US ARMY RDECOM

Screening Adhesively Bonded Single-Lap-Joint Testing Results Using Nonlinear Calculation Parameters – Statistical Analysis

ARL

TECHNOLOGY DRIVEN. WARFIGHTER FOCUSED.

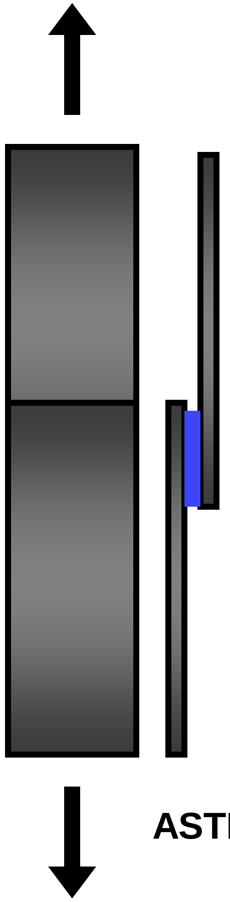
Robert Jensen, Daniel Deschepper, David Flanagan
U.S. Army Research Laboratory
Weapons and Materials Research Directorate

Goal

Generate experimental data for parametric studies of high strain to failure (damage tolerant) adhesives in the single-lap-joint configuration

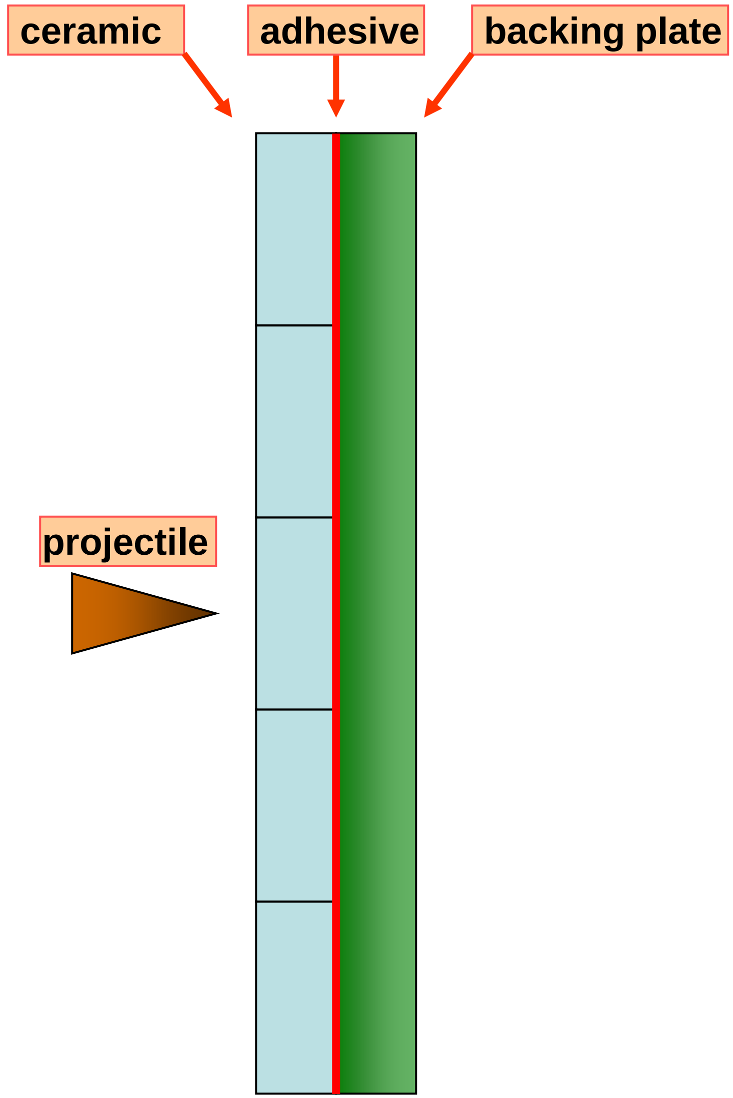
- **Gains in the Education of Mathematics and Science (GEMS) student fabrication**

