



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

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Benjamin Henrie**

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Army Research Laboratory

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14. ABSTRACT Adhesive needs for Army ground vehicles are driven by high strength and high damage tolerance. These basic materials properties requirements do not coincide with traditional aerospace adhesive demands of high strength and high stiffness, which are derived from linear-elastic stress-strain behavior and very little energy absorption. High damage tolerance requires significant energy absorption and the accompanying nonlinear stress-strain response. Therefore, the simplified approach of defining adhesive bond strength as peak load per unit surface area to screen potential adhesives for ground vehicle use is inadequate. Any potential Army interest in defining adhesive property requirements must take the increased complexity of the nonlinear adhesive response into consideration, but without introducing an overburdensome calculation process into the standardization scheme. The single-lap-joint load-displacement behavior for promising ground vehicle adhesives could be captured using Marquardt's nonlinear least-squares regression, but the level of difficulty would be beyond the scope of a simple screening process. Therefore, in this research we propose to use a polynomial regression fit and subsequent first and second derivatives of the load-displacement curves to measure key loads and displacements consistently across a wide range of experimental single-lap-joint test results. The polynomial regression analysis is intentionally designed to perform under the constraints of a common spreadsheet program, thus eliminating the need for specialized software if this proposed analysis scheme yields robust and meaningful data insight for implementation into an Army-derived single-lap-joint adhesive standard.					
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SCREENING ADHESIVELY BONDED SINGLE-LAP-JOINT TESTING RESULTS USING NONLINEAR CALCULATION PARAMETERS

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Introduction

Adhesive needs for Army ground vehicles are driven by high strength and high damage tolerance. These basic materials properties requirements do not coincide with traditional aerospace demands of high strength and high stiffness, which are derived from linear-elastic stress-strain behavior and very little energy absorption. High damage tolerance requires significant energy absorption, which is often accompanied by nonlinear stress-strain response. Therefore, the simplified approach of defining adhesive bond strength as peak load per unit surface area to screen potential adhesives for ground vehicle use is inadequate. Any Army interest in potentially defining adhesive property requirements must take the increased complexity of the nonlinear adhesive response into consideration, but without introducing an over-burdensome calculation process into the standardization scheme. The single-lap-joint load-displacement behavior for promising ground vehicle adhesives could be captured using the Levenberg-Marquardt nonlinear least-squares regression algorithm [1,2], but the level of difficulty would be beyond the scope of a simple screening process without introducing the use of specialized computer software programs. Therefore, in this research it is proposed to use a polynomial regression fit and subsequent 1st and 2nd derivatives of the load-displacement curves to measure key loads and displacements consistently across a wide range of experimental single-lap-joint test results. The polynomial regression analysis is intentionally designed to perform under the constraints of a common spreadsheet program. Therefore, the need for specialized software may be eliminated if this proposed analysis scheme proves to yield robust and meaningful data insight for implementation into a potential Army-derived single-lap-joint adhesive standard.

Discussion

The single-lap-joint is a tremendously convenient geometry for screening adhesive performance. This joint geometry is relatively straightforward, both with respect to fabrication and testing. While the distribution of stress is non-uniform [3] and fundamental constitutive adhesive properties difficult to derive, the overwhelming experi-

mental simplicity, with respect to both fabrication and testing, heavily favors the single-lap-joint geometry. Likewise, this joint geometry has also been studied extensively by academia, which provides a robust library of testing and analysis results for comparison and understanding. [4]

Standardized calculations [5] of the maximum lap shear strength (LSS) are performed by dividing the maximum failure load (P_{max}) by the surface area of the adhesive bond (A), as shown in the following equation.

$$LSS = \frac{P_{max}}{A}$$

This simplified first-screening analysis approach is perfectly acceptable for adhesives with reasonably linear-elastic load versus displacement response, as shown in Figure 1 for an epoxy adhesive.

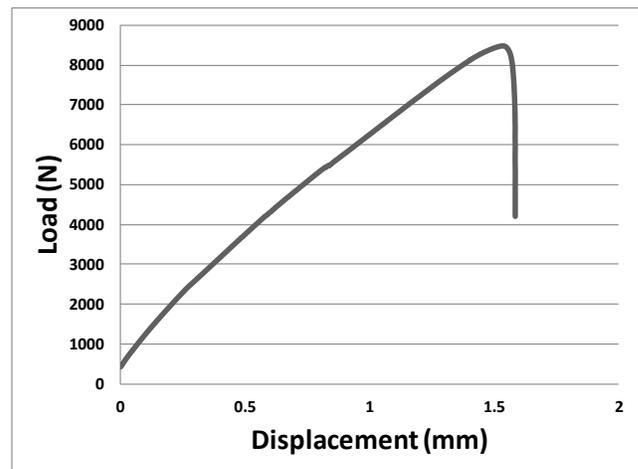


Figure 1. Typical load versus displacement response for a single-lap-joint bonded with an epoxy adhesive.

