Impact Damage of the Challenger Crew Compartment

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A free-fall water impact of the nose section of the Challenger Orbiter including the crew compartment is investigated. Assuming the structure to be perfectly rigid, forces and accelerations acting on the capsule on entering the water are determined and compared with the survivability limits of the occupants. The peak decelerations corresponding to terminal velocities of 140 and 180 mph (62.6 and 80.5 m/s) were found to be 100 and 150 *g*, respectively, with a duration of approximately 25 ms. On the NASA human endurance diagrams, the calculated parameters fell within the area of severe injuries. The local pressures were also calculated and found to be of an exponentially decaying character with a maximum value in the range of 4-6 MPa (600-900 psi). A simplified rupture analysis of the outer shell acted upon by the transient pressure pulse was performed and it was found that tearing and fracture of the fuselage will certainly occur almost instantly on contacting water. It can be concluded that abrupt decelerations and loss of integrity of the cockpit upon water impact must have produced severe or fatal injuries. The present findings also shed some light on the problem of survivability of the *primary explosion*.

Nomenclature

a	= acceleration or deceleration
a_{max}	= maximum acceleration
A	= submerged area
C_D	= air drag coefficient
F	= total force
g	= gravitational acceleration
h	= depth of submergence
h_1	= distance at maximum acceleration
$2L$	= spacing of frames or bulkheads
M	= added mass
M_0	= mass of the impacting body
p	= local pressure
p_c	= static collapse pressure of the panel
$(p_0)_c$	= critical pressure to cause first fracture
p_0	= maximum value of local pressure
S	= cross-sectional area of the fuselage
S_{min}	= minimum cross-sectional area of the fuselage
S_{max}	= maximum cross-sectional area of the fuselage
t	= time
t_1	= time to maximum acceleration
t_{eq}	= equivalent thickness of the stiffened panel
V	= instantaneous velocity
V_0	= terminal velocity
$(V_0)_c$	= critical terminal velocity
$\forall$	= volume of the submerged body
w_f	= maximum displacement of the panel
α	= coefficient in Eq. (14)
γ	= dimensionless parameter, Eq. (18)
ϵ	= strains
ϵ_c	= critical rupture strain
ϵ_{max}	= maximum strains
θ	= pitch (contact) attitude
η	= dimensionless maximum pressure
μ	= coefficient of added mass
ρ	= mass density of water
ρ_a	= mass density of air
ρ_{Al}	= mass density of aluminum
σ_y	= yield stress
τ	= time constant

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Introduction

THE investigation of the Challenger accident has focused on the factors that led to the disastrous explosion. Little emphasis has been given to the possible effect of the *secondary water impact* on the passenger compartment should the capsule survive the primary air blast. With current advances in hydrodynamics and crashworthiness engineering,[5] it is feasible to reconstruct the whole sequence of events associated with the crash of a vehicle into the ocean.‡

In this context, it is important to answer the following two questions: 1) Can the integrity of the vehicle be maintained under a free-fall water impact? 2) Are the resulting decelerations and forces survivable by the occupants?

The purpose of the present pilot study is to give a partial answer to these questions. A closed-form solution of the transient impact problem of an axisymmetric rigid body into water will be derived. Force and acceleration time histories will be determined and a parametric study will be performed. The predicted values will be compared with human tolerance limits to rapidly applied accelerations. The local pressures with which water acts on the structure will also be found and a preliminary estimate of damage and rupture suffered by the outer shell will be made.

The present analysis is based on the premise that the primary explosion resulted in the separation of the entire nose section from the rest of the Orbiter, just behind the aft bulkhead. Photographic evidence released by NASA appears to justify this assumption. The fate of the "intact" capsule is studied.

A comprehensive theoretical and experimental program was undertaken by NASA in the late 1950's and 1960's to determine the water landing characteristics of the Apollo command module. One-twelfth-scale dynamic models were tested as well as a full-scale capsule.[7] A theoretical investigation was also conducted using the principle of conservation of momentum along with the concept of an added mass. The agreement among the data obtained from the model and full-

‡A note added when revising the paper on Aug. 6, 1986. The paper was based on the information released by the National Transportation Safety Board and NASA up to the end of May 1986. The Presidential Commission on the Challenger Accident issued its final report on June 16, 1986. Six weeks later NASA presented new evidence on the accident. It was found that not only the capsule, but also its crew, might have survived the primary blast. These revelations make the problem of water impact of prime importance in determining the fate of the astronauts.

scale tests and theory was found to be very good. The correlation of the three types of results is shown below in Fig. 4 for the case of a vertical entry ($\theta = 90$ deg, contact attitude of 0 deg). It is important to note that the maximum deceleration was as high as 50 g for an impact velocity of $V_0 = 10$ m/s, which is relatively small compared to the terminal velocity of the Challenger capsule. In our opinion, the early NASA results may have made some scientists believe that a water impact with a velocity six to eight times larger would produce deceleration one or two orders of magnitudes higher. Actually, this is not the case, as evidenced by the present solution where the maximum deceleration is not larger than 150 g. The reason for such large decelerations reported in Ref. 7 is that the base of the capsule was designed as the segment of a sphere of large radius. According to von Kármán's theory, the added mass increases very rapidly with vertical displacement, in this case, accounting for large forces and decelerations. The maximum decelerations, however, were reported by the same authors to diminish rapidly with increasing pitch attitudes.

In a series of reports,[11,12] Stubbs studied the local water pressures and pressure distributions during landings of the Apollo spacecraft. In the rigid model, the pressure profiles were found to be nonuniform with the highest maximum value of 1.47 MPa. The flexibility of the bottom decreased the peak values of the pressure distribution but resulted in increased total forces and decelerations.[12]

A detailed analysis of the water landing dynamics of the Apollo module, reported in the above-mentioned papers and a dozen other carefully executed projects, resulted in safe operation during the entire Apollo program.

