8. Excavation design in stratified rock

8.1 Design factors

- Principal engineering properties of bedding planes
  - Low or zero tensile strength in direction perpendicular to the plane
  - Low shear strength of surface
- Features of excavations in a stratified rock mass
  - Immediate roof and floor of the excavation coincide with bedding planes.
- Factors to be considered in the design of excavation in a stratified rock mass

(a) State of stress compared with the strength of the anisotropic rock mass

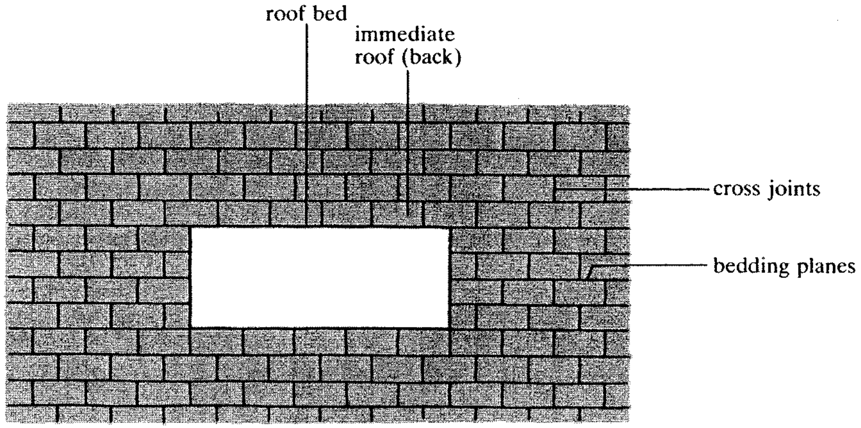
- Surface spalling and internal fractures

(b) Stability of the immediate roof

- Detachment/deflection into the void

(c) Floor heave in the excavation

- Weak rock under the excavation



8.2 Rock mass response to mining

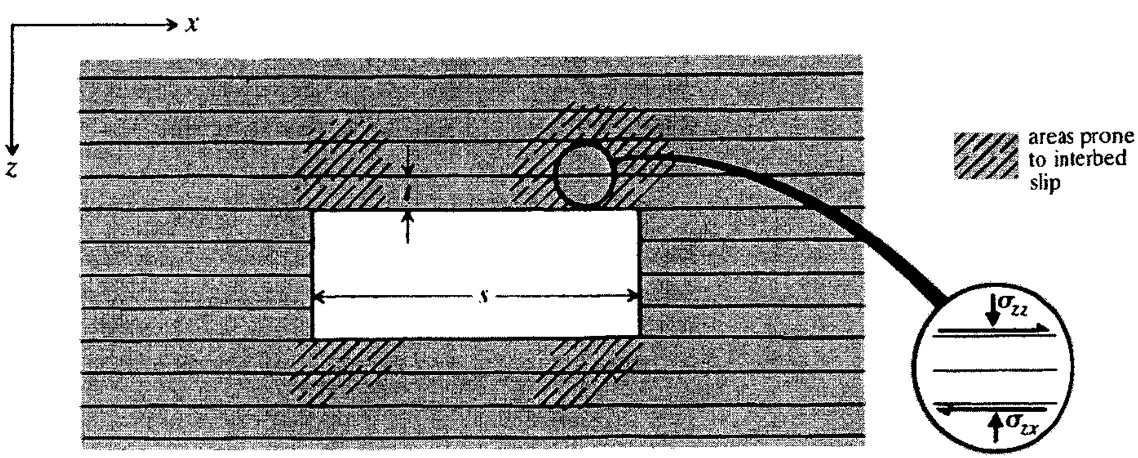
- Design process

1) Determining the elastic stress distribution around the excavation in plan

2) Define the zones of tensile/compressive stress exceeding the rock mass strength and a zone of slip on bedding planes.

