Effects of Pre-Pressurization on Plastic Deformation of Blast-Loaded Square Aluminum Plates

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Abstract

The effects of static pre-pressurization on the blast-induced deformation of square aluminum plates were studied both experimentally and numerically. In this study, small (0.152 x 0.152 x 0.0016 meter) clamped plates were used as a basic model of the fuselage skin of a commercial aircraft. Both un-pressurized and pre-pressurized plates (static pressure of 62.1 KPa (9.0 psi)) were considered to simulate the minimum and maximum in-flight loads experienced by a commercial aircraft due to cabin pressurization. This work extends previous research on blast loading of plates to incorporate the effects of pre-pressurization.

Experimentally, a vacuum vessel system was used to apply a pressure differential to the test plate. Bare spherical explosive charges of C4 were then detonated at fixed distances from the plate. The permanent plate deformations were measured for twenty-four explosive tests that considered four different blast load cases.

In addition to the experimental work, numerical predictions of the permanent plate deformations were determined using finite element analysis and the commercial software ANSYS/LS-DYNA. A comparison of plate deformations determined experimentally with those predicted with the finite element method shows good correlation. For the four explosive load cases studied, no significant change in permanent plate deformations was observed as static pre-pressurization increased from 0.0 kPa to 62.1 kPa.

INTRODUCTION

From 1971 to 1995, there were 47 in-flight attacks on commercial aircraft using on-board explosive devices, of which 31 resulted in complete loss of the aircraft [1]. Since the bombing of Pan Am 103 over Lockerbie, Scotland, in 1988, significant efforts have been made to develop methods for reducing the damage threat posed by internal explosions on commercial aircraft. These research efforts have typically focused on protecting aircraft structures against detonations of relatively small quantities of explosives that can be difficult to detect.

As a result of this research, it has been concluded that on-board explosive devices can be particularly damaging to commercial aircraft due to the combined effects of transient explosive forces and normal cabin pressurization [2]. Aircraft compression systems are designed to maintain sea-level atmospheric pressure inside the fuselage up to a given altitude at which a maximum pressure differential is reached. For flights at higher altitudes, a maximum pressure differential in the range of 51.7 to 62.0 kPa (7.5 to 9.0 psi) between the aircraft cabin and the ambient atmosphere is maintained [3].

Of particular interest in the present study is the effect of cabin pressurization on plastic deformation of fuselage skin under blast loading. Although it would be ideal to utilize full-scale explosive testing on aircraft for this study, the cost and size of such an endeavor are not amenable to a parametric study. For this reason, a square clamped aluminum plate was selected as a basic model of the skin of a commercial aircraft fuselage.

Several recent studies of the blast loading of plates have provided a useful background for the present study. Türkmen and Mecitoglu [4] studied the non-linear response of square composite plates subjected to blast loading. Analytical solutions for the blast response of plates were then compared to those predicted by the finite element method. These predictions were compared to measured dynamic plate strains under blast loading by the detonation of a fuel-air mixture. Rudrapanta, Vaziri and Olson [5] investigated finite element damage predictions for blast-loading of steel plates with an integral stiffening rib. Ramajeyathilagam, Vendhan and Rao [6] compared experimental measurements of plastic deformation with finite element predictions for an air-backed steel plate subjected to underwater explosive loading. Rajendran and Narasimhan [7] presented empirical analysis and experimental results of the plastic deformation in steel circular plates subjected to underwater contact explosions. Wiehan, Nurick, and Bowles [8] considered the effects of temperature dependent material properties on the deformation and tearing of circular steel plates due to blast loading. Langdon and Schleyer [9] presented an analytical and experimental study of the inelastic deformation and failure by rupture of clamped rectangular aluminum plates under pressure pulse loading.

In all these studies, the effects of static pre-pressurization on plate blast response were not expressly considered. The present study will build upon previous work to include pre-pressurization, specifically as experienced by a commercial aircraft fuselage.

EXPERIMENT AND ANALYSIS

Static Deflection of Plates Under Uniform Pressure

The static deflection of a thin rectangular plate under uniform pressure has been studied extensively [10]. For small deflections of clamped square plates, the maximum plate deflection (w_{max}) varies linearly with the applied static pressure. For clamped thin plates, linear bending theory is appropriate for deflections of less than one half of the plate thickness, h. For plate deflections where w_{max} /h >0.5, membrane stresses must also be included [11] which results in nonlinear plate behavior.

In order to predict plate deflections and strains under static pressurization, a finite element model of a fully clamped square (0.152 x 0.152 x 0.0016 meter) plate was created using the commercial software ANSYS, version 5.7. The plate material was was 2024-T3 aluminum, which was approximated as a bi-linear material (Table 1).

