NASA Technical Memorandum 4082

Analysis of the Space Shuttle Orbiter Skin Panels Under Simulated Hydrodynamic Loads

Huey D. Carden, Edwin L. Fasanella,
and Lisa E. Jones

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Huey D. Carden
Langley Research Center
Hampton, Virginia

Edwin L. Fasanella and Lisa E. Jones
PRC Systems Services
A Division of Planning Research Corporation
Hampton, Virginia

National Aeronautics
and Space Administration

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Summary

The Space Shuttle orbiter skin panels were analyzed under pressure loads simulating hydrodynamic loads to determine their capability to sustain a potential ditching and to determine pressures that typically would produce failures. Two DYCAST (Dynamic Crash Analysis of Structures) finite element models were used in the study. One model was used to represent the skin panels in the center body (bays 1 to 11) while a second model was used to analyze a fuselage skin panel in the wing region (bay 12) of the orbiter. Three types of pressure loads were applied to the DYCAST skin models: a uniform pressure load, a nonuniform pressure distribution representative of that produced by a body planing on a water surface, and a nonuniform pressure applied over different portions of the panels representative of a shifting load that would occur as the orbiter pitched over on the water surface.

Typical uniform pressure loads that produced failures (defined as onset of plasticity in the stiffeners or skin panels using conservative yield stresses) ranged from 7.5 psi to approximately 9 psi depending on the skin and/or stiffener thicknesses in selected bays from 1 to 11. Failure pressure for the wing region (bay 12) was found to be about 2.5 psi.

For the nonuniform pressure loads, typical peak pressures of about 25 psi were found to produce initial failures for the various bays selected for analysis. A peak pressure of 25 psi corresponds to a planing velocity of approximately 36 knots. By contrast, typical ditching velocity for the Shuttle orbiter would be in the 215-knot range, which could produce a peak pressure of approximately 900 psi.

From an assessment of the DYCAST nonlinear computer results, it is concluded that the probability is extremely high that most, if not all, of the lower skin panels would rupture under ditching conditions. Extremely high pressure loads which are produced during hydrodynamic planing far exceed the very low predicted failure pressures for the skin panels. Consequently, a ditching of the orbiter is not considered to have a high probability of success and should not be considered a means of emergency landing unless no other option exists.

Introduction

After the tragic loss of the Space Shuttle *Challenger* and its crew, the President's commission recommended that various aspects of the operations of the Space Shuttle be examined in detail (ref. 1). As part of the NASA response to the commission's recommendations, the potential capabilities for ditching the Shuttle orbiter were assessed. At the request of the NASA Lyndon B. Johnson Space Center, NASA Langley Research Center undertook this assessment. Available reports (refs. 2 to 5) on aircraft ditching and reference 6, which deals with model ditching studies of the Shuttle, were reviewed. It was concluded from this review that no definite statement about the potential safe ditching of the orbiter could be expressed with desired certainty. Consequently, additional analyses were proposed to provide additional data to assist in determining the capability of the Shuttle structure to withstand a ditching. As part of the assessment, Johnson Space Center conducted simplified analyses of the lower skin panels and requested that Langley Research Center conduct more detailed, nonlinear finite element analyses of the same regions for an independent evaluation.

This report presents analytical results from the nonlinear, finite element program DYCAST (Dynamic Crash Analysis of Structures, ref. 7) for pressure loadings that were applied to the Shuttle orbiter skin panels to simulate hydrodynamic loads. Results are presented for center-body and wing region skin panels (bays) to determine the pressure-carrying potential of the Shuttle orbiter in a ditching situation.

DYCAST Analytical Program

DYCAST is a nonlinear structural finite element computer code developed by Grumman Aerospace Corporation with principal support from NASA and the FAA. A general discussion of some features of the program is included here; however, for complete details reference 7 should be obtained. The program may be run for static or dynamic loading conditions. The element library consists of stringers, beams, membrane triangles, plate bending triangles, and nonlinear spring elements.

Material nonlinearities (plasticity) are accommodated by one of three options: (1) elastic and perfectly plastic, (2) elastic and linear hardening plastic, or (3) elastic and nonlinear hardening plastic of the Ramberg-Osgood type. Option (1) was used in the current study. Geometric nonlinearities are handled in an updated Lagrangian formulation by reforming the structure into its deformed shape after small load (or time) increments while accumulating deformations, strains, and forces. The failure option may be imposed automatically whenever a material failure strain criterion is met.

Point, line, and surface loadings are available. In this study, surface loads were gradually applied to represent water loading (see refs. 8 and 9). Both constant and spatially varying loads were applied to the panel models.

Panel Finite Element Models

Assumptions

In conducting the analytical study on the Shuttle orbiter (fig. 1), certain assumptions were made to limit the size of the analytical modeling effort, the cost of computing results, and the time to conduct the investigation. The assumptions included the following:

1. Failure was assumed to have occurred when loads produced onset of plasticity in either the 2024-T351 aluminum skin or stiffeners of the Shuttle bottom panels. Allowable *compressive* yield stress at room temperature (39 to 45 ksi) was reduced to 35 ksi for a 350°F temperature condition on the Shuttle skin, and this value was also used for *tensile* yield stress in the analysis. (See table 3.2.3.0(b_1) and fig. 3.2.3.1.2(a) in ref. 10.) Under this assumption, the pressures that produce plasticity should be conservative.
2. The impact phase of the ditching was not considered. The analysis was conducted assuming steady-state conditions of planing on the water.
3. Three pressure distributions used in the analysis are shown pictorially in figure 2: a nonuniform pressure distribution over the panel (fig. 2(a)) similar to those presented in references 8 and 9 for planing flat bodies, a uniform pressure distribution (fig. 2(b)), and a variation of the nonuniform distribution (fig. 2(c)) wherein the location of the leading edge of the distribution was moved to distinct locations along the panel to represent a traveling wave (to simulate movement because of pitch-over of the Shuttle). Figure 2(d) shows the approximation made for the pressure distribution for input in DYCAST as the loading function.
4. The above pressure distributions were applied in a static analysis since the desired distributed pressure loading was not available in the computer program's dynamic analysis section.
5. Symmetric conditions were assumed about the Shuttle's longitudinal centerline; thus only one-half of the panel had to be modeled.
6. Strength of backup and support structure of the panels was not considered in the analysis nor were tiles accounted for in the assessment. Panels were assumed flat (although they are slightly curved) and were clamped along the appropriate edges. Symmetry boundary conditions were enforced on the centerline edge.

