16.622 Final Report

Expandable Foam Impact Attenuation for Small Parafoil Payload Packages

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Background and Motivation

Impact attenuation for small payloads delivered by UAV's

Current mechanisms:

•Airbags/ Parachute Retraction

•Paper Honeycomb

Alternative:

•Expanding Foam Impact Attenuation (EFIA)

Hypotheses

1. 75% less *pre-deployment volume* and *crush thickness efficiency* loss of no more than 30%.
2. Increase in *cost* of no more than 50% and a decrease in *reliability* of no more than 10%.

Objective

Assess the ability of an EFIA to protect a payload having a 50g-impact shock limit from a 15 ft/s* vertical descent rate.
Compare the pre-deployment volume, crush efficiency, cost and reliability of the EFIA against paper honeycomb.

Success Criteria

Evaluate the aforementioned metrics for an EFIA and for paper honeycomb to an accuracy such that the hypotheses can be assessed.

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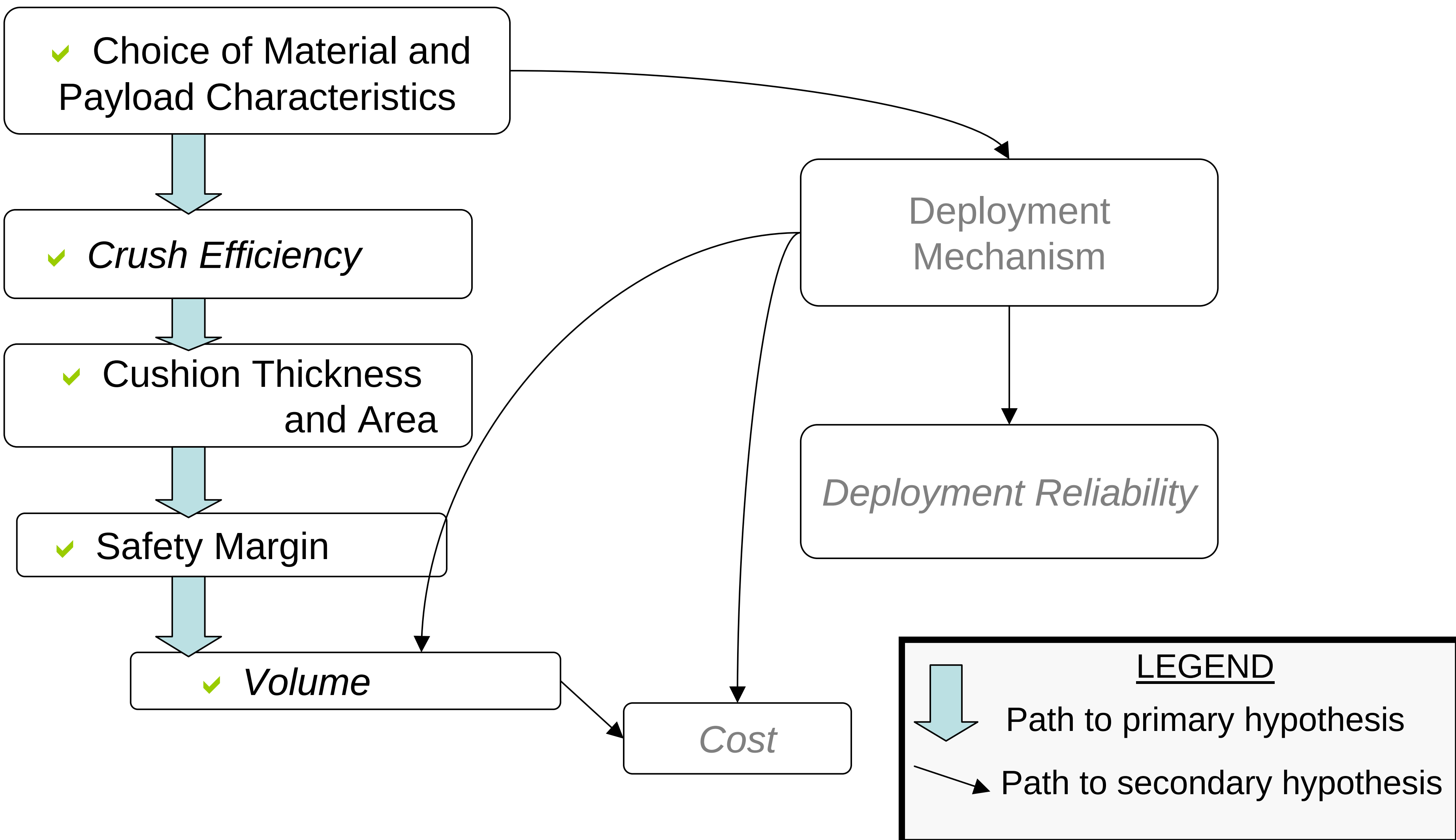
*Impact velocity was 13.5 ft/s during drop tests

Hypotheses Assessment

- Confirmed "*crush thickness efficiency* loss of no more than 30%"
- Refuted "decrease in *reliability* of no more than 10%"
- Uncertain assessment of "75% less *pre-deployment volume*"

Experimental Overview and Methods



Crush Efficiency Test Matrices

- <u>Static</u>

Thickness

Honeycomb

1/2”
3/4”
1”

Trial Number	Initial Cushion Thickness (inches)	Crush Displacement (inches)	Crush Thickness Efficiency
1-5			
Average			

Thickness

Expanding Foam

1/2”
1”

Trial Number	Initial Cushion Thickness (inches)	Crush Displacement (inches)	Crush Thickness Efficiency
1-5			
Average			

- <u>Dynamic:</u> Same only for ½” samples

Test Matrices (Cont.)