Table 1 – Bi-Linear Material Properties for Aluminum 2024-T3

Property	Value
Yield Stress	0.345 GPa (50x10^3 psi)
Young’s Modulus	71.0 GPa (10.3x10^6 psi)
Tangent Modulus	0.46 GPa (67x10^3 psi)
Ultimate Stress	0.427 GPa (62x10^3 psi)
Ultimate Strain	0.186 m/m
Density	2923 Kg/m^3
Poisson Ratio	0.334

The plate was modeled using 4-node, quadrilateral shell elements (ANSYS SHELL181). Based on a convergence study, a 20 x 20 element mesh scheme was determined to be adequate for accuracy in both static and dynamic analyses (Figure 1). Static pressures in the range of 0.0 to 62.0 kPa (0.0 to 9.0 psi) were used in this analysis to correspond to the maximum pressure differential (between aircraft cabin and ambient atmosphere) experienced by commercial aircraft at various flight altitudes.

To measure static plate deflections, a vacuum vessel and pressure regulator were used to apply a negative static pressure to the internal face of a 0.152 x 0.152 x 0.0016 meter, 2024-T3 aluminum plate. The external side of the test plate was exposed to atmospheric pressure. For measuring static plate deflections, a mechanical gauge was used to indicate displacement at the plate center.

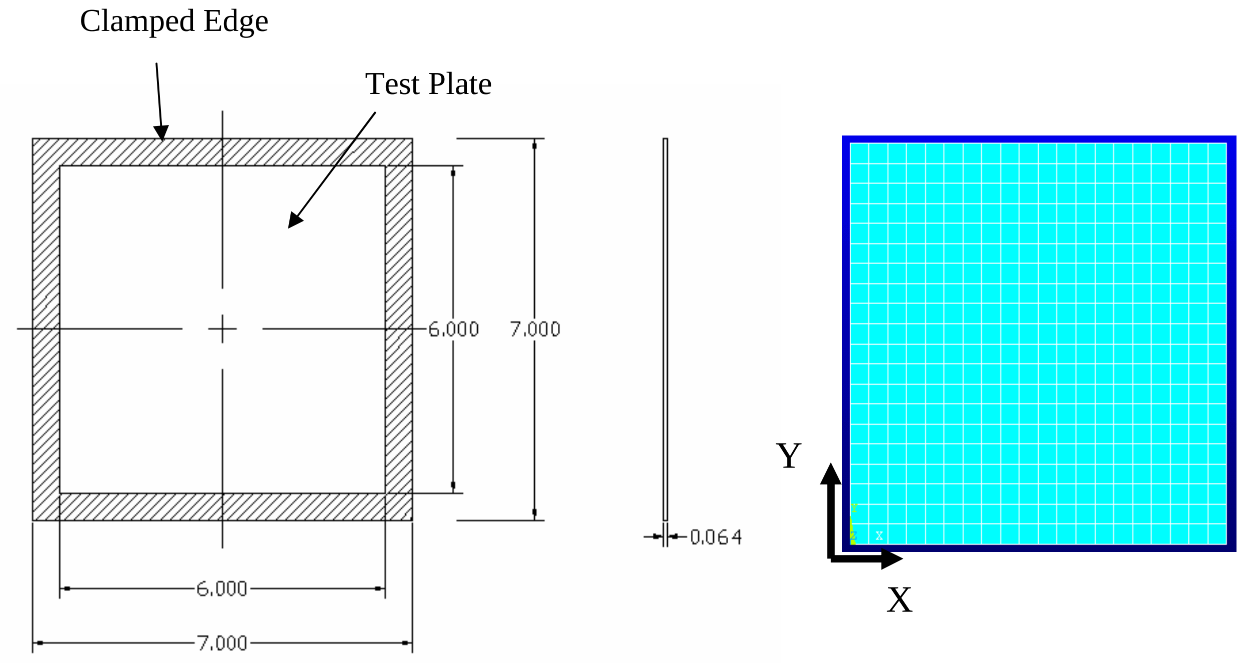


Figure 1 – Drawing of Aluminum Test Plate (Dimensions in Inches) (Left) and a Mesh Plot of the Finite Element Model of the Test Plate (Right).

A comparison of maximum static plate deflections, w_{max}, from: 1) linear bending theory; 2) non-linear bending and membrane theory; 3) finite element analysis; and 4) experiment are plotted in Figure 2, with good correlation.

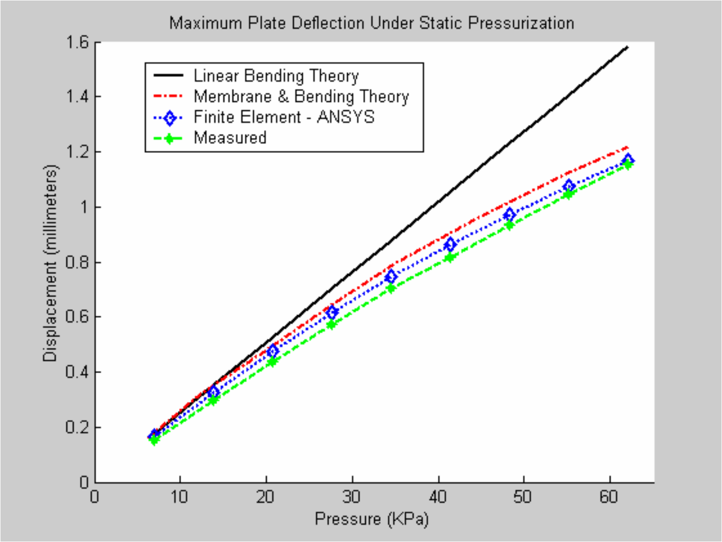


Figure 2 – Static Plate Deflections from Finite Element Analysis, Theoretical Predictions, and Experimental Measurements.

