic energy of the aircraft has been effectively attentuated to varying degrees. This attentuation shows that the 1/2 meter thick walls would be satisfactory for the design.

Both penetration and acceleration of the building can probably be further reduced by elimination of some potential conservatisms in the more refined model. Such refinement could include a more detailed aircraft model, consideration of floor loads of steel equipment in the building, and credit for interior steel structures.

The analysis conducted herein only calculates the gross force and impact velocities on the Hardcore Area, and only a limited estimate of the frequency response of equipment can be made.

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TABLE I WALL RESISTANCE PARAMETERS

WALL REINFORCEMENT		WALL RESISTANCE		NON-LACED REINFORCEMENT			LACED REINFORCEMENT		
RATIO, ρ (AS /bd)	REBAR & SPACING(cm)	FULLY PLASTIC (t)	AFTER PARTIAL FAILURE (t)	WALL DEFLECTION(m) PARTIAL FAILURE	WALL DEFLECTION(m) COMPLETE FAILURE	ENERGY CAPACITY (t-m)	WALL DEFLECTION(m) PARTIAL FAILURE	WALL DEFLECTION(m) COMPLETE FAILURE	ENERGY CAPACITY (t-m)
0.002	D16 @ 15	416	213	0.31	0.62	201	0.28	0.56	179
0.004	D18 @ 15	832	416	0.16	0.32	200	0.28	0.56	349
0.006	D22 @ 15	1216	608	0.10	0.20	190	0.28	0.56	511
0.008	D25 @ 15	1582	791	0.078	0.156	185	0.28	0.56	664
0.010	D28 @ 15	1924	962	0.062	0.124	180	0.28	0.56	808
0.012	D32 @ 15	2248	1124	0.052	0.104	176	0.28	0.56	944
0.014	D34 @ 15	2550	1275	0.045	0.090	171	0.28	0.56	1071
0.016	D36 @ 15	2832	1416	0.039	0.078	166	0.28	0.56	1189

TABLE II
RESULTS OF AIRCRAFT IMPACT ON MIDSPAN OF EXTERIOR SOFT SHELL WALL

COMPUTER RUN NO.	SHEAR REINFORCING (LACING)(1)	EXTERIOR WALL EFFECTIVE WALL MASS ($T-SEC^2/M$)	EXTERIOR WALL MAXIMUM WALL PLASTIC RESISTANCE (T)	AIRCRAFT CRUSHED (%)	REMAINING AIRCRAFT KINETIC ENERGY (%)	MAXIMUM FORCE TRANSMITTED TO HARDCORE (T)	ESTIMATED HARDCORE STRUCTURAL ACCELERATION(2) (g)
1	NO	3	750	16	83.6	378	<0.10
2	NO	3	1500	30	69.0	928	0.10
3	NO	5.2	750	30	68.6	463	<0.10
4(3)	NO	5.2	1500	45	54.2	1068	0.10
5	NO	5.2	2250	55	43.2	1786	0.20
6	NO	8.0	1500	55	42.9	1165	0.10
7	NO	8.0	2250	67	32.1	1906	0.20
8	YES	3	750	53	48.5	589	<0.10
9	YES	3	1500	63	38.4	1278	0.10
10	YES	5.2	750	70	30.8	668	<0.10
11(3)	YES	5.2	1500	74	26.6	1424	0.15
12	YES	5.2	2250	77	22.6	2288	0.20
13	YES	8.0	1500	79	20.3	1574	0.15
14	YES	8.0	2250	83	16.4	2526	0.20

Notes:
(1) Lacing reinforcement does not develop greater wall strength (resistance), but provides greater ductility and wall displacements.
(2) Based on effective Hardcore mass of 1400 tons.
(3) Run Nos. 4 and 11 represent most likely situations. Other runs are parametric variations of Run Nos. 4 and 11.
(4) Exterior wall is RUPTURED, in all cases.