The only published work dealing with water landing of the Space Shuttle Orbiter, to our knowledge, is the ditching study of 1/20 scale model performed for NASA by the Grumman Aerospace Corporation.[13] The landing (horizontal) speed was 53–104 m/s, while the sink speed was not greater than 2 m/s. Moderate impact accelerations up to 9 g were recorded. The report concluded that considerable fuselage bottom damage was to be expected, but did not substantiate this statement and thus gave few clues to the present problem of vertical entry.

Discussion of Input Parameters

The state of the body immediately before the water impact is described by three parameters: the mass of the compartment M_0, the terminal vertical velocity V_0, and the contact attitude θ. See Fig. 1.

In addition, there may be a horizontal component of the velocity V_h and rigid-body angular velocity. Those two components will not be considered in this preliminary analytical treatment of the impact problem. The mass M_0 of the broken nose section of the Challenger was estimated by Rockwell International to be $M_0 = 18{,}160$ kg (40,000 lb). Almost half of the total mass (20,000 lb) is in the crew module, which is a heavy pressurized vessel machined from aluminum. This weight includes onboard avionics. The mass of the outer shell itself is equal to approximately 9000 lb. The landing gear and other internal structural members account for the remaining mass. The front section of the Orbiter can thus be viewed as a two-degree-of-freedom model with an inner shell within the outer shell and supported by a deformable structure primarily by the aft bulkhead. It is feasible to study the crash response of such a model. However, for the purpose of the present note, only a one-degree-of-freedom model characterized by the total mass M_0 will be considered.

The terminal velocity V_0 is a key variable that determines the level of forces, accelerations, and pressures. In the absence of precise data from radar surveillance of the falling pieces of the Shuttle, we made an estimate of the terminal velocity using the formula

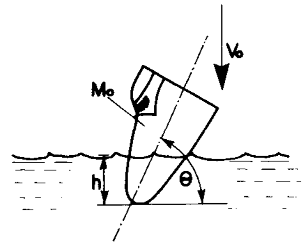

Fig. 1 Parameters describing the state of a rigid body immediately before impact.

$$V_0 = \sqrt{2M_0 g/\rho_a C_D S} \tag{1}$$

where g is the gravitational acceleration, ρ_a the mass density of air, S the cross-sectional area of the falling body, and C_D the air drag coefficient. The diameter of the Orbiter is $D = 4.57$ m,[4] so that the minimum cross-sectional area $S_{min} = \pi D^2/4 = 16.4$ m^2. The longitudinal cross section gives the maximum area $S_{max} = \pi DL/4$, where a (half) elliptical shape is assumed and the length L, as estimated from the drawings,[4] is approximately equal to two diameters $L = 2D$. The maximum area then becomes $S_{max} = \pi D^2/2 = 32.8$ m^2. The air drag coefficient C_D depends on the orientation of the body in the air. It can vary from $C_D \cong 0.1$ for a sphere to $C_D \cong 1$ for a blunt body. In addition, the tumbling motion of the nose section may significantly affect C_D. Taking all of these factors into consideration, we estimated that the terminal velocity should be in the range $V_0 = 50$–100 m/s.

Our calculations are fully compatible with the information revealed by the National Transportation Safety Board (NTSB). From experience with similar airplane accidents, it was determined by the NTSB team that the terminal velocity must have been in the range of 140–180 mph (62.6–80.5 m/s). The best estimate of the terminal velocity provided to us by the Presidential Commission on the Challenger Accident[1] was $V_0 = 82.3$ m/s, which again is consistent with the present estimate. In this report, we shall perform lower and upper bound calculations taking the terminal velocity to be respectively $V_0 = 62.6$ and 80.5 m/s.

The contact attitude θ is most probably unknown for the Challenger crash. This pitch attitude, described by the angle θ, may affect the solution in many ways. It can change the coefficient of added mass. It also determines how the shock is transmitted from the seat and the restraint system to the occupants and sets different injury limits depending on the direction of the acceleration vector. Out of the whole range of entry angles θ, three typical values are considered in the present analysis: $\theta = 0$, 45, and 90 deg. Together with the known geometrical shapes of the compartment, these angles give rise to three different idealized geometries of the water impact problem. See Fig. 2. As can be seen, the variation in the coefficient of added mass μ (Eq. 3) is relatively small from case to case; however, certainly, this variation is overshadowed by the uncertainties in the other estimates, especially the terminal velocity.

In our study, results are shown for the following values of the coefficient of added mass μ, which cover the possible variations in the pitch angle: 0.8, 1.0, 1.25, and 1.5.

Analysis

Depending on the severity of the impact, defined by the set of parameters M_1, V_0, θ, and the strength and stiffness of the capsule, four possible crash scenarios are envisaged, as sketched in Fig. 3.

In the present pilot study of the water impact problem, we are in the position to analyze only the first three scenarios in which the capsule is assumed to plunge into water without the loss of integrity. Our solution provides a conservative estimate on the transient forces and acceleration and may serve as a starting point for considering the remaining crash

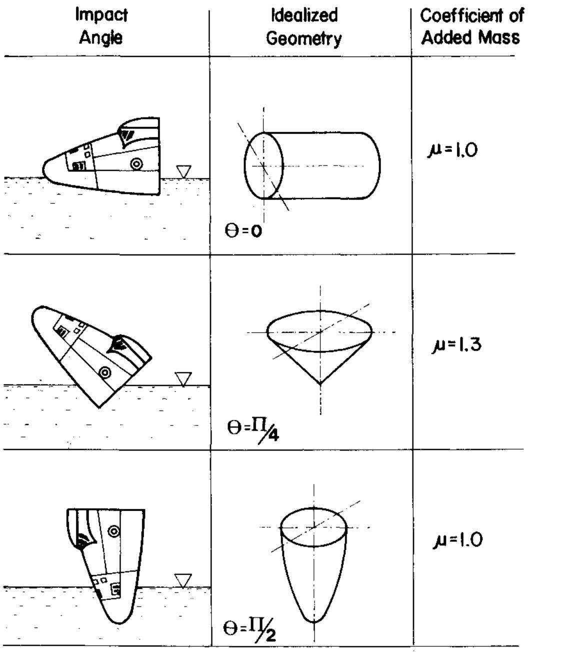

Fig. 2 Three idealized geometries of the water impact problem and the corresponding coefficients of added mass.

