

Characterizing the Response of Composite Panels to a Pyroshock Induced Environment using Design of Experiments Methodology

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This experimental study seeks to quantify the impact various composite parameters have on the structural response of a composite structure in a pyroshock environment. The prediction of an aerospace structure's response to pyroshock induced loading is largely dependent on empirical databases created from collections of development and flight test data. While there is significant structural response data due to pyroshock induced loading for metallic structures, there is much less data available for composite structures. One challenge of developing a composite pyroshock response database as well as empirical prediction methods for composite structures is the large number of parameters associated with composite materials. This experimental study uses data from a test series planned using design of experiments (DOE) methods. Statistical analysis methods are then used to identify which composite material parameters most greatly influence a flat composite panel's structural response to pyroshock induced loading. The parameters considered are panel thickness, type of ply, ply orientation, and pyroshock level induced into the panel. The results of this test will aid in future large scale testing by eliminating insignificant parameters as well as aid in the development of empirical scaling methods for composite structures' response to pyroshock induced loading.

Nomenclature

DOE	=	Design of Experiments
gpf	=	Grains Per Foot
LSC	=	Linear Shaped Charge
MSFC	=	Marshall Space Flight Center
PV	=	Pseudovelocity
SRS	=	Shock Response Spectrum
TA	=	Test Article

Introduction

For several decades the Marshall Space Flight Center (MSFC) has collected a large database of vibroacoustic test and flight data for use with empirical methods for launch vehicle (LV) environment prediction. The collection of valid test data is an integral part of the development of these empirical methods. For pyroshock environment predictions however, MSFC has used development testing with flat panels or flight-like test structures, or the method described in the Pyrotechnic Shock Design Guidelines Manual (Kacena, McGrath, & Rader, 1970). This design manual approximates pyroshock environments by attenuating the source pyroshock environment with distance utilizing empirically developed attenuation curves based on structure type. However, with the growing use

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of composite structures in LV design, the current attenuation curves for predicting pyroshock propagation for composite structures are insufficient. Considering that the propagation of pyroshock is sensitive to structure and material, the problem of developing a composite test database is compounded by the wide array of parameters available for composite structures.

Over the past several months, and continuing through fiscal year 2014, MSFC has been conducting a wide range of composite panel pyroshock tests (Ordway, 2012). Though the applicability of flat panel testing is limited in its application to full scale structures, the key parameters that influence a composite structures response to pyroshock induced loads may be isolated from irrelevant parameters by utilizing design of experiment (DOE) techniques (Smith, 1986). The knowledge gained could aid in future testing, in particular for costly large-scale testing, by eliminating unnecessary parameters from composite test matrices. Furthermore, the insight gained in understanding the primary parameters as well as potential parameter interactions can potentially aid in the development of empirical scaling methods tailored to composite structures.

The focus of this paper is on the design and implementation of the test series as well as the post processing of the measured data for use with statistical analysis techniques.

Test Design

A total of 28 tests are planned for this test series utilizing the composite panel configurations listed in Table 1. The tests evaluate the following composite parameters: panel thickness, type of ply, ply orientation, and pyroshock core load induced into the panel. The composite parameters and parameter values were chosen based on commonly selected composite properties for LVs. The balance of these test panels are inspected using both flash thermography and pulse echo ultrasound for the sandwich panels, but only pulse echo ultrasound for the solid panels prior to test.

Table 1: Pyroshock Composite Material Characterization Test Matrix

Group I – Monolithic Composite	Thickness (inch)	Ply and Orientation	Fill	LSC Core Load (gpf)	Number of Tests
	Thin	0 degree, unidirectional, tape	N/A, solid	10	4
	Thin	Quasi Isotropic, fabric	N/A, solid	10	4
	Thin	Quasi Isotropic, tape	N/A, solid	22	4
	Thick	Quasi Isotropic, tape	N/A, solid	10	4
	Thick	Quasi Isotropic, fabric	N/A, solid	22	4
Group II – Filled Composite	Thickness	Ply Orientation	Fill	LSC Core Load	
	8 Ply Fill	Quasi Isotropic, tape	Al Honeycomb	10	4
	8 Ply Fill	Quasi Isotropic, tape	Rohacell Foam	10	4

The panels are suspended at two corners from the facility and secured at the opposite corners of the panel to minimize panel swing. Twelve accelerometers, PCB 350C02 or PCB 350D02, are mounted approximately every 12 inches along the length of the plate, beginning at 9 inches from the location of the Linear Shaped Charge (LSC) and 3 inches from either side of the panel centerline, shown in Figure 1. Acceleration data was measured at 10⁶ samples per second for one second. Data was provided as acceleration time history.

