Evaluation of non-uniform tyre contact stresses on thin asphalt pavements

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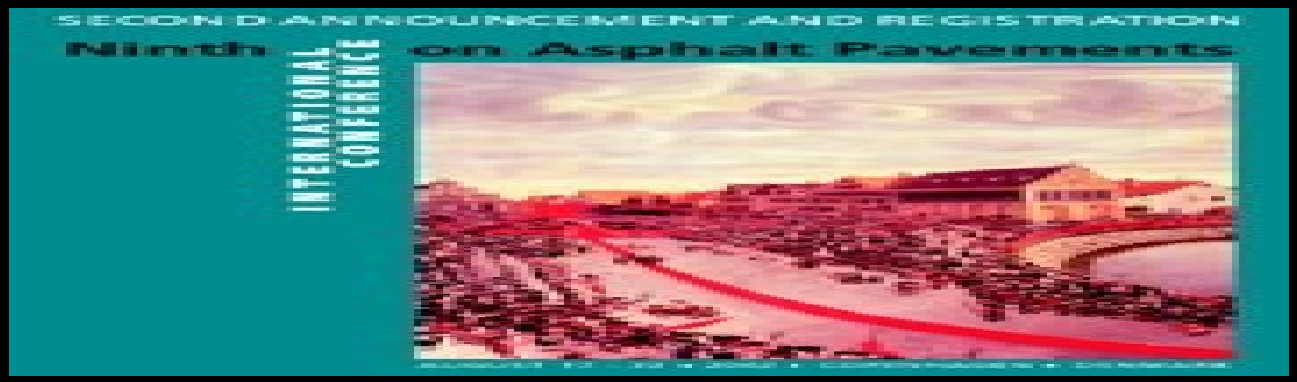
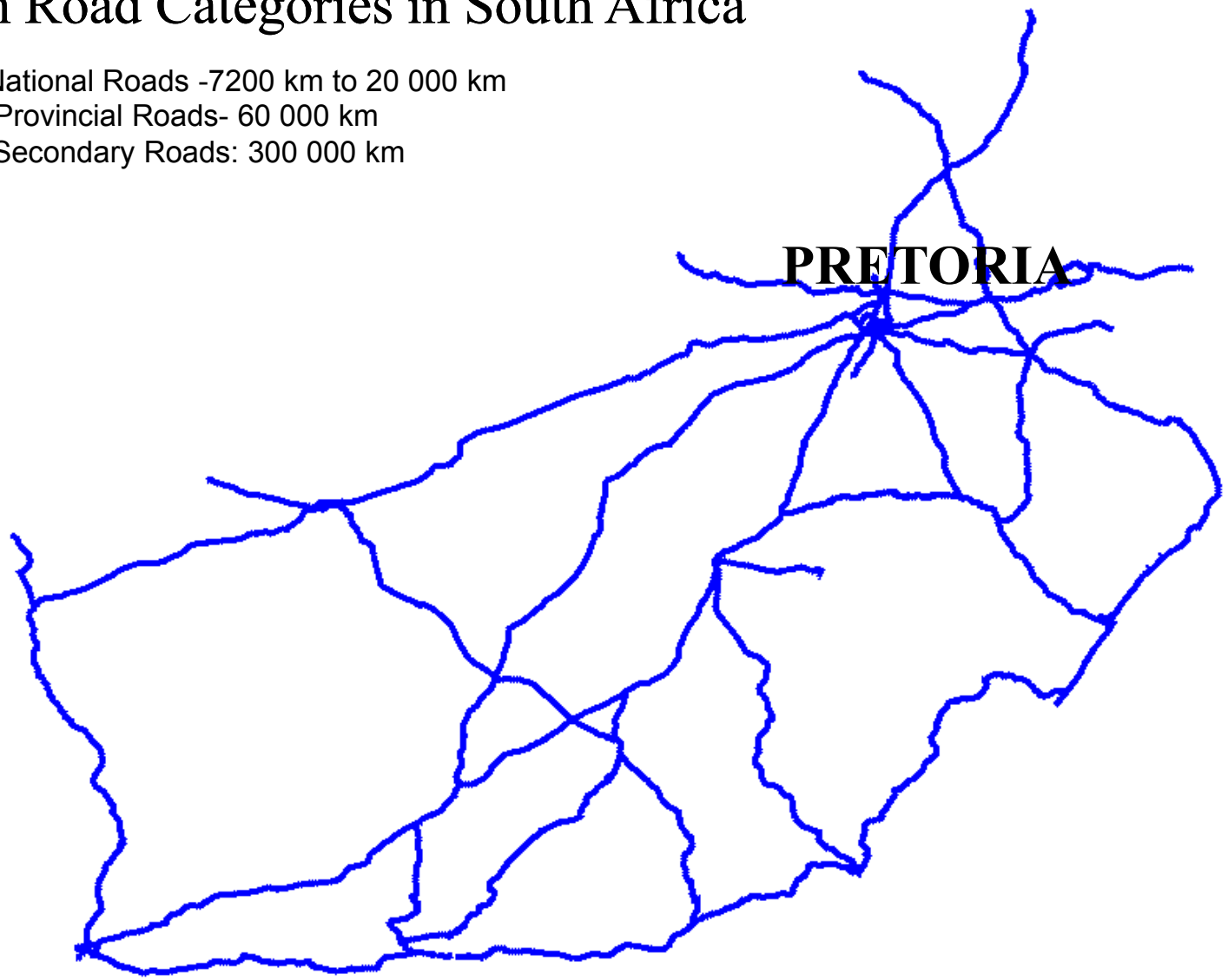