Single-lap-Joint

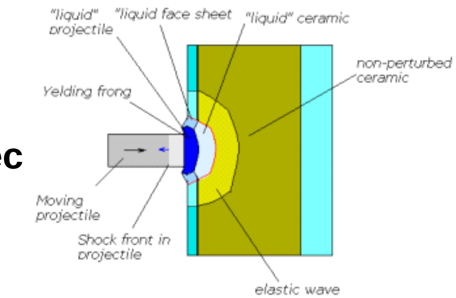


ASTM D1002

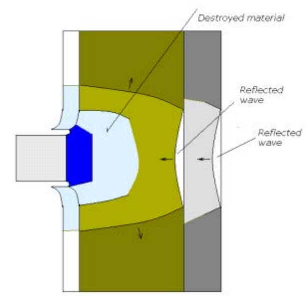
Understanding adhesive failure mechanisms at high loading rates is a challenge



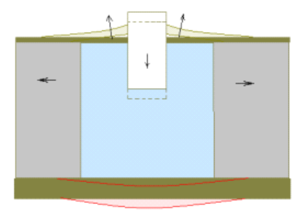
Acoustic 0.5μsec



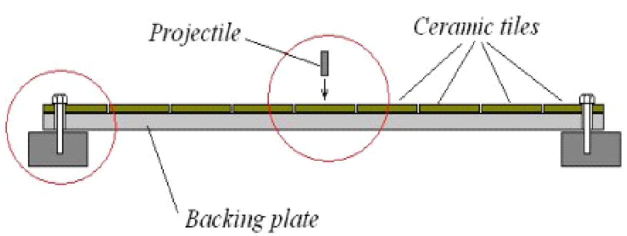
Hydrodynamic 10μsec



Hydrostatic 50μsec

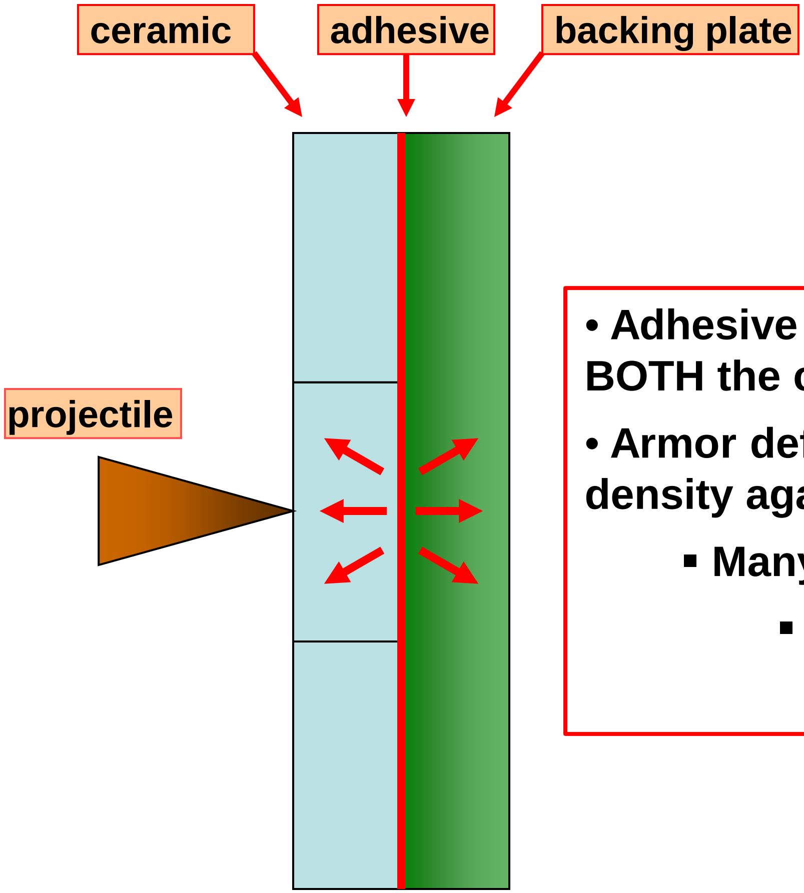


Long term



Lopatnikov, Gama, Gillespie Jr.
UD-CCM, W911NF-06-2-0011

Understanding adhesive failure mechanisms at high loading rates is a challenge



- Adhesive influences the performance and damage in BOTH the ceramic strike face and backing plate.
- Armor defeat mechanisms are optimized for lowest areal density against specific threats.
  - Many threats
    - Many armor configurations
      - Variable adhesive properties are needed.

