5th Int'l CROW-Workshop

Parameter Studies on 3-D Finite Element Analysis of Rigid Pavements

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March 31~ April 03, 2004

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INTRODUCTION

- Determine critical structural responses
- Closed-form solutions ➔ 2-D FEM (ILLI-SLAB) ➔ 3-D FEM (ABAQUS)
- Previous work on alternative stress estimation procedures (TKUPAV program)
  - Dimensional analysis, modern regression techniques
  - Validated ILLI-SLAB's Applicability (Arlington Road Test, AASHO Road Test, and Taiwan's Second Northern Highway data) (Lee, 1999)

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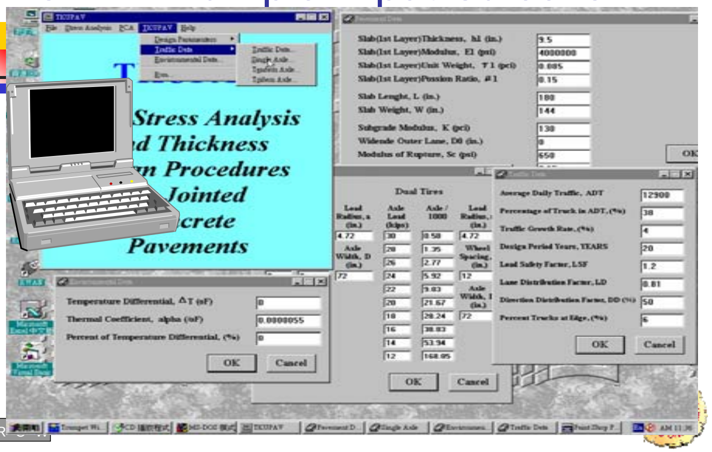
TKUPAV Example Input Screens



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(Lee, 1999)

OBJECTIVES

- Current problems in pavement analysis
  - Closed-form and 2-D analysis: inadequate
  - 3-D analysis: very complicated
  - Lack of explicit guidelines in 3-D mesh generation
  - Accuracy of the results: variable / questionable
- Parameter studies on 3-D FEM model building
  - Study stress & deflection convergence characteristics
  - Provide mesh generation & element selection guides
  - Develop an automatic procedure & predictive models for future design & evaluation
  - Bridge the gap among these solutions

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Comparisons of Various Solutions

- Theoretical solutions (edge loading)

$$\delta_{we} = \frac{\sqrt{2+1.2\mu}P}{\sqrt{Eh^3k}}\left[1-\frac{(0.76+0.4\mu)a}{\ell}\right]$$

$$\sigma_e = \frac{3(1+\nu)P}{\pi(3+\nu)h^2}\left[\ln(\frac{Eh^3}{100ka^4})+1.84-\frac{4\nu}{3}+\frac{1-\nu}{2}+\frac{1.18(1+2\nu)a}{\ell}\right]$$

- 2-D Model: simple, short analysis time, more assumptions, can model actual pavement well
- 3-D Model: more complicated, longer analysis time, not easy to model, can best model actual pavement structural response
- Scope: a single edge loaded slab (Winkler foundation)

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PARAMETER ANALYSIS AND MODEL BUILDING

- Definition of mesh generation
- Deflection / Stress convergence characteristics
  - 3-D shell elements (Horizontal mesh fineness)
  - 3-D solid elements (Horizontal and vertical mesh)
- Convergence characteristics due to different slab thicknesses and load sizes
  - Deflection convergence & Stress convergence
- Determine the length of finer mesh
- Recommendations on mesh fineness & element selection

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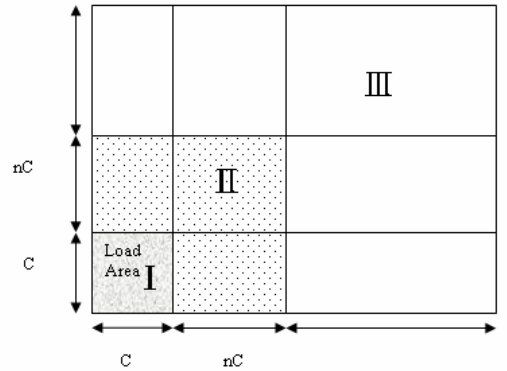
Definition of Mesh Generation



