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Determination of the Load-carrying Capacity of a Reinforced Concrete Shell Subjected to Impact Loading

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ABSTRACT

The numerical evaluation of the response of reinforced and prestressed concrete structures subjected to impact and impulsive loading has been a topic of research at the Laboratory of Structural Dynamics and Reliability (LDEC) of the Federal University of Rio Grande do Sul (Brazil) since the late 70's. In order to determine the response when fracture and fragmentation of the target structure is possible, a discrete representation of the latter was preferred over a continuum formulation. The approach, often designated as Discrete Element Method (DEM), to distinguish it from Finite Element or Finite Difference procedures, consists of modelling the solid as a system of discrete nodal masses interconnected by massless structural elements characterized by an arbitrary set of constitutive relations. In previous contributions by the authors, the equations of motion of the system are integrated in the time domain using an explicit finite difference algorithm and several aspects of the discrete representation discused in detail.. In this paper, the method is used to determine the response of a thick concrete cylindrical shell subjected to the transient load associated to impact of a large commercial aircraft. The influence of the reinforcing steel is explicitly accounted for, as well as the fracture energy dissipated in the fracture process. The random distribution of concrete properties was taken into consideration by means of Monte Carlo simulation, using parameters for the relevant concrete properties (Young's modulus, tensile strength, specific fracture energy) determined by calibration with static test results. Thus, it is believed that both size as well as rate effects were adequately accounted for. It is shown that the load distribution and the impact area, as well as size and rate effects, have important roles in the (local) behavior of structures subjected to short duration localized impact or impulsive loading, in which the resistance to perforation is not sensitive to global bending.

KEY WORDS: Impact Loading, Aircraft Impact, Dynamic Response, Concrete Shells, Reinforced Concrete, Discrete Elements, Perforation, Penetration, Size Effects, Rate Effects, Monte Carlo Simulation.

1. INTRODUCTION

The numerical evaluation of the response of reinforced and prestressed concrete structures subjected to impact and impulsive loading has been an area of research at the Laboratory of Structural Dynamics and Reliability (LDEC) of the Federal University of Rio Grande do Sul (Brazil) for about a quarter of a century. In order to determine the response when fracture and fragmentation of the target structure is possible, a discrete representation of the latter was preferred over a continuum formulation. The approach, often designated as Discrete Element Method (DEM), to distinguish it from Finite Element or Finite Difference procedures, is briefly described below. Previous contributions along this line were due to Riera [1], Rocha & Riera [2], Riera & Iturrioz [3] and Rios [4]. In connection with aircraft impact, it was proposed in the late 60's to evaluate the global response of containment structures in NPPs by means of an uncoupled analysis, in which the target structure is subjected to the dynamic loads induced by the aircraft crash. The latter were to be determined in an independent analysis of the impacting aircraft , as discussed by Riera [5]. The approach was later validated by numerous numerical and experimental studies and will likewise be adopted in the present paper, which aims at a reliable estimation of the strength of concrete plates and shells subjected to impact of a large commercial aircraft - a Boeing 767-300 - normally to the shell middle surface. To achieve this purpose, a detailed description of the load is needed, including the evolution with time of the contact surface between aircraft and target structure, and the load distribution within this surface. Furthermore, the uncertainty involved in the specification of material parameters requires specific consideration. Both issues are addressed in the paper.

2. THE DISCRETE ELEMENT METHOD

The computational method employed is based on the representation of a continuum by means of an array of nodal masses interconnected by one-dimensional elements without mass. The cubic array shown in fig 1, consisting of a cubic cell with eight nodal points at the vertices plus a central node, each with three degrees of freedom, was adopted. The masses are linked by longitudinal and diagonal elements of lengths L_c and $\sqrt{3}/2\ L_c$, respectively. The equivalence between an orthotropic elastic solid with the principal material axes oriented in the direction of the longitudinal elements and the cubic lattice model was clearly demonstrated (Riera & Iturrioz, [6], [7]) within the framework of linear elasticity. The equations of motion of the resulting N DOF system may be expressed in the form:

$$\boldsymbol{M}\ddot{\vec{u}} + \vec{f}(t) = \vec{Q}(t) \qquad (1)$$

In which $\boldsymbol{M}$ denotes the (diagonal) mass matrix, $\vec{u}$ the vector of generalized coordinates (nodal displacements), $f(t)$ the internal nodal forces, which may depend on present (elastic) and past time; nodal displacements, and $Q(t)$, the externally applied forces. Thus, in linear elastic systems, $f(t)=\boldsymbol{K}u$, $\boldsymbol{K}$ being the stiffness matrix. In a system with linear viscous forces, $f(t)=\boldsymbol{K}u + \boldsymbol{C}\dot{u}$, $\boldsymbol{C}$ is assumed to be proportional to the mass matrix, the system (1) may be numerically integrated in the domain by means of the explicit central finite difference algorithm. By updating the nodal coordinates at each time step, the approach allows the consideration of large displacements, i. e., geometrical non-linearity. The convergence of the solutions in linear elasticity, as well as in inelastic instability problems, was also verified by the authors. More recently, Rocha and Riera [8], extended the method to fracture analysis of brittle structures, such as concrete or cohesive soils. The stress-strain or force-displacement relationship for the material is given by a triangular diagram, as shown in fig 2. The limit strain ε_r is chosen to satisfy the condition that when an element fails and a crack opens, an amount of energy is dissipated. This energy is equal to the product of the ruptured surface area, which is related to L_c , times the critical surface energy G_f of the material. A second assumption is that material properties may be modeled as random fields,i.e. vary from element to element.

Only a restriction on the value of Poisson's ratio must be imposed for a complete equivalence ($\nu = 0.25$). For other values of ν the model results in minor differences in the shear terms.

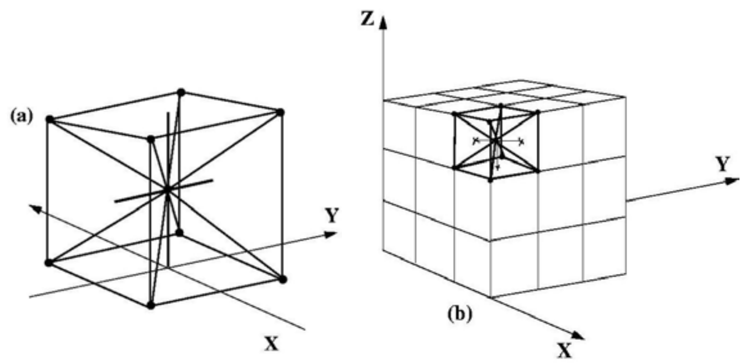

Fig. 1 Cubic array (a): a basic module, (b) Composition of prisms.

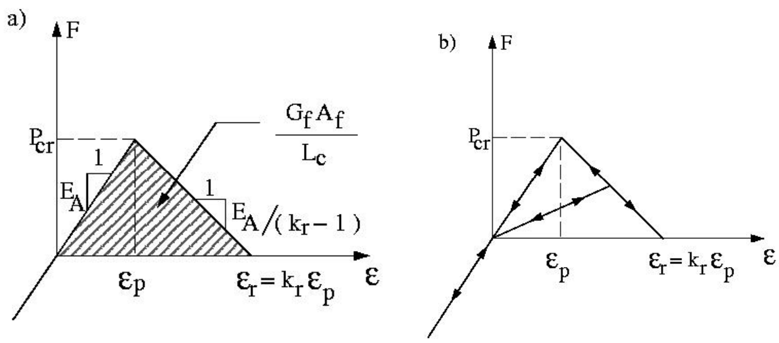

Fig 2: Constitutive bilinear law of brittle material

3. ASSESSMENT OF THE LOAD-TIME FUNCTION

As indicated before, the load induced on a rigid target by an impinging aircraft must be previously determined. In case of stiff structures that do not fail during impact, the real interface forces will differ little from the load-time function thus evaluated, which may then be used in the stability analysis of the target structure. In the following, the load-time function, as well as necessary complementary information for a Boeing 767-300, will be presented. For such purpose, a detailed Finite or Discrete Element model of the aircraft may be used, in conjunction with a fully non-linear numerical integration scheme of the equations of motion. In the situation under consideration, such approach cannot be readily implemented, due to large uncertainties concerning the structural properties of the aircraft structure, which is proprietary information, unavailable in the open literature, Iturrioz and Riera [9]. A robust alternative is the use of a uni-dimensional discrete model of the aircraft, consisting of N masses m_i , interconnected by rigid-plastic columns characterized by the work W_i ($i = 1, N-1$) needed to completely smash the elements and by their initial lengths Δx_i . The initial velocity V_0 must be specified. The main dimensions of the aircraft are shown in Fig. 3.1, while other relevant characteristics are indicated in Table 3.1. The numerical procedure to evaluate the load-time function is well known and will not be described here [10].