Layout of Presentation:

- Introduction and Background - Thin layered Asphalt Pavements in South Africa;
- Approach in study;
  - Dynamic tyre loads-convert to contact stress values;
  - Tyre contact stress equipment, information and artificial neural networks;
- PART 1: Pavement Modeling using FEM on 4 load cases – comparing circular assumption with measured SIM data;
- PART 2: Uncracked vs cracked pavement- semi-analytical FEM;
- Conclusions and Recommendations.

Main Road Categories in South Africa

National Roads -7200 km to 20 000 km
Provincial Roads- 60 000 km
Secondary Roads: 300 000 km



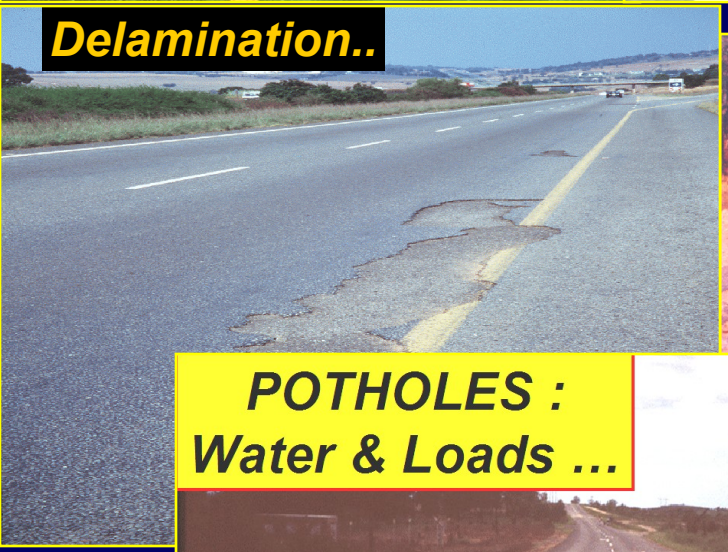
Thin AC layers in South Africa:

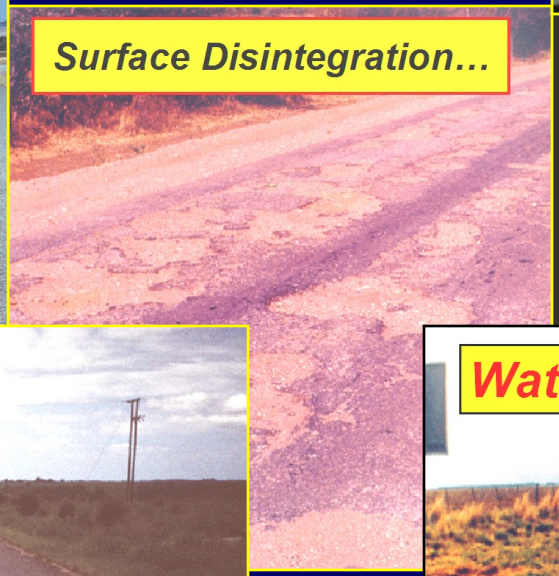
1. 90 % of paved roads in SA using “thin” asphalt surfacings (20 mm to 50 mm) including asphalt, single and multiple seals (Double and Cape seals, etc);
2. Used in Urban and Rural environment totaling approx. 230 000 km;
3. 13 % of these pavements uses asphalt base layers of 80 mm to 120 mm thick, mostly in wetter areas (KwaZulu-Natal);


RUTTING


Longitudinal Flow of Asphalt


Fatigue Cracking and aging


Delamination..