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Convergence Characteristics of Mesh Fineness Study

- Input Parameters / Dominating Parameters

L=197 in., W=197in.	a/ℓ=0.1
E=1,200,000psi, h=8.5in.	L/ℓ=7
k=100pci, P=2,250lbs	W/ℓ=7
C=5in., p=90psi, ν=0.15	h/a=3

- Mesh fineness: horizontal 1~10, vertical 1~4, Zone I = Zone II, Extended (8*C)
- Deflection ratios & stress ratios

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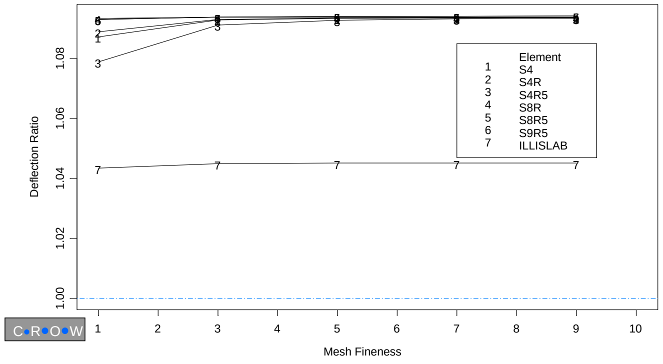
Edge Deflection Ratio (2-D Shell)



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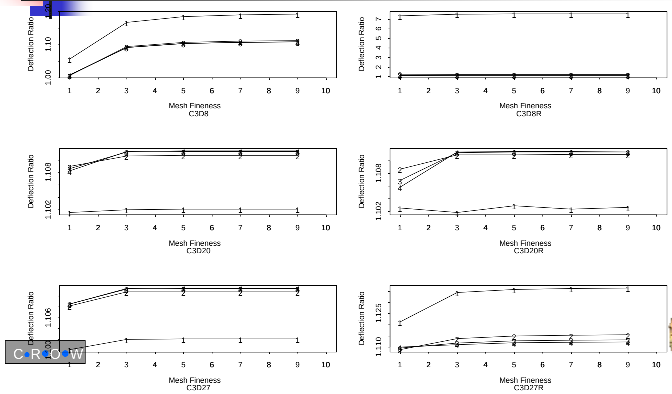
Edge Deflection Ratio (3-D Solid)



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Deflection convergence

- 3-D Solid elements > 2-D Shell elements > ILLI-SLAB > Westergaard solutions
- Similar deflections: S8R, S8R5, and S9R5 elements (S9R5=S8R5)
- Coarser mesh: S4R5<S4<S4R
- Vertical mesh fineness = 1 layer ➔ NG
- Finer vertical mesh (w/ Horizontal=3)
  - C3D20, C3D27, and C3D20R deflections increase
  - C3D8 andC3D8R deflections decrease
- Mesh fineness recommendation: horizontal=3, vertical = 3 (layers), C3D20 or C3D27 elements

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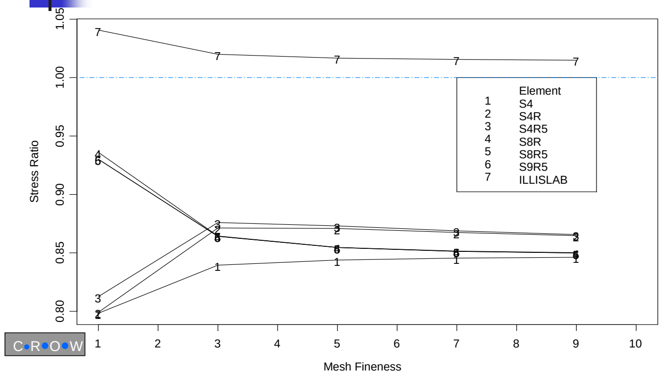
Edge Stress Ratio (2-D Shell)