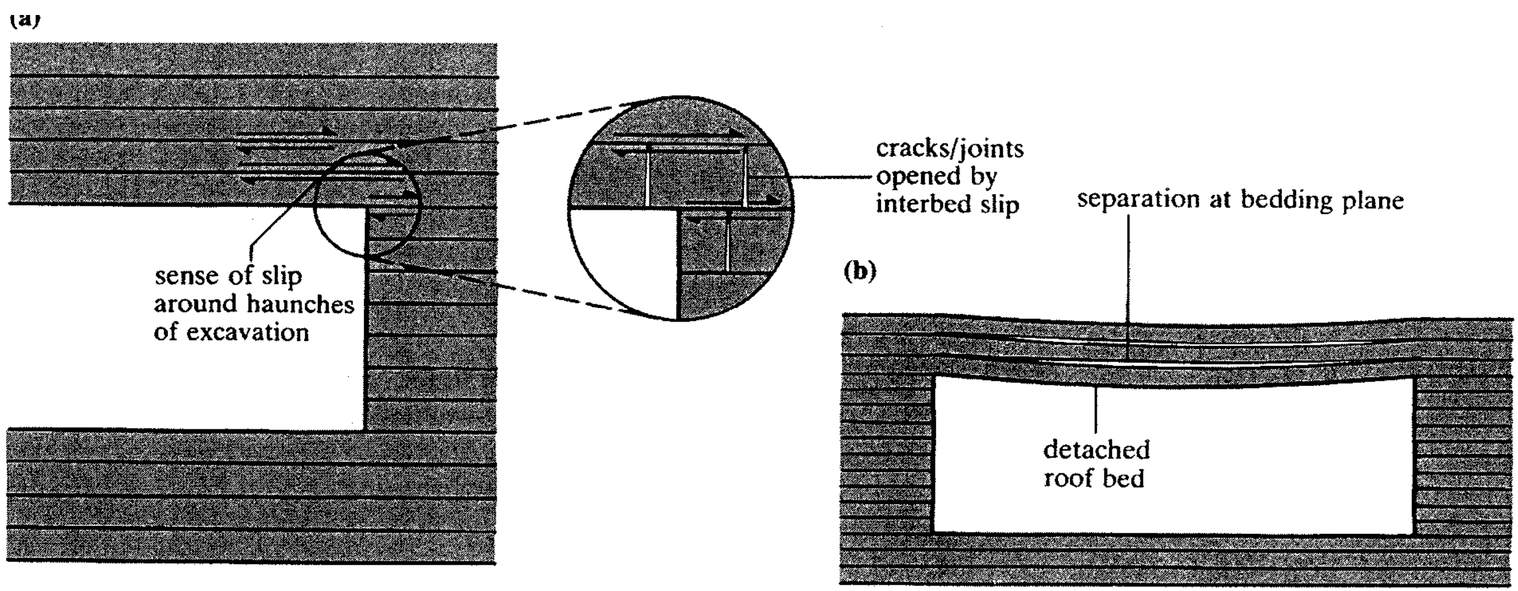
3) Excavation shape is modified or support/reinforcement zone is defined.

$$|\sigma_{zx}| = \sigma_{zz} \tan\phi + c$$



8.2 Rock mass response to mining

- General rules of potential slip on bedding planes
  - Low span/bed thickness (s/t): slip occurs only in the haunch area with opening of cracks subperpendicular to bedding
  - High span/bed thickness (s/t): slip occurs throughout the whole span of immediate roof, and downward deflection /separation occur at the roof center