Natural Frequency of Pre-pressurized Plate

In order to evaluate the effectiveness of the finite element model under dynamic loading, a modal analysis was conducted for the pre-stressed plate using the commercial software ANSYS, version 5.7.

The fundamental plate frequency was also determined experimentally. For this procedure, the test plate was affixed to a vacuum tank, and an optical displacement sensor measured deflections as the plate was tapped with a rubber-tipped hammer. The deflection data were recorded with a digital oscilloscope and analyzed using the power spectral density (PSD) tool in the numerical analysis software MATLAB. From this analysis, the fundamental frequency peak was recorded as a function of static pre-pressurization (Figure 3).

A comparison of the predicted and measured fundamental frequencies of the plate showed good correlation, with differences of less than 5% for static pre-pressures below 20 kPa and negligible differences for static pre-pressures above 20 kPa. From these data it can be seen that the fundamental plate frequency increases with an increasing static pre-pressurization. Thus the plate becomes stiffer with an increasing static pre-load.

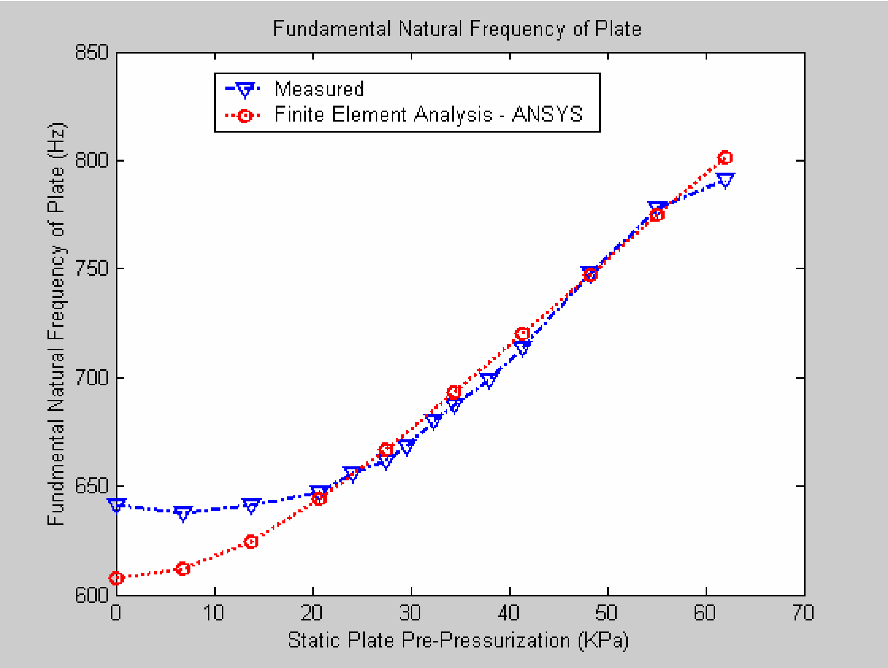


Figure 3 –Fundamental Natural Frequency of Clamped Plate.

Determination of the Plastic Dynamic Response of a Blast-Loaded Plate

An experimental configuration was devised to impart a blast pressure wave on the pre-pressurized aluminum test plate (Figure 4).