Center-Body Panel Model

Figure 3 illustrates details of the construction of the Shuttle orbiter along with the finite element model (fig. 3(c)) of the fuselage panels. The bottom structure of the orbiter center body (figs. 3(a) and 3(b)) is comprised of 11 bays between frames spaced from 50 to 65 in. apart. A 56-in. spacing was used as a representative average with the width being typically about 100 in. from centerline to the outer edge. T-shaped stiffeners (approximately 2.4 in. high with a 1.0-in. top flange) run longitudinally on the skin at 4-in. lateral spacing. Thickness of the 2024-T351 aluminum skin and stiffeners varied for different bays (see table I). The panel model in figure 3(c) is comprised of 728 triangular plate elements and 350 T-section beams with offsets from the panel which represent the stiffeners of the panels. Except for the centerline, which had symmetric boundary conditions, all edges were clamped. The resulting model had 1664 degrees of freedom. The same model was used for the various bays (1 to 11) of the center-body section of the orbiter with appropriate changes to the dimensions of the orbiter's skin and stringers.

Wing Region Panel Model

The finite element model of the fuselage in the wing region of the orbiter was similar to that shown in figure 3(c). For this region (bay 12) the panels had rectangular or blade-type stiffeners oriented in both the longitudinal and the lateral direction to form a waffle-like pattern (see inset sketch on bottom right of fig. 3(c)). Skin thickness and stringer spacings varied over the bay. Skin thickness ranged from 0.09 in. to a maximum of 0.25 in. Longitudinal and lateral spacing of the stiffeners was generally 4.0 in. by 4.0 in. The resulting finite element model had 672 triangular plate elements and 576 rectangular section offset beam elements with a total of 1534 degrees of freedom after imposition of boundary conditions and the symmetric boundary along the centerline of the section.

Results And Discussion

Center-Body Panel Model With Uniform Pressure Loads

Results of the finite element analysis of the Shuttle orbiter panels under uniform pressure loading (simulated hydrodynamic loads) are summarized in figures 4 and 5 . Figure 4 shows results for selected Shuttle orbiter bays in the center body (bays 1, 3, 5, and 6) and wing (bay 12) regions. The bar chart beneath the figure presents the uniform pressure loading in pounds per square inch (psi) which produced failure in the panels for several bays. The DYCAST predictions indicate that failure would occur in the panel stiffeners of the center-body region at pressures between 7.50 psi (bay 3) and 9.00 psi (bay 6). Failure pressure for bays 1 and 5 was 8.25 psi. Displacements for the panels along the centerline of the Shuttle orbiter at time of failure (onset of plasticity) are presented in figure 5 for these four bays (1, 3, 5, and 6). As may be noted in the figure, at most only 0.14 in. of deflection along the longitudinal centerline of the orbiter was associated with failure, which occurred in the panel stiffeners near the boundary of the panels.

Center-Body Panel Model With Nonuniform Pressure Loads

For the nonuniform pressure distribution, five locations (shifted leading edge locations) of the pressure were used on the center-body panels to simulate the movement of the pressure as the orbiter pitched over. The analytical results for the various shifted positions are shown in figure 6 for bay 1. The DYCAST results indicate that for shifts of the nonuniform pressure from 0 to 24 in. from the front edge of bay 1, failures occurred in the stiffeners along the edge of the panel at a peak pressure of 25 psi. Failure produced by pressure on the bay 1 panel at 32 and 40 in. from the front edge of the bay occurred at somewhat higher peak pressure. Pressure p relates to planing velocity V as follows:

$$p = \frac{1}{2}\rho V^2$$

where ρ is water density. The 25-psi peak pressure corresponds to a planing (horizontal) velocity of only 36 knots, whereas the landing velocity of the Shuttle orbiter in a ditching emergency would more likely range from 200 to 220 knots. At such speeds the pressure could be over 900 psi. For this reason, ditching the Shuttle orbiter is likely to result in complete failure of most of the lower skin panel structure; thus a ditching is not considered to have a high probability of success. Reference 11 presents an analytical procedure for predicting the pressures and distribution on vehicles during a ditching situation.

The vertical deflection of the symmetric boundary of the panel in figure 6(a) shows that only between 0.11 to 0.15 in. of panel motion was associated with the 25-psi peak nonuniform pressure that produced the failure loads. However, as may be noted in the figure, much less panel displacement was associated with the higher failure pressures of the other shifted distributions. Figure 6(b) shows the overall panel displacement pattern for the pressure distribution shifted 16 in. on the panel. The displacements have been magnified 50 times in the figure to show overall deflected shape of the panel associated with the pressure loading.

Wing Region Panel Model With Uniform Pressure Loads

Results of the DYCAST model of the bay in the wing region of the Shuttle orbiter are also shown in figure 4 for the uniform pressure case. Data indicated that failure was initiated in the blade stiffeners along the edges of the panel in this region (bay 12) at a pressure load of about 2.5 psi. Although the panel has stiffeners in both the longitudinal and the lateral direction, the region is relatively weak under a uniform surface load such as hydrodynamic loadings. Since the panel failed at the low 2.5-psi pressure loading, no attempt was made to analyze the panel under the nonuniform and shifted loadings as was done for the center-body bays.