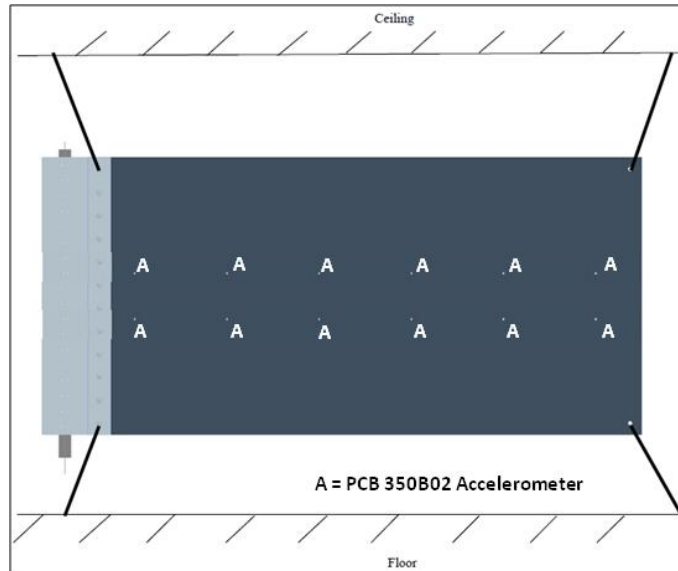


Figure 1: Panel Attachment to Test Facility.

The separation device used to impart the pyroshock environment into the Test Article (TA) is a LSC with a charge of 10 grains per foot (gpf) or 22 gpf. The separation event occurs on an aluminum sacrificial plate that is bolted to the composite panel as shown in Figure 2. The sacrificial plate is sized in thickness to ensure complete severance of the plate.

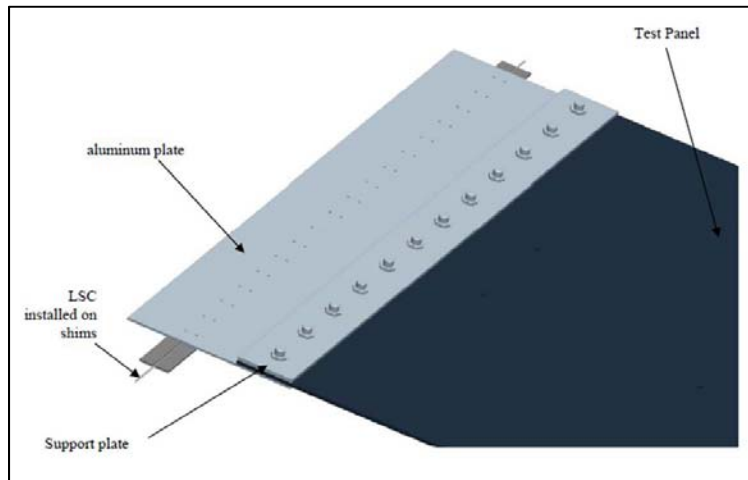


Figure 2: LSC Severance Plate to Test Panel Mounting.

Test Configurations

In an effort to mitigate effects of unwanted noise variables on the test data, randomness is introduced into the order in which the combinations of the test parameters are run. A summary of the test parameter combinations are listed in the Test Matrix, shown in Table 1, to develop the test configurations, shown in Table 2 and Table 3, which describe the first 18 tests planned in the series. The remaining ten tests will be configured based upon the analysis of the first 18 tests focusing on what has been determined to be the most pertinent composite material parameters.

Table 2: Pyroshock Composite Material Characterization Test Matrix, Group I.

