shear method had some issues but was the most convenient device, triaxial compression tests were accurate but sample preparation was considerably longer, and ring shear could not shear the sample slow enough, among other issues. Ultimately, the direct shear device was the favorable method, as its ease of use and availability outweighed the benefits of a triaxial compression test (Castellanos, 2014).

5. ANALYSIS AND STRENGTH SELECTION

5.1.Curved Failure Envelope

The development of the strength envelope can proceed after completion of laboratory testing. The results should be plotted on a normal stress to shear stress plot. An example of a test of a single sample of EFCS is shown in Figure 17, and will be used throughout the rest of this section to illustrate the development of a curved failure envelope. This sample was tested with the Stephens & Branch method of DS-FSS.

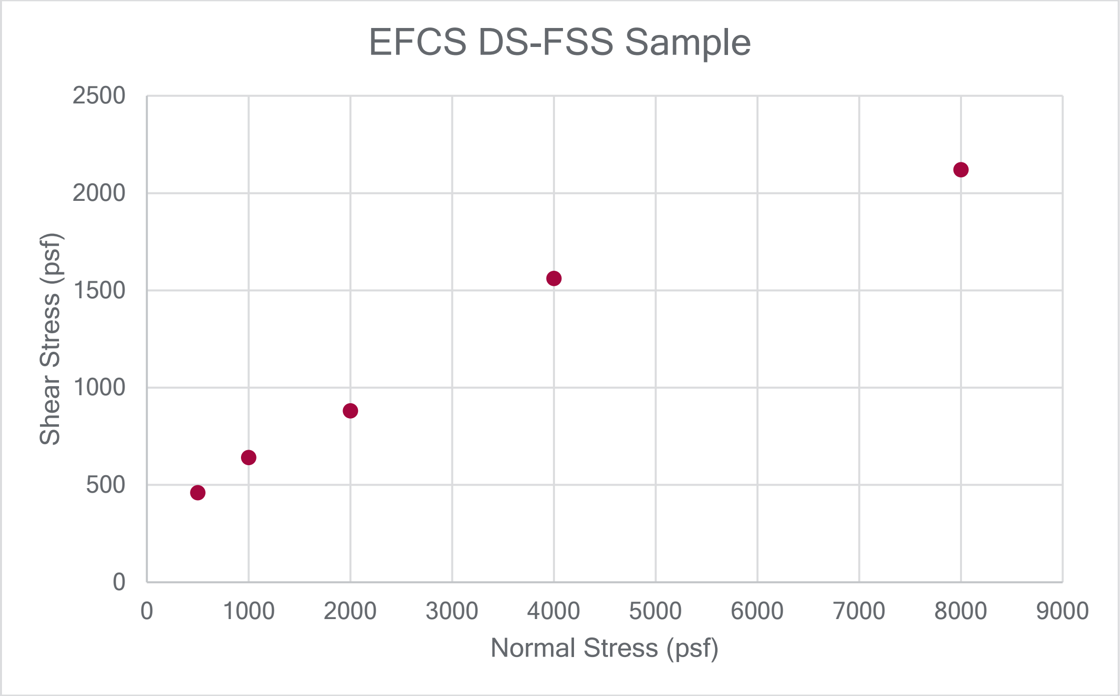

Figure 17 EFCS sample DS-FSS test

As stated in Section 2, the FSS strength envelope is curved, with no cohesion and terminating at the origin. Lade 2010 explores this, and produced an expression that models the curved failure envelope:

$$\tau = a * p_a * \left(\frac{\sigma_n}{p_a}\right)^b$$

Equation 2 Power function for curved strength envelopes

where *a* and *b* are unitless constants, p_a is the atmospheric pressure, and σ_n’ is the normal stress.

The constants *a* and *b* can be obtained graphically by plotting the normal and shear stresses normalized to atmospheric pressure plotted on a log-log scale; *a* is the shear stress value at which the normalized normal stress is equal to one, and *b* is the geometric slope of the line. This is presented graphically in Figure 18.