Effect of Yield Stress on Failure of Panels

If the panels had been loaded with the pressure distributions using a room temperature value of 42 ksi as the allowable *tensile* yield stress of the aluminum material, the pressures at which onset of plasticity (failure) occurred would be approximately 21 percent higher than those pressures reported herein. However, the conclusions which were drawn from the conservative approach of this report concerning the lack of ditching capability of the Shuttle would not be altered.

Conclusions

The Space Shuttle orbiter skin panels were analyzed under simulated hydrodynamic loads to determine their capability to sustain potential ditching loads and to determine pressures that typically would produce failures. Two DYCAST (Dynamic Crash Analysis of Structures) finite element models were constructed for the study. One model was used to represent skin panels in the center body (bays 1 to 11), while a second model was used to analyze a skin panel in the wing region (bay 12) of the orbiter. Three types of pressure loads were applied to the DYCAST skin models: a uniform pressure load, a nonuniform pressure distribution representative of a distribution produced by a body planing on a water surface, and a nonuniform pressure applied over different portions of the panels representative of a shifting load on the panel that would occur as the orbiter pitched over on the water surface.

Typical uniform pressure loads that produced initial failures (defined as onset of plasticity in stiffeners or skin panels) ranged from 7.5 psi to approximately 9 psi depending on the skin or stiffener thicknesses in selected bays from 1 to 11. Failure pressure for the wing region (bay 12) was found to be about 2.5 psi. The room temperature allowable *compressive* yield stress of aluminum (39 to 45 ksi) was reduced to 35 ksi at 350°F as a conservative value of both tensile and compressive yield stress in the analyses. The use of the higher room temperature value of allowable *tensile* yield stress would produce approximately 21-percent higher failure pressures, but conclusions concerning the lack of ditching capability of the Shuttle would not be altered.

For the nonuniform pressure loads, typical peak pressures of about 25 psi were found to produce initial failures for the various bays selected for analysis. A peak pressure of 25 psi corresponds to a planing velocity of approximately 36 knots. By contrast, typical ditching velocity for the Shuttle orbiter would be in the 215-knot range which could produce a peak pressure of approximately 900 psi.

From an assessment of the DYCAST nonlinear computer results, it is concluded that the probability is extremely high that most, if not all, of the lower skin panels would rupture under ditching conditions. Extremely high pressure loads that are produced during hydrodynamic planing far exceed the very low predicted failure pressures for the skin panels; thus ditching of the Shuttle orbiter is not considered to have a high probability of success and should not be considered a means of emergency landing unless no other option exists.

NASA Langley Research Center
Hampton, VA 23665-5225
November 7, 1988

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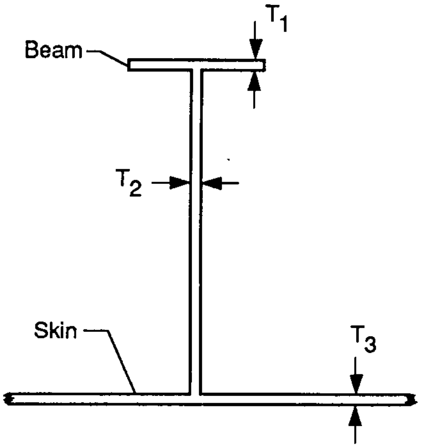
Table I. Thickness Data on Skin Panels
(Bays 1 to 6)



Bay	T_1, in.	T_2, in.	T_3, in.
1	0.083	0.056	0.177
2	.086	.058	.107
3	.089	.061	.095
4	.091	.062	.096
5	.096	.065	.094
6	.105	.072	.094

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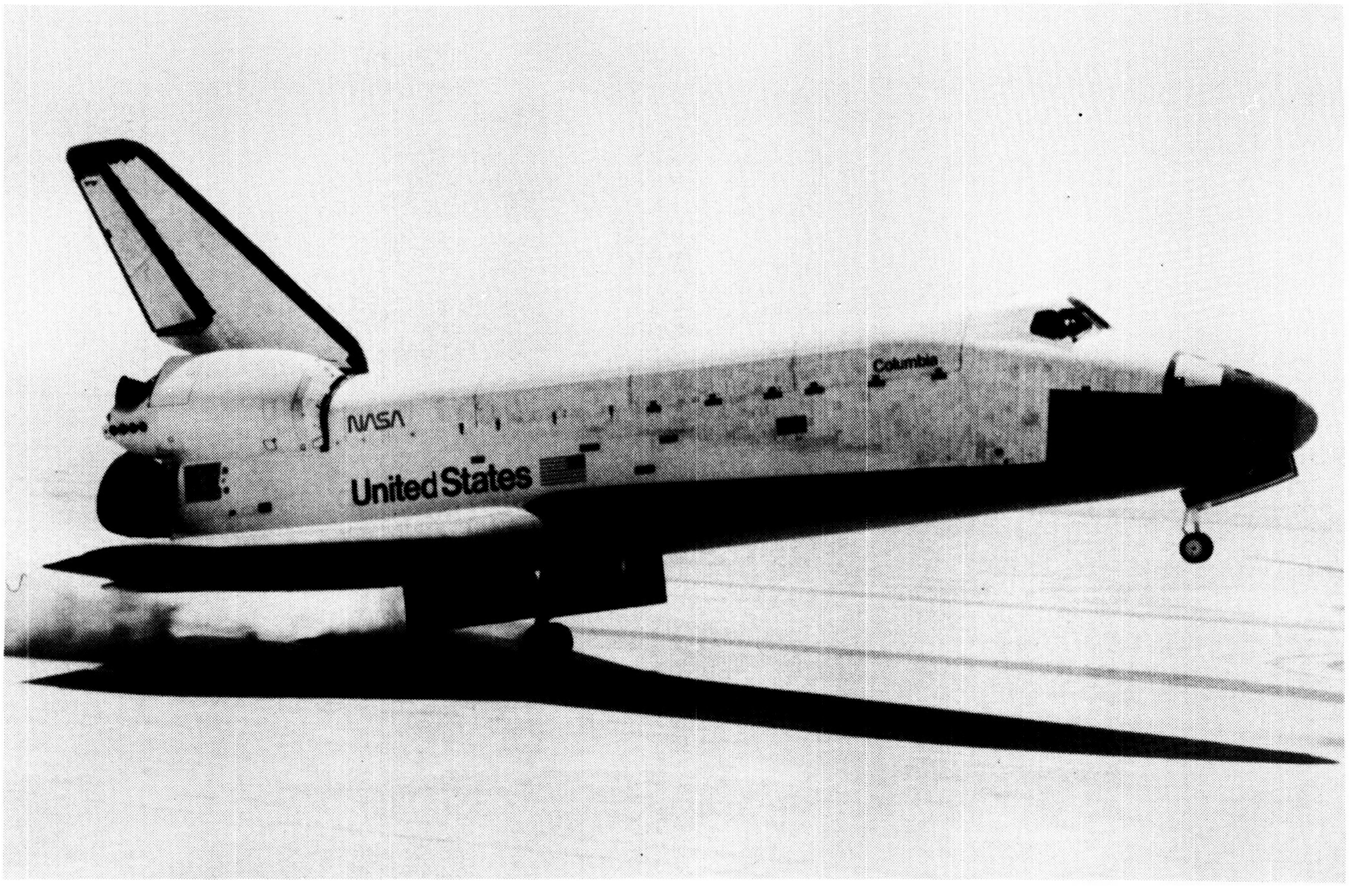