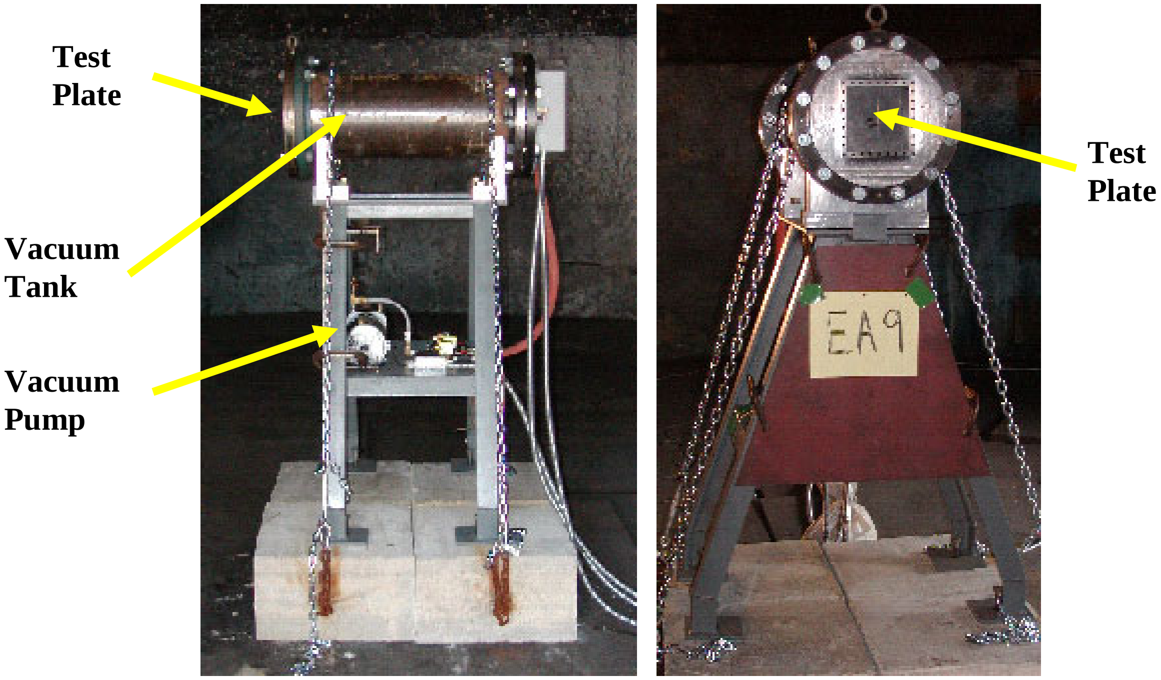


Figure 4 – Side view (left) and front view (right) of experimental configuration for blast loading of pre-pressurized plate.

A vacuum tank was used to pre-load the test plate and a bare spherical charge of the explosive composition C4 was placed outside the tank at a fixed distance from the plate face. Charge standoff distances were selected to be sufficiently large so as to produce a generally planar blast wave on the face of the test plate. The vacuum tank was placed on an elevated test stand to delay the arrival of ground reflections of blast pressures at the test plate surface.

Preliminary tests were conducted to determine the transient pressure distributions on the plate surface. A 25 mm thick steel flange was mounted to the end of the vacuum vessel. This flange was machined to accept an array of 4 Kistler 211B3 miniature pressure sensors that were used to simultaneously measure dynamic pressures at the locations shown in Figure 5. The face of each pressure sensor was coated with a thin film of silicone sealant to serve as an ablative coating. Using this array of four pressure transducers, the transient pressure mapping tests were carried out for four unique charge weights and standoff distances (defined as load cases C, D, E, and F). Dynamic blast pressures were recorded with a digital oscilloscope that was triggered by an output signal from an electronic detonation pulsing unit. Blast arrival time is defined as the elapsed time from the instant of detonation unit pulsing to the first rise in pressure recorded by the pressure transducers.

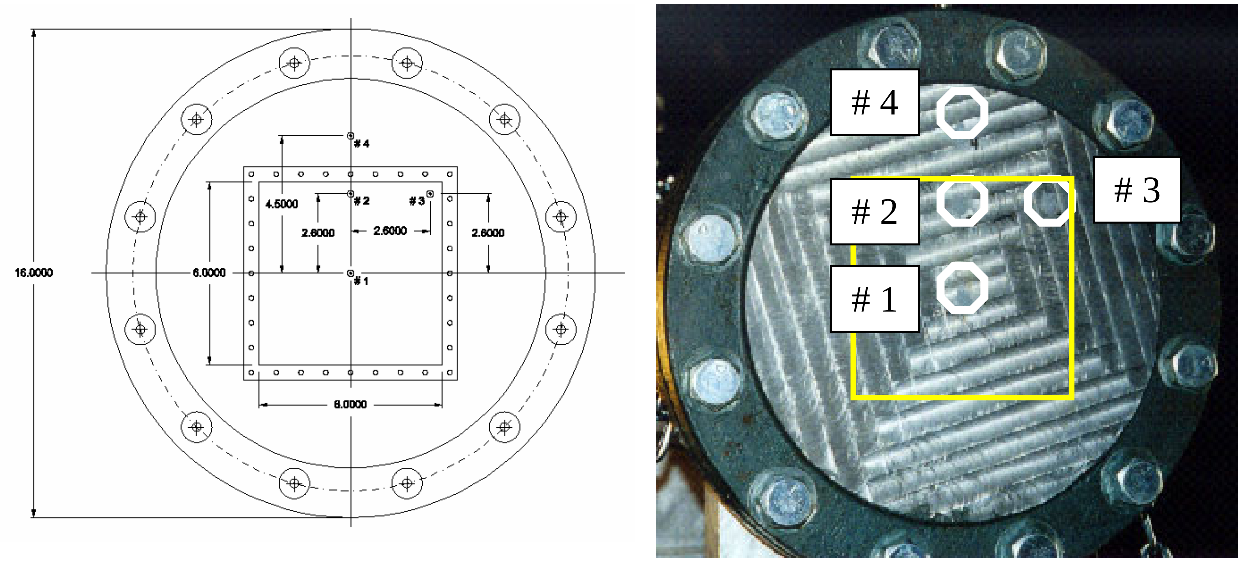


Figure 5 – Pressure characterization test flange indicating the locations of the four pressure transducers (#1 - 4) in comparison to the superimposed location of the aluminum test plate (Dimensions in Inches)

Measured pressure history data indicate that for four unique charge weights and standoff distances (defined as load cases C, D, E, and F), the blast arrival time for all four pressure sensors agreed within 5%. It was thus concluded that the incoming pressure wave could be adequately considered a plane wave across the face of the test plate.