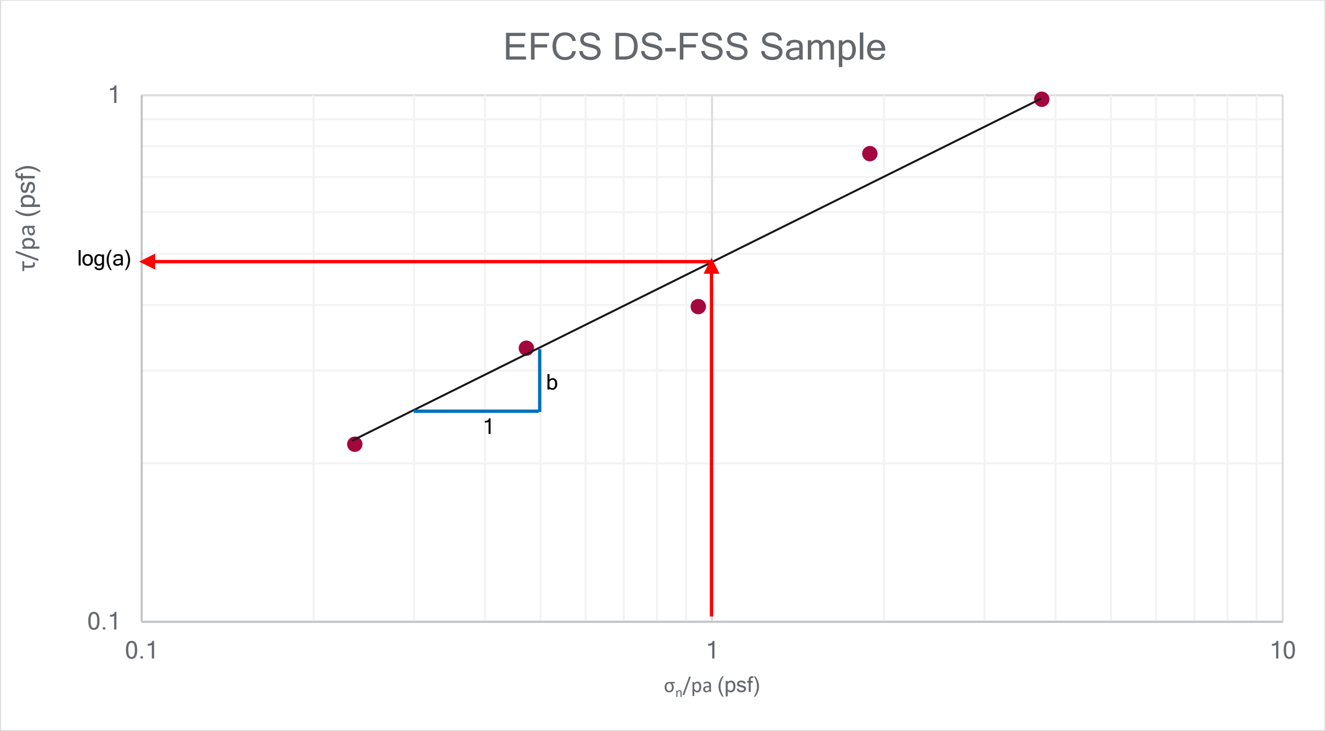

Figure 18 Normalized Shear Stress Plot

In the example above, a is ≈ 0.48, and b ≈ 0.55, and p_a is 2116.22psf giving the formula for shear stress as:

$$\tau = 1015.79\, psf * \left(\frac{\sigma'}{2116.22\, psf}\right)^{0.55}$$

This curve, plotted with the original data points on a standard plot, is shown in Figure 19; this includes a linear envelope developed through standard techniques to illustrate the differences in shear stress, especially at lower normal stresses. There is a 45% reduction in strength at a normal stress of 250 psf, and a 9% increase at 4000 psf normal stress.