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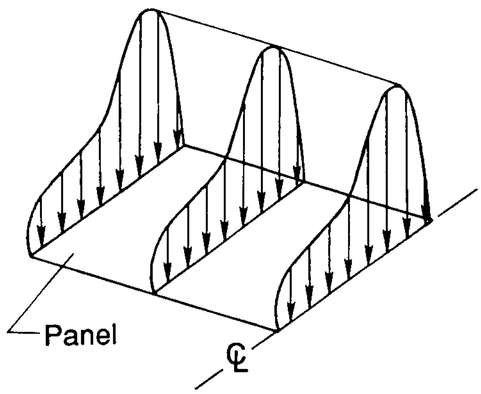
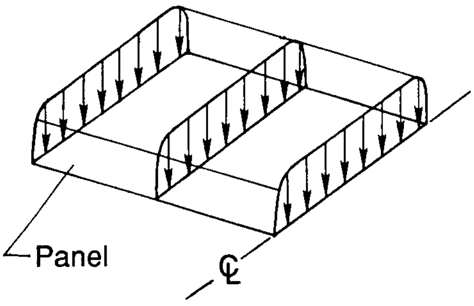
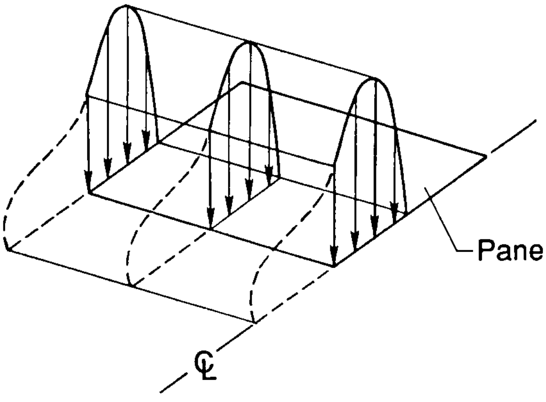
Figure 1. Space Shuttle orbiter.



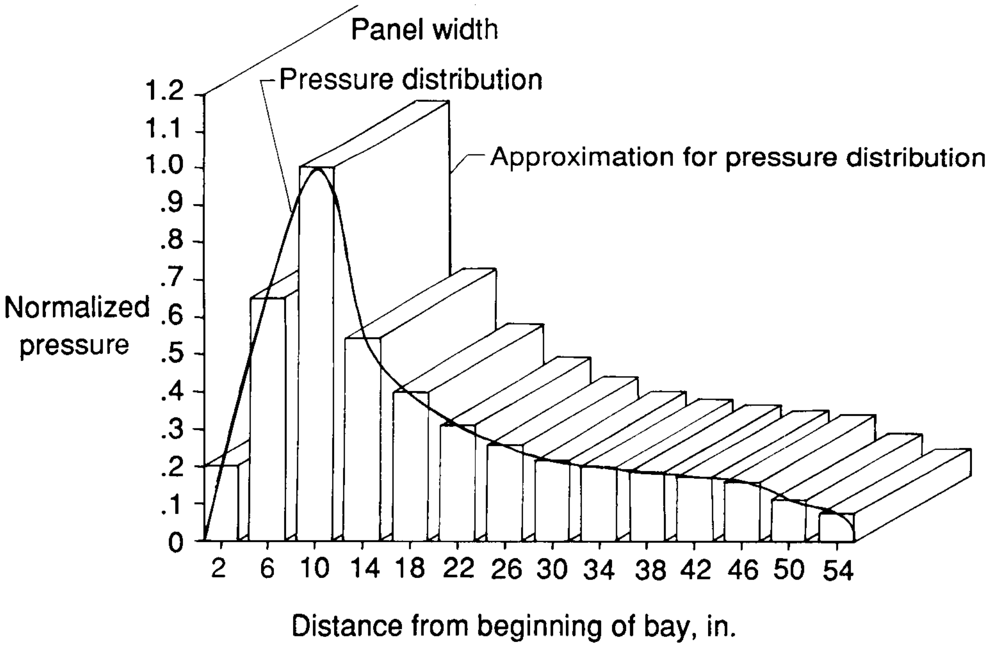
(a) Nonuniform distribution.