It was also concluded from these tests that a reference pressure sensor, located on the test flange adjacent to the mid-side plate edge (Figure 6), would be used in all subsequent tests to record the dynamic pressure acting on the plate. A comparison of the measured blast pressures for cases C, D, E, and F normalized to the peak pressure of load case C is shown in Figure 7. The average normalized peak pressures of 4 tests for each load case are shown in Table 2. Note that the peak pressure for load case F, the most intense case of the four load cases, is about 6 times the peak pressure as for the least intense case, load case C.

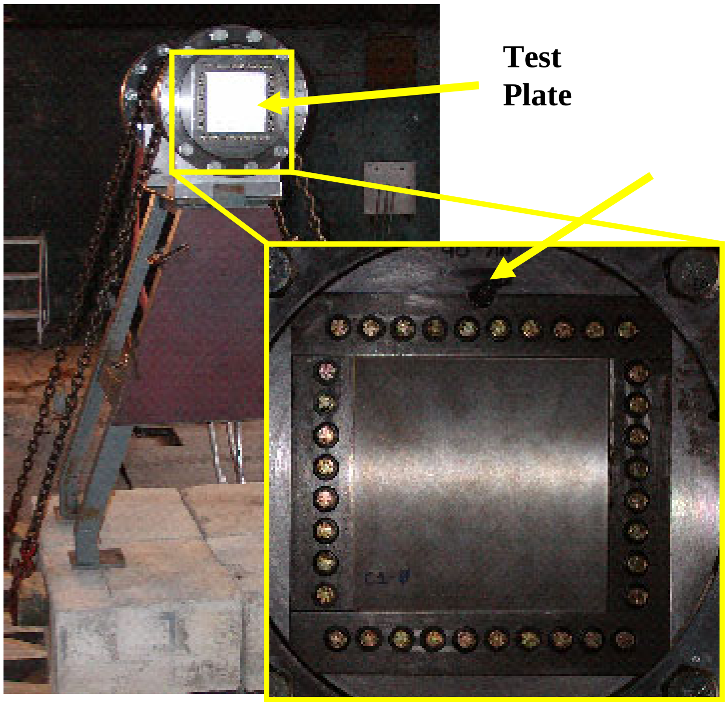


Figure 6 – Front view of experimental configuration for blast loading of pre-pressurized plate and close-up (inset) of test plate.

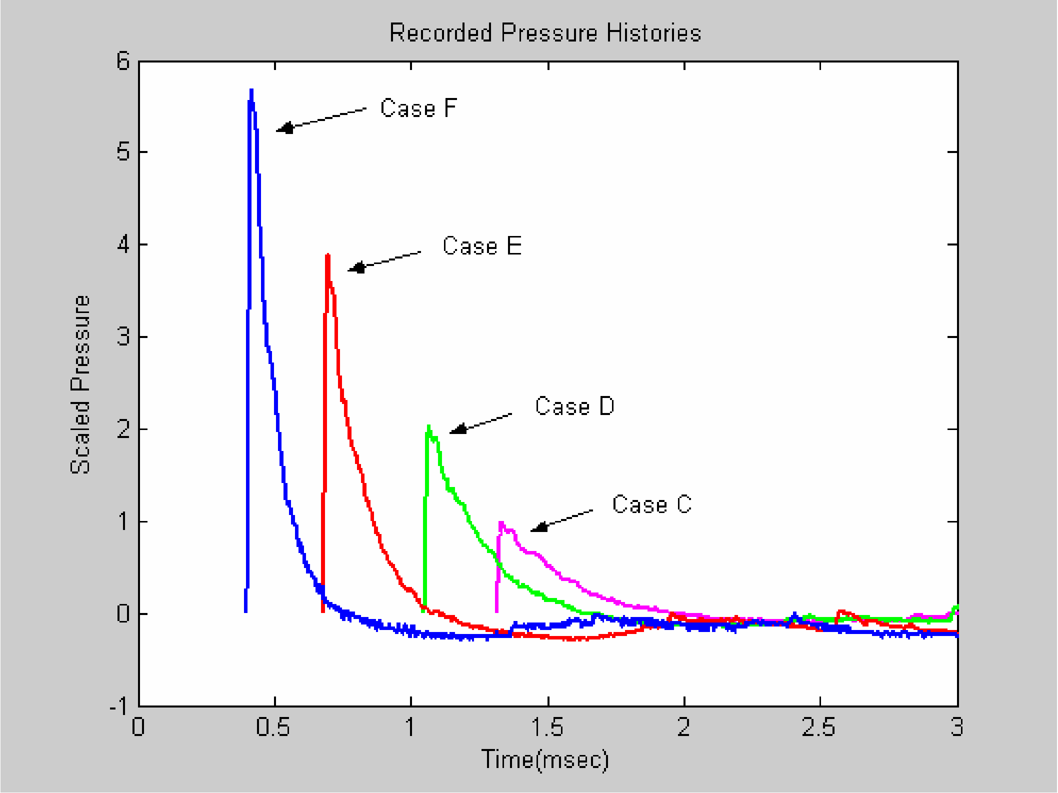


Figure 7 – Typical recorded pressure histories for load cases C,D,E, and F (normalized to the peak pressure of load case C).