TECHNOLOGY DRIVEN. WARFIGHTER FOCUSED.

Understanding adhesive failure mechanisms at high loading rates is a challenge - obstacles

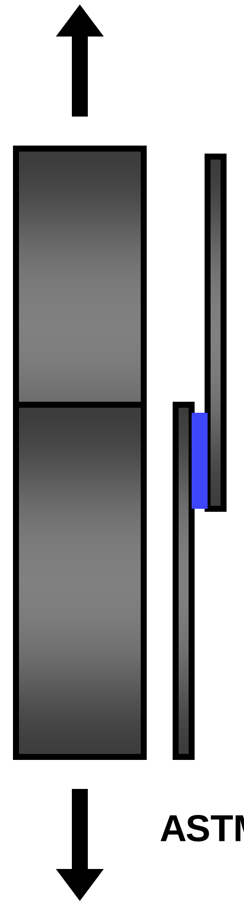
- **Army development timelines are pressured by emerging threats from the battle field**
- **> 400 commercial adhesive formulators***
- **Engineering data difficult to obtain outside of aerospace applications**
- **Army unique high loading rate extreme environment****
  - **Inadequate ability to relate or predict the roles of materials structure, processing, and properties on performance**
  - **The lack of experimental capabilities to quantify multiscale response and failure**

*Adhesives and Sealants. *MarketResearch.com*, Global Industry Analysts, market survey dated 01 March 2008.
**Collaborative Research Alliance (CRA) for Materials in Extreme Dynamic Environments (MEDE), funding opportunity title announced by the U.S. Army Research Laboratory, 2011.

Understanding adhesive failure mechanisms at high loading rates is a challenge - solutions

- Army development timelines are pressured by emerging threats from the battle field
  - Rapid screening
- > 400 commercial adhesive formulators*
  - Industry standard
- Engineering data difficult to obtain outside of aerospace applications
  - Army driven performance criteria
- Army unique high loading rate extreme environment**
  - Inadequate ability to relate or predict the roles of materials structure, processing, and properties on performance
  - The lack of experimental capabilities to quantify multiscale response and failure
- Can a simple quasi-static experiment indicate potential high loading rate performance?

Single-lap-Joint



ASTM D1002

*Adhesives and Sealants. *MarketResearch.com*, Global Industry Analysts, market survey dated 01 March 2008.

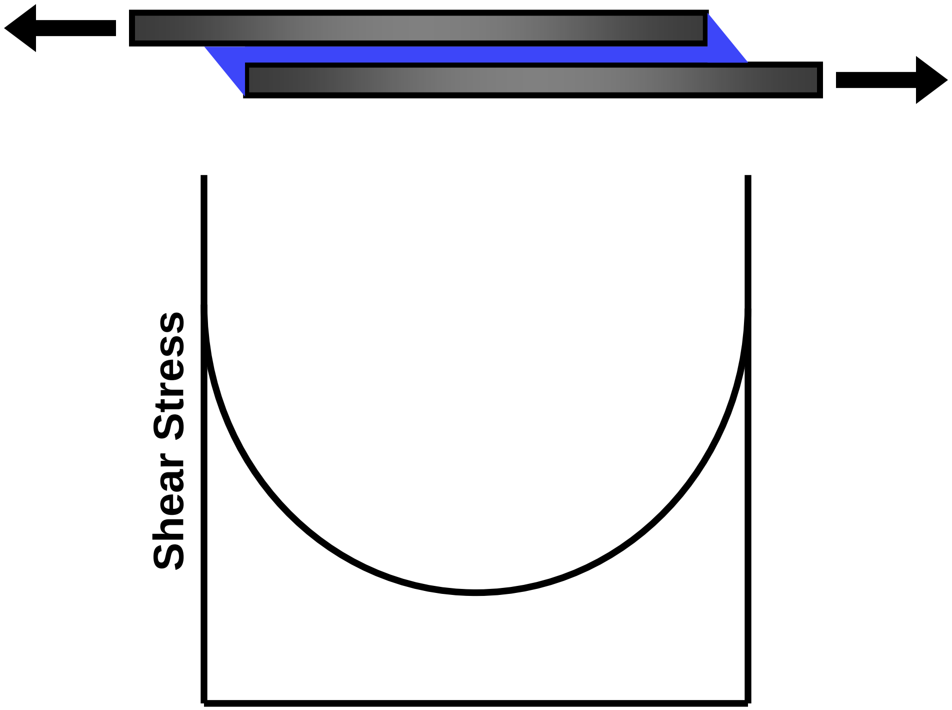
**Collaborative Research Alliance (CRA) for Materials in Extreme Dynamic Environments (MEDE), funding opportunity title announced by the U.S. Army Research Laboratory, 2011.