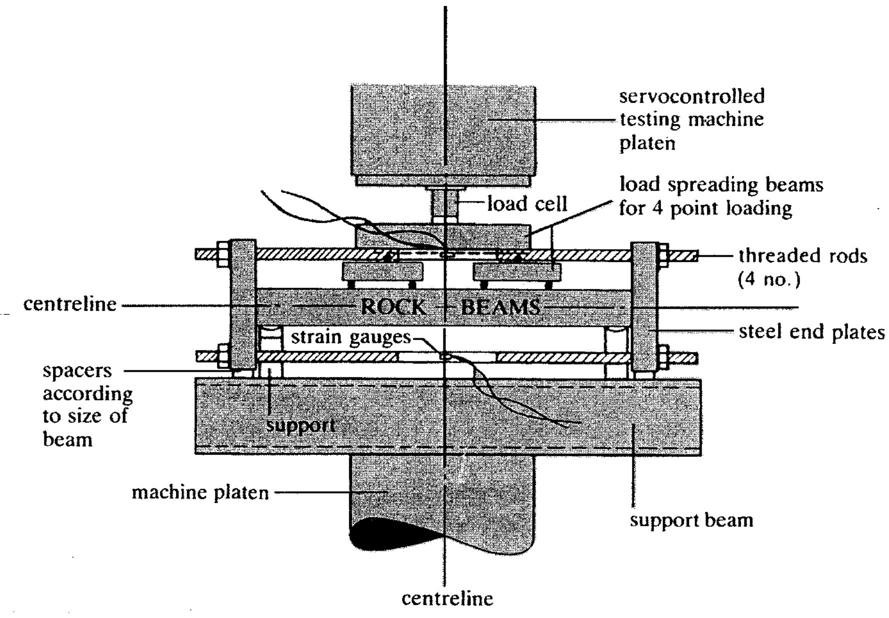


8.3 Roof bed deformation mechanics

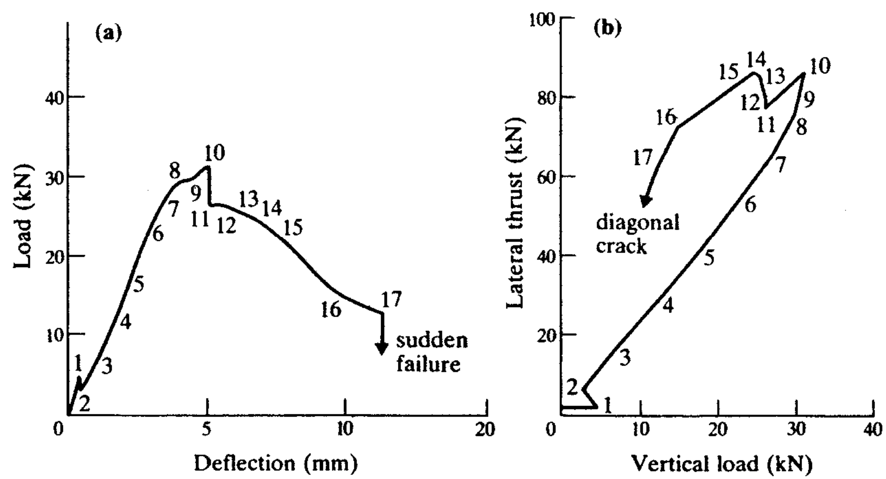
- History

- Fayol (1885): rock arching is formed in beams and load of the uppermost beam is transferred laterally.
- Jones & Llewellyn-Davies (1929): mapped the morphology of roof failure.
- Bucky & Taborelli (1938): a vertical tension fracture is induced at the center of the lower beam of a particular span.
- Evans (1941): recognizing the relation between vertical deflection, lateral thrust and stability of fractured roof bed, developed an analytical procedure for assessing roof beam stability.
- Sterling (1980): studied beam deflection, induced lateral thrust and eccentricity of the lateral thrust.