Safety Margin

Material: Honeycomb		**Material: Expanding Foam**	
Trial Number	Maximum Acceleration	Trial Number	Maximum Acceleration
1-25		1-25	

Expanding Foam Deployment Reliability

Trial Number	**Successful Deployment**
1 - 25	

Pre-Deployment Volume

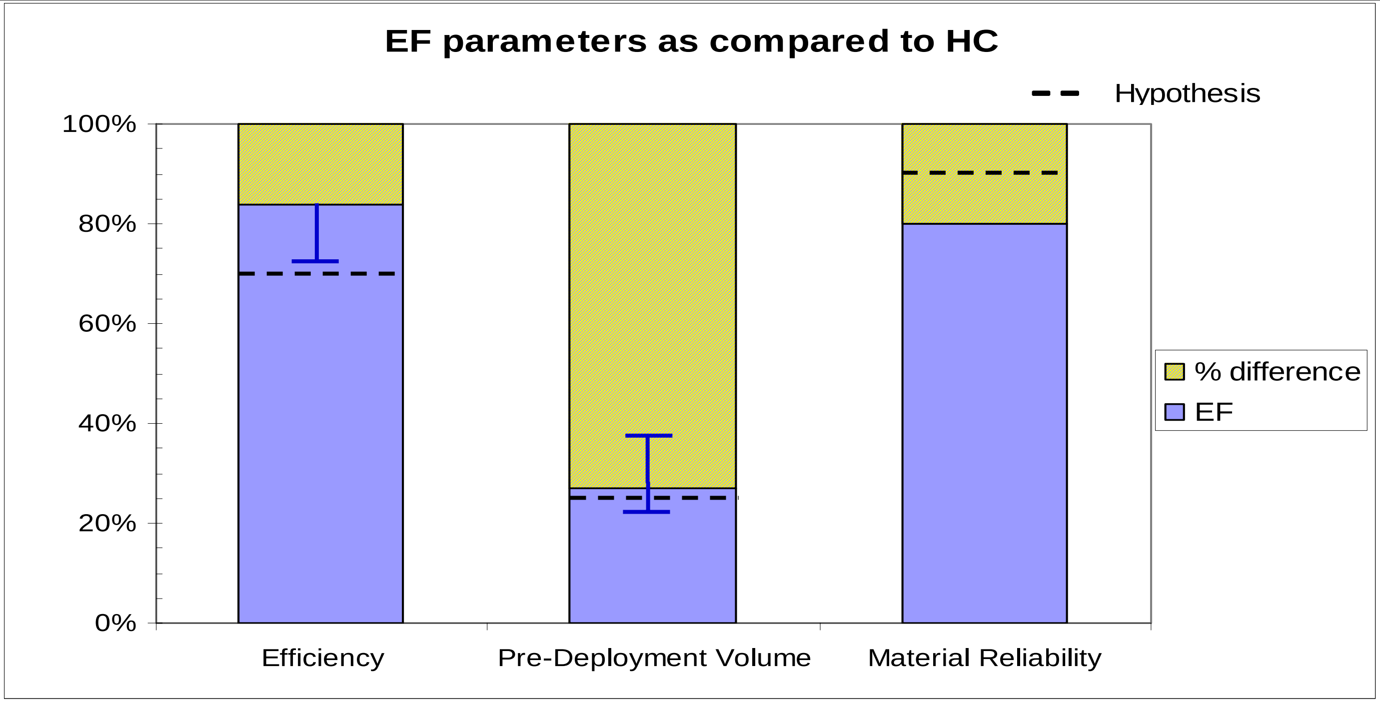
Material	**Volume**
Honeycomb	
Expanding Foam	

Error Mitigation

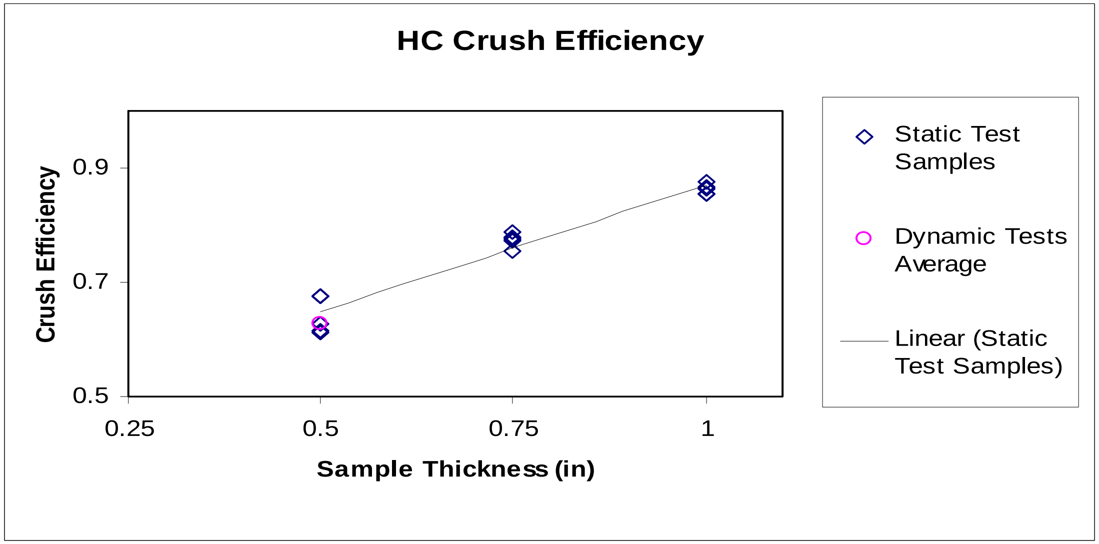
- Sampled at high data rates on accelerometer (5000Hz) and high-speed camera (2000Hz)
- Calibrated high speed camera before each session
- Confirmed impact velocity after each drop (13.5 +/- 0.3 ft/s)