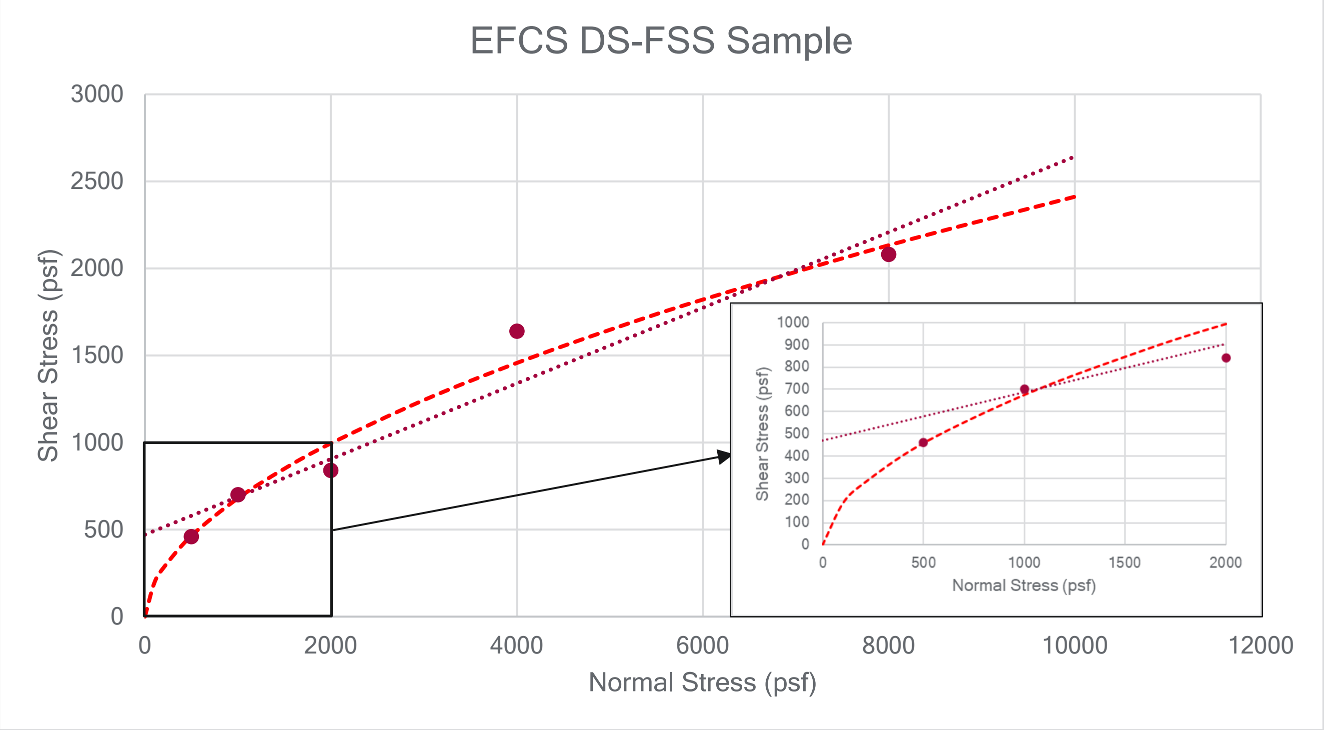

Figure 19 Curved failure envelope

This method is simple enough to perform with the aid of computer calculations; the spreadsheet software Microsoft Excel has functions that can be used to determine the curved strength envelope. Applying an power trendline to a normal stress to shear stress plot will produce the curve, and can provide the formula to the curve. The advantage of this method is the curve and formula can be developed without utilizing the stress normalized to atmospheric, as shown in Figure 20. The power trendline can be verified numerically by using built in Excel formulas without the need to for plotting; Appendix C has a guide on performing these calculations in Excel. When comparing the Lade method of calculating shear strength with the Excel method, the values have a maximum difference of 5% at 20 psf, and a minimum difference of 0% at 2000psf, illustrated in Figure 21. This error comes from graphically determining the values for coefficients *a* and *b*, and the precision of the Excel software. Using Excel, *a* and *b* from Lade's formulation are 0.4798 and 0.5582 respectively compared to 0.48 and 0.55 graphically. The formula produced in Excel is in the form of:

$$y = a * \sigma_n^b$$

Equation 3 Excel power function form

For the example used above, the formula is:

$$\tau = 14.137 * \sigma_n^{0.5582}$$

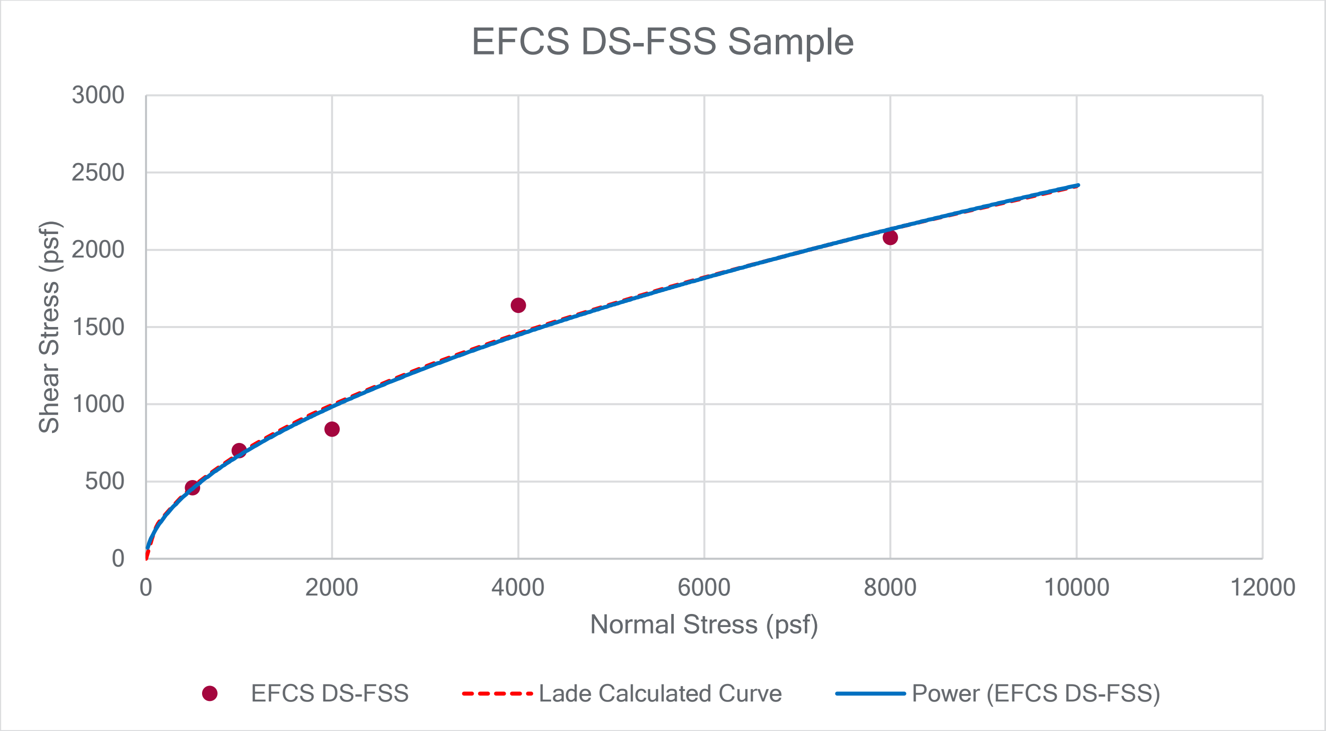

Figure 20 Comparison between Lade and Excel curves

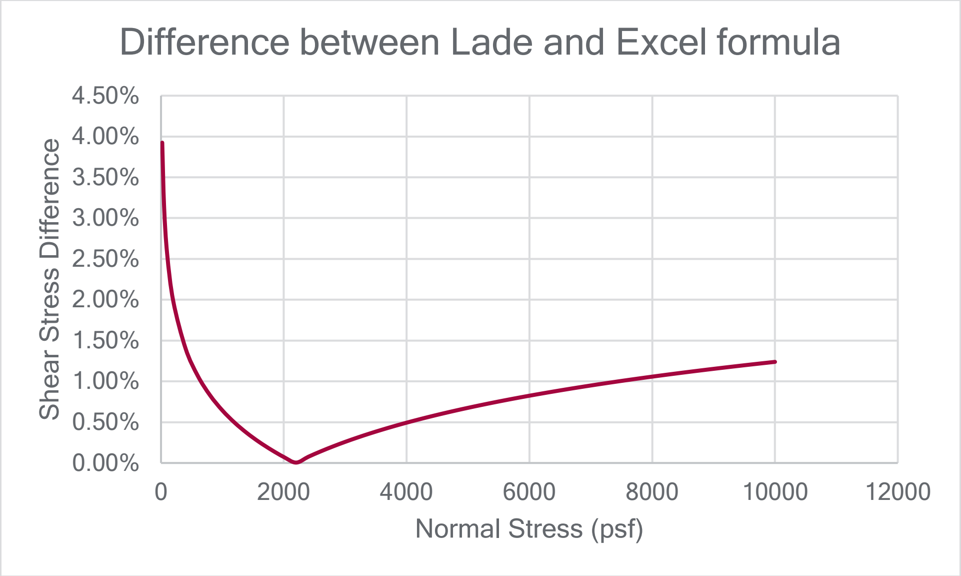

Figure 21 Difference between Lade and Excel formula

The curved failure envelope is the recommended method for use in slope stability software programs.