The single-lap-joint is well established with testing standards and scientific literature

ASTM D1002 Standard Test Method for Apparent Shear Strength of Single-Lap-Joint Adhesively Bonded Metal Specimens by Tension Loading (Metal- to-Metal)

$$Strength = \frac{P_{\max}}{A_{Bonded}}$$

The single-lap-joint is well established with testing standards and scientific literature

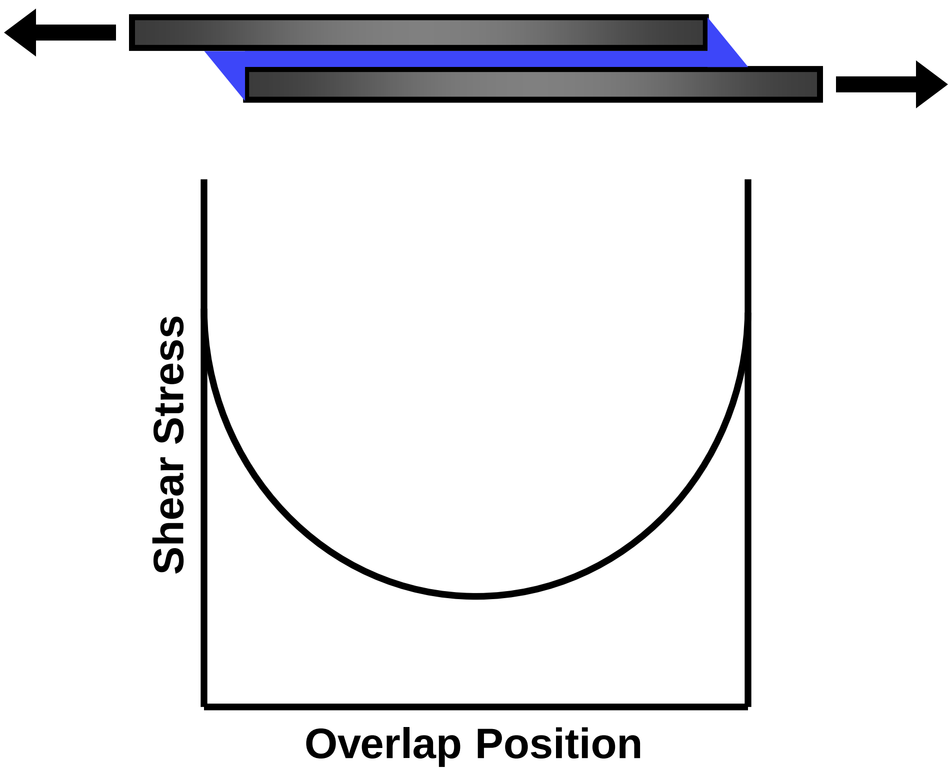


ASTM D1002 Standard Test Method for Apparent Shear Strength of Single-Lap-Joint Adhesively Bonded Metal Specimens by Tension Loading (Metal- to-Metal)

$$Strength = \frac{P_{\max}}{A_{Bonded}}$$

Volkersen – differential shear - 1938

The single-lap-joint is well established with testing standards and scientific literature