Hypothesis Assessment Results

	Efficiency	**Pre-Deployment Volume**	**Reliability**
Hypothesis	At least 70%	At most 25%	At least 90%
Results	83.8% (- 11.1)	27% (- 5.4, + 7.5)	83% (95% confidence)



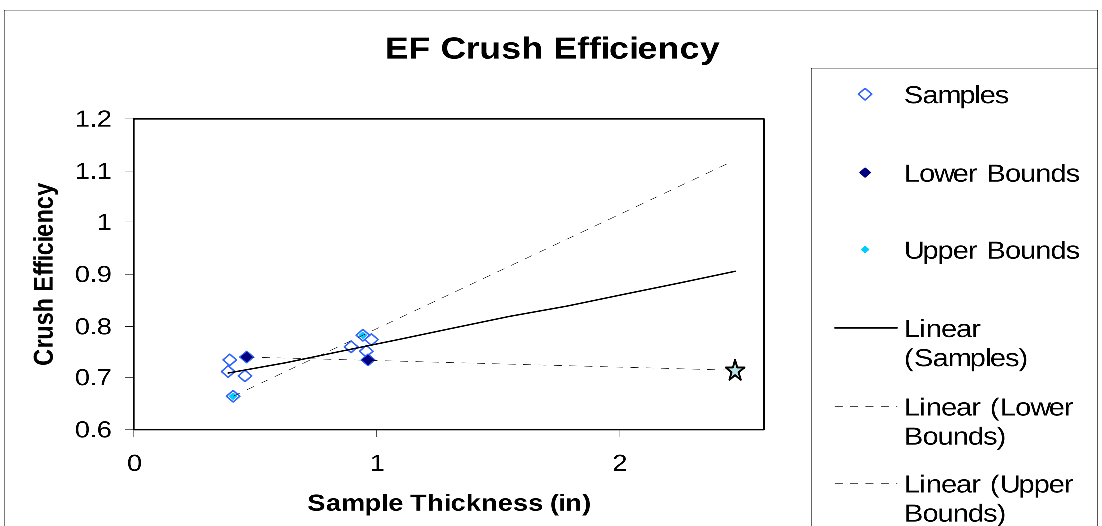
Analysis of Crush Efficiency



Honeycomb

- Final cushion thickness of 2.7 inches requires three 1-inch pieces of honeycomb stacked together.

- Used efficiency for 1” honeycomb



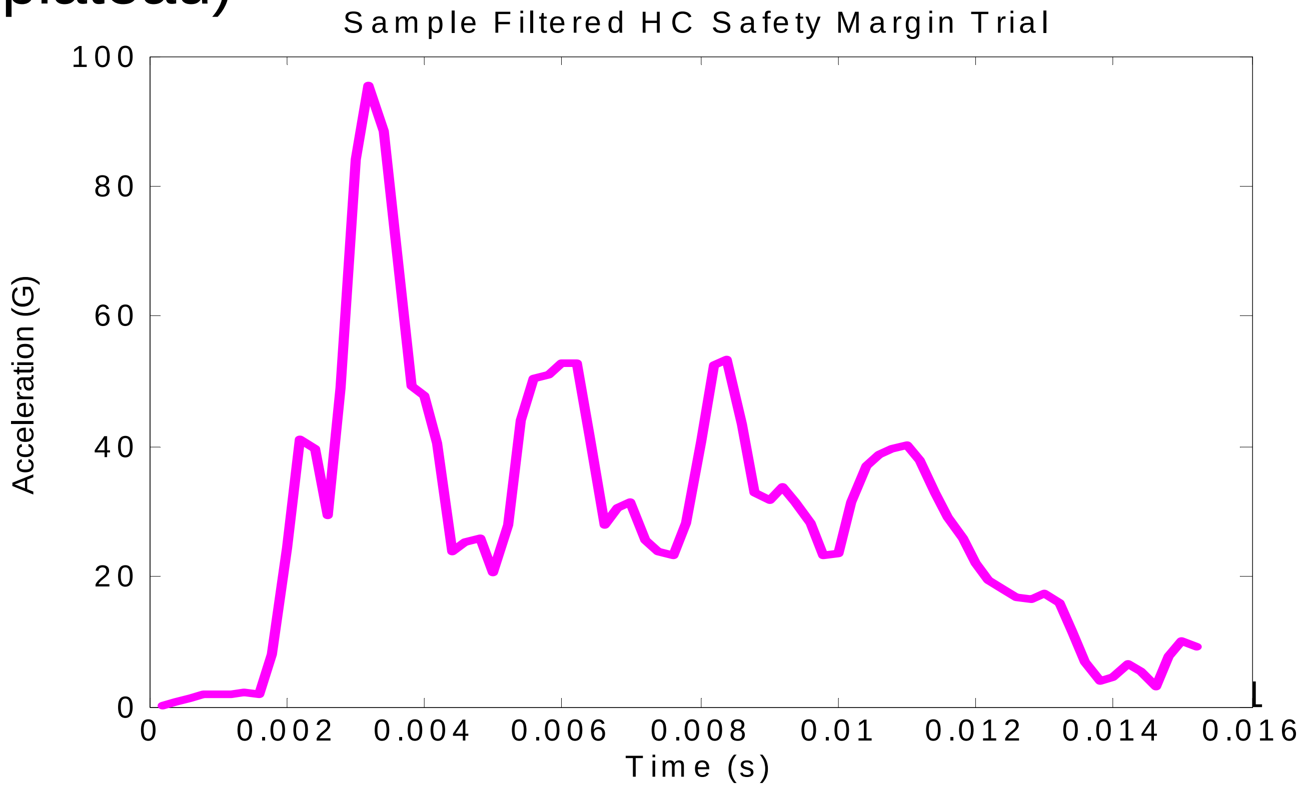
Expanding Foam

Used lower bound to extrapolate efficiency to final cushion thickness of 2.5 inches.