TABLE III
AIRCRAFT IMPACT CONDITIONS ON SOFT SHELL INTERIOR WALL

COMPUTER[1] RUN NO.	SHEAR REINFORCEMENT (LACING)	AT EXTERIOR WALL RUPTURE: UNCRUSHED AIRCRAFT MASS (T-SEC²/M)	AT EXTERIOR WALL RUPTURE: UNCRUSHED AIRCRAFT VELOCITY (M/SEC)	AT EXTERIOR WALL RUPTURE: CRUSHED AIRCRAFT MASS (T-SEC²/M)	AT EXTERIOR WALL RUPTURE: CRUSHED AIRCRAFT VELOCITY (M/SEC)	UPON INTERIOR WALL IMPACT[2]: UNCRUSHED AIRCRAFT MASS (T-SEC²/M)	UPON INTERIOR WALL IMPACT[2]: UNCRUSHED AIRCRAFT VELOCITY (M/SEC)	UPON INTERIOR WALL IMPACT[2]: CRUSHED AIRCRAFT MASS (T-SEC²/M)	UPON INTERIOR WALL IMPACT[2]: CRUSHED AIRCRAFT VELOCITY (M/SEC)
1FF	NO	1.67	214	0.33	16.0	0.64	195	1.34	176
3FF	NO	1.39	213	0.61	19.4	0.39	191	1.61	145
4FF	NO	1.17	213	0.83	22.5	0.16	184	1.84	129
5FF	NO	0.90	212	1.10	26.4	0.02	115	1.98	108
7FF	NO	0.66	210	1.34	20.9	0.0	-	2.00	90
8FF	YES	0.95	211	1.05	50.4	0.07	175	1.93	124
10FF	YES	0.60	208	1.40	41.8	0.0	-	2.00	92
11FF	YES	0.52	207	1.48	38.3	0.0	-	2.00	84
12FF	YES	0.46	206	1.54	34.8	0.0	-	2.00	74
14FF	YES	0.34	204	1.66	25.4	0.0	-	2.00	63

Notes: (1) 3FF, 4FF, etc., designates the free-flight computer runs using the exterior wall rupture aircraft conditions found in Computer Run Nos. 3, 4, etc.
(2) Assuming an unobstructed free flight of 8.0 meters.

TABLE IV
RESULTS OF AIRCRAFT IMPACT ON MIDSPAN OF INTERIOR SOFT SHELL WALL[1]

RESULTS OBTAINED ASSUMING AIRCRAFT INITIAL CONDITIONS THE SAME AS AT TIME OF EXTERIOR WALL RUPTURE: USING RESULTS OF RUN NO.	AT INTERIOR WALL RUPTURE: AIRCRAFT CRUSHED (%)	REMAINING AIRCRAFT KINETIC ENERGY (%)	MAXIMUM FORCE TRANSMITTED TO HARDCORE (T)	ESTIMATED HARDCORE STRUCTURAL ACCELERATION (g)	RESULTS OBTAINED ASSUMING AIRCRAFT INITIAL CONDITIONS AS DETERMINED BY FREE-FLIGHT COMPUTATIONS: USING RESULTS OF RUN NO.	AT INTERIOR WALL RUPTURE: AIRCRAFT CRUSHED (%)	REMAINING AIRCRAFT KINETIC ENERGY (%)	MAXIMUM FORCE TRANSMITTED TO HARDCORE (T)	ESTIMATED HARDCORE STRUCTURAL ACCELERATION (g)
1	56	42.6	178	<0.10	1FF	73	24	60	<0.10
3	69	28.9	168	<0.10	3FF	83	15	64	<0.10
4	76	23.7	167	<0.10	4FF	90	6	65	<0.10
5	78	20.6	174	<0.10	5FF	100	2	75	<0.10
7	81	17.9	236	<0.10	7FF	100	1	90	<0.10
8	76	23.5	140	<0.10	8FF	100	2	66	<0.10
10	82	16.3	186	<0.10	10FF	100	1	89	<0.10
11	86	12.7	204	<0.10	11FF	100	1	97	<0.10
12	94	7.0	226	<0.10	12FF	100	1	110	<0.10
14	99	2.0	235	<0.10	14FF	100	0	145	<0.10

Notes: (1) Interior wall conventionally reinforced, resistance reduced by half to account for openings (1/2 of resistance curve in Figure 3.7). Effective mass = 5.2 tons.