Table 2 – Average Peak Recorded Pressures for Load Cases C, D, E, and F (normalized to the peak pressure of load case C)

Load Case	Normalized Peak Recorded Pressure (Average of 4 Tests for Each Case)
C	1.00
D	2.02
E	3.84
F	5.82

For blast loading of the test plates, a separate 25 mm thick flange, machined to accept the aluminum sample plates, was mounted to the end of the vacuum tank. Static pressures of either 0.0 kPa (un-pressurized) or 62.0 kPa (fully pressurized) relative to ambient atmospheric pressure were applied to the test plate using a vacuum vessel and vacuum pump.

After each explosive test, the deformed test plate (Figure 8) was removed from the tank for later measurement and recording of permanent deflection along the plate center-lines (Figure 9).

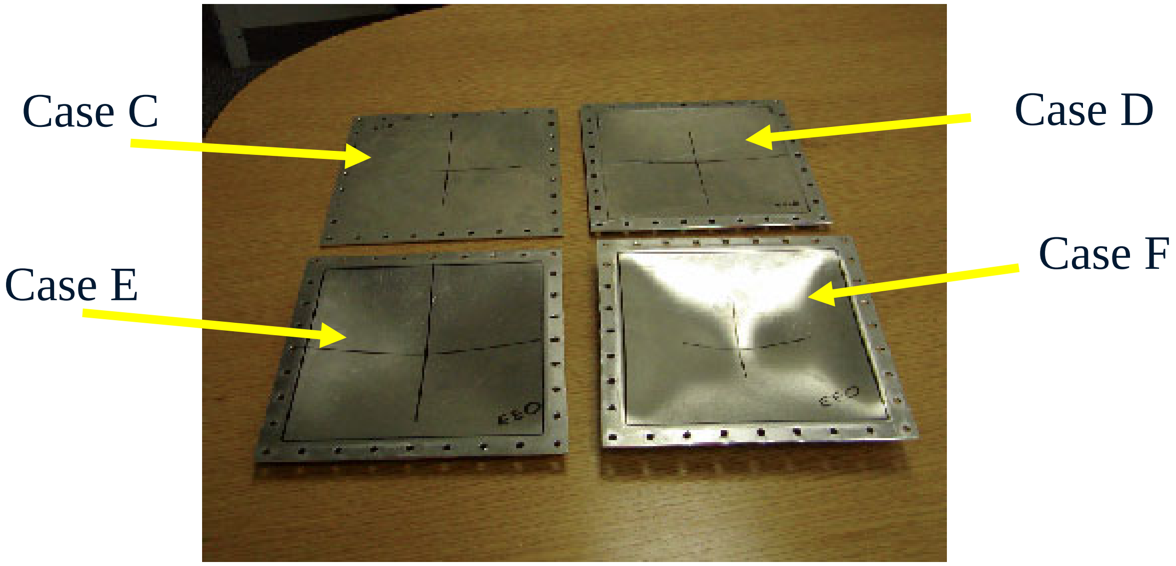


Figure 8 - Sample Deformed Plates After Blast Loading.

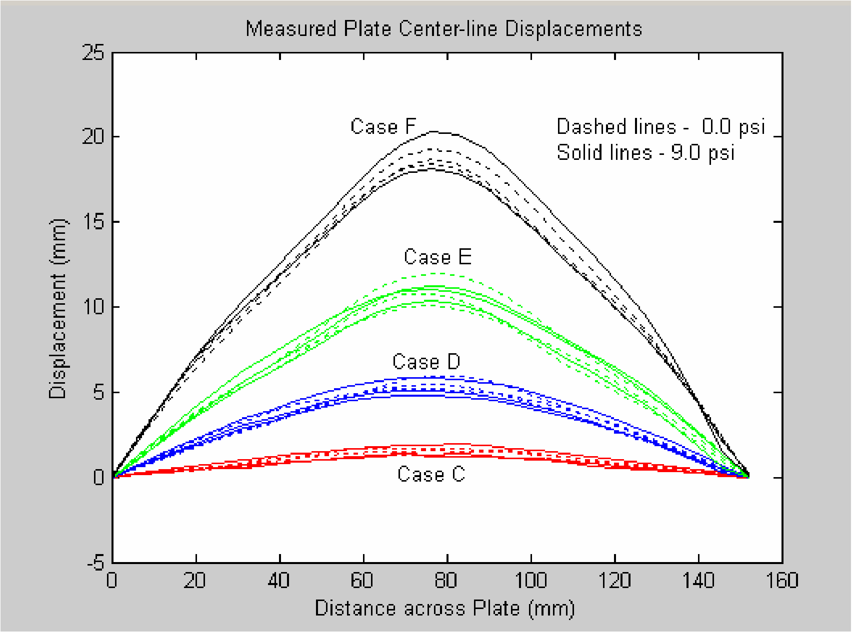


Figure 9– Final Deformed Plate Deflections along Center-line for Several Experimental Trials. (Solid Lines – Pre-pressurized Plates, Dashed Lines – Un-Pressurized Plates.)