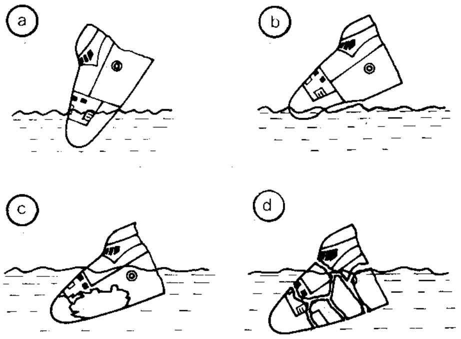

Fig. 3 Four possible scenarios of the water impact of the nose section of the Challenger Orbiter.

scenario in which the outer shell is torn open on impact. Such an improved analysis will be justified if more precise information is available on the input parameters and structural arrangement of the Shuttle.

In view of the uncertainties about the pitch angle, it was decided to make simplified calculations using the concept of the added mass rather than an exact numerical integration of the equations describing the transient process of solid/fluid interaction. Such an analysis was proved in the past to yield reliable results on the splash landing of the Apollo command module.[7] A comparison of the acceleration time-histories obtained in this reference from model and full-scale tests and theoretical solutions using the von Kármán theory is shown in Fig. 4. The agreement is seen to be good, which justifies the application of a similar theoretical approach in the present paper.

The first step in the solution is the equation of the conservation of linear momentum

$$V(M_0+M)=V_0M_0 \tag{2}$$

where V is the instantaneous velocity of the body and M the added mass defined by

$$M=\mu\rho\forall \tag{3}$$

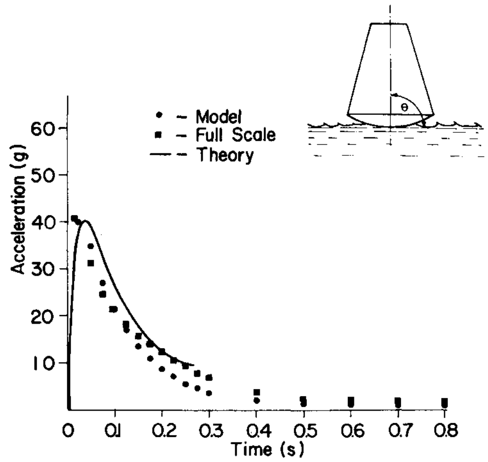

Fig. 4 Correlation between the acceleration time histories obtained from the model and full-scale tests and theory ($\theta = 90$ deg). (After Ref. 7.)

in which ρ is the mass density of water and $\forall$ the submerged volume. For example, for an ellipsoid $\forall = 4/3\pi R^2 h$ and for a right circular cone $\forall = \frac{1}{3}\pi h^3$, where h is the depth of the submerged mass defined in Fig. 1. In the subsequent calculation, we shall represent the added mass by

$$M=\alpha\rho h^3 \tag{4}$$

In such a formulation, *all the nonlinearity of the solid-fluid interaction and shape of the impacting body are lumped together into a single coefficient* α. We have used a numerical solution for the cone, incorporating the effect of the rising of water,[10] and an exact solution for an elliptical sphere derived by us, to select the appropriate values of α. The correspondence of μ and α is

$\mu=$	0.8	1.0	1.25	1.5
$\alpha=$	0.74	1.05	1.34	1.46

Using the definition for instantaneous velocity,

$$V=\frac{\mathrm{d}h}{\mathrm{d}t} \tag{5}$$

a closed-form solution can be derived for all quantities of interest as a function of either depth of penetration into water h or time t. The total reaction force F with which the water acts on the body is found from

$$\frac{\mathrm{d}}{\mathrm{d}t}(M_0V)=-F \tag{6}$$

Discussion of Results

The normalized shape of the force and acceleration pulses is given by the expression

$$\bar{a}=\bar{F}=\frac{2.12\bar{h}^3}{(1+0.285\bar{h}^3)^3} \tag{7}$$

where the dimensionless acceleration and force are normalized with respect to the peak acceleration and peak force, respectively,

$$\bar{a}=a/a_{\max}, \quad \bar{F}=F/F_{\max} \tag{8}$$

As the depth of penetration h or dimensionless depth $\bar{h}$ increases, the acceleration first increases, attains a maximum at

$h = h_1$, and then decays. The time required to reach peak acceleration is inversely proportional to the initial velocity

$$t_1 = \frac{0.0756}{V_0}(M_0/\alpha\rho)^{1/3} \tag{9}$$

and for the set of input parameters is of the order of $t_1 = 25$ ms.

On the other hand, the corresponding displacement is independent of the initial velocity

$$h_1 = 0.6586(M_0/\alpha\rho)^{1/3} \tag{10}$$

which, in our case, equals 1.05 m. The total submerged depth at which the deceleration drops practically to zero is $2h_1 = 2.1$ m. These results are significant in that the nose-down impact configuration (pitch attitude $\theta = 90$ deg) can cut the deceleration in half by providing additional crush space of a magnitude comparable to $2h_1$.

Figure 5 shows the dependence of the solution on the pitch angle (which enters our solution through the dependence on α) for a fixed terminal velocity of $V_0 = 50$ m/s. The dependence is relatively weak.