Group I – Solid Composite Panels						
Test Number	Material	Panel Thickness	Ply	Orientation	Type	LSC Core Load
1	Composite, IM7/TC350	Thin	Fabric	0-Deg, 18 ply	Solid	10
2	Composite, IM7/TC350	Thin	Fabric	+45°/-45°, 0° (2x), +45°/-45°, 90° (2x), 18 ply	Solid	10
3	Composite, IM7/TC350	Thick	Tape	+45°/-45°, 0° (2x), +45°/-45°, 90° (2x), 54 ply	Solid	10
4	Composite, IM7/TC350	Thick	Fabric	+45°/-45°, 0° (2x), +45°/-45°, 90° (2x), 27 ply	Solid	22
5	Composite, IM7/TC350	Thin	Tape	+45°/-45°, 0° (2x), +45°/-45°, 90° (2x), 38 ply	Solid	22
Analyze results from Tests 1-5 and re-plan as necessary						
6	Composite, IM7/TC350	Thin	Fabric	0-Deg, 18 ply	Solid	22
7	Composite, IM7/TC350	Thin	Fabric	+45°/-45°, 0° (2x), +45°/-45°, 90°, 18 ply	Solid	22
8	Composite, IM7/TC350	Thick	Fabric	+45°/-45°, 0° (2x), +45°/-45°, 90° (2x), 27 ply	Solid	10
9	Composite, IM7/TC350	Thick	Tape	+45°/-45°, 0° (2x), +45°/-45°, 90° (2x), 54 ply	Solid	22
10	Composite, IM7/TC350	Thin	Tape	+45°/-45°, 0° (2x), +45°/-45°, 90° (2x), 38 ply	Solid	10

Table 3: Pyroshock Composite Material Characterization Test Matrix, Group II.

Group II – Sandwich Composite Panels							
Panel Number	Test Order Number	Material	Panel Thickness	Fill/Ply	Orientation	Type	LSC Core Load
11	1	Composite, IM7/TC350	8 Ply Fill	Al Honeycomb & Tape	90°/+45°/-45°/0°/0°/ -45°/+45°/90°, 8 ply both faces	Sandwich	10
12	4	Composite, IM7/TC350	8 Ply Fill	Al Honeycomb & Tape	90°/+45°/-45°/0°/0°/ -45°/+45°/90°, 8 ply both faces	Sandwich	22
13	3	Composite, IM7/TC350	8 Ply Fill	Rohacell Foam & Tape	90°/+45°/-45°/0°/0°/ -45°/+45°/90°, 8 ply both faces	Sandwich	10
14	2	Composite, IM7/TC350	8 Ply Fill	Rohacell Foam & Tape	90°/+45°/-45°/0°/0°/ -45°/+45°/90°, 8 ply both faces	Sandwich	22
15	7	Composite, IM7/TC350	8 Ply Fill	Al Honeycomb & Tape	90°/+45°/-45°/0°/0°/ -45°/+45°/90°, 8 ply both faces	Sandwich	10
16	5	Composite, IM7/TC350	8 Ply Fill	Al Honeycomb & Tape	90°/+45°/-45°/0°/0°/ -45°/+45°/90°, 8 ply both faces	Sandwich	22
17	8	Composite, IM7/TC350	8 Ply Fill	Rohacell Foam & Tape	90°/+45°/-45°/0°/0°/ -45°/+45°/90°, 8 ply both faces	Sandwich	10
18	6	Composite, IM7/TC350	8 Ply Fill	Rohacell Foam & Tape	90°/+45°/-45°/0°/0°/ -45°/+45°/90°, 8 ply both faces	Sandwich	22
Evaluate results from tests 11-18 and determine test panel configuration for tests 19-28							

Characterization of Test Data

In the aerospace industry, the most common method to characterize a pyroshock response is with the shock response spectrum (SRS) followed by the pseudovelocity spectrum (PV). However, in order to statistically evaluate the pyroshock response parameters of the TA, the analysis team chose to start with response parameters measured as single value inputs. Therefore, the two response spectrums, SRS and PV, need to be characterized in terms of single values. In order to put the response spectrums in terms of single value inputs, the assumption can be made that the SRS and PV response spectrums will show similar characteristics: SRSs tend to have a slope, a breakpoint

frequency, and a plateau; PVs plotted on four-coordinate paper tend to have a positive slope on the displacement line, a plateau on the velocity line, and a negative slope on the acceleration line. The typical characteristics of SRS and PV are shown in Figure 3 and Figure 4.