(b) Uniform distribution.

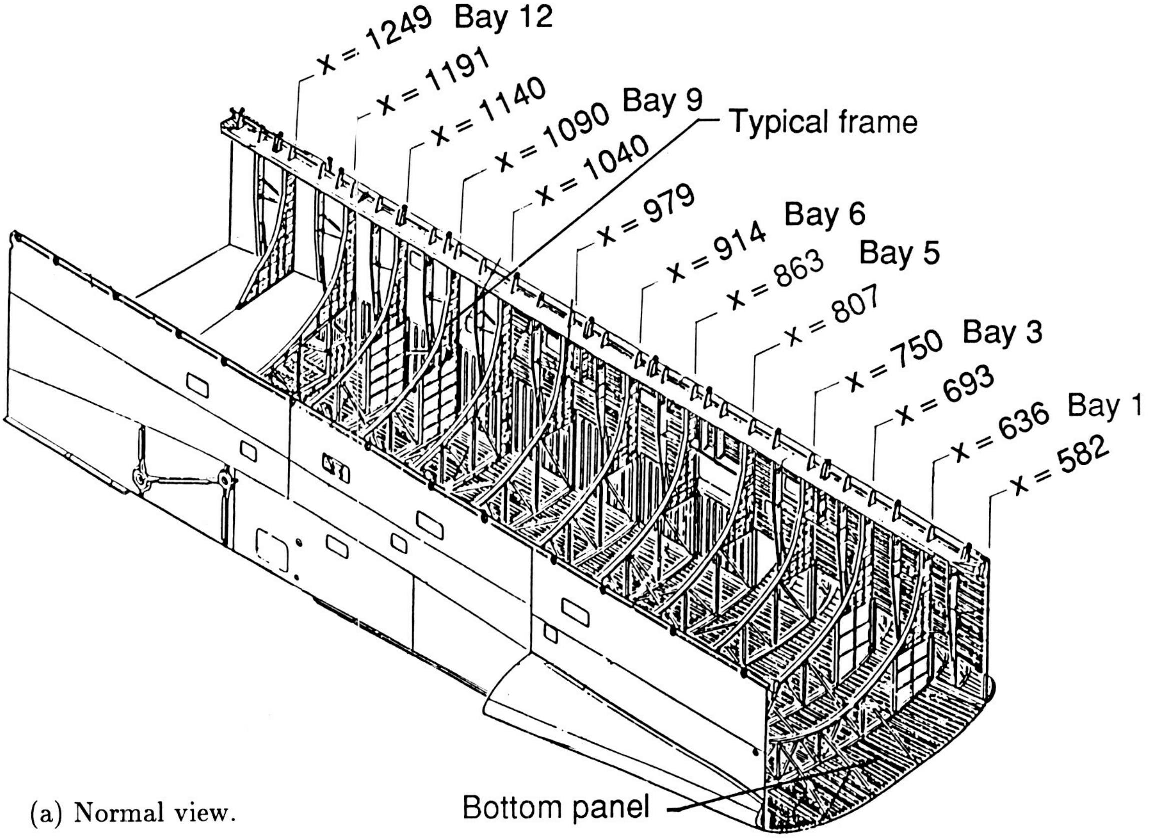


(c) Nonuniform, shifted distribution.

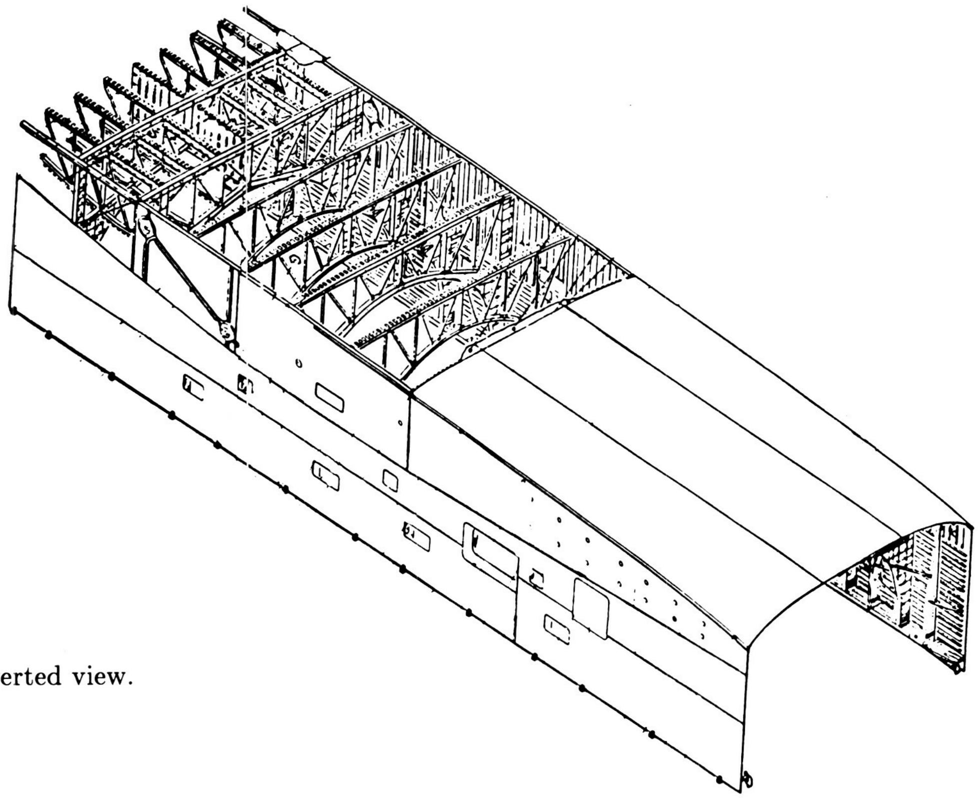


(d) Approximation for pressure distribution.