8.3 Roof bed deformation mechanics

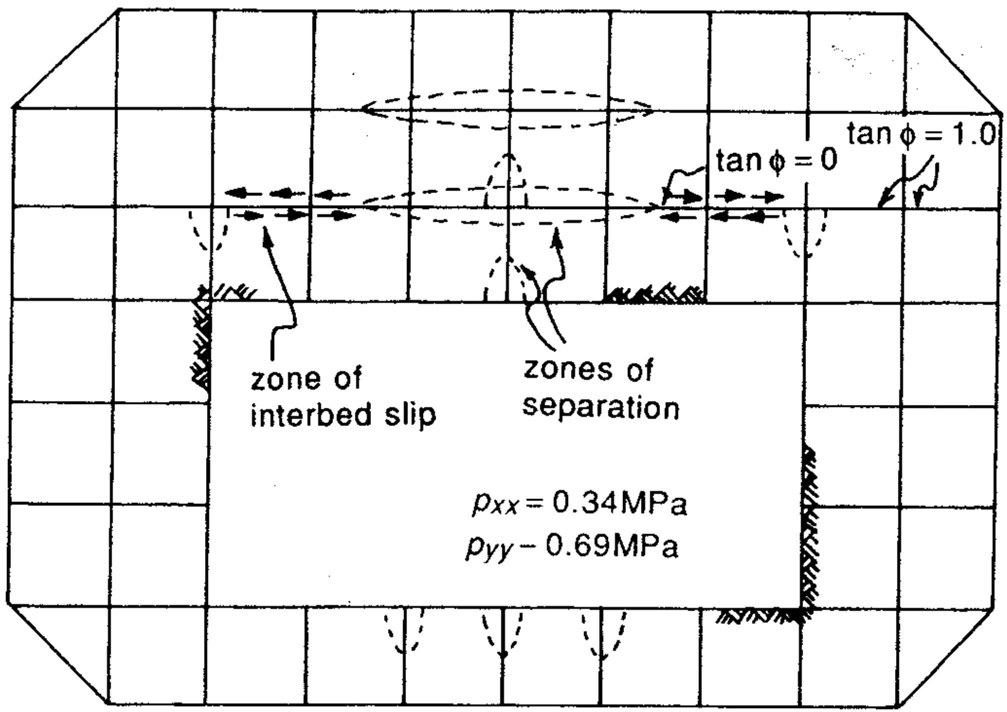


0~1: initial elastic range
2: central crack developed
2~7: (reversible) linear load-deflection
7~10: non-linear response with crushing at either top center or lower edge
10~17: spalling at upper center or lower ends



8.3 Roof bed deformation mechanics

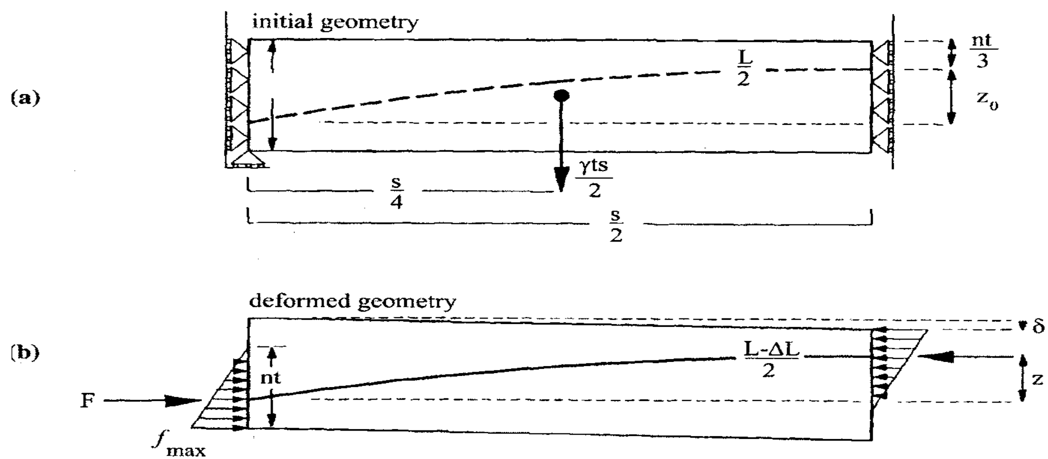
- Lorig & Brady (1983): adopted a linked BE-DE scheme to analyze roof deformation mechanics. Bed separation over only the center of the span is major difference from Evans model (1941).



8.4 Roof design procedure for plane strain

- Voussoir beam model (Diederichs and Kaiser)