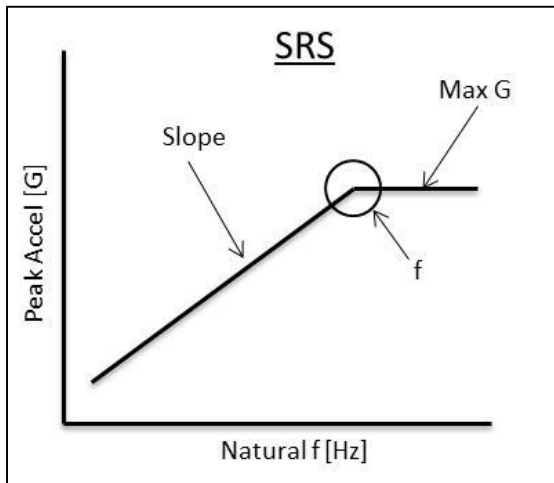


Figure 3: SRS Single Value Inputs

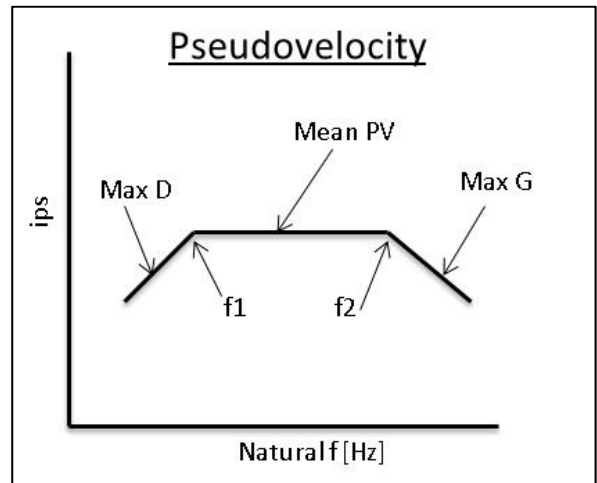


Figure 4: PV Single Value Inputs

Another aspect of statistically detecting potential trends in data is to characterize the measured response in as many ways as possible. Therefore, in addition to the standard response spectrums, SRS and PV, the measured data is also post processed into temporal and spectral moments. These moments also have the added benefit of being calculated directly from the time history data, unlike response spectrums which only calculate the peak response of a single-degree-of-freedom system subjected to the time history. Table 4 provides a breakdown of the components calculated for temporal and spectral moments. Though not used for statistical analysis, additional figures were also developed to aid in evaluating the statistical results. These figures include the integrated velocity and displacement time history, the energy spectral density, the Fourier spectrum, and the time-frequency analysis plot (Hacker, 2012).

Table 4: Single Value Inputs: Temporal and Spectral Moments

Single Value Inputs: Temporal and Spectral Moments	
Temporal Moment Calculated Values	Spectral Moment Calculated Values
Temporal Energy	Spectral Energy
Temporal Mean	One Sided Spectral Mean
Temporal Variance	One Sided Spectral Variance
Root-Mean-Square Duration	One Sided RMS Bandwidth
Variance Normalization	Variance Normalization
Temporal Skewness	One Sided Spectral Skewness
Temporal Kurtosis	One Sided Spectral Kurtosis
Root Energy Amplitude	

Since post-processing of pyroshock data and enveloping of response spectrums is often subjectively determined by the analyst, in an effort to eliminate human subjectivity, the entire post-processing procedure, from time history data cleanup to response spectrum enveloping, is automated. Table 5 and Table 6 provide the general algorithms used from enveloping the response spectrums while Table 7 provides the general algorithm for post processing the measured data.