The resulting load functions are consequently dependent on the impact velocity V_0. With the simplified uni-dimensional model, the load-time function shown in Fig. 3.2, corresponding to a Boeing 767-300 impacting at the velocity of landing and taking-off, equal to 360 km/h, i.e. 100 m/s, was determined. The load represented in Fig. 3.2 with a traced line is applied in the fuselage region (Area type 1 in Fig. 5), while the load identified with a full line is distributed between Regions type 1 (25%) and type 2 (75%) in the same figure .

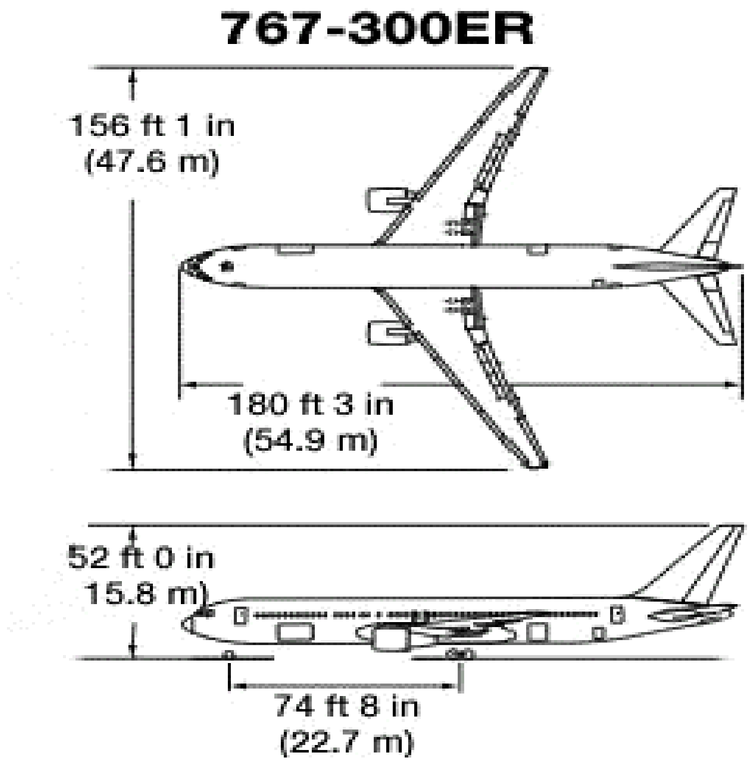

Fig. 3.1. Principal dimensions of the Boeing 767-300 aircraft.