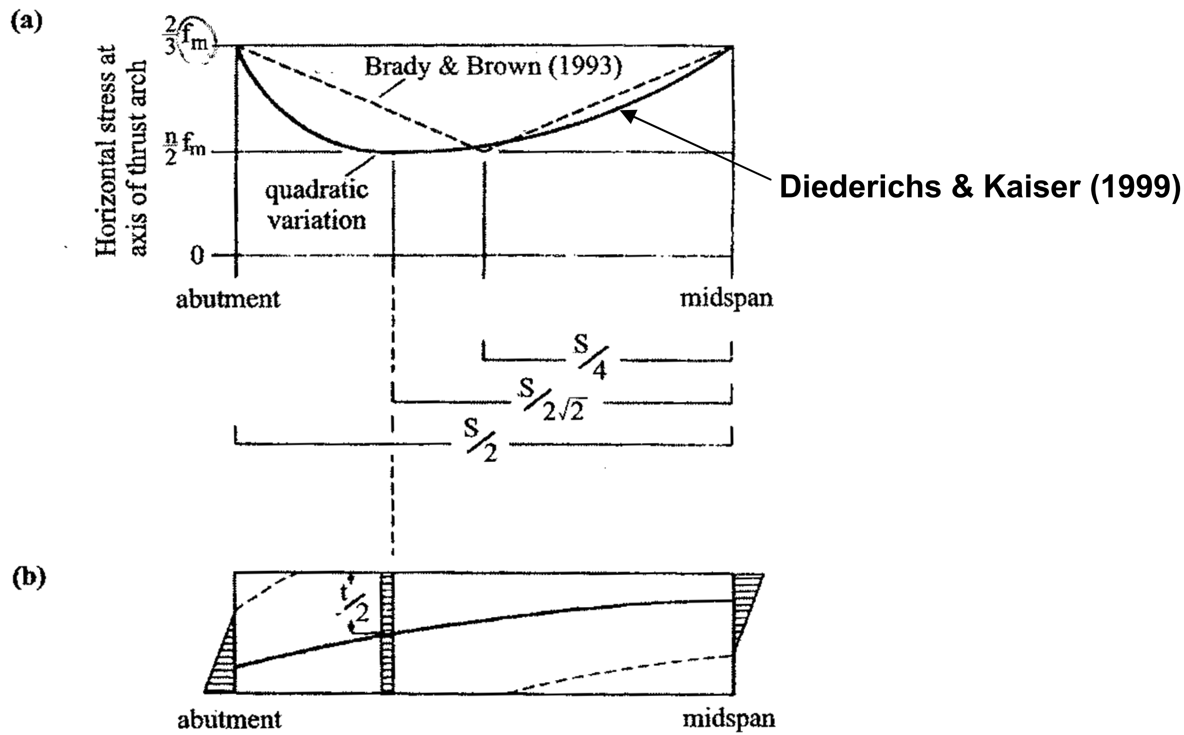
- Indeterminate problem: requires assumptions on unknown properties
- Assumptions: triangular load distribution, line of thrust tracing parabolic arch
- *s*: span, *t*: thickness, *h:* height of the load distribution, $n=h/t$
- z_0 , z : (initial) moment arm $z_0 = t - \frac{2}{3}h = t\left(1 - \frac{2}{3}n\right)$ $z = \sqrt{z_0^2 - \frac{3s}{8}\Delta L}$
- δ: deflection = $z_0 - z$



8.4 Roof design procedure for plane strain

- *L:* length of parabolic arch of the thrust line

$$L = s + \frac{8}{3}\frac{z_0^2}{s}, \quad \Delta L = L\frac{f_{av}}{E} \quad where \;\; f_{av} = \frac{f_c}{3}\left(\frac{2}{3} + n\right)$$