Table 5: SRS Enveloping - General Algorithm

- Read in SRS plot points.
- Determine a temporary frequency break point (Lowest frequency that is one standard deviation below the highest peak value).
- Calculate the slope of the data points from 100Hz to the temporary frequency break point (Least Squares Fit).
- For the plateau, calculate the mean value of the data points from the temporary frequency break point to 10,000Hz.
- Calculate where the sloped line and the plateau intersect; this is the new frequency break point.
- Create the sloped portion of the curve from 100Hz to the new frequency break point.
- Create the plateau from the new frequency break point to 10,000Hz.
- Output the frequency break point, the slope, and the plateau values.

Table 6: PV Enveloping - General Algorithm

- Read in PV plot points.
- Determine break points (lowest and highest frequencies that correspond to peaks that are two standard deviations below the highest peak.)
- Calculate the slope of the max displacement line.
- Calculate the mean of the max pseudovelocity line.
- Calculate the slope of the max acceleration line.
- Calculate the two break frequencies by calculating where the max displacement and max acceleration line intersect the max pseudovelocity line.
- Create the enveloping curves.
- Output the max displacement value, the pseudovelocity, and the max acceleration value.

Both of the enveloping algorithms follow a similar procedure which revolves around estimating the initial frequency breakpoints by locating all local peaks within one or two standard deviations of the highest peak, then using those breakpoints as the initial estimation of the frequency breakpoints of the response spectrum being enveloped. It should be noted that the purpose of the enveloping algorithms is not to create a maximum envelope but to capture the behavior of the curve, hence why least square fit and mean are used rather than simply finding the maximum values.

The purpose of the post processing algorithm, described in Table 7, is to eliminate human subjectivity and error by creating a procedure that is consistent for each data set. Key aspects of the algorithm include identifying the beginning of the shock pulse, clipping the time history down to the first 20 msec, and detrending the shock pulse. Detrending the shock pulse is a particularly important procedure for calculating PV so that the integrated velocity and displacement time histories end with zero amplitude. This allows for the max displacement line to be calculated for the PV response spectrum; otherwise, the max displacement line trends towards infinity.

Table 7: Post Processing Automation - General Algorithm

- Import time history data.
- Identify the beginning of the shock pulse in the time history.
- Remove the bit error from the time history.
- Take the first 20msec of the shock pulse.
 - Detrend the shock pulse.
- Perform calculations on post-processed data.
 - Time history plots
 - Shock Response Spectrum
 - Pseudovelocity Response Spectrum
 - Temporal Moments
 - Spectral Moments
 - Fourier Spectrum
 - Generalized Harmonic Wavelet Transform
- Print and plot results for statistical evaluation.

Discussion of Results

Figure 5 and Figure 6 demonstrate the performance of the enveloping algorithms. For each figure, the blue curve is the response spectrum curve developed from the measure time history data; the black dots are the initial estimated frequency break points that are selected from the local peaks that occur throughout the spectrum curves. Note that the enveloping algorithms rely heavily on the spectrum curves having local peaks. From the initial break points the least squares fit is determined from the sloped portions of the curve and the mean value is calculated from the plateau region. Once these properties are calculated they are used to develop straight line curves. These curves (red, green, and/or purple) are connected to form the enveloping curve that represents the mean properties of the overall response spectrum. While testing is ongoing, initial observations show that the algorithms perform well. Potential errors could occur if the response spectrums are overly smooth since the algorithm relies on local peaks.