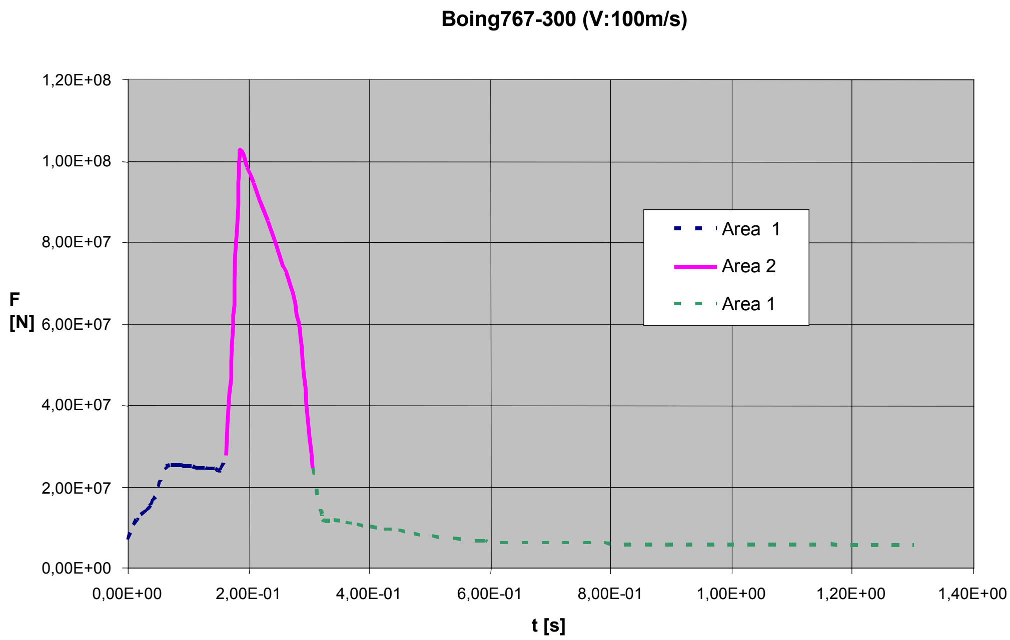

Fig. 3.2. Reaction-time function for a fully loaded Boeing 767-300 impacting at 100m/s (360 km/h) against a rigid target.(upper bound)

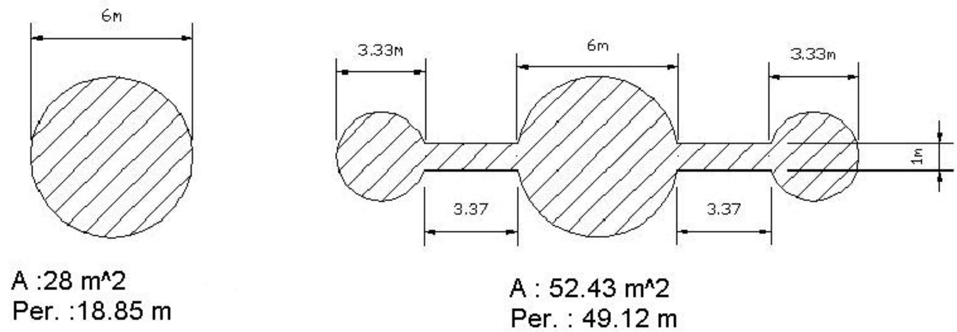

Fig.3.3. Geometrical properties and dimensions of contact areas: at left, type 1, at right, type 2.

4. DESCRIPTION OF THE CONCRETE MODEL AND MATERIAL PROPERTIES

For evaluating the strength of a reinforced or prestressed concrete shell to penetration by an impinging aircraft, the analyst faces two options: to model the entire structure, but sacrificing details, for example, by admitting large elements in the critical regions, due to storage capacity limitations, or to limit the model to only part of the target structure, but resorting to a more refined mesh in the region of interest. The authors selected the second option, limiting the model to a cilindrical panel. The influence of the boundary conditions along the edge of the panel was verified to be small by comparing the *punching strength* computed for extreme conditions (fixed and free boundaries). Geometrical properties of the panel and DEM model are specified in Table 1. The concrete is modelled as a non-homogeneous material characterized by its elastic modulus E and specific fracture energy G_f , which are defined as three-dimensional gaussian random fields. Also note that there is still scarce experimental evidence on the statistical properties of these fields.

Table 1. Geometrical properties of concrete panel and DEM model

	DEM
External shell radius R	18.33m
Arc in circumferential direction	56 degrees
Number of elements in thickness	5 modulae
H (panel length)	7.5m
Reinforcement	Two layers of 25mm rebars

5. DETERMINATION OF THE PUNCHING STRENGTH OF THE SHELL

In order to *pinpoint* the failure load of the shell by punching through, it was decided to monitor the evolution with time of the total reaction along the panel supports, which should remain equal (in the mean) to the load applied to the target structure throughout the duration of impact. Thus, Fig 5.1 shows the evolution of the total applied load, corresponding to normal impact of a Boing 767 300, as well as the reaction for one simulation, i.e. one realization of the random fields that define E and G_f.

In order to assess the dynamic punching strength of the shell, similar analyses were performed for load-time functions multiplied by a reduction factor η. Fig. 5.1 presents the evolutions of the load and the total reaction along the edges of the panel for η= 0.7, clearly indicating that in this case, *punching through does not occur.* Of course, this result corresponds to just one simulation of the concrete properties. Also note that the results presented in this section were obtained with the nominal properties of concrete, that is, 28 days strength, without considering strain rate or other effects.