8.4 Roof design procedure for plane strain

- M_A: moment by beam weight, M_R: moment by lateral (thrust) stress

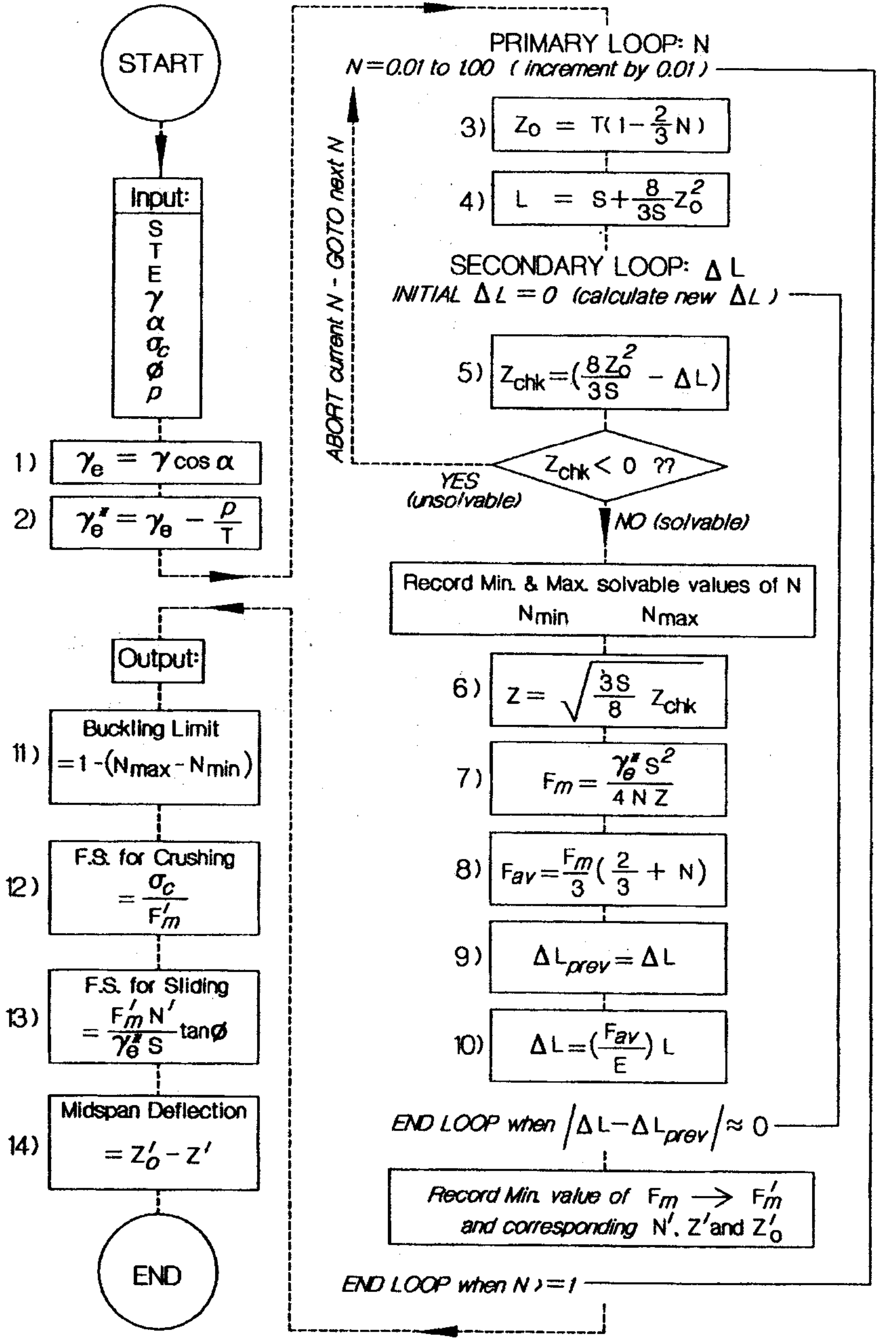
$$M_A = \frac{1}{8}\gamma t s^2, M_R = \frac{1}{2} f_c n t z$$

$$M_A = M_R \rightarrow f_c = \frac{\gamma s^2}{4nz}$$

- Determination of deflection and stability by numerical analysis

1) Find out solvable n among predefined values (0.01~1.0 by 0.01).
2) Calculate z, f_c (f_m) and ΔL (initially set 0).
3) Find out n (and corresponding z) making f_c minimum.
4) Calculate deflection and safety factors.

- n is known to be around 0.75 for stable beams at equilibrium and below 0.5 for critical (unstable) beam state.