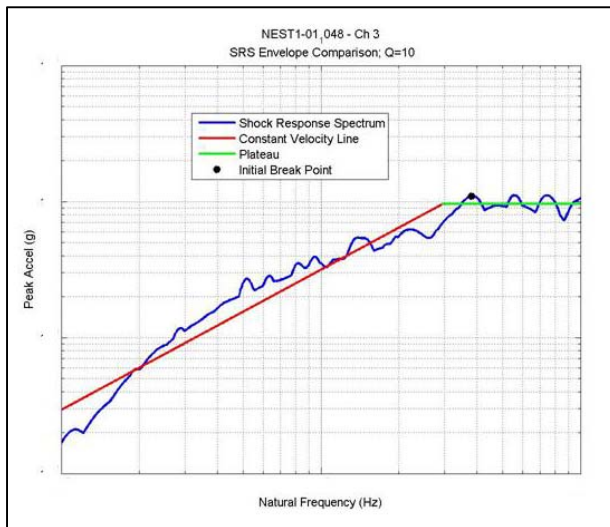


Figure 5: Demonstration of SRS Enveloping Algorithm

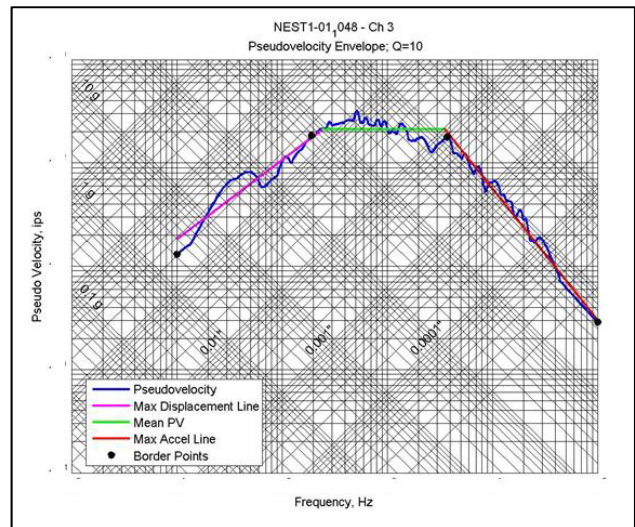


Figure 6: Demonstration of PV Enveloping Algorithm

While this paper's primary focus is on the test setup and data post-processing, the figures below provide a very preliminary glance at some of the statistical techniques being utilized to quantify the differences in effects and variability in responses due to changes in the input factors. Figure 7 plots max acceleration parameters, i.e. the enveloped plateau of the SRS, with distance. The overall means attenuate with distance as is typically expected with shock environments. The panel thickness appears to influence the propagation of the shock environment with distance while core load has an indeterminate effect and ply type has a negligible impact. While there is

considerably more work needed to quantify these effects, an initial understanding of the different composite parameter effects can be gained.