TABLE V
AIRCRAFT IMPACT VELOCITIES UPON HARDCORE

EXTERIOR WALL		INTERIOR WALL(2)		AIRCRAFT IMPACT VELOCITY ON HARDCORE(1) — WITHOUT FREE-FLIGHT CONDITIONS			AIRCRAFT IMPACT VELOCITY ON HARDCORE(1) — USING FREE-FLIGHT CONDITIONS		
REINFORCEMENT AND SPACING (CM)	EFFECTIVE MASS ($T\text{-}SEC^2/M$)	REINFORCEMENT AND SPACING (CM)	EFFECTIVE MASS ($T\text{-}SEC^2/M$)	CORRESPONDING RUN NO.	AIRCRAFT DESTROYED (%)	IMPACT VELOCITY (M/SEC)	CORRESPONDING RUN NO.	AIRCRAFT DESTROYED (%)	IMPACT VELOCITY (M/SEC)
D18 @ 15	3.0	D25 @ 15	5.2	1	56	107.1	1FF	73	80.3
D18 @ 15	5.2	D25 @ 15	5.2	3	69	82.7	3FF	83	60.7
D25 @ 15	5.2	D25 @ 15	5.2	4	76	67.2	4FF	90	37.9
D34 @ 15	5.2	D25 @ 15	5.2	5	78	58.8	5FF	100	29.6
D34 @ 15	8.0	D25 @ 15	5.2	7	81	50.1	7FF	100	24.4
D18 @ 15(3)	3.0	D25 @ 15	5.2	8	76	67.1	8FF	100	34.4
D18 @ 15(3)	5.2	D25 @ 15	5.2	10	82	49.0	10FF	100	24.8
D25 @ 15(3)	5.2	D25 @ 15	5.2	11	87	40.5	11FF	100	22.7
D34 @ 15(3)	5.2	D25 @ 15	5.2	12	94	26.8	12FF	100	19.9
D34 @ 15(3)	8.0	D25 @ 15	5.2	14	99	15.9	14FF	100	14.9

Notes: (1) Based on conservation of linear momentum of crushed and uncrushed portions of aircraft at time of interior wall failure.
(2) Interior wall does not use shear reinforcement. Resistance is reduced by 1/2 to account for openings.
(3) Exterior walls using shear reinforcement (lacing).