From the point of view of survivability of the impact, the quantities of most interest are the accelerations, particularly, the maximum acceleration. Since the latter quantity depends on the square of velocity

$$a_{\max} = 0.6123 V_0^2 \alpha(\rho/M_0)^{1/3} \tag{11}$$

it is difficult to provide accurate predictions of $a_{\max}$ in the absence of reliable estimates for the terminal velocity. Figure 6 shows plots of acceleration vs time for the two limiting values of the impact velocity, $V_0 = 62.5$ and 80.5 m/s. Those accelerations should be compared to the known injury criteria for restraint occupants. The level of survivable accelerations depends on the duration of the impact and the direction of the force application. Studies with animals, volunteers, and dummies performed in the late 1950's and 1960's by NASA resulted in the construction of the human tolerance diagrams, shown in Figs. 7 and 8 (see Ref. 2). The coordinate of the present water impact problem with two different terminal velocities are denoted on those diagrams by triangles. *In all cases, the calculated parameters of the acceleration pulse fall within the area labeled "severe injuries."* For headward and tailward longitudinal accelerations (Fig. 7) the present predictions are well above the border line between moderate and severe injuries, suggesting that such impact configurations are not likely to be survivable. The limits of endurance without injuries are much higher if the decelerations are applied in the transverse direction (Fig. 8). It is seen that the points corresponding to the present solution only slightly exceed the envelope of moderate injuries. Thus, it is possible that the reduction of peak acceleration due, for example, to shell rupture and crushing of the internal structure can result in a survivable crash scenario.

The above conclusions are valid as long as the survivable space around the Challenger crew is maintained. Any rupture of the crew module, detachment of seats, and/or penetration of foreign objects inside the cabin could result in a secondary impact that can be much more devastating than the primary water impact of the outer shell.

We can conclude that no definite statement as to the fate of the crew can be made without addressing the problem of damage and rupture of the nose section of the Orbiter.

Determination of Local Pressures

As discussed earlier, the precise determination of pressure distribution in the shell could only be determined through a numerical solution of the nonlinear fluid/solid interaction problem. Since the deformability of the structure has a tendency to level off the contact pressure, it is reasonable to assume that, in the first approximation, the pressure is uniformly distributed over the whole solid/fluid interface.[12] A simple estimate on local pressure can thus be obtained by dividing the total force by the area (see Fig. 9a),

$$p(t) = F/A \tag{12}$$

Note that the area A is a function of either submerged depth h or time and that the pressure becomes a time-varying step function traveling with the velocity V down the lateral surface of the shell. For a right-angle cone $A = \pi h^2$, Eq. (12) yields

$$p = \frac{3\alpha}{\pi}\rho V_0^2 \frac{1}{[1 + (\alpha\rho h^3/M_0)]^3} \tag{13}$$

The plot of the normalized pressure vs the penetration depth is shown in Fig. 9. This curve can be replotted using the transformation of variables. The resulting time variation

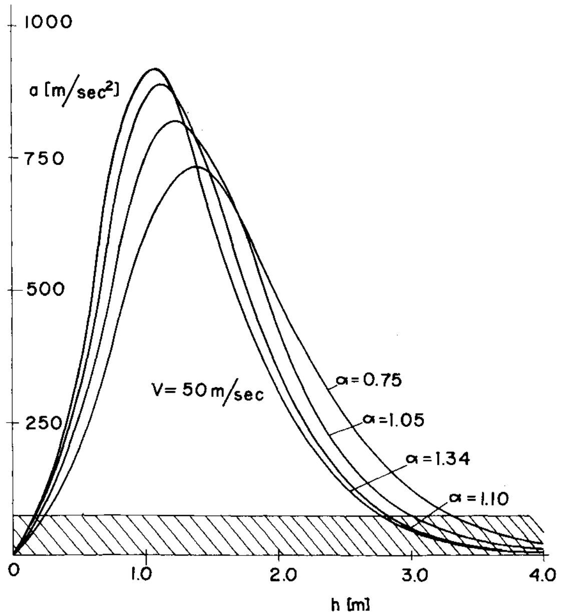

Fig. 5 Weak dependence of the deceleration pulse on the pitch angle θ.

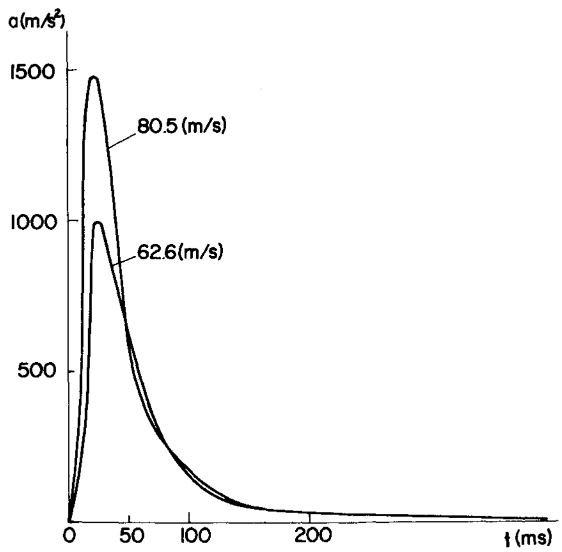

Fig. 6 Time histories of the deceleration for two limiting values of the terminal velocity.