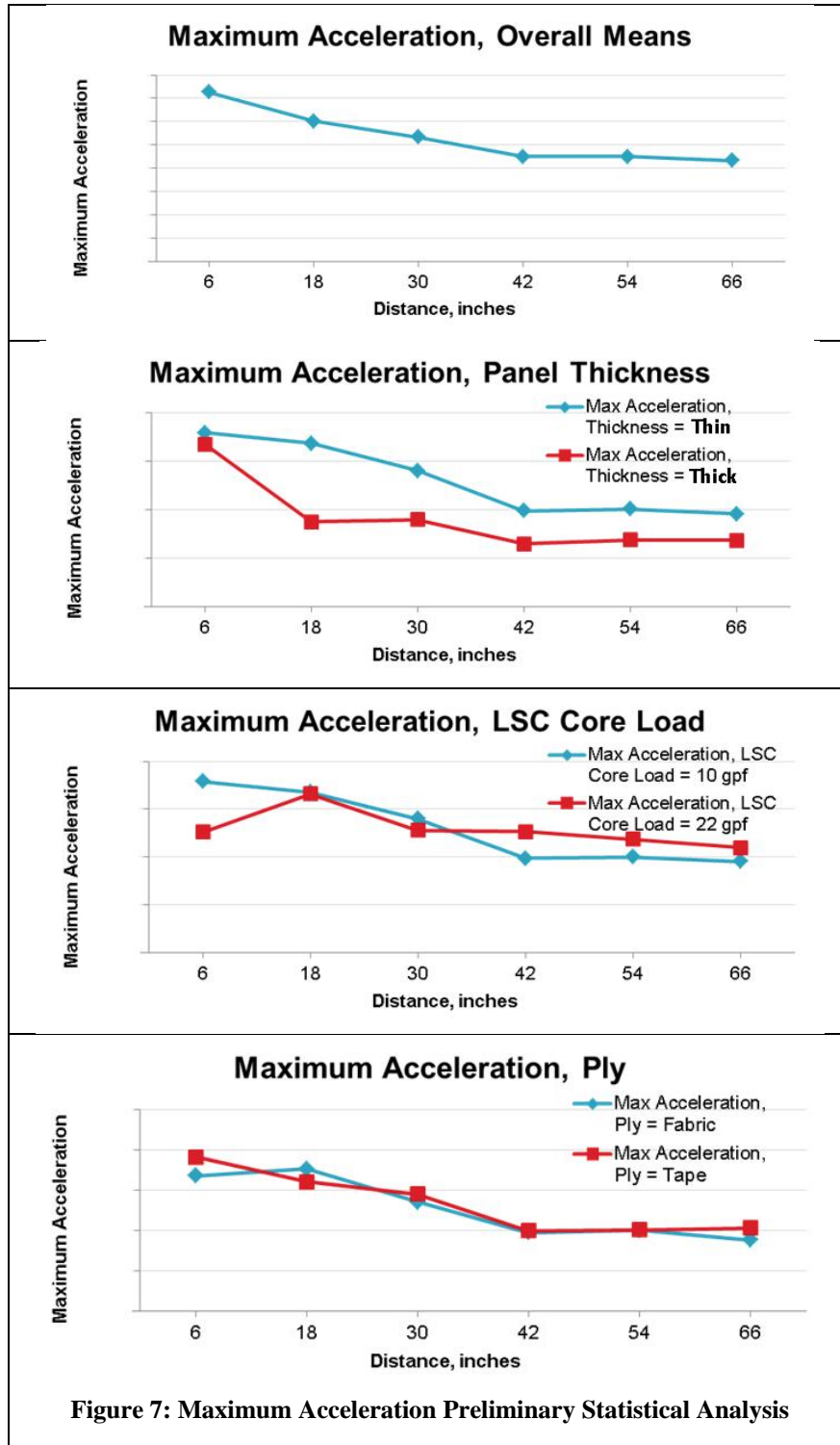


Figure 8 provides insight into the mean PV calculated at each accelerometer location across group I of the test matrix. The mean PV values appear to cluster into groups with each test, with the exception of obvious outliers,

which would indicate that mean PV values are sensitive to the composite parameters of group I. The cause of the outliers will need to be investigated and at this time is considered future work.

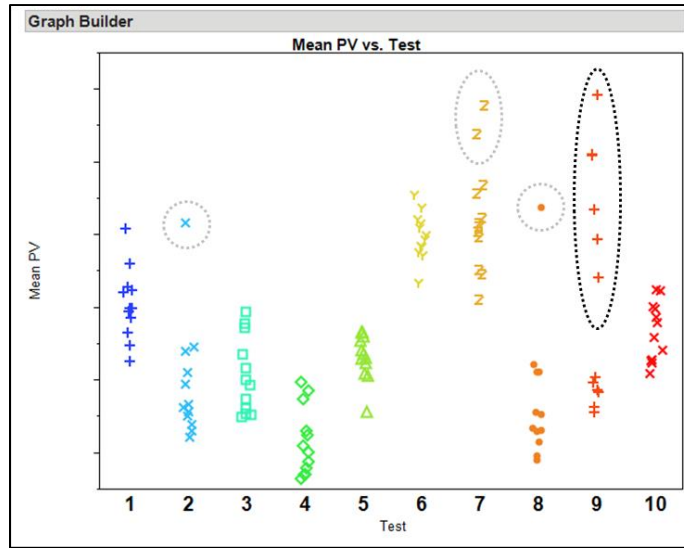


Figure 8: Mean PV Preliminary Statistical Analysis

Conclusions

The results of these tests will examine which variables influence a composite structures response to a pyroshock induced load. While testing is ongoing through 2014, preliminary results indicate that the enveloping and post-processing algorithms will provide a useful approach to calculating quantifying values useful for statistical methods. Current and future work includes continuing to identify ways to characterize a pyroshock environment that is suitable of DOE and updating and analyzing the current statistical results as the testing is completed. The overall goal of this test program is to identify non-essential composite parameters that can be eliminated from future test matrices of larger test programs with the end goal to develop a pyroshock scaling method for composite structures from the large body of empirical data that is being collected.

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