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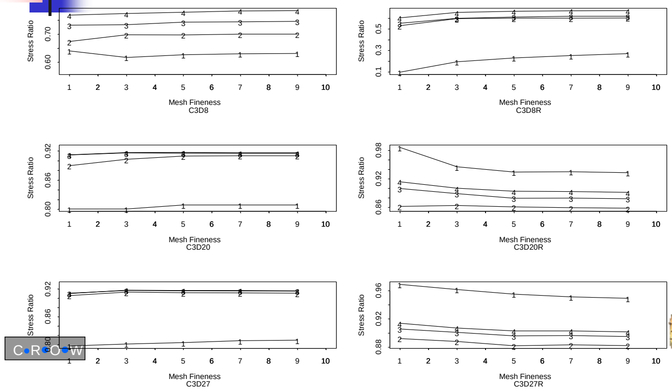
Edge Stress Ratio (3-D Solid)



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Stress convergence

- ILLI-SLAB > Westergaard > 3-D Solid elements > 2-D Shell elements solutions
  - Similar stresses: S8R5=S9R5
  - 8-point solid elements ➔ NG
  - Vertical mesh fineness = 1 layer ➔ NG
- Finer horizontal mesh
  - 8-point & 9-point elements stresses decrease to convergence
  - 4-point elements stresses increase to convergence
- Finer vertical mesh
  - C3D20 & C3D27 stresses increase to convergence
- Mesh fineness recommendation: horizontal=3, vertical = 3, C3D20 or C3D27 elements

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Convergence Characteristics due to Thickness and Load Size Effects

- Use C3D27 elements
- Horizontal mesh fineness (w/ vertical=3)
- Vertical mesh fineness (w/ horizontal=3)
- Cases Analyzed

a/ℓ	h/a	C	h	E	k
		in.	in.	psi	pci
0.05	2	10	11.284	1.99E+08	150
0.1	2	15	16.926	2.48E+07	200
0.2	2	5	5.642	1.03E+06	400
0.3	2	7.5	8.463	3.83E+05	500
0.05	4	5	11.284	3.31E+07	400
0.1	4	10	22.568	6.20E+06	600
0.2	4	6	13.541	5.82E+04	150
0.3	4	7	15.797	1.16E+04	130

註：L/ℓ=7,W/ℓ=7,p=90psi

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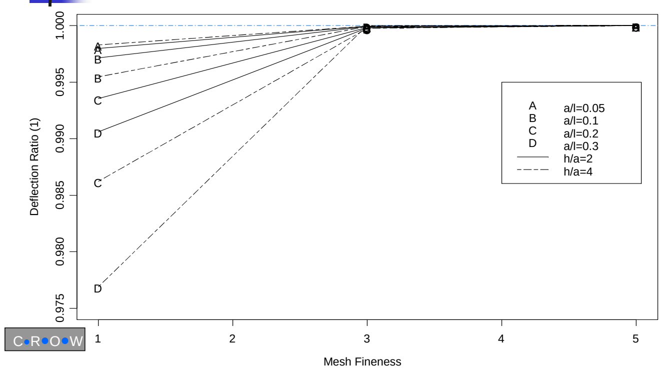
Edge Deflection Ratio (vertical=3)



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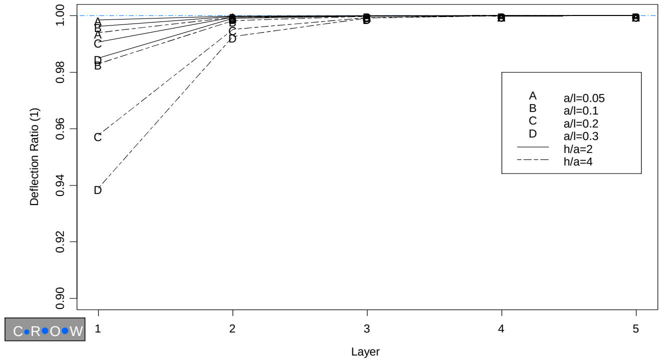
Edge Deflection Ratio (Horizontal=3)



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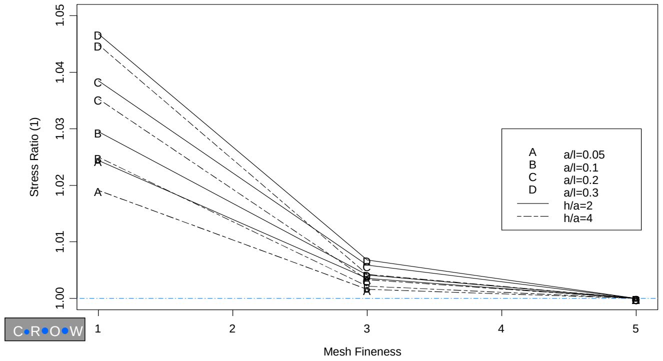
Edge Stress Ratio (Vertical=3)