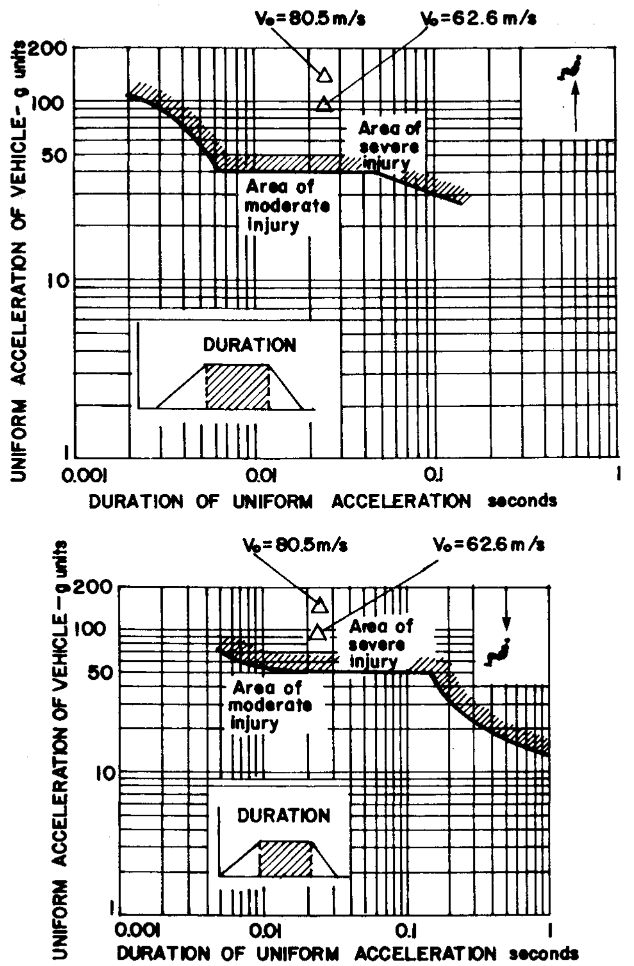

Fig. 7 Position of the maximum calculated decelerations on the human endurance diagrams for a) headward, and b) tailward longitudinal decelerations.

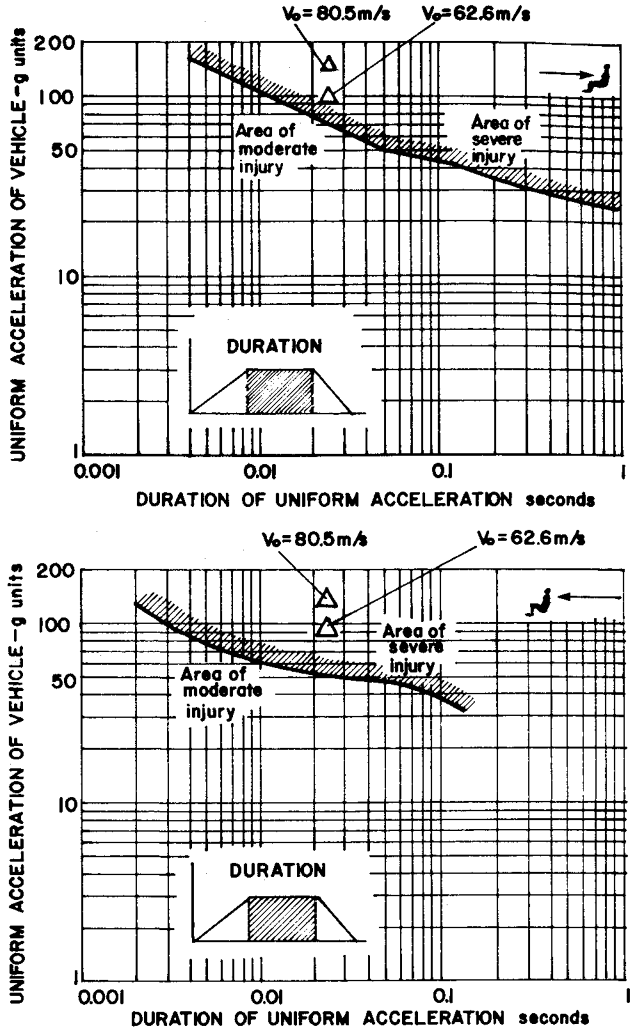

Fig. 8 Position of the maximum calculated decelerations on the human endurance diagrams for a) back-to-chest acceleration, and b) chest-to-back transverse accelerations.

of the pressure is depicted in Fig. 10 by a solid line. The exponential fit of this curve is shown in Fig. 10 by the dotted line and is

$$p(t) = p_0 e^{-t/\tau} \tag{14}$$

where the peak pressure is equal to $p_0 = 1.25\rho V_0^2$ and the time constant $\tau = 20$ ms.

The advantage of working with an exponential rather than any other pressure pulse is that solutions are readily available in the literature for impact damage and the rupture of longitudinally stiffened shells under exponential transient pressure loading.

Denting and Rupture of Challenger Fuselage

The outer shell of the Space Shuttle is built as a conventional airplane fuselage with a system of almost equally spaced rings and stringers. In the case of extreme dynamic pressure, failure of the fuselage can take several different forms:

1) Tearing fracture of longitudinally stiffened shell between main rings, Fig. 11a.

2) Shearing of the stiffened shell at the supporting frames or bulkheads, Fig. 11b.

3) Global collapse and flexural fracture of rings, Fig. 11c.

4) Crushing of bulkheads and decks.

From the point of view of the integrity of the capsule, buckling per se is not considered to be a critical failure model. However, buckling may precede any of the above-mentioned failure modes. In this paper, we shall examine the tearing model only. It should be mentioned that the presence of the ceramic tiles glued to the aluminum skin considerably increases the

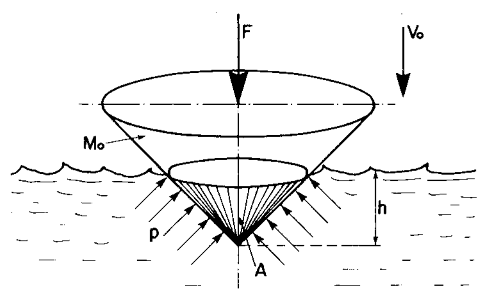

Fig. 9a Modeling concept for calculating uniform pressures.