Analysis of Safety Margin Tests Results
Paper Honeycomb

Tests show two dominant G-loading modes:

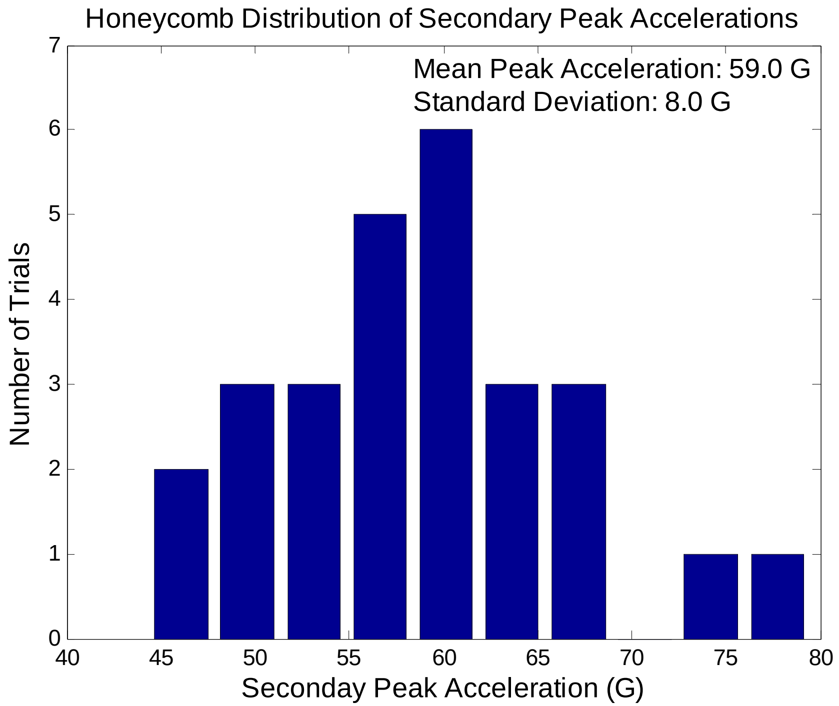
- Buckling (first peak)
- Crushing (~plateau)



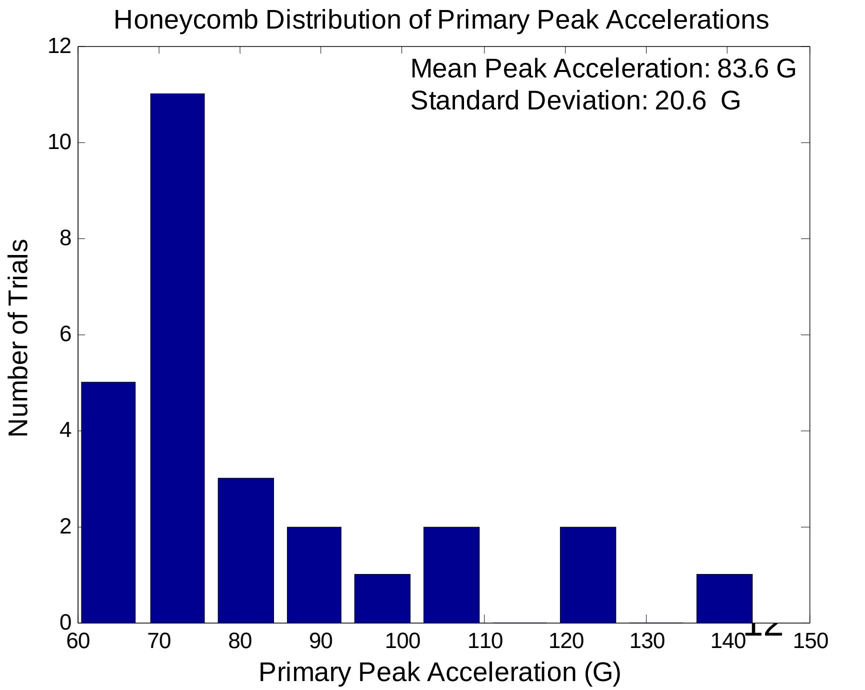
Analysis of Safety Margin Tests Results
Paper Honeycomb (Cont.)

