Appendix U - Coal Properties Input

Agapito Associates Inc. (AAI) assigned calculated coal properties using a "method of slices" approach to approximate the load bearing capacity of pillars in LaModel. The method assumes that the strength of a pillar element is a function of its distance from the nearest rib. AAI modeled the Crandall Canyon Mine workings using 5-foot elements. As illustrated in Table 15, eight sets of peak and residual strength values were calculated to correspond to depths up to 37.5 feet from a pillar rib. These parameters were determined using the following relationships:

$$\sigma_v = S_i[0.71 + 1.74(\frac{x}{h})] \qquad \text{(Equation 1)}$$

where σ_v = Confined coal strength
$\quad$ S_i = In situ coal unconfined strength
$\quad$ x = Distance from the nearest rib
$\quad$ h = Pillar height

$$\varepsilon_v = \sigma_v / E \qquad \text{(Equation 2)}$$

where ε_v = Peak strain
$\quad$ σ_v = Confined coal strength
$\quad$ E = Coal elastic modulus

$$\sigma_r = 0.2254 \times \ln(x) \times \sigma_v \qquad \text{(Equation 3)}$$

where σ_r = Residual stress
$\quad$ x = Distance from the nearest rib, and
$\quad$ σ_v = Confined coal strength

$$\varepsilon_r = 4 \times \varepsilon_v \qquad \text{(Equation 4)}$$

where ε_r = Residual strain
$\quad$ ε_v = Peak strain.

Table 15 - LaModel Confined Coal Strength

Confined Coal Distance into Rib (ft)	Confined Strength (psi)	Peak Strain	Residual Strength (psi)	Residual Strain
2.5	2,059	0.004	425	0.017
7.5	3,845	0.008	1,746	0.032
12.5	5,631	0.012	3,206	0.047
17.5	7,417	0.016	4,785	0.062
22.5	9,203	0.019	6,459	0.077
27.5	10,989	0.023	8,209	0.092
32.5	12,775	0.027	10,025	0.107
37.5	14,562	0.031	11,896	0.122

These relationships are very similar to those that Karabin and Evanto[14] proposed to be used as a first approximation of stress and strain values for a strain softening coal model. AAI used a constant of 0.71 in the confined coal strength formula whereas Karabin and Evanto used 0.78. Also, Karabin and Evanto used two points to define the post-peak slope of the stress-strain curve whereas AAI used only one. As illustrated in Figure 114, the slope of the post-peak curve that

AAI used departs somewhat from that proposed by Karabin and Evanto. However, this approach is reasonable given the assumptions inherent in using strain softening properties. Karabin and Evanto acknowledged that information was lacking at the time that they wrote their paper:

> *"The strain-softening approach has been identified as a reasonable method of describing coal seam behavior. While that concept has been widely discussed, little specific information is available concerning the actual construction of a strain-softening model."*