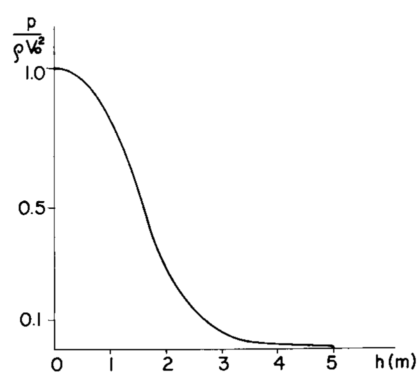

Fig. 9b Plot of normalized pressure vs the penetration depth.

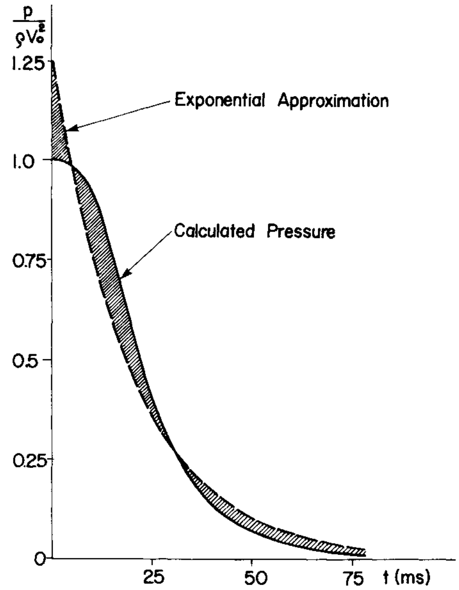

Fig. 10 Calculated pressure-time variation (solid line) and the exponential decay approximation (dotted line).

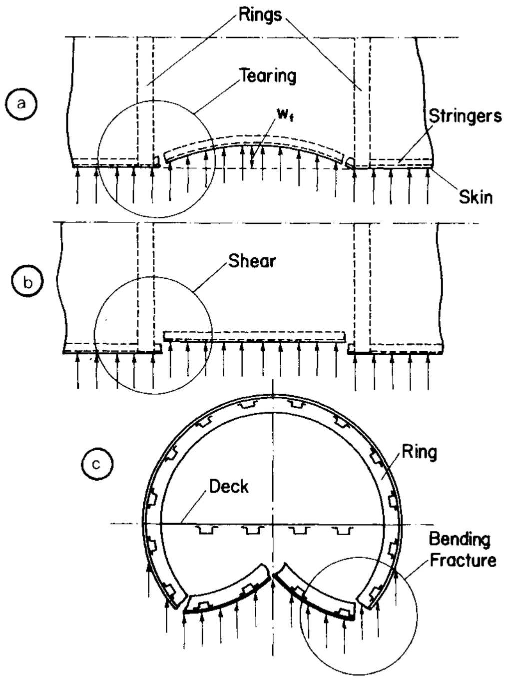

Fig. 11 Three possible failure modes of the fuselage: a) tearing fracture, b) shear of the longitudinally stiffened shell, and c) flexural failure of rings.

buckling strength of the shallow cylindrical shell. Also, the tiles will tend to distribute the loads over a larger area, thus preventing some localized failure mode, such as shear failure, from occuring. In this report, we shall disregard the effect of the tiles on the damage analysis of the fuselage.

An approximate analysis of the rupture of ship plating due to hydrodynamic wave impact is presented in Ref. 14. With minor modification, this theory can now be applied to predict the tearing fracture suffered by airplane fuselage hitting water. Consider a typical longitudinally stiffened panel located in the contact area between the fuselage and water. The distance between the bulkheads or heavy rings is denoted by $2L$ and the equivalent thickness of the panel is t_{eq}. See Fig. 12. The equivalent thickness is larger than the thickness of the skin and takes into account the presence of stringers. The analysis is carried out using the rigid-plastic material idealization. The static

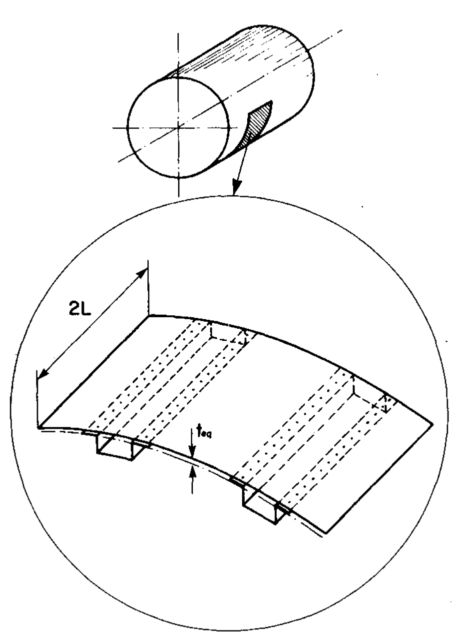

Fig. 12 Geometry of the stiffened panel assumed in the rupture calculation.

plastic load-carrying capacity of the plate strip clamped on both sides is

$$p_c = \sigma_y (t_{eq}/L)^2 \tag{15}$$

where σ_y is the yield stress of the material. It is convenient to nondimensionalize dynamic pressure p_0 with respect to p_c

$$\eta = \frac{p_0}{p_c} = 1.25\frac{\rho V_0{}^2}{\sigma_y}\left(\frac{L}{t_{eq}}\right)^2 \tag{16}$$

Assuming that the local stiffened panel resists the dynamic pressures by plastic ductile bending and stretching, the depth of the local dent w_f can be calculated from the approximate formula, derived in Ref. 14,

$$\frac{\omega_f}{t_{eq}} = \eta \frac{\tau\gamma}{\tau\gamma + \pi/2} \tag{17}$$

where the dimensionless parameter γ is defined by

$$\gamma^2 = 3\sigma_y / L^2 \rho_{Al} \tag{18}$$

The first term in Eq. (17) gives the dimensionless deflection resulting from the statically applied load, while the second term represents the correction due to the transient character of the load.