ASTM D1002 Standard Test Method for Apparent Shear Strength of Single-Lap-Joint Adhesively Bonded Metal Specimens by Tension Loading (Metal- to-Metal)

$$Strength = \frac{P_{\max}}{A_{Bonded}}$$

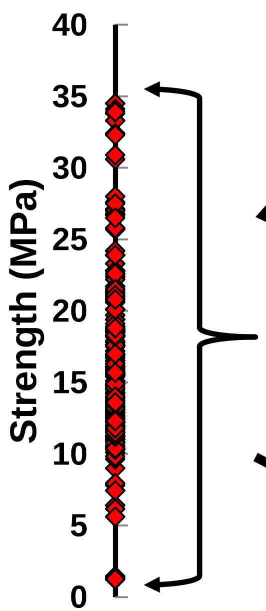
Volkersen – differential shear - 1938

The single-lap-joint has been the subject of extensive academic study

- **Volkersen's work sited 345 times[a]**
- **639 papers between 1978 and 2012[a]**
- **Numerous parametric studies**
- **24 linear and non-linear analytical models reported in the literature[b]**

[a] ISI Web of Knowledge, keyword search "single lap joint adhesive", retrieved May 23, 2012.
[b] L.F.M. da Silva et at., Int. J. Adhesion & Adhesives, 2009

From a traditional "strength" perspective it appears that a wide range of adhesives have been screened for potential Army applications



Traditional perspective

<u>ARL experimental range</u>[c]

Traditional parameter

ASTM D1002 Standard Test Method for Apparent Shear Strength of Single-Lap-Joint Adhesively Bonded Metal Specimens by Tension Loading (Metal- to-Metal)