Unfortunately, little research has been done to improve our understanding of strain-softening behavior in coal since this was written.
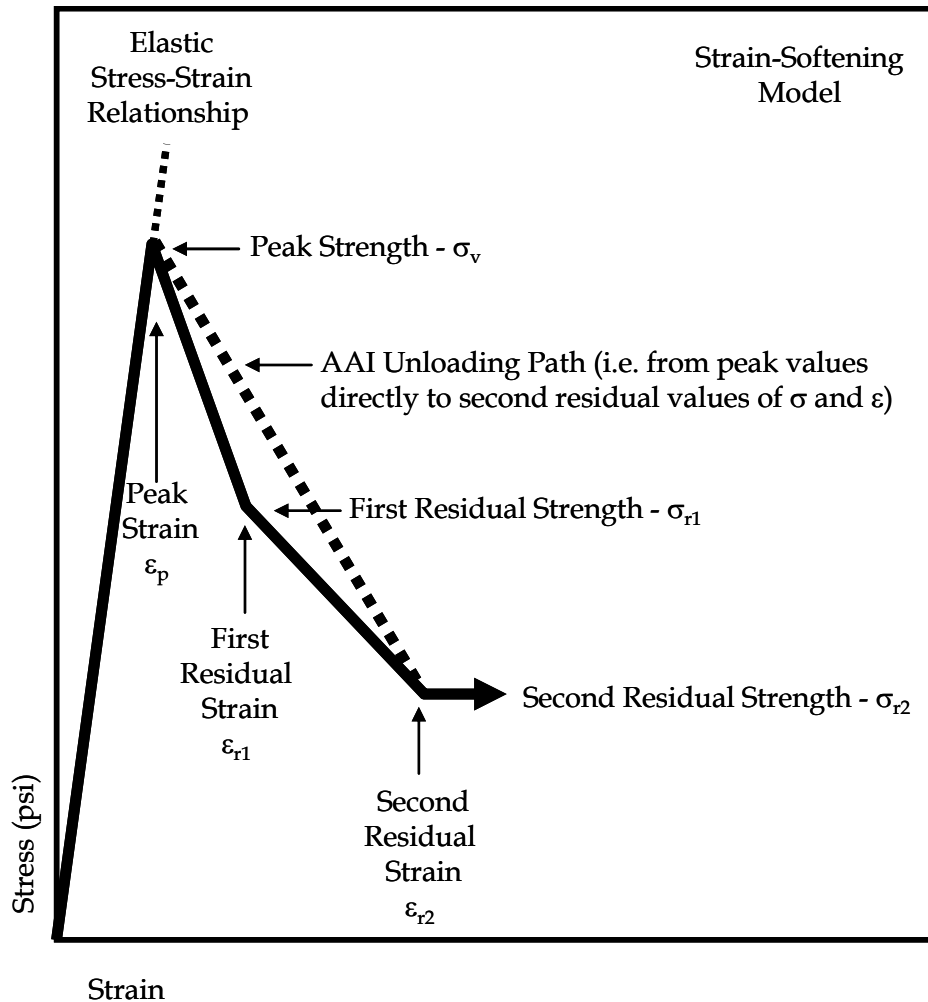

Figure 114 - General Strain-Softening Element Characteristics

Traditionally, strain softening properties have been deployed in a displacement-discontinuity pillar model as a series of concentric rings with the weakest material on the perimeter and progressively stronger materials approaching the center (see Figure 115)[14]. In reality, pillar corners experience less confinement and, therefore, have lower peak strengths. However, this simplification (i.e., not considering corner effects) has proven to be generally acceptable. At least one BEM program, BESOL, assigned yielding properties in this manner when the user elected to use the program's "automatic yield allocation" feature.
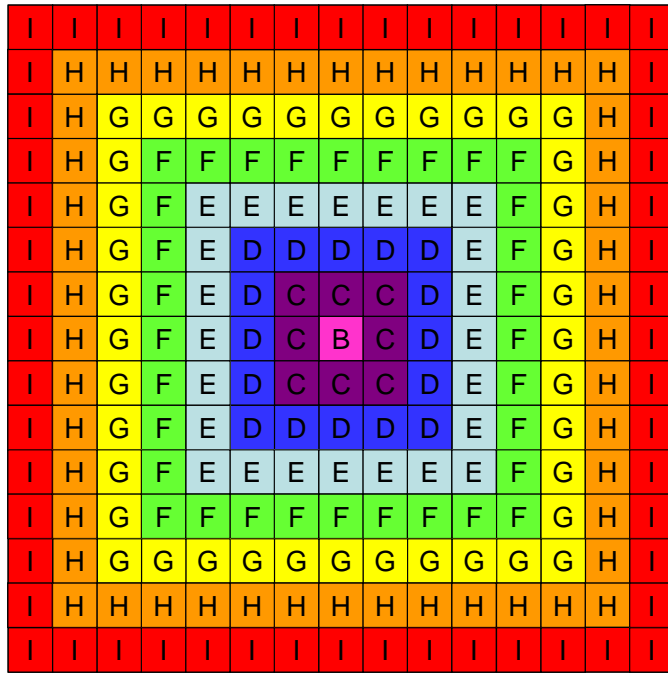
Figure 115 - Traditional Strain-Softening Element Distribution

The LaModel preprocessor, LamPre, has an automatic yield property allocation feature. However, the "apply yield zone" utility in LaModel distributes properties in the manner illustrated in Figure 116. This distribution provides a separate element designation (i.e., letter code) for corners so that modeled pillar strengths can be more consistent with empirically derived pillar strength formulas and the assumed stress gradient.