The impact damage calculations of the Challenger's fuselage are performed for the set of input parameters shown in Table 1. With these parameters, the maximum permanent plastic deflection is found to be equal to 234 thicknesses of the

Table 1 Parameters for impact damage calculations

Loading
Peak pressure $p_0 = 4$ MPa (600 psi)
Time constant $\tau = 20$ ms
Material
Mass density $\rho_{Al} = 3.5 \times 10^{-4}$ lb²/in.⁴
Yield stress $\sigma_y = 48{,}000$ psi
Geometry
Frame distance $2L = 0.711$ m
Equivalent thickness $t_{eq} = 2.54$ mm

plating. Clearly, such large deflections, exceeding by two orders of magnitude the thickness of the shell, cannot be tolerated by the structure. Tearing or shear rupture of the outer shell will occur almost instantly upon contact with the water.

The question arises as to what impact velocities or pressures could then be tolerated by the structure? An estimate of the critical pressure can be given using the concept of a maximum fracture strain ϵ_c. This concept has been previously used in the ship and offshore industry for predicting rupture of hull plating due to collisions or hydrodynamic wave impact.[9,14] Following the experimental work of Menkes and Opat,[8] Jones[6] found that a good correlation between theory and experiment on the plastic failure of impulsively loaded aluminum beams was obtained by taking $\epsilon_c = 17\%$. On the other hand, $\epsilon_c = 8\%$ was taken as a correct magnitude of the fracture strain of aluminum extruded rings of transport aircraft sections subjected to drop tests. The tests and calculations using the DYCAST beam-type numerical code were performed at NASA Langley and are reported in Ref. 3. Generally, the thicker a member is, the smaller the critical fracture strain should be.

The uniform membrane strains can be related to the maximum displacement of the plate by

$$\epsilon_{\max} = \tfrac{1}{2}(\omega_f/L)^2 \tag{19}$$

Fracture occurs when $\epsilon_{\max} = \epsilon_c$, i.e., when

$$\frac{\omega_f}{t_{eq}} = \sqrt{2\epsilon_c}\,\frac{L}{t_{eq}} \tag{20}$$

Comparing Eqs. (17) and (20), one finds the peak pressure p_0 at which the tearing fracture of the fuselage first occurs,

$$\sqrt{2\epsilon_c}\,\frac{L}{t_{eq}} = \frac{(p_0)_c}{p_c}\,\frac{\tau\gamma}{\tau\gamma + \pi/2} \tag{21}$$

The dynamic load factor $\tau\gamma/(\tau\gamma + \pi/2)$ is of the order of unity for the present set of input parameters. Taking ϵ_c as an average between the two numbers quoted earlier, $\epsilon_c = 0.125$, the critical local pressure can be estimated from the simple equation

$$(p_0)_c = 0.5\sigma_y(t_{eq}/L) \tag{22}$$

Alternatively, the threshold impact velocity $(V_0)_c$ can be calculated from

$$(V_0)_c = 0.63\sqrt{\frac{\sigma_y}{\rho}\,\frac{t_{eq}}{L}} \tag{23}$$

In the case of the Challenger fuselage, $(p_0)_c = 171$ psi and $(V_0)_c = 18.8$ m/s. The above calculations clearly show that the Challenger fuselage can *tolerate water impact without tearing rupture for velocities three or four times smaller than the estimated terminal velocity.*

The above conclusion applies to the tensile fracture of the skin. The bending fracture of rings was observed in drop tests on transport aircraft fuselage sections at much lower impact velocities.[3] A detailed analysis of this problem, albeit possible, is beyond the scope of this paper. Also, at this point, no comment can be made as to the integrity of the inner shell. Such an analysis can be made if the geometry and material properties of the crew compartment are given.

From the above crude damage analysis of the Challenger Space Shuttle, we can conclude that shattering of the fuselage must certainly have taken place on impact. The integrity of the crew capsule itself cannot be determined at this stage of the research.

Shear Failure

Transverse shear failure of impulsively loaded clamped rigid-plastic beams was studied by Jones.[6] The present loading with a traveling steep pressure pulse is different from that of uniformly distributed impulsive loading. However, in both cases, points near the beam support are imparted a suddenly applied initial velocity. We believe that the solution presented in Ref. 6 is still valid with a reasonable approximation. The critical velocity that causes shear failure to occur was shown by Jones to be

$$(V_0)_c = \frac{2\sqrt{2}}{3}\sqrt{\frac{\sigma_y}{\rho}} \tag{24}$$

A distinctive feature of the above solution is that it does not depend on the geometry of the structure (L, t_{eq}). The critical velocity is the function of the mechanical properties of the material. On comparing Eqs. (24) and (23), we see that the transverse shear failure can be the governing failure mode for velocities which are one order of magnitude higher than the terminal velocity. Such high velocities are typically encountered in the contact explosion problems. The present preliminary analysis appears to indicate that shear should be excluded as a possible failure mode of the Challenger fuselage on contacting water.

Implications of the Damage Effects of the Explosion

The present analysis gives some clue as to the survivability of the primary explosion. At the instant of the blast, the entire Orbiter was subjected to an abrupt acceleration. Soon after, the aerodynamic forces began to decelerate the Orbiter. It is not quite clear which of the two (explosion or aerodynamic forces) broke off the nose section from the rest of the Orbiter. Recent experience with the mislaunch of the Delta rocket appears to indicate that the aerodynamic forces during the tumbling motion were not strong enough to break the cylindrical shell in half. On the other hand, the Space Shuttle fuselage is weakened by the cargo bay door. The forces and accelerations necessary to break the Orbiter could be estimated using the model of a free-free beam subjected to transient pressure pulse. See Fig. 13. Such calculations rest on knowledge of the structural details of the Orbiter, specifically right behind the aft bulkhead.