Finite Element Analysis of the Plastic Dynamic Response of a Blast Loaded Plate

In order to evaluate the structural response of the blast loaded plate, a nonlinear transient finite element analysis was conducted accounting for large deformation effects but neglecting strain rate effects. This study was performed using the commercial code, ANSYS/LS-DYNA – Release 5.7.1. The plate was modeled with a 20 by 20 mesh of 4-node quadrilateral explicit thin shell elements (SHELL163). The SHELL163 element used with the explicit finite element code, DYNA, is the equivalent element to SHELL181 used with the implicit code, ANSYS. Material properties of 2024-T3 aluminum were used for the plate with a bi-linear isotropic plasticity assumption (Table 1). Pressure histories for load cases C, D, E, and F were modeled as a decaying exponential functions based on experimental data, thus neglecting both the slight negative phase and the small ground reflection peak that were present in the actual measured pressure data.

The final permanent plate displacements (w) along the plate center-line predicted by finite element analysis (Figure 10 were then compared (Figure 11) to experimental measurements.

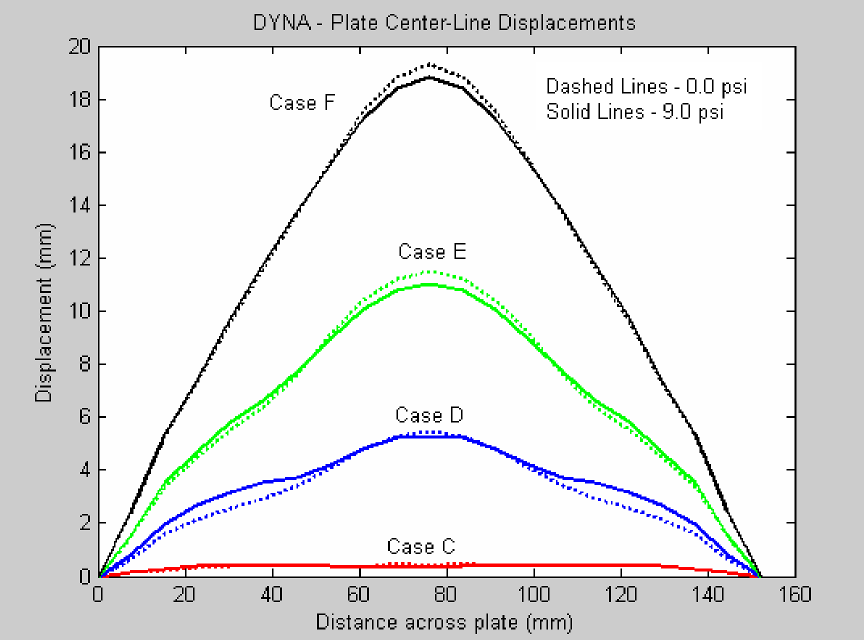


Figure 10 - Finite Element Predictions of Final Deformed Plate Deflections along Plate Center-line (Solid Lines – Pre-pressurized, Dashed Lines – Un-Pressurized).

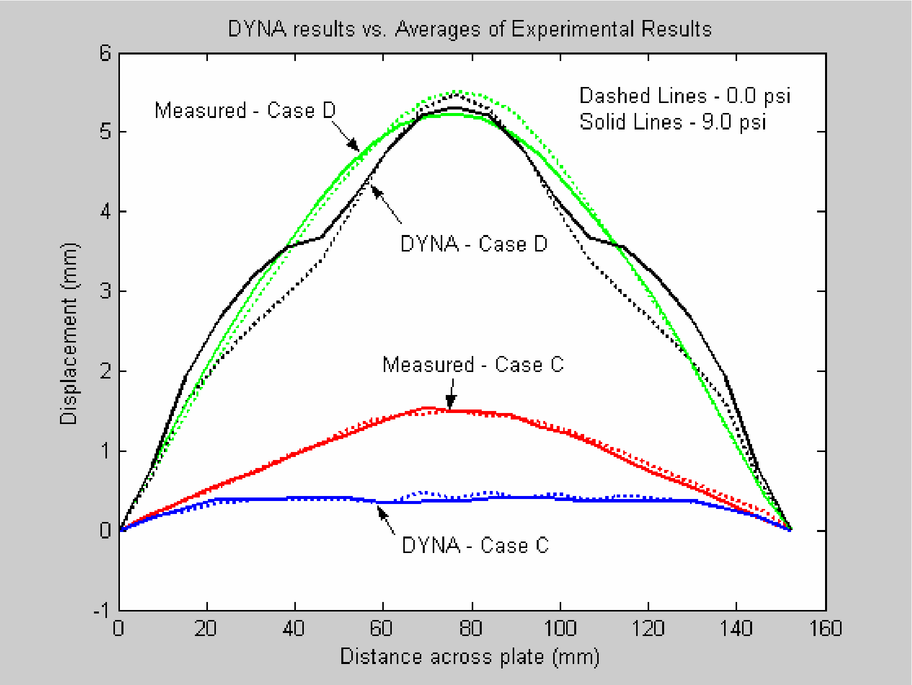
RESULTS

As shown in Figure 11and Table 3 good overall correlation (agreement to within 5.3%) between finite element predictions and experimental results for final deformed plate shapes were observed for load cases D, E, and F. However, the correlation for load case C, which produced plastic deflections that were smaller than the plate thickness, was not as good. It is believed that the finite element model for load case C is most sensitive to the specific bi-linear material properties of 2024-T3 aluminum assumed in the analysis.