5.2. Secant Phi Angle Method

For other applications that require a single phi angle, such as a spreadsheet or program requirement, the secant phi angle method can be used. The secant phi angle method produces an equivalent Mohr-Coulomb phi angle for a given normal stress. It is the angle of the line between the origin and the shear stress for the normal load, as shown in Figure 22.

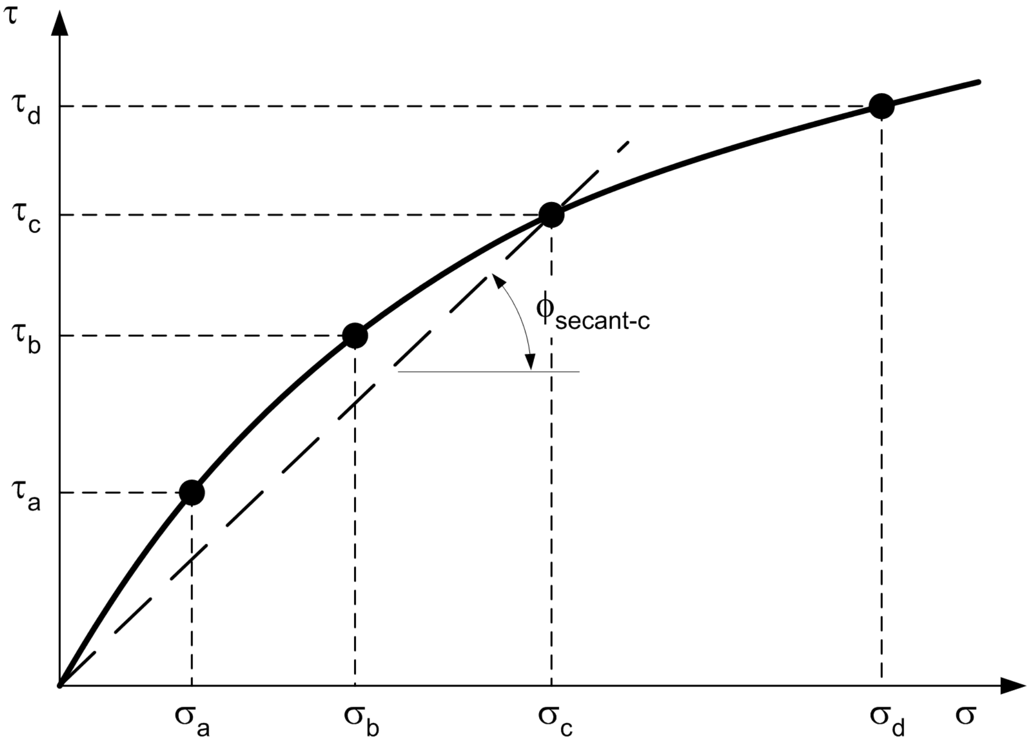

Figure 22 Secant phi angle (USACE, 2003)

The secant phi can be determined numerically in Equation 4. This formula is derived trigonometrically as the inverse tangent of the right triangle formed between the origin and the shear stress value.

$$\phi = \tan^{-1}\frac{a \cdot \sigma_n^b}{\sigma_n}$$

Equation 4 - Secant phi equation

This secant phi is only functional for a very narrow range of normal stresses near the normal stress used for calculation. Table 1 below shows a comparison of the shear stresses of the secant phi for 2000 psf when applied to other normal stresses. Figure 23 is a graph depiction of the different.