Peak Distribution Curves

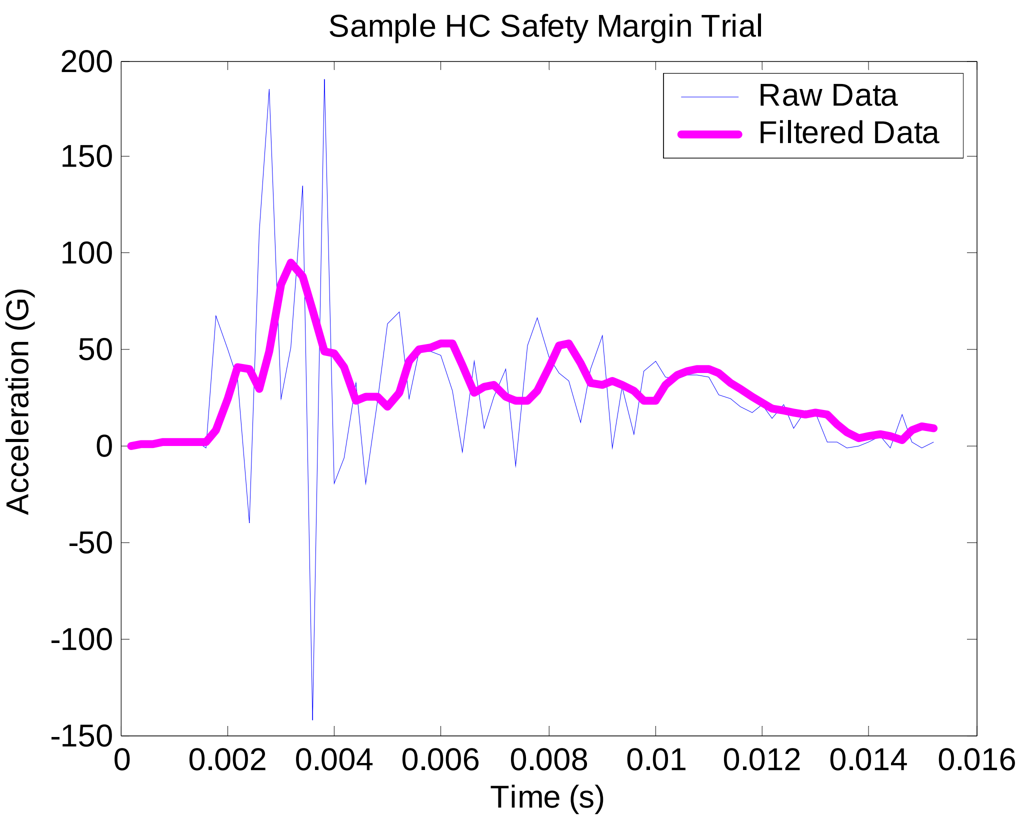
- Crush: G-load peak predicted by theory



- Buckling: G-load peak during drop-tests



Analysis of Safety Margin Tests Results
Paper Honeycomb (Cont.)



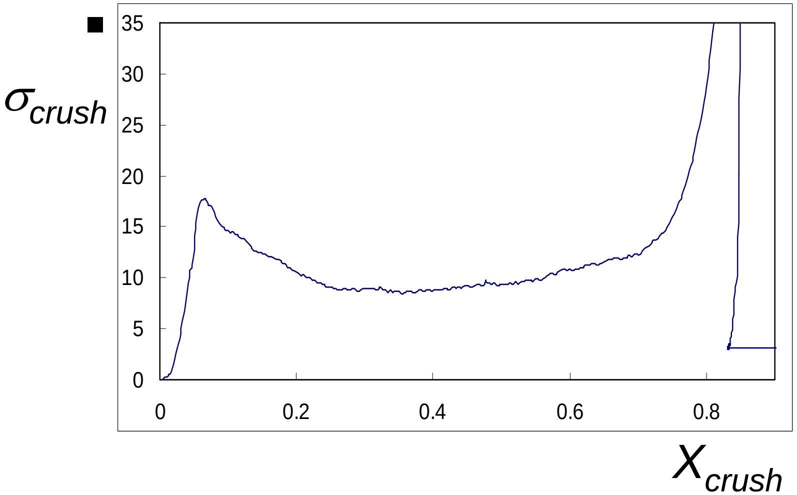
<u>Issue:</u>

- High Frequency Vibrations

<u>Solution:</u>

- Data filtered above 580Hz

<u>Motivation:</u>

- 

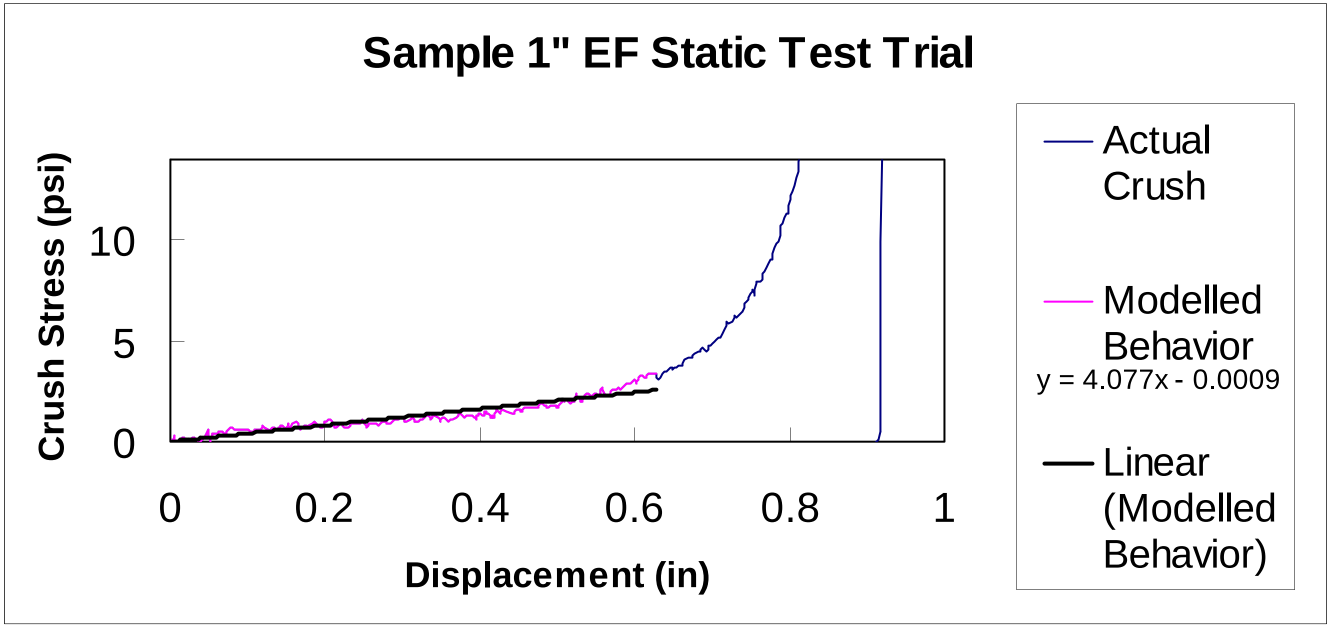
Comparison to Previous Theory:
Analysis of EF Crush Stress