Figure 2. Pressure distributions applied to Shuttle orbiter skin panels.

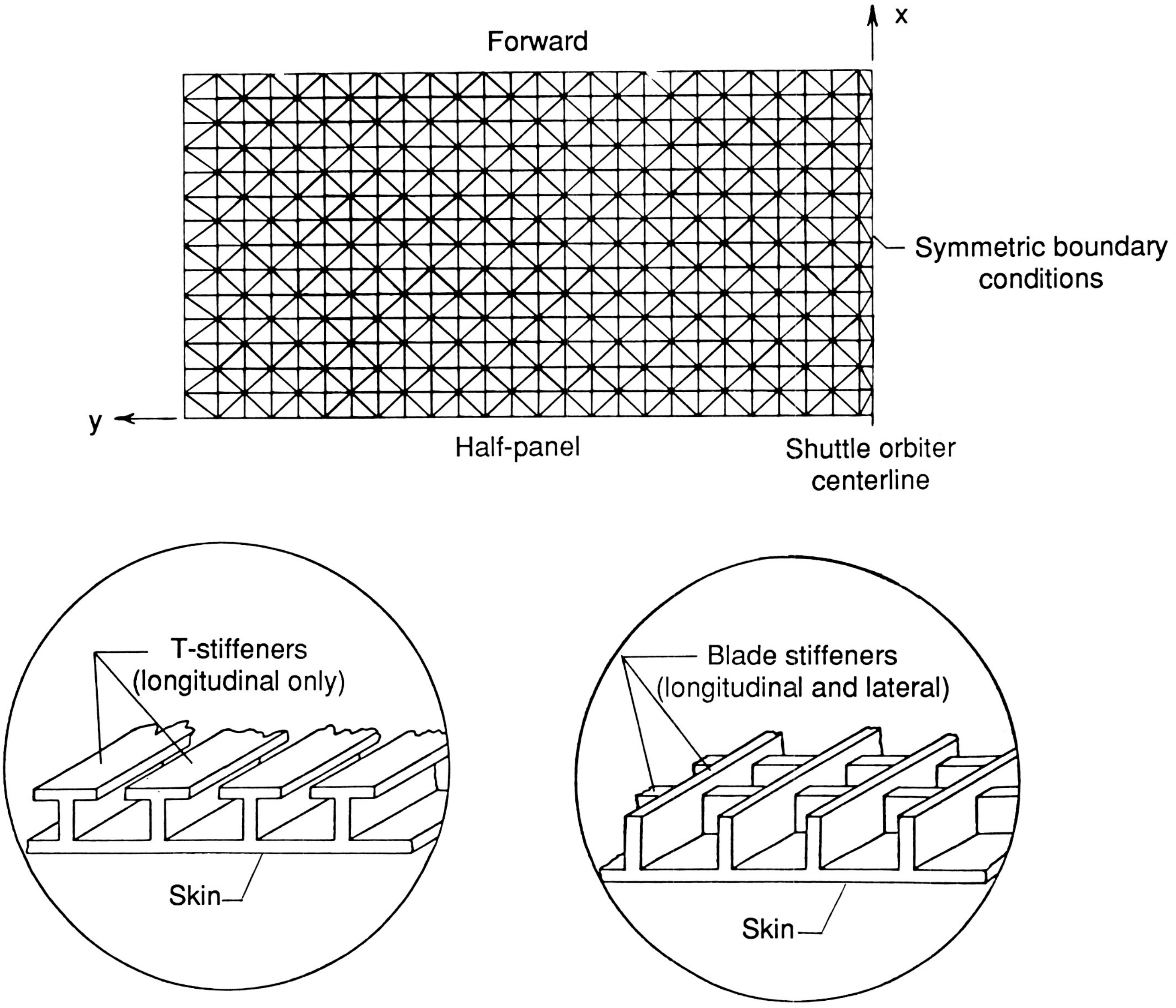


(a) Normal view.



(b) Inverted view.

Figure 3. Details of construction of Shuttle orbiter bottom in cargo bays. (Fuselage station x is given in inches.)



Center body

Wing region

(c) Finite element model details.

Figure 3. Concluded.