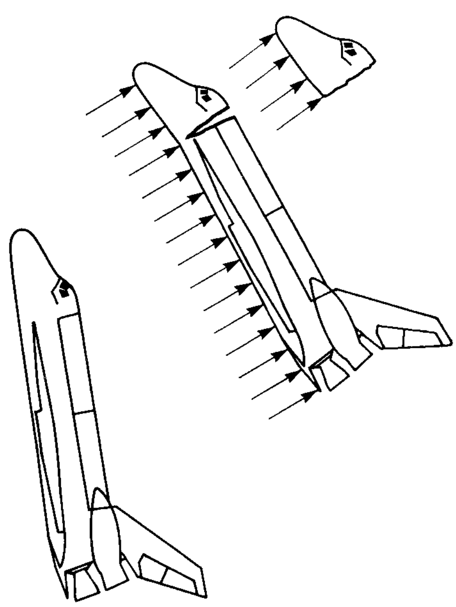

Fig. 13 Free-free beam model for calculating the overall bending failure of the Orbiter.

There is some photographic evidence that the outer shell of the separated cockpit was "virtually intact." If this observation is true, then the local pressures acting on the fuselage must have been below the critical values $(p_0)_c$, which would cause local denting and/or tearing fracture irregardless of the nature of those pressures. An estimate for $(p_0)_c$ was given by Eq. (22). Multiplying $(p_0)_c$ by the maximum cross-sectional area of the nose section of the Orbiter S_{max}, we obtain the total force from which the acceleration can be calculated

$$a_{max} = (p_0)_c S_{max} / M_0 \tag{25}$$

Substituting the known quantities into Eq. (25), we conclude that the maximum rigid-body acceleration of the crew compartment is equal to $a_{max} = 210$ g. This level of acceleration is hardly survivable, but the actual accelerations must have been considerably smaller. Until lower bound calculations are performed, no definite statement can be made as to the fate of the crew during the first second after the explosion. Such calculations are currently being done by us.

Conclusions

This paper reports a pilot study of the response of Challenger's Orbiter to splash landing and provides first-order estimates of the forces, accelerations, and pressures associated with the rigid-body impact. Since the preliminary calculations show that an instantaneous rupture and shattering of the Shuttle's outer shell will occur upon impact, the problem must now be reformulated, taking into account the penetration of water inside the outer shell and secondary impact of the inner shell.

1) The acceleration pulses for the Challenger crew compartment hitting water surface at a terminal velocity are calculated. The analysis is done under the assumption that the capsule enters the water at a right angle as a rigid body and that no structural damage is suffered. The peak decelerations are found to be 100 and 150 g for the terminal velocity equal to 140 and 180 mph (62.6 and 80.5 m/s), respectively. The duration of the acceleration pulse is 25 ms.

2) The calculated decelerations are in the range of "severe injuries," as specified by NASA endurance limit diagrams. The endurance limit strongly depends on the direction of the acceleration vector. For the present pulse duration, the boundary separating moderate and severe injuries is in the vicinity of 40–50 g in the longitudinal direction and 60–80 g in the transverse direction.

3) The local pressures are found to vary exponentially with time. The maximum amplitude is of the order of 4–6 MPa (600–900 psi) with the time constant equal to 20 ms.

4) The approximate rupture analysis appears to indicate that the outer shell of the Challenger Orbiter will be shattered upon impact. The maximum vertical velocity that the fuselage will tolerate is of the order of 18.5 m/s, i.e., three to four times less than the estimated terminal velocity of the cockpit.

5) The level of acceleration of the crew compartment will be diminished by allowing a relative motion of the inner shell with respect to the outer shell. At the same time, the chances of survival will depend on the structural integrity of the crew module itself. This problem can be tackled by us, provided the internal structural arrangements of the Shuttle cabin and dimensions of the inner shell are at hand. Before such an analysis is done, no definite conclusions can be drawn as to the fate of the Challenger's crew upon water impact.

6) The accelerations suffered by the crew compartment as a result of the explosion can be bounded from below by the overall flexural fracture strength of the Orbiter in the critical section right after the aft bulkhead. The upper bound accelerations associated with the local tearing fracture of the fuselage was found to be 210 g. This problem is currently being studied by us.

Appendix: Summary of Calculations

Time-displacement transformation

$$t = \frac{1}{V_0}\left[h + \frac{\alpha\rho h^3}{4M_0}h\right] \tag{A1}$$

Force-displacement relation

$$F = V_0^2 \frac{3\alpha\rho h^2}{[1 + (\alpha\rho h^3/M_0)]^3} \tag{A2}$$

Displacement at maximum force

$$h_1 = \left(\frac{2}{7}\frac{M_0}{\alpha\rho}\right)^{1/3} = 0.6586\left(\frac{M_0}{\alpha\rho}\right)^{1/3} \tag{A3}$$

Maximum force

$$F_{max} = 0.6123 V_0^2 \alpha M_0^{2/3} \rho^{1/3} \tag{A4}$$

Maximum deceleration

$$a_{max} = 0.6123 V_0^2 \alpha \left(\frac{\rho}{M_0}\right)^{1/3} \tag{A5}$$

Dimensionless force

$$\bar{F} = F/F_{max} \tag{A6}$$

Dimensionless displacement

$$\bar{h} = h/h_1 \text{ and time } \bar{t} = t/t_1 \tag{A7}$$

Pulse shape

$$\bar{a} = \bar{F} = \frac{2.12\bar{h}^2}{(1 + 0.285\bar{h}^3)^3} \tag{A8}$$

Time at maximum force

$$t_1 = \frac{1}{V_0}\,0.7056\left(\frac{M_0}{\alpha\rho}\right)^{1/3} \tag{A9}$$

Time-displacement transformation

$$\bar{t} = 0.093\bar{h}(1 + 0.07\bar{h}^3) \tag{A10}$$

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