From both experimental measurements and finite element predictions it is concluded that no significant change in permanent plate deformations was found as the static pressurization of the test plate increased from 0.0 to 62.1 KPa.

Table 3– Average Peak Recorded Pressures for Load Cases C, D, E, and F

Load Case	Pre-Pressurization	Peak DYNA Displacement	Average Peak Measured Displacement	Percent Difference
C	0.0 psi	0.40 mm	1.51 mm	73.8 %
C	9.0 psi	0.36 mm	1.51 mm	76.1 %
D	0.0 psi	5.48 mm	5.52 mm	0.8 %
D	9.0 psi	5.31 mm	5.24 mm	1.4 %
E	0.0 psi	11.53 mm	11.53 mm	5.3 %
E	9.0 psi	11.03 mm	10.88 mm	1.5 %
F	0.0 psi	19.30 mm	18.80 mm	2.7 %
F	9.0 psi	18.81 mm	19.21 mm	2.1 %



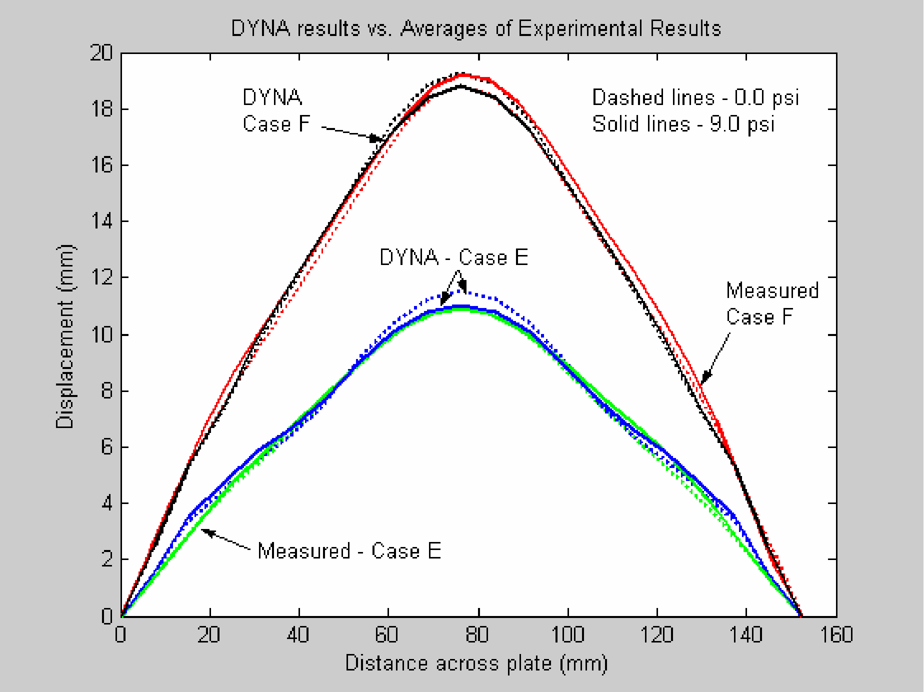


Figure 11– Comparison of Finite Element Predictions and Average Experimental Results for Final Deformed Plate Deflections along Center-line (Solid Lines – Pre-pressurized, Dashed Lines – Un-Pressurized).

CONCLUSIONS AND RECOMMENDATIONS

The primary conclusion from this study is that, for the case of a clamped aluminum plate under four different blast load cases, no significant increase in plate deformation was observed as static pressurization increased from 0.0 kPa to 62.1 kPa. This result was not entirely expected, since conventional wisdom indicates that the pre-pressurization of an aircraft fuselage will increase the structural damage due to the detonation of an on-board explosive device.

Based on the results of both finite element predictions and experimental verification, it is apparent that the pre-pressurization had very little effect on the blast damage of the plates. It should be noted that the plates in this study were never loaded to the point of tearing, and thus no cracks were induced in the course of testing. Due to the ductile nature of aluminum 2024-T3, the clamped plates in this study experienced significant deformation without cracking. It is possible that pre-pressurization effects would be more evident in the case where the blast damage induces a rupture in the aluminum plate.

In the next phase of this study, the complexity of the modeled structure will be increased by using a larger test panel, including panel curvature and adding riveted stringer reinforcements to the panel. These changes will produce test panels that more closely resemble the structural details of a commercial aircraft fuselage, while still allowing a cost-effective parametric study of the effects of pre-pressurization on blast damage.

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