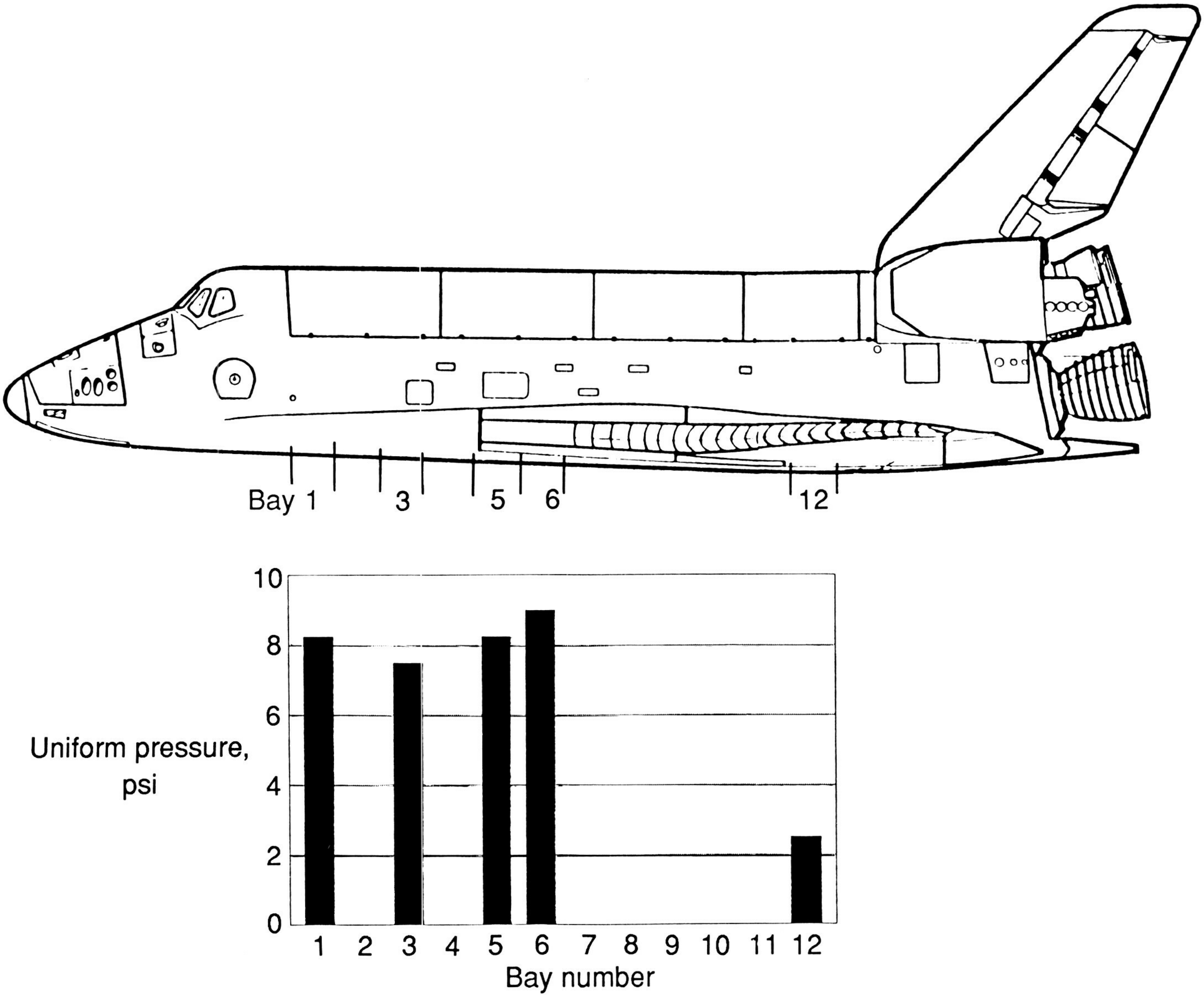


Figure 4. Uniform pressure that produced onset of plasticity (failure) in Shuttle orbiter bottom panels.