Table 1 - Comparison of Shear Strengths

Normal Stress	2000 psf Secant Phi (26.2°)	Shear Stress Calculation	Percent Difference
2000 psf	984 psf	984 psf	0%
500 psf	246 psf	453 psf	-46%
6000 psf	2952 psf	1816 psf	+63%

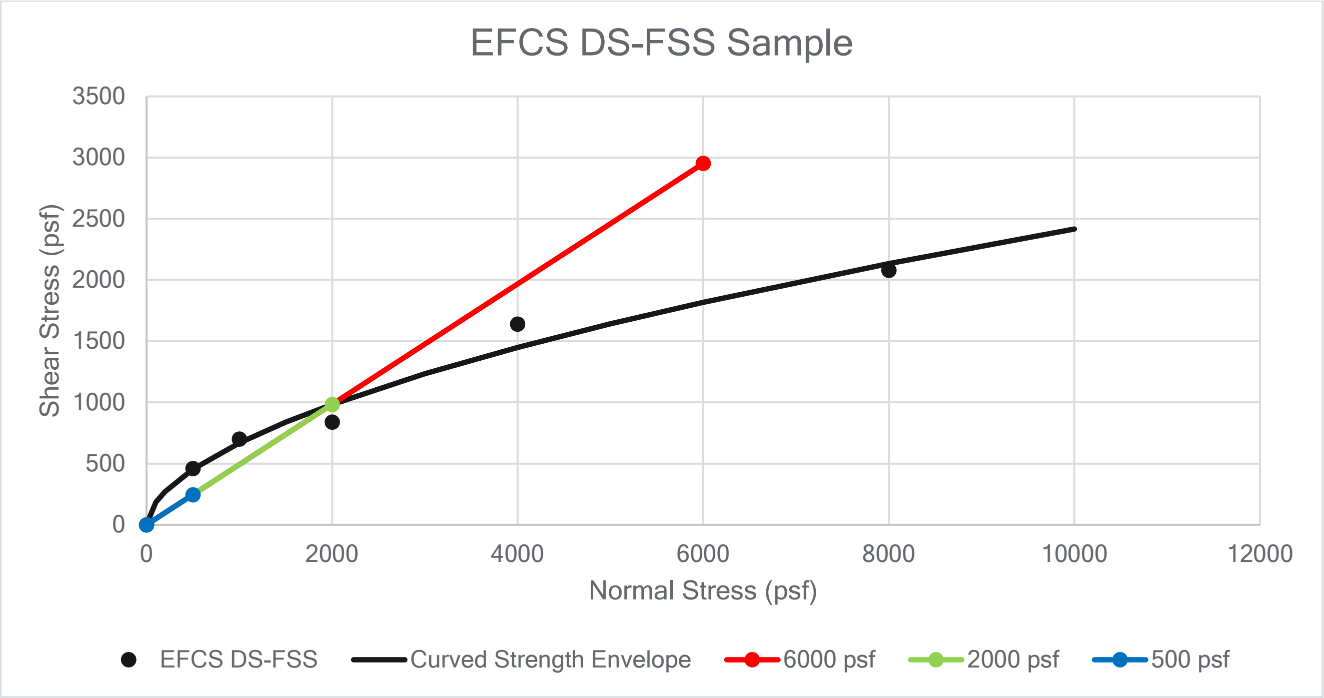

Figure 23 Secant Phi applied incorrectly with different normal stresses

6. APPLICATION TO SLOPE STABILITY AND EXAMPLES

6.1.Implementing FSS to Slope Stability

As stated in the previous sections, the curved fully softened shear strength should be used as the long-term strength for soils susceptible to fully softening soils. Three slope stability examples were calculated for the slope in Figure 24 using the method of ordinary slices: one using an equivalent curved fully softened envelope with a secant phi calculated for each slice, one using a linear fully softened envelope, and one using a standard consolidated drained strength. The secant phi method required calculating the normal stress acting on the failure surface for each slice, then calculating the shear stress for that slice using Equation 4. All analyses used the failure envelope are utilized in the examples in Section 5. The calculations are located in Appendix A.

Strength Type	Factor of Safety
Fully Softened Secant Phi Method	1.141
Fully Softened Linear	1.154
Consolidated Drained Linear	1.54

The results show that not applying the fully softened shear strength gives an incorrectly high factor of safety. Under United States Army Corps of Engineers (USACE) Engineer Manual 1110-2-1902, the required long-term factory of safety for new earth and rock fill dams is 1.5. Applying the consolidated drained strength will give the example slope an incorrect acceptable factor of safety.