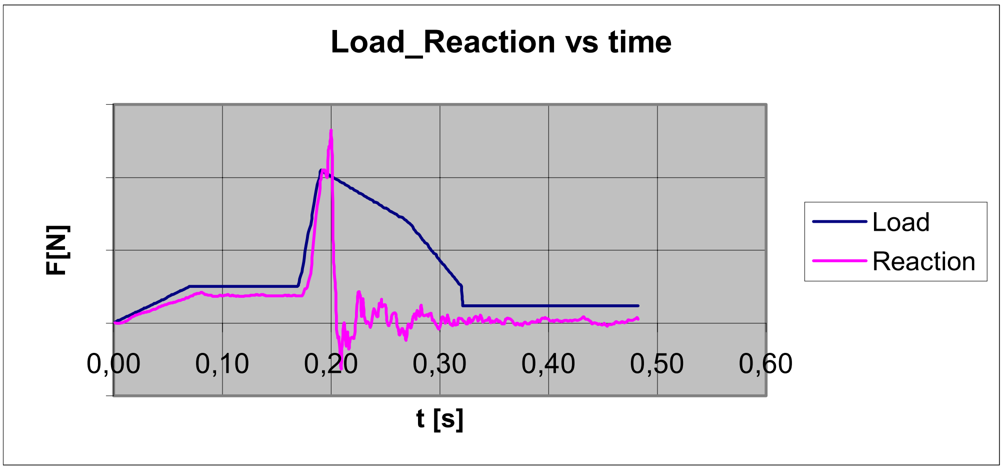

Figure 5.1. Evolution of the reaction showing a punching-through type failure at t= 0.5 seg

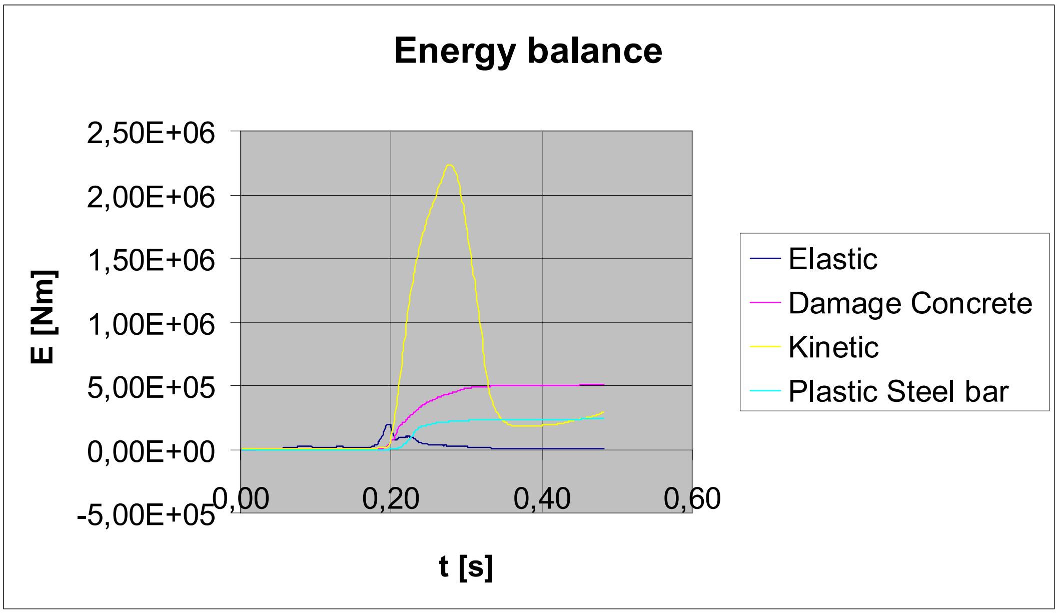

Figure 5.2. Energy balance through the impact duration

6. INFLUENCE OF AGE AND STRAIN RATE ON SHELL STRENGTH.

As previously indicated, the results presented in Section 5 were obtained assuming nominal properties for concrete and steel, applicable to static loading. It is known that concrete strength increases with age and with the strain rate, which leads to the expectation that the real capacity of an existing structure to resist punching is higher than predicted by the results of Section 5, based on its *nominal initial properties*. A mean compressive strength was adopted for *in situ* concrete. On the other hand, the mean strain rate during loading was estimated as:

$d\varepsilon/dt$ = 1.4E-4/0.02=7E-3/s= 10E-2/s

According to Suaris & Shah [11] the increase of the tensile strength for this strain rate reaches 35%. This resulted in Model E, considered a *lower bound* of the conditions assumed for young concrete, i.e. just after construction. Most experimental evidence suggests larger values for the strength under impact, both for concrete and steel. Moreover, the influence of age should also be taken into consideration. Consequently, it is herein proposed to lump both factors in a single coefficient $\xi > 1$ which, by multiplying the strength parameters used in model E, estimates the *real* values, in a structure N years old.