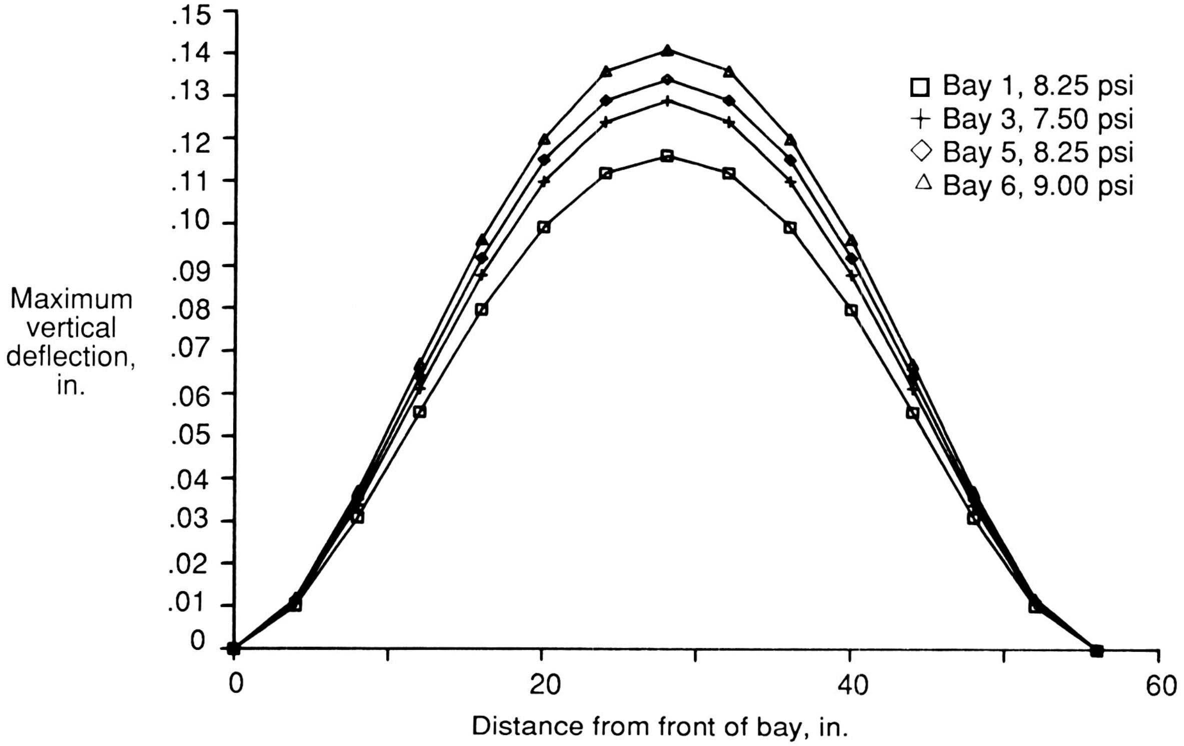
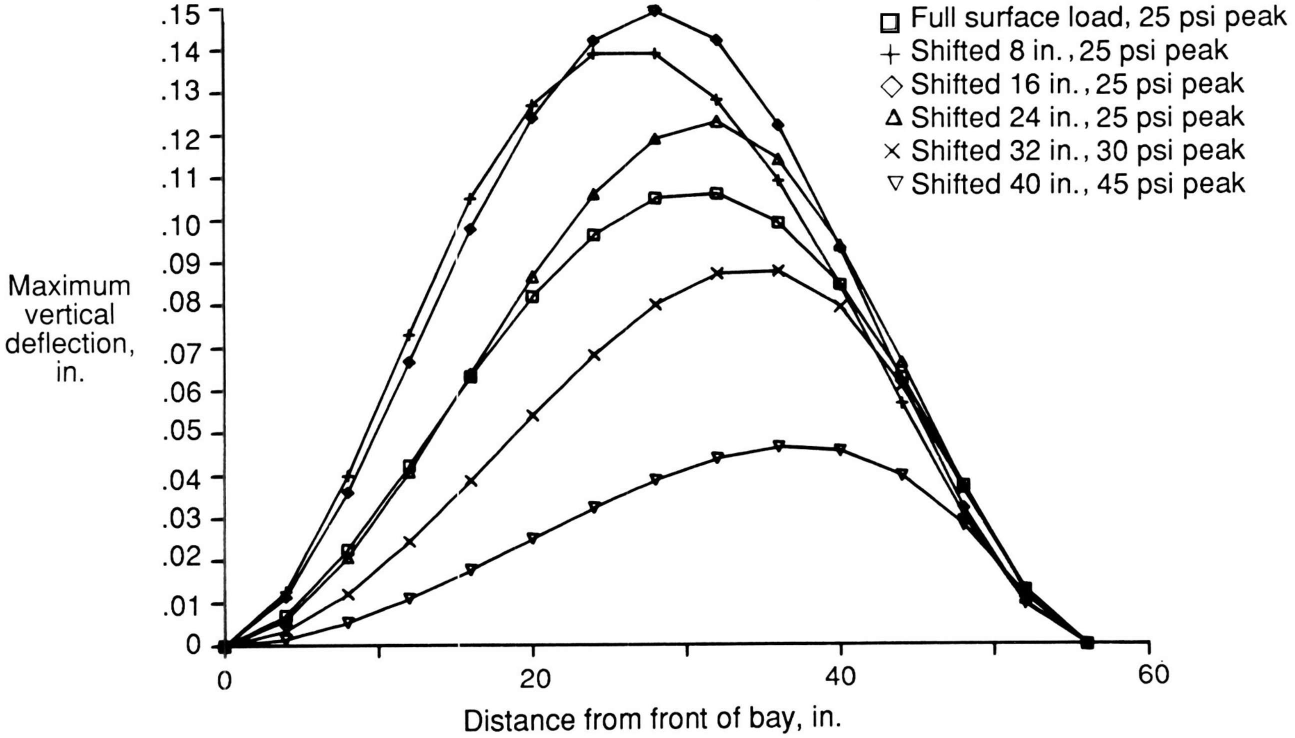
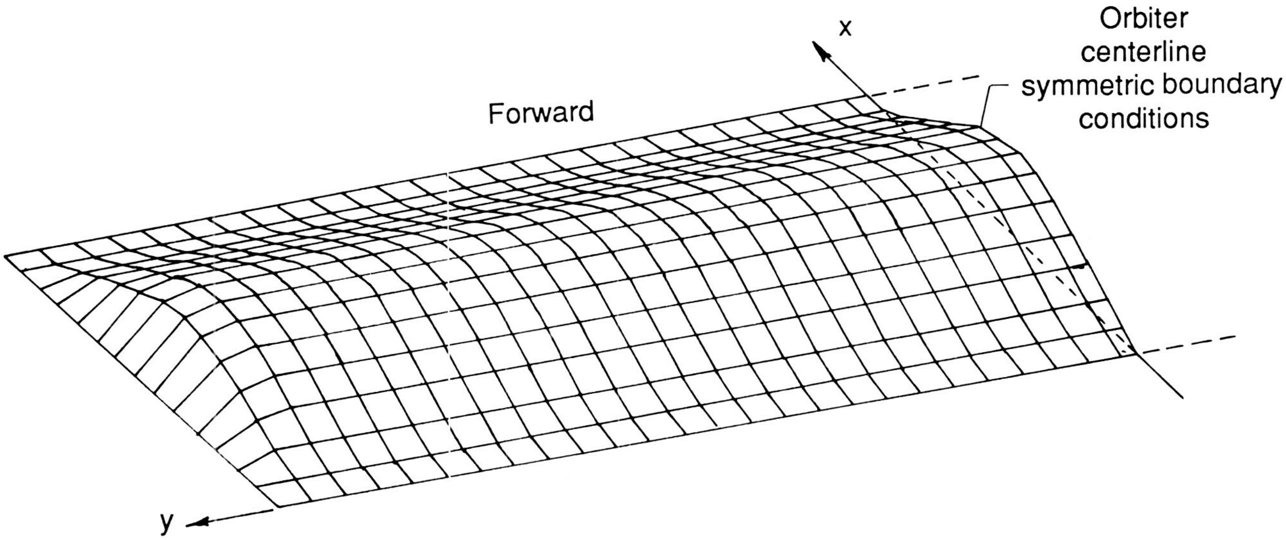


Figure 5. Bottom panel vertical deflections along the longitudinal centerline of Shuttle orbiter at onset of plasticity (failure) under uniform pressure loads.



(a) Displacements along fuselage longitudinal centerline.



(b) Overall displacement for load shifted 16 in. (25 psi). (Deflections magnified 50 times.)

Figure 6. Bottom panel vertical deflections of bay 1 at onset of plasticity (failure) under nonuniform pressure and shifted nonuniform pressure loads.

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16. Abstract

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