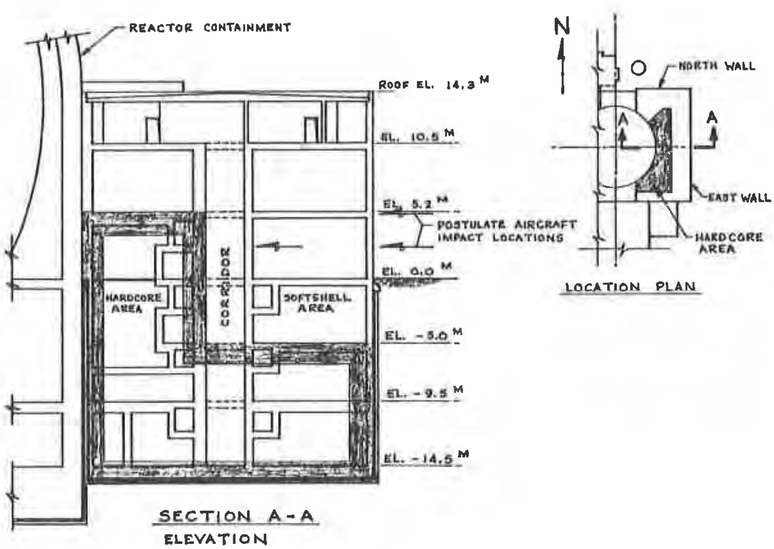


FIGURE 1
SKETCH AND LOCATION PLAN OF SOFT SHELL HARDCORE CONCEPT

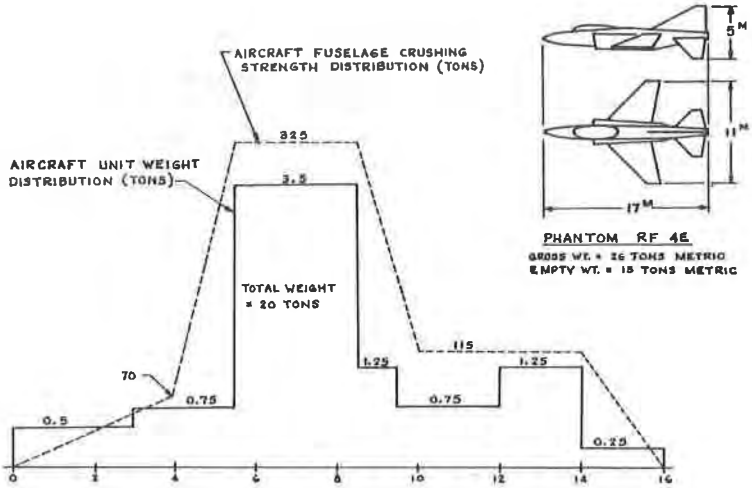
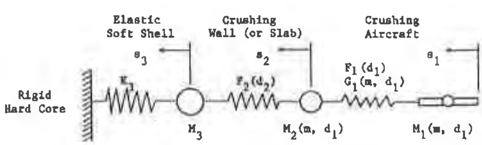


FIGURE 3

AIRCRAFT STRUCTURAL CHARACTERISTICS



$M_1(m, d_1)$ - Mass of uncrushed part of aircraft.

$M_2(m_1\ d_1)$ - Effective mass of crushing wall and crushed mass of aircraft.

M_3 - Effective mass of elastic part of Soft Shell.

$F_1(d_1)$ - Aircraft impact fuselage crushing force on wall.

$G_1(m, d_1)$ - Mass flow impact force upon wall.

$F_2(d_2)$ - Crushing resistance of wall.

K_3 - Effective stiffness of elastic part of Soft Shell.

s_1, s_2, s_3 - Global displacements of mass points.

$d_1 = s_1 - s_2$ - Crushed length of aircraft.

$d_2 = s_3 - s_2$ - Plastic deformation of wall.

$m = m(l)$ - Mass/unit length along length of aircraft, where l = distance from front of undeformed aircraft.

Figure 2 Description of 3 Mass Dynamic Model

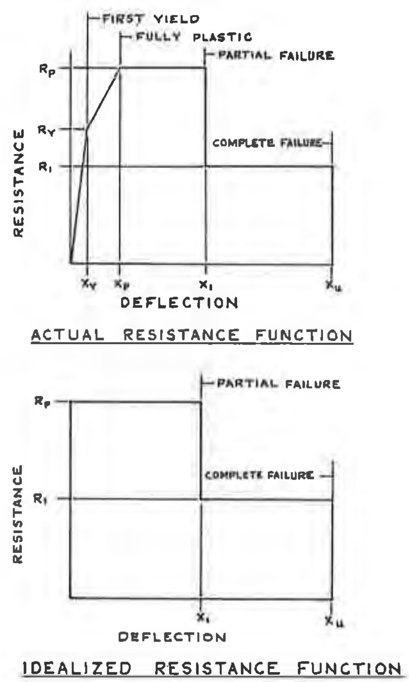
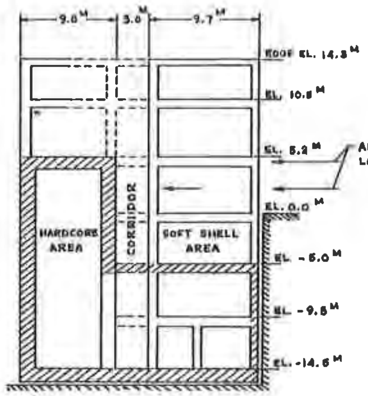
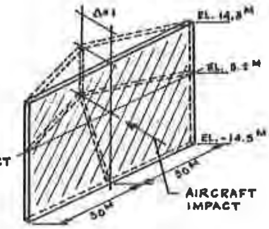