Previous Model: Assumes constant crush stress

$$\tau_{cushion} = \frac{\nu^2}{2gG\eta_t}$$

$$A\sigma_{dynamic} = mGg$$

Findings: Crush stress is not constant



New Model

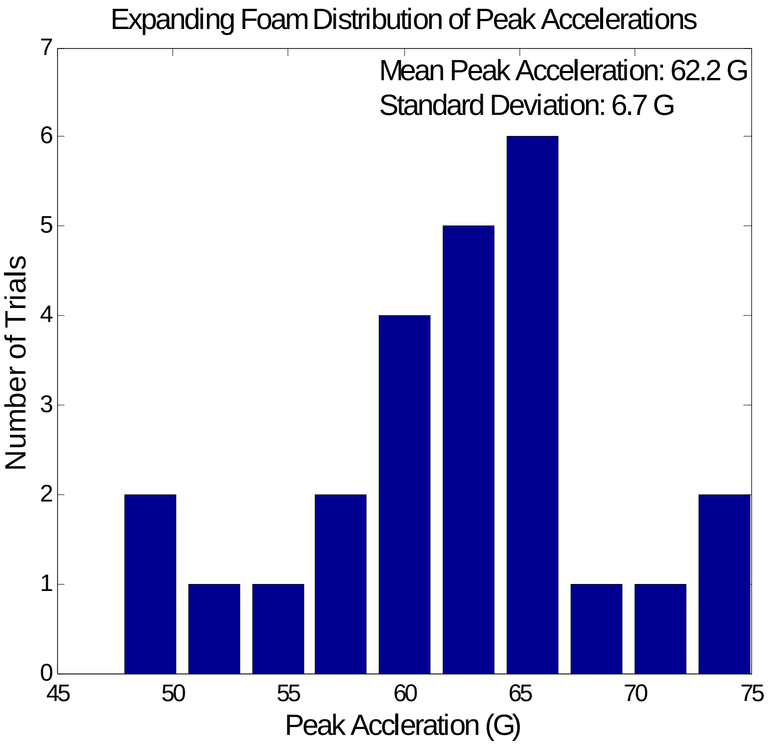
Model crush stress as a linear function, solve ODE

$$A\sigma_{dynamic} = m\ddot{x}$$

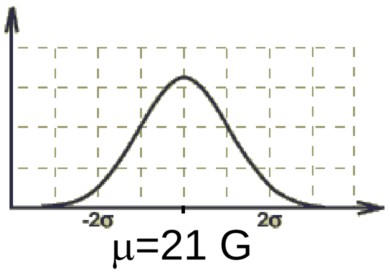
$$\ddot{x} + \frac{kA}{m}x = 0$$

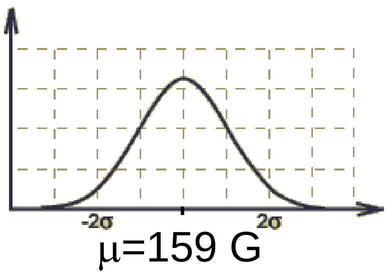
Analysis of Safety Margin Tests Results
Expanding Foam

<u>Experiment Results</u>



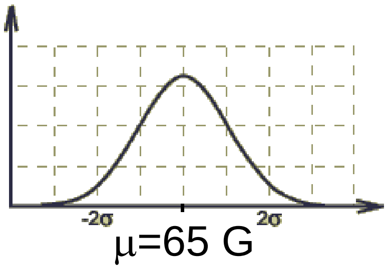
<u>Errors in Model</u>





= calculation error when determining parameters + modeling error of stress vs. displacement slope

<u>Corrected Model Prediction</u> ✔



Analysis of Volume and Reliability Results

Volume:

- Use modified models and the results of the Safety Margin Tests to calculate new Area and Cushion Thickness.
  - Honeycomb Pre-Deployment Volume = Area * Cushion Thickness
  - Expanding Foam Post-Deployment Volume = Area * Cushion Thickness, then scale to find pre-deployment volume

Expansion Reliability:

- Use sample size and number of failures to determine Reliability and Confidence through Larson’s Binomial Distribution Graph

Sources of Error

	Honeycomb	**Expanding Foam**	**Sources of Error**
Crush Efficiency	7.4 %	4.2%	- Instron Machine Error - Estimating Crush Displacement
Volume	11%	3.7%	- Impact Velocity - Acceleration Measurement