However, the typical load versus displacement response for single-lap-joints bonded with damage-tolerant adhesives, such the polyurea adhesive plotted in Figure 2, is much more complex.

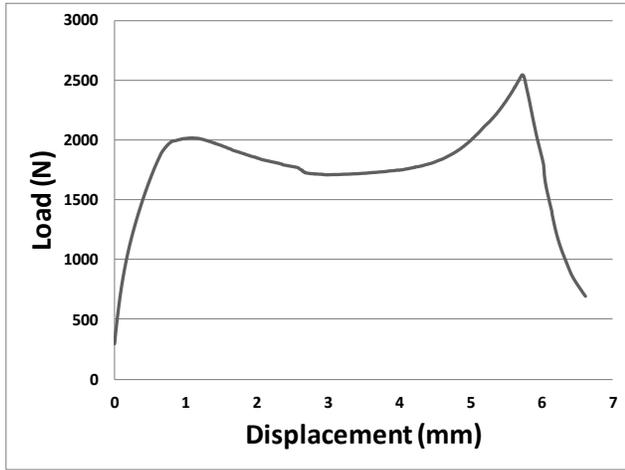


Figure 2. Typical load versus displacement response for a single-lap-joint bonded with a polyurea adhesive.

Complex x-y plots are commonly fitted using the Levenberg-Marquardt algorithm (LMA), as described in the following equation.

$$S(\beta) = \sum_{i=1}^m [y_i - f(x_i, \beta)]^2$$

The LMA is an iterative method that relies upon an initial guess for the parameter vector (β). The LMA is reported as a standard fitting routine built into Mathematica, MATLAB, and Origin. [6,7,8,9]

Despite the widespread acceptance and availability of the commercial software needed to perform the LMA, it remains desirable to further simplify the analysis of complex load versus displacement curves using an even more commonplace computer program. Excel [10] is universally familiar at the most basic levels of mathematical analysis but would be burdensome for manually programming the LMA. However, building an Excel analysis protocol is attainable using an adaptation of Christensen's assumption that yield can be defined as follows. [11]

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

Christensen's definition of yield stress is easily solved from basic polynomial fits of load versus displacement plots in Excel. Additionally, the resolution of the raw data typically exported from single-lap-joint testing is fine enough to allow for simple Riemann sum (S) calculations for area under the curve.

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

These simplifying assumptions for yield and area under the curve were used to program an Excel-based spreadsheet for single-lap-joint analysis. The results for the load versus displacement plots shown in figures 1 and 2 are shown in the Table 1. The results indicate the expected

decrease in maximum strength for the polyurea in comparison to the epoxy, which could have been obtained using a traditional analysis approach. However, the more extensive derivative and area-based analysis shows increased area under the curve and extension at failure for the polyurea, which could be related to its observed higher damage tolerance.

Table 1. Single-lap-joint curve fitting parameter comparison between an epoxy and polyurea adhesive.

Parameter	Epoxy	Polyurea
constant	364.05	369.14
X	10670	4181.7
X ²	-21573	-3623.1
X ³	50785	1184.3
X ⁴	-63610	-50.687
X ⁵	38444	-44.615
X ⁶	-8848.3	5.8765
Load at 1st maximum in 2nd derivative (N)	3028	1874
Strength at 1st maximum in 2nd derivative (MPa)	9.387	5.808
Extension at 1st maximum in 2nd derivative (mm)	0.3768	1.892
Area under the curve to 1st maximum in 2nd derivative (N mm)	686.2	3284
Max Load (N)	8474	2548
Max Strength (MPa)	26.27	7.900
Extension at Max Load (mm)	1.537	5.726
Area under the curve to max load (N mm)	7648	10460
Extension at complete failure (mm)	1.586	6.615
Total area under the curve (N mm)	8033	11750

The spreadsheet was also made compatible for direct input into the U.S. Army Research Laboratory's (ARL's) Materials Selection and Analysis Tool (MSAT) database by leveraging the platform support from NASA. Adjusting the spreadsheet protocol for compatibility with the baseline GRANTA MITM [12] MSAT software package also had the benefit of significantly decreasing the manual operator time required for analysis to less than 5 minutes per sample. The rapid analysis protocol will be coupled with the increasing population of adhesive samples in ARL's MSAT database to allow for data mining of relevant properties that are desirable for Army applications.

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