FIGURE 4

WALL RESISTANCE FUNCTIONS



a. CROSS-SECTION OF IDEALIZED LAYOUT

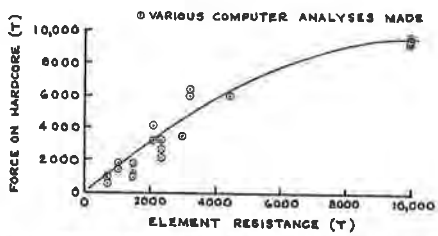


b. ASSUMED SOFT SHELL DEFLECTION DURING AIRCRAFT IMPACT

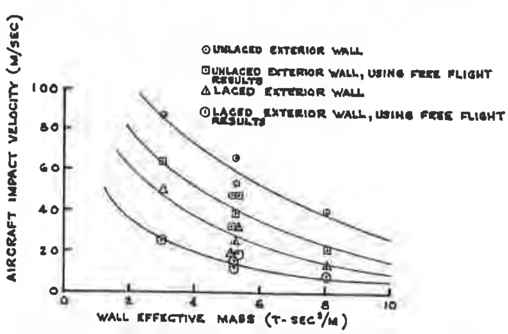
NOTES: 1. HARDCORE EFFECTIVE MASS = 1400 T-SEC²/M
2. SOFT SHELL EFFECTIVE MASS = 302 T-SEC²/M
3. SOFT SHELL EFFECTIVE STIFFNESS = 172,000 TONS/METER
4. NEGLIGIBLE CORRIDOR COUPLING ASSUMED.
5. WALLS AND FLOOR SLABS ARE 1/2 METER THICK.

FIGURE 5

SKETCH OF SOFT SHELL IDEALIZED MODEL



a. EFFECT OF ELEMENT (WALL OR SLAB) RESISTANCE TO FORCE TRANSMITTED TO HARDCORE



b. EFFECT OF WALL EFFECTIVE MASS TO AIRCRAFT IMPACT VELOCITIES ON HARDCORE

FIGURE 6

ELEMENT RESISTANCE AND EFFECTIVE MASS EFFECTS ON HARDCORE

EXTERIOR WALL REINFORCEMENT
D25 @ 15 CM, NO LACING

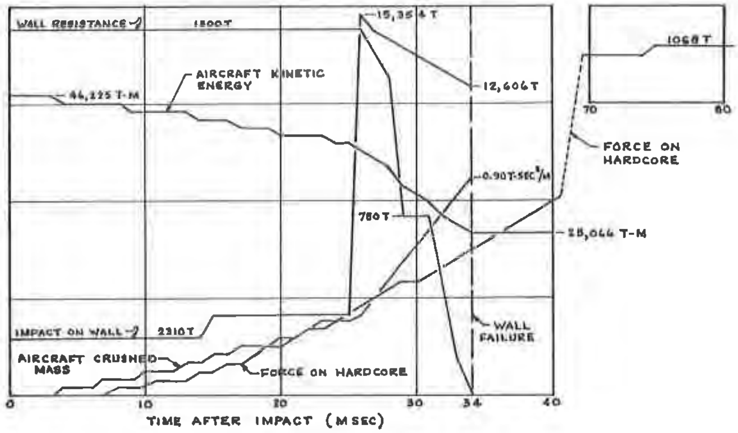


FIGURE 7

PARAMETER TIME HISTORIES, EXTERIOR WALL IMPACT, RUN NO. 4

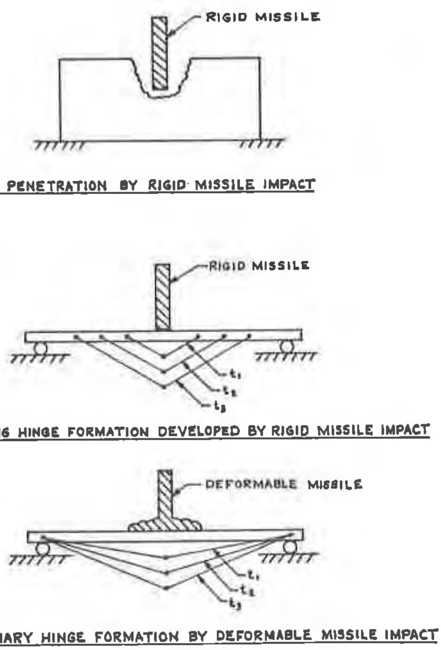


FIGURE 8

WALL STRUCTURAL RESPONSE TO MISSILE IMPACT