Conclusion:
Assessment of Hypothesis

- Confirmed "*crush thickness efficiency* loss of no more than 30%"
- Refuted "decrease in *reliability* of no more than 10%"
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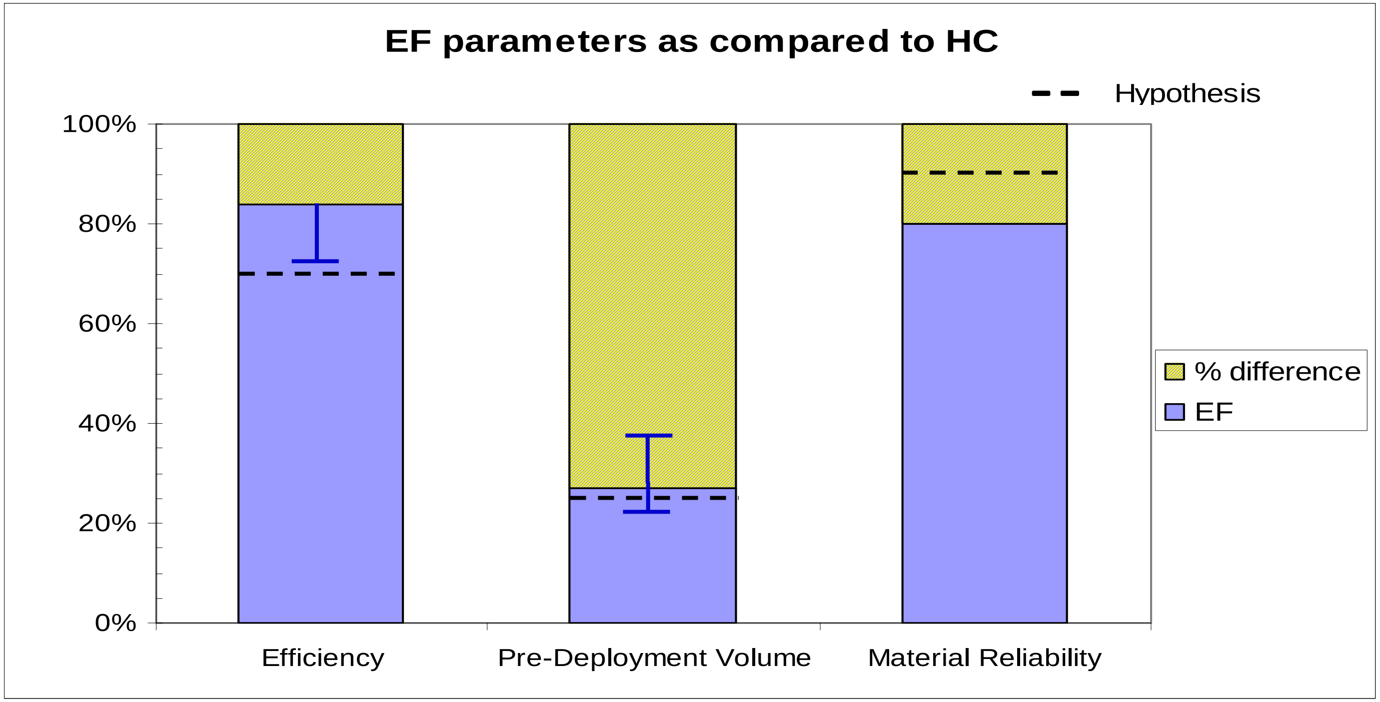


Conclusion:

Summary of Principal Findings

1) The pre-deployment volume of expanding foam is at most 34.5% the pre-deployment volume of paper honeycomb, under given test conditions.

2) The crush efficiency of expanding foam is at least 72.7% of the crush efficiency of paper honeycomb, for given test conditions

3) The expanding foam is 83% reliable (95% confidence) to expand to expected volume within 30 seconds.

4) Honeycomb crush efficiency is a function of cushion thickness.

5) Honeycomb buckling results in peak acceleration during impact.

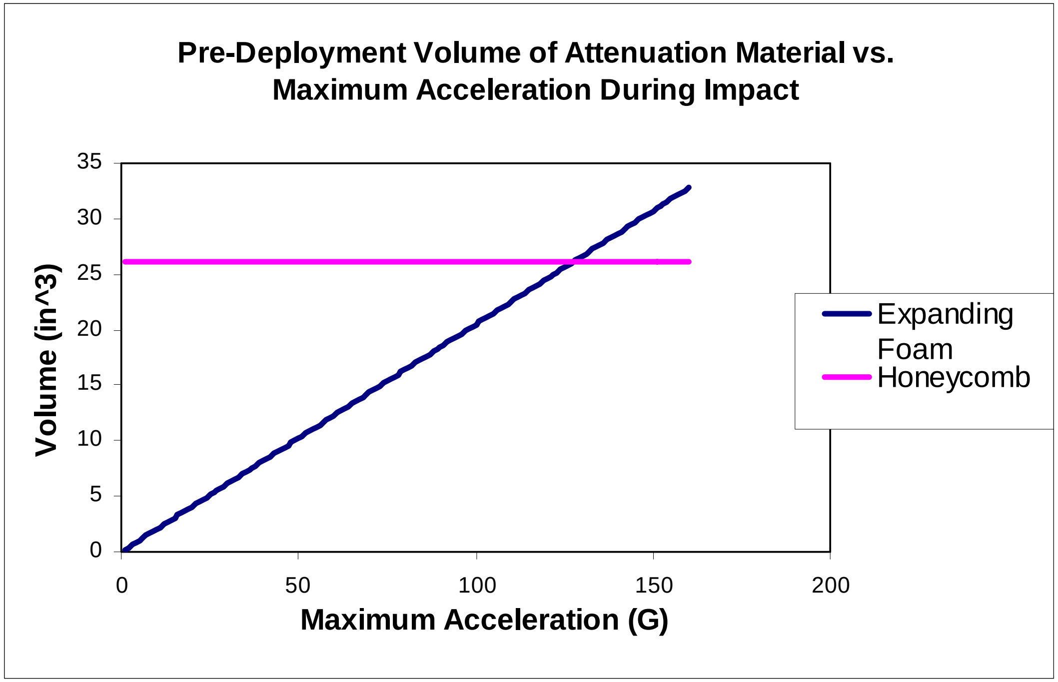
6) Expanding Foam crush stress is not constant. Instead behavior during crush can be characterized using a linear approximation of crush stress.