Series of 5 simulations for each value of ξ were generated , estimating the failure probability by the ratio between the number of simulations in which punching occurred and the total number of simulations. The results permit estimating the conditional probability of failure of the cylindrical panel, defined as punching of the concrete external wall for normal impact of a fully loaded B 767-300 at 100m/s.

7. INFLUENCE OF THE LOAD-TIME FUNCTION FOR THE BOEING 767-300

The total load-time function employed in the previous sections is based on conservative assumptions for the mass and crushing strength distributions of the aircraft, since it was developed as a design tool. Revising the available data for the aircraft and the ensuing assumptions, the diagram shown in Fig. 7.1 was obtained. This diagram presents a peak approximately 10% lower than the peak of the diagram in Fig. 3.2. In addition, the shape is rounded rather than sharp-pointed, which would result in less damage in connection with perforation and shear. In view of the lack of data to conduct an elaborate probabilistic study of the aircraft properties, the curves in Figs. 3.2 and 7.1 were herein considered as upper and lower bounds, respectively, of an actual load-time function for the Boeing 767-300.

Five simulations for Model E, subjected to an impact defined by the total load-time function of Fig. 7.1, did not result in punching of the shell. It is then obvious that, for this loading function, the conditional probability of failure would be negligibly small.

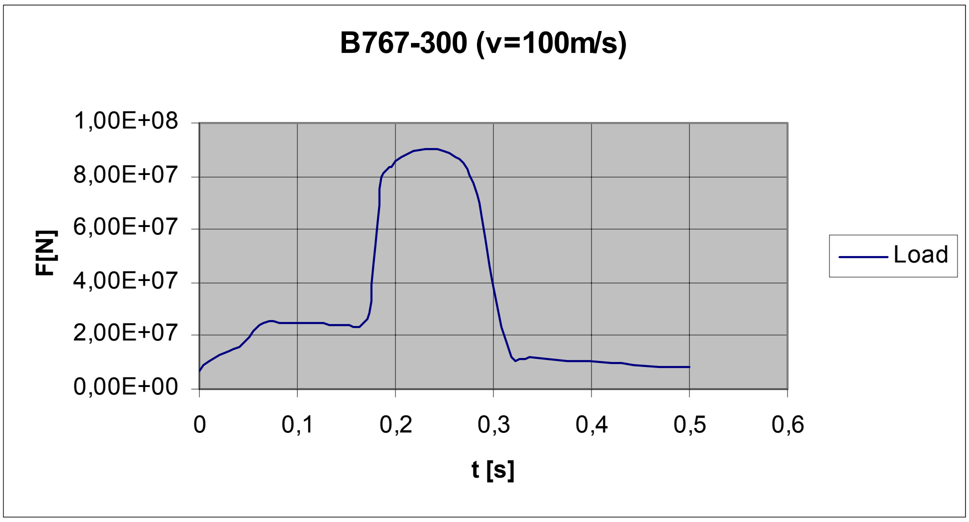

Fig. 7.1. Load time function for a fully load Boeing 767-300 at 100m/**s.** (Lower bound)

8. CONCLUSIONS

The effect of a large commercial aircraft impacting normally on the cylindrical wall of a typical containment building of a NPP was studied in detail. In this paper results for a panel are presented, which are part of a wider study that includes cylindrical and spherical shells. It was concluded that for the concrete wall considered in this example, perforation is the type of failure that has to investigated. Therefore, a global analysis of the entire building is not necessary.

In this paper, impact of a fully loaded Boeing 767-300 at 100m/s on the cylindrical wall of a typical containment building is used for illustration purposes. Considering that large uncertainties exist in relation to both the material properties of existing target structures and the aircraft mass and stiffness distributions, a probabilistic analysis seems a logical approach. Defining failure of the containment as a damaged state in which perforation or punching-through of the concrete wall occurs at any point on the shell, a procedure for evaluating the conditional probability of failure for any prescribed impact event is described. For the example structure and impact velocity discussed in the paper, this conditional probability of failure was found by simulation to be negligible.

ACKNOWLEDGEMENTS

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