LaModel provides up to 26 different material property inputs. These properties can be deployed <u>manually</u> in any manner deemed appropriate by the user. However, LamPre's automatic yielding property allocation utility limits the depth of yielding to 4 elements. Although the utility utilizes nine material properties, the depth of the yield zone is still limited to four elements deep. One of the nine codes represents linear elastic behavior, four represent yielding ribs, and four are slightly lower strength yielding elements used to more accurately represent reduced corner confinement.

Models constructed by AAI utilized eight strain-softening material properties (as shown in Table 1 of AAI's July 2006 report). These properties are consistent with equations 2 through 5 using in situ coal strength (S_i) of 1640 psi and element depths (from the ribline) from 2.5 to 37.5 feet. However, the properties actually were deployed in AAI's models as illustrated in Figure 116. One result of this element configuration is to limit the maximum depth of pillar yielding to 20 feet when 5-foot elements are used. Another is to substantially increase the modeled pillar strength beyond the value that traditional pillar strength formulae (such as those used to determine Equation 2) would predict.
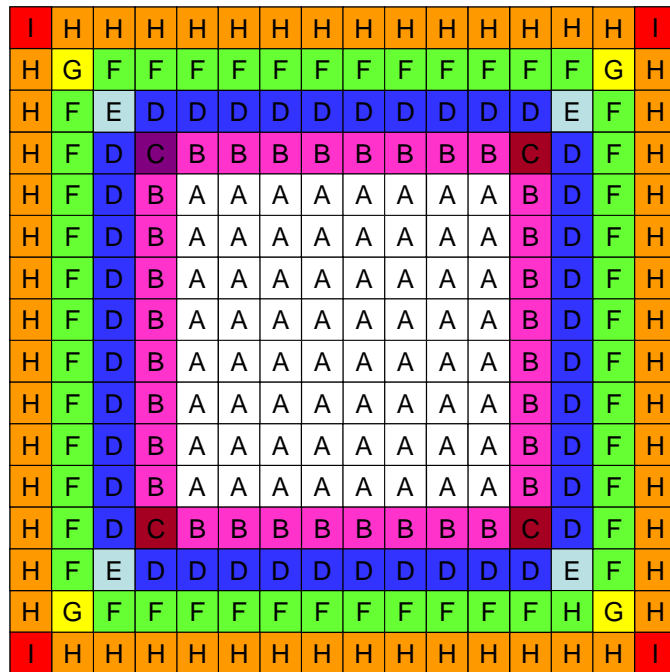
Figure 116 - Strain-Softening Element Distribution to Account for Corner Effects (as Deployed by AAI)

If eight elements ("B" through "I") are assigned yielding (e.g., strain-softening properties), as distributed and shown in Figure 115, any pillar 16 elements wide or less would be comprised of "yieldable" elements. If 5-foot wide elements are employed, pillars up to 80 feet would be capable of yielding and transferring load to adjacent pillars once the peak strengths of the elements within the pillar were exceeded. In contrast, the same properties distributed as shown in Figure 116 will provide full yielding only for pillars up to 8 elements wide, which is 40 feet in width (8 elements x 5 feet/element). The group of elements labeled "A" in Figure 116 corresponds to linear elastic elements that have no peak strength and cannot transfer load to adjacent structures. In effect, any pillar over 40 feet in width will be represented in the model with a linearly elastic core that will not fail.