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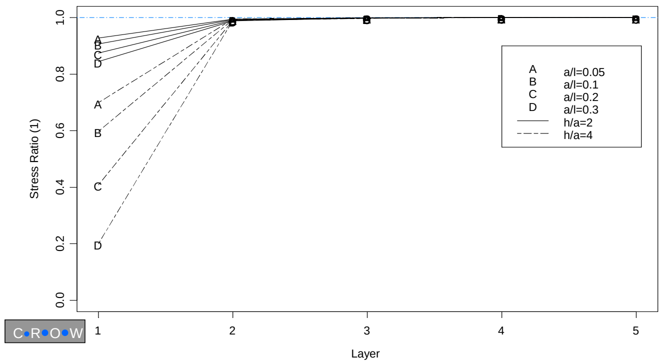
Edge Stress Ratio (Horizontal=3)



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Thickness and Load Size Effects

- Deflection convergence
  - Finer horizontal or vertical mesh ➔ Deflections increase to convergence
- Stress convergence
  - Finer horizontal mesh ➔ Stresses decrease to convergence
  - Finer vertical mesh ➔ Stresses increase to convergence
- Sensitivity: Vertical mesh > Horizontal mesh
- Smaller h/a & smaller a/ℓ conditions have better convergence characteristics
- Larger h/a & larger a/ℓ ➔ More difficult to converge
- Recommendation: horizontal=3, vertical = 3 ➔ good convergence & efficiency

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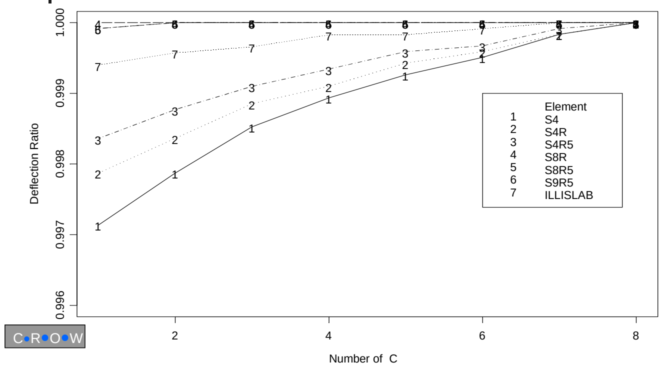
Determining the Length of Finer Mesh (nC) – Deflection Ratio



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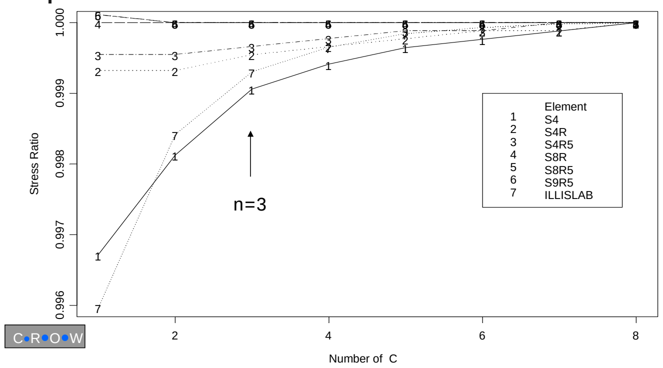
Determining the Length of Finer Mesh (nC) – Stress Ratio



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Mesh Generation and Element Selection Recommendations

- Mesh fineness: Horizontal=3, Vertical=3, Length of Finer Mesh (Zone II)=3*C
  - Vertical mesh fineness = 1 layer ➔ NG
- Element selection: 20- or 27-point solid elements
  - 8-point solid elements ➔ NG (different from 20- and 27-point elements solutions)
  - reduced integration or 20-point element ➔ stress reduction 1~2%
  - The execution time of 20-point elements ≈ 60% of 27-point elements

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IDENTIFICATION OF ADDITIONAL DIMENSIONLESS PARAMETER

$$\frac{\sigma h^2}{P} = f\left(\frac{a}{\ell}, \frac{L}{\ell}, \frac{W}{\ell}, \frac{h}{a}\right)$$

$$\frac{\delta k \ell^2}{P} = f\left(\frac{a}{\ell}, \frac{L}{\ell}, \frac{W}{\ell}, \frac{h}{a}\right)$$