START
Input:
S
T
E
γ
α
σc
ø
p
1) γe = γ cos α
2) γe* = γe − p/T
PRIMARY LOOP: N
N=0.01 to 1.00 (increment by 0.01)
3) Zo = T(1 − 2/3 N)
4) L = S + 8/3S Zo^2
SECONDARY LOOP: Δ L
INITIAL Δ L = 0 (calculate new Δ L)
5) Zchk = (8 Zo^2 / 3 S − Δ L)
Zchk < 0 ??
YES (unsolvable)
ABORT current N - GOTO next N
NO (solvable)
Record Min. & Max. solvable values of N
Nmin Nmax
6) Z = √(3S/8 Zchk)
7) Fm = γe* S^2 / 4 N Z
8) Fav = Fm/3 (2/3 + N)
9) Δ Lprev = Δ L
10) Δ L = (Fav/E) L
END LOOP when |Δ L − Δ Lprev| ≈ 0
Record Min. value of Fm → F′m
and corresponding N′, Z′ and Z′o
END LOOP when N >= 1
Output:
11) Buckling Limit = 1 − (Nmax − Nmin)
12) F.S. for Crushing = σc / F′m
13) F.S. for Sliding = F′m N′ / γe* S tanø
14) Midspan Deflection = Z′o − Z′
END

8.4 Roof design procedure for plane strain

- Safety factor against crushing at lower abutments and top midspan

$$S.F. = \frac{\sigma_c}{f_c}$$

- Safety factor against shear failure (slip) at abutments

$$\text{Capacity}: \quad T = \frac{1}{2} f_c nt \tan\phi \,, \quad \text{Demand:} \;\; V = \frac{1}{2}\gamma st$$

$$S.F. = \frac{Cacpacity}{Demand} = \frac{f_c n}{\gamma s} \tan\phi$$

- Threshold of midspan deflection δ

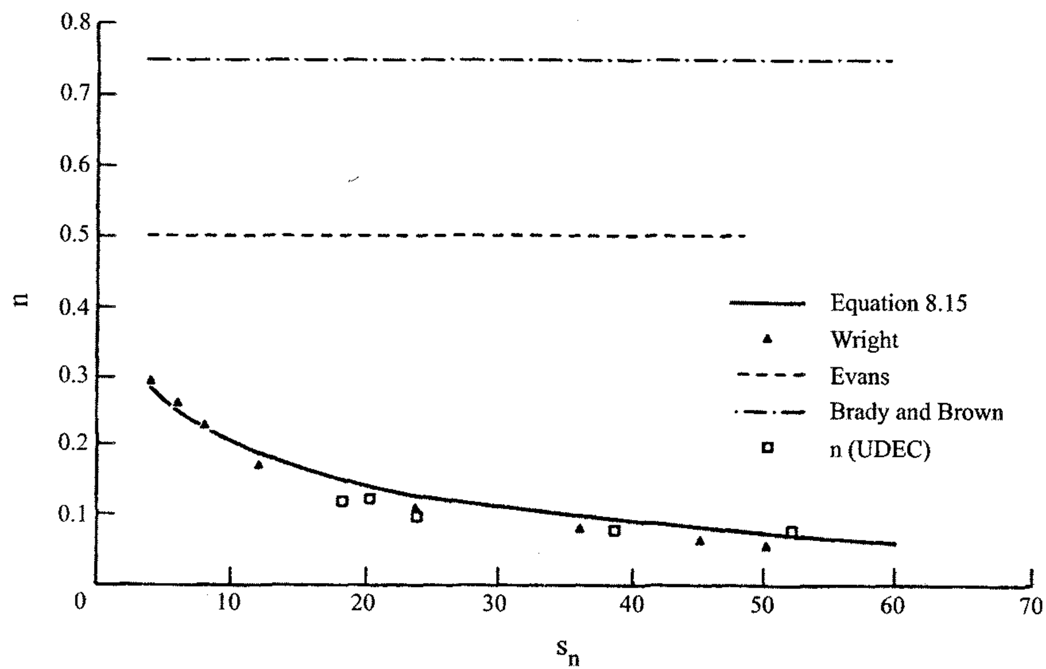
Onset of non-linear behavior: $\delta = 0.1t$ (allowable yield limit in roof design)

Ultimate failure: $\delta = 0.25t$

8.5 Roof beam analysis for large vertical deflection

- Load depth fraction, n

$$n = \frac{1}{0.22 s_n + 2.7}$$



8.5 Roof beam analysis for large vertical deflection

- Normalized deflection, $\delta_n\ (= \delta/z_0)$