$$Strength = \frac{P_{\max}}{A_{Bonded}}$$

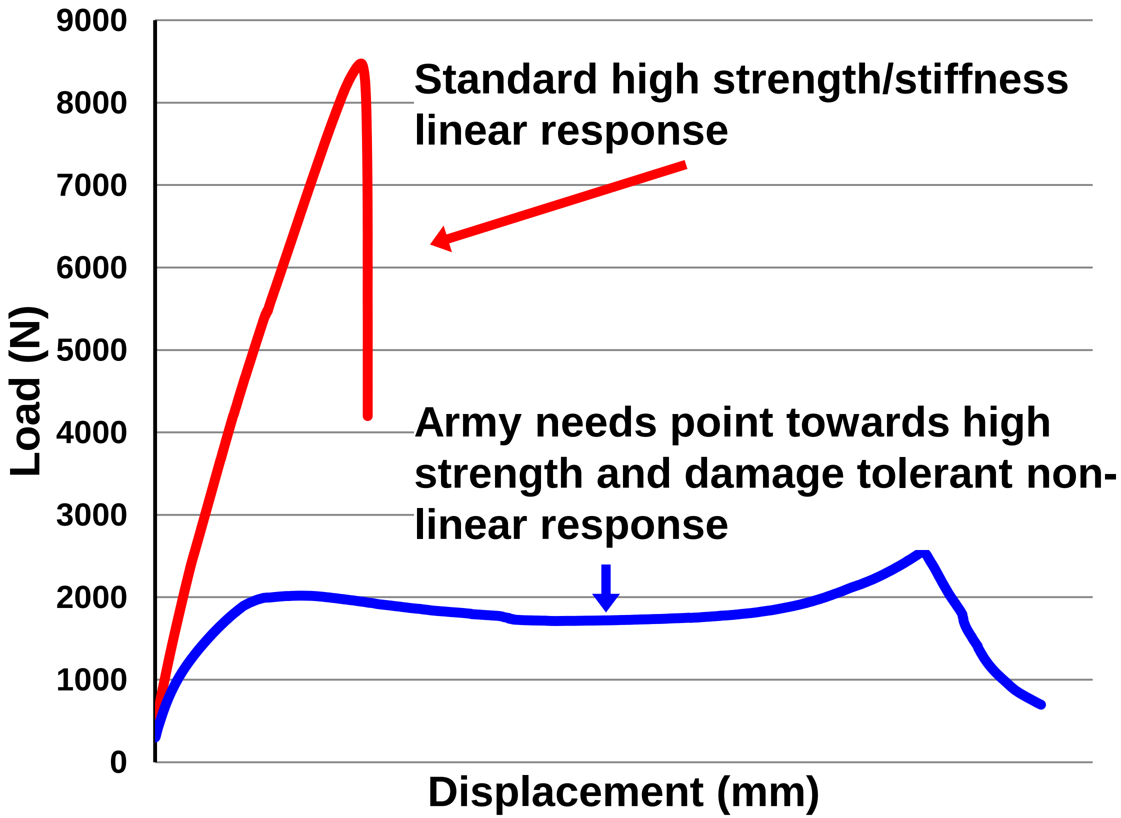
Volkersen – differential shear - 1938

The single-lap-joint has been the subject of extensive academic study

- **Volkersen's work sited 345 times**[a]
- **639 papers between 1978 and 2012**[a]
- **Numerous parametric studies**
- **24 linear and non-linear analytical models reported in the literature**[b]

[a] ISI Web of Knowledge, keyword search "single lap joint adhesive", retrieved May 23, 2012.
[b] L.F.M. da Silva et at., Int. J. Adhesion & Adhesives, 2009
[c] RT, quasi-static, dry conditioning

Empirically observed "damage tolerant" adhesives show non-linear loading response



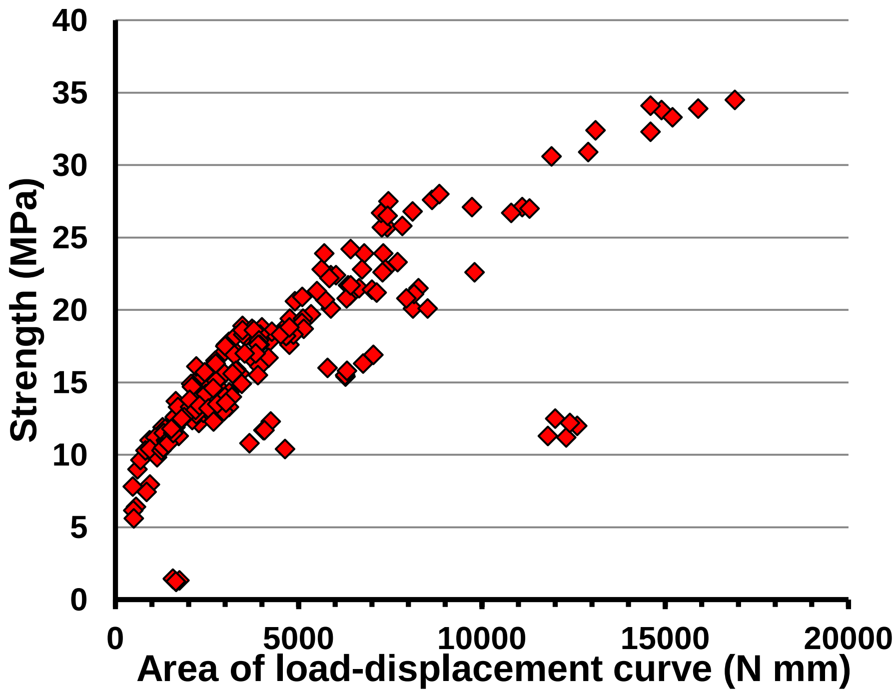
$$Strength = \frac{P_{\max}}{A_{Bonded}}$$

$$Area = \sum_{i=1}^{n} f(x_{i-1})(x_i - x_{i-1})$$

$$\frac{d^3\sigma}{d\varepsilon^3} = 0$$ **, at yield***

*R.M. Christensen, *Acta Mech*, 2008, 196, pp 239–244.