Inspired by the solutions & charts of Burmister's layered theory (1943, 1945)

h/a	a/ℓ	L/ℓ	h cm	L=W m	E GPa	k MN/m^3	P kN	σh^2/P	δ*kℓ^2/P
3.0	0.1	2	21.5	1.43	13.78	44.1	7.8	2.3983	1.0200
3.0	0.1	2	32.2	2.15	10.34	22.0	22.5	2.3984	1.0199
3.0	0.1	2	32.2	2.15	13.78	29.4	20.0	2.3984	1.0199
3.0	0.1	2	43.0	2.87	24.12	38.6	44.5	2.3985	1.0200
3.0	0.1	2	43.0	2.87	31.01	49.6	66.8	2.3989	1.0200
3.0	0.1	2	53.7	3.58	20.67	26.4	90.4	2.3976	1.0200
3.0	0.1	2	53.7	3.58	27.56	35.2	41.7	2.3983	1.0199
3.0	0.1	2	64.5	4.30	13.78	14.7	120.2	2.3993	1.0199
3.0	0.1	2	64.5	4.30	41.34	44.1	90.1	2.3982	1.0199
3.0	0.1	2	64.5	4.30	27.56	29.4	100.1	2.3985	1.0200
6.0	0.2	3	43.0	1.07	13.78	5639.9	7.8	1.3991	1.1148
6.0	0.2	3	64.5	1.61	10.34	2820.0	22.5	1.3993	1.1147
6.0	0.2	3	64.5	1.61	13.78	3760.0	20.0	1.3994	1.1147
6.0	0.2	3	86.0	2.15	24.12	4934.9	44.5	1.3991	1.1147
6.0	0.2	3	86.0	2.15	31.01	6344.9	66.8	1.3987	1.1147
6.0	0.2	3	107.5	2.69	20.67	3384.0	90.4	1.3989	1.1148
6.0	0.2	3	107.5	2.69	27.56	4512.0	41.7	1.3991	1.1147
6.0	0.2	3	129.0	3.22	13.78	1880.0	120.2	1.3990	1.1147
6.0	0.2	3	129.0	3.22	41.34	5639.9	90.1	1.3993	1.1147
6.0	0.2	3	129.0	3.22	27.56	3760.0	100.1	1.3992	1.1147

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Discussion of the Additional Parameter Identification

- Identification of the additional parameter (*h/a*) was originally inspired by Burmister's layered theory (Burmister, 1943, 1945)
- Other literature also indicated that analytical solutions derived for thick elastic plates are governed by the ratio of a circular load radius (*a*) to the thickness of the slab (*h*). Different *a/h* ratios were used to compute the maximum bending stress (σ) in terms of the percent of the applied pressure (*p*) (Shi & Yao, 1989; Van Cauwelaert, 1990; Ioannides & Khazanovich, 1994; Khazanovich & Ioannides,1995).
- The conventional Westergaard's ordinary theory solution results in an overestimate in the bending stress. The correction introduced by Westergaard's special theory results in bending stress reduction, bringing it in line with Burmister's layered solutions (Ioannides & Khazanovich, 1994).

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DEVELOPMENT OF DATABASES AND PREDICTION MODELS

- Development Of An Automated Analysis Program
- ABAQUS batch processing & Databases
  - L/ℓ = 2~7 (step by 1)
  - W/ℓ = 2~7 (step by 1)
  - a/ℓ = 0.05, 0.1~0.5 (step by 0.1)
  - h/a = 0.5~6.0 (step by 0.5)
  - C3D27, Horizontal=3, Vertical=3, Zone II=3*C
- Stress adjustment prediction model
- Deflection adjustment prediction model

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Estimation of 3-D FE Solutions