Conclusion:

Summary of Principal Findings (Cont.)

7) For a given crush stress, payload mass, and impact velocity:

- Honeycomb volume as a function of maximum acceleration during impact is constant.
- Expanding foam volume as a function of maximum acceleration during impact is linear.



Recommendations for Future Research

- Experimentally verify and improve the corrected models of material behavior during impact
- Characterize payload resonance for HC attenuation
- Expand experiment scope:

  - lowest pre-deployment volume impact attenuation material may depend on touch-down conditions

- Design reliable, low-volume, low-weight mechanism to expand foam onboard

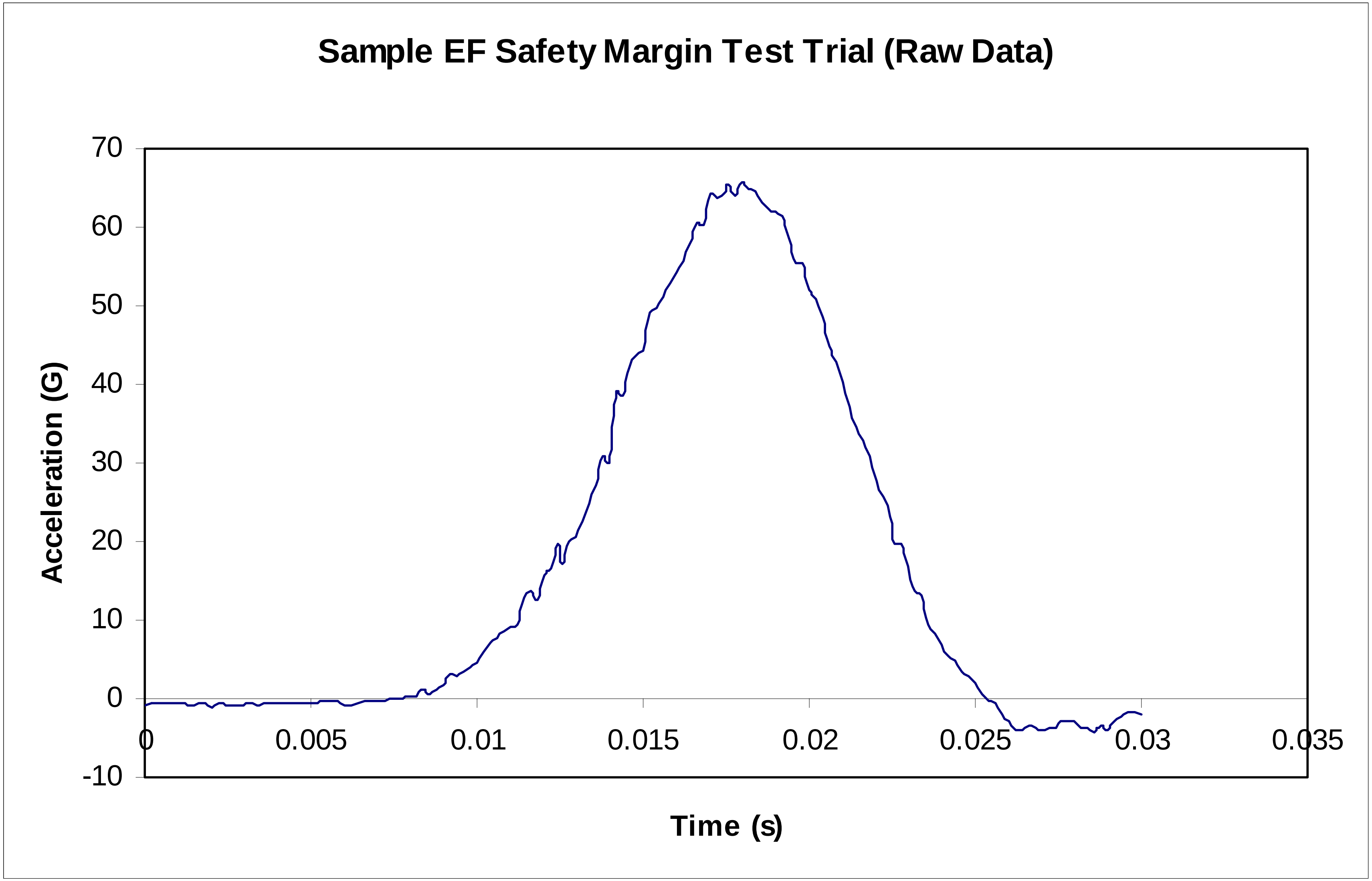
Acknowledgements

Christian Anderson

Technical Staff

16.62X Faculty

Questions?


Sample EF Safety Margin Test Trial (Raw Data)
Acceleration (G)
70
60
50
40
30
20
10
0
-10
0
0.005
0.01
0.015
0.02
0.025
0.03
0.035
Time (s)