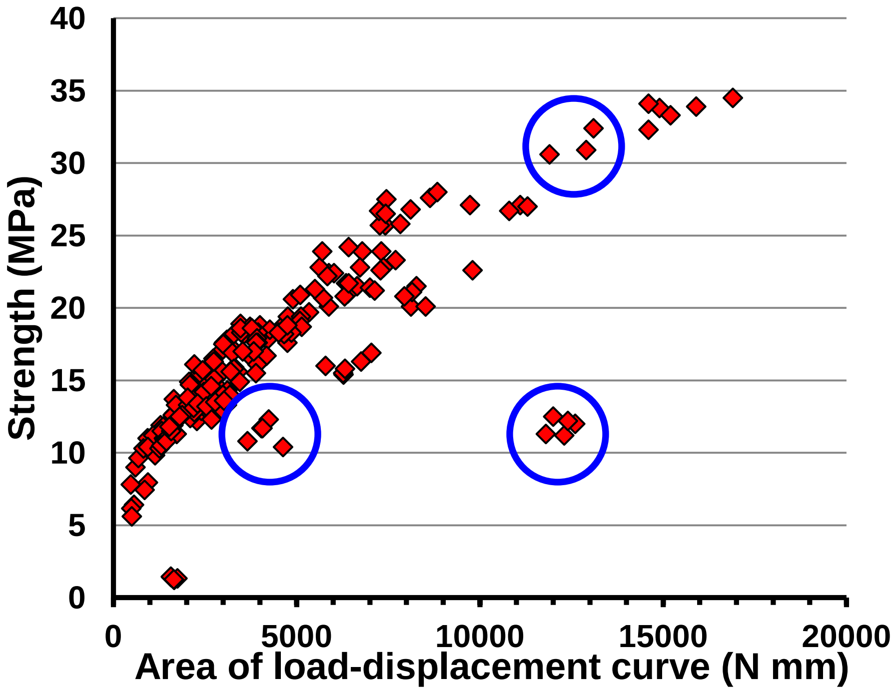
What if "strength" provides only a partial descriptor needed to define Army driven performance criteria?



Extension shift (mm)		-0.6
constant		
x	x	
x^2	x^2	
x^3	x^3	
x^4	x^4	
x^5	x^5	
x^6	x^6	
Row of 1st minimum in 2nd derivative curve		31
Load at 1st minimum in 2nd derivative (N)		
Strength at 1st minimum in 2nd derivative (MPa)		
Extension at 1st minimum in 2nd derivative (mm)		
Area under the curve to 1st minimum in 2nd derivative (N mm) - integration		
Row of 1st maximum in 2nd derivative curve		31
Load at 1st maximum in 2nd derivative (N)		
Strength at 1st maximum in 2nd derivative (MPa)		
Extension at 1st maximum in 2nd derivative (mm)		
Area under the curve to 1st maximum in 2nd derivative (N mm) - integration		
Row of Max Load		994
Max Load (N)		**1444**
Max Strength (MPa)		**4.48**
Extension at Max Load (mm)		**1.4387**
Area under the curve to max load (N mm) - Riemann Sums		**1011**
Extension at complete failure (mm)		**1.6746**
Total area under the curve (N mm) - Riemann Sums		**1096**

Single-lap-joint "Maximum Strength" represents only one of many easily measured experimental parameters

Experimental fabrication for the parametric study will be performed by GEMS students



3 adhesives

- Linear-elastic fracture mechanics to cohesive zone model

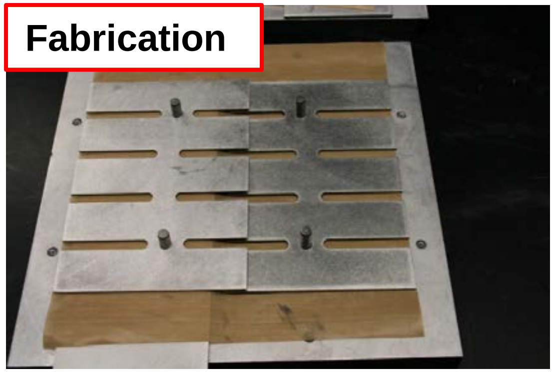
Joint parameters

- Coupon thickness
- Bond thickness
- Surface preparation
- With and without overflow fillet

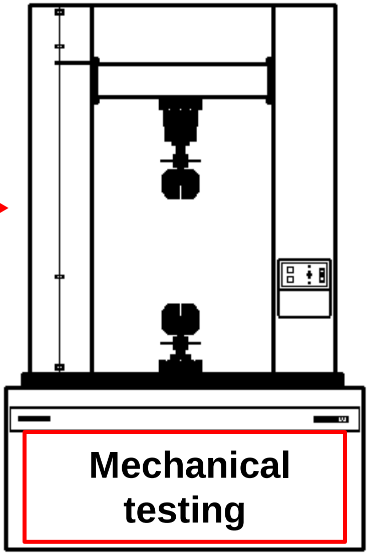
48 GEMS students x 5 samples per tool x 4 weeks = 960 joints fabricated