- Deflection Ratio (1/R1=0~1)

$$R1 = \frac{\delta_{3-D\ FEM}}{\delta_W} = f\left(\frac{a}{\ell}, \frac{L}{\ell}, \frac{W}{\ell}, \frac{h}{a}\right)$$

$$\delta_{3-D\ FEM} = \delta_W \times R1$$

- Stress Ratio (R2=0.25~1.03)

$$R\mathbf{2} = \frac{\sigma_{3-D\ FEM}}{\sigma_W} = f\left(\frac{a}{\ell}, \frac{L}{\ell}, \frac{W}{\ell}, \frac{h}{a}\right)$$

$$\sigma_{3-D\ FEM} = \sigma_W \times R\mathbf{2}$$

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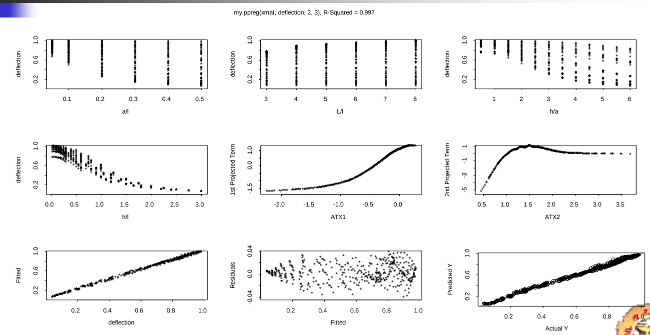
Deflection Ratio (1/R1) Predictive Model



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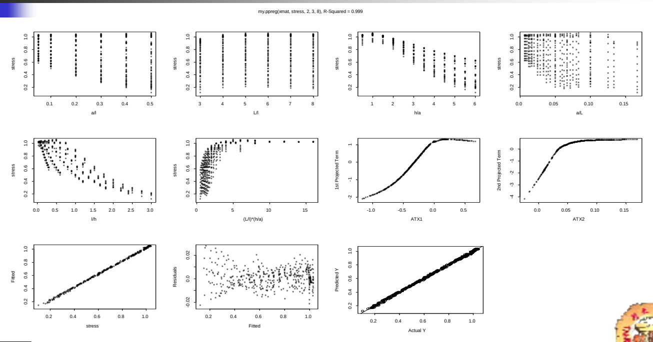
Stress Ratio (R2) Predictive Model



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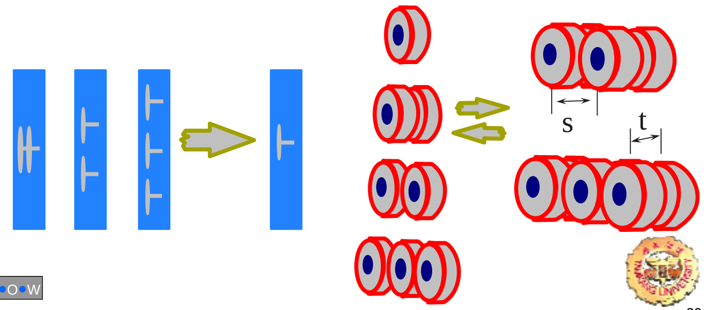
Tentative Critical Stress Predictive Model

$$\sigma_e = (\sigma_w * R_G * R2 * R_S * R_O * R_M + R_T * \sigma_c)$$



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DISCUSSIONS & CONCLUSIONS(1)

- Compare 2-D and 3-D FEM results
- Expand the closed-form solutions and previous 2-D FEM findings to facilitate 3-D analysis
- Deflection: 3-D Solid elements > 2-D Shell elements > ILLI-SLAB > Westergaard solutions
- Stress: ILLI-SLAB > Westergaard > 3-D Solid elements > 2-D Shell elements solutions
- Vertical mesh fineness = 1 layer ➔ NG

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DISCUSSIONS & CONCLUSIONS(2)

- Sensitivity: Vertical mesh > Horizontal mesh> Length of Finer Mesh (Zone II)
- Smaller h/a & smaller a/ℓ conditions have better convergence characteristics
- Larger h/a & larger a/ℓ ➔ More difficult to converge
- Recommendations: Horizontal=3, Vertical=3 (layers), Zone II=3*C, C3D20 or C3D27 elements

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DISCUSSIONS & CONCLUSIONS(3)

- Identified and verified an additional parameter (h/a) for 2-D shell and 3-D solid elements (from Burmister's layered theory and thick elastic plates)
- Developed an automated analysis program for ABAQUS batch processing & creating databases
- Developed deflection and stress adjustment prediction models
- Implications to future applications & validations

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THANKS FOR YOUR ATTENTION

Questions?

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