Experimental workflow is set-up to efficiently channel testing results to and from online database

Fabrication



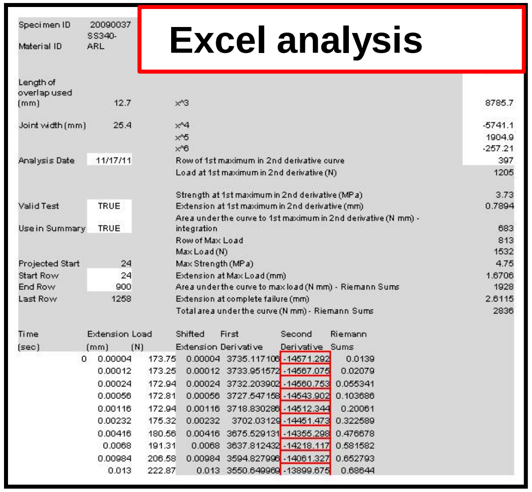
1 →



Mechanical testing

2 ↓

Excel analysis

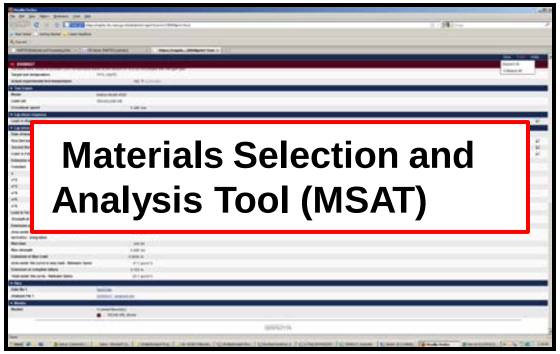


Specimen ID	20090037					
Material ID	SS340-ARL					
Length of overlap used (mm)	12.7	x^3				8785.7
Joint width (mm)	25.4	x^4				-5741.1
		x^5				1904.9
		x^6				-257.21
Analysis Date	11/17/11	Row of 1st maximum in 2nd derivative curve				397
		Load at 1st maximum in 2nd derivative (N)				1205
		Strength at 1st maximum in 2nd derivative (MPa)				3.73
Valid Test	TRUE	Extension at 1st maximum in 2nd derivative (mm)				0.7894
Use in Summary	TRUE	Area under the curve to 1st maximum in 2nd derivative (N mm) - integration				683
		Row of Max Load				813
		Max Load (N)				1532
Projected Start	24	Max Strength (MPa)				4.75
Start Row	24	Extension at Max Load (mm)				1.6706
End Row	900	Area under the curve to max load (N mm) - Riemann Sums				1928
Last Row	1258	Extension at complete failure (mm)				2.6115
		Total area under the curve (N mm) - Riemann Sums				2836

Time (sec)	Extension (mm)	Load (N)	Shifted Extension	First Derivative	Second Derivative	Riemann Sums
0	0.00004	173.75	0.00004	3735.117106	-14571.292	0.0139
	0.00012	173.25	0.00012	3733.951572	-14567.075	0.02079
	0.00024	172.94	0.00024	3732.203902	-14560.753	0.055341
	0.00056	172.81	0.00056	3727.547158	-14543.902	0.103686
	0.00116	172.94	0.00116	3718.830286	-14512.344	0.20061
	0.00232	175.32	0.00232	3702.03129	-14451.473	0.322589
	0.00416	180.56	0.00416	3675.529131	-14355.298	0.476678
	0.0068	191.31	0.0068	3637.812432	-14218.117	0.581582
	0.00984	206.58	0.00984	3594.827996	-14061.327	0.652793
	0.013	222.87	0.013	3550.649969	-13899.675	0.68644

3 ↗ **4** ↙

NASA Marshall Space Flight Center



Materials Selection and Analysis Tool (MSAT)

← **5**

ARL Bayesian statistics
External academic studies

Questions???