Surface Disintegration…


POTHOLES :
Water & Loads …

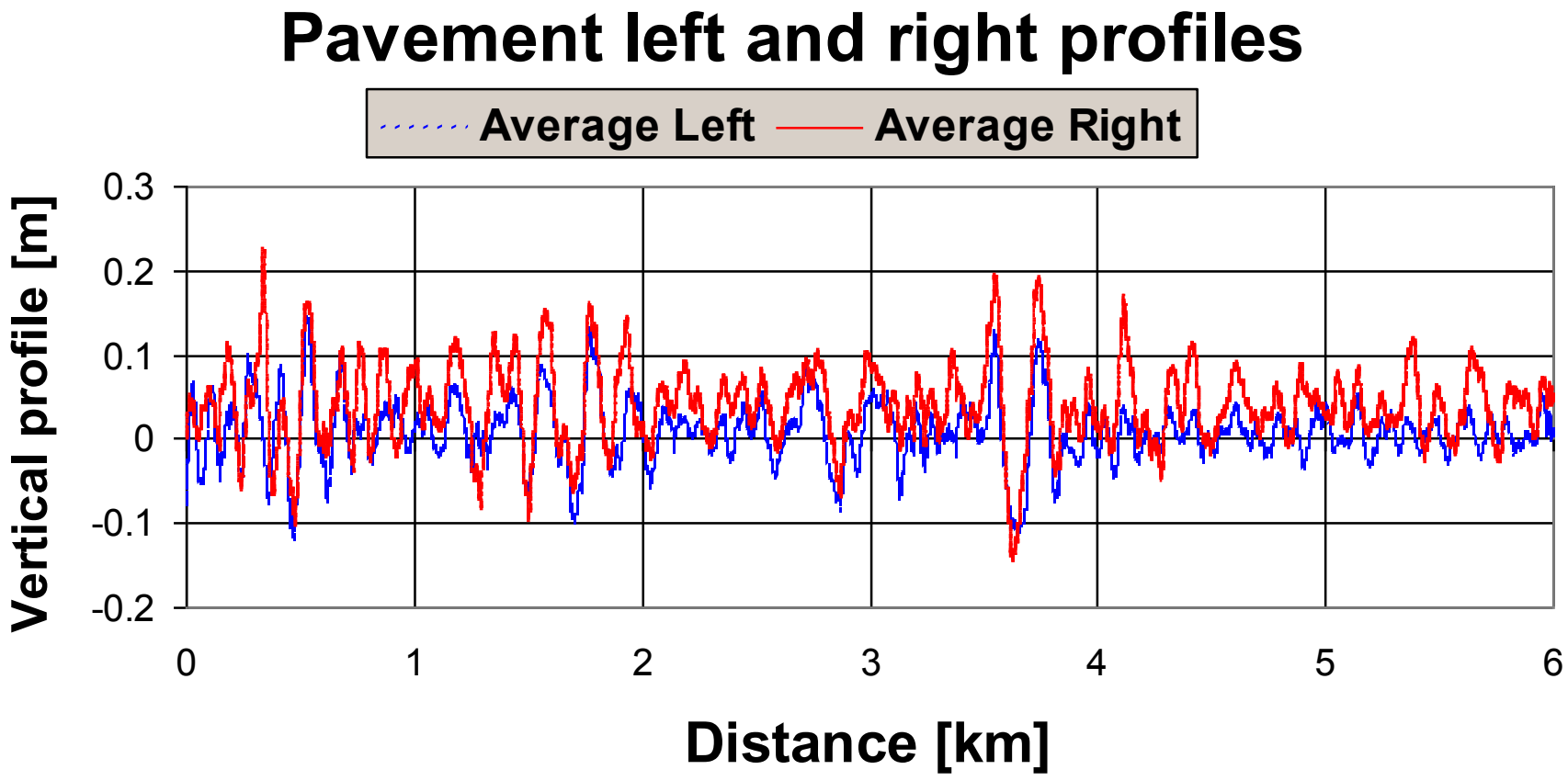

Water & Safety…

Heavy Vehicle Simulator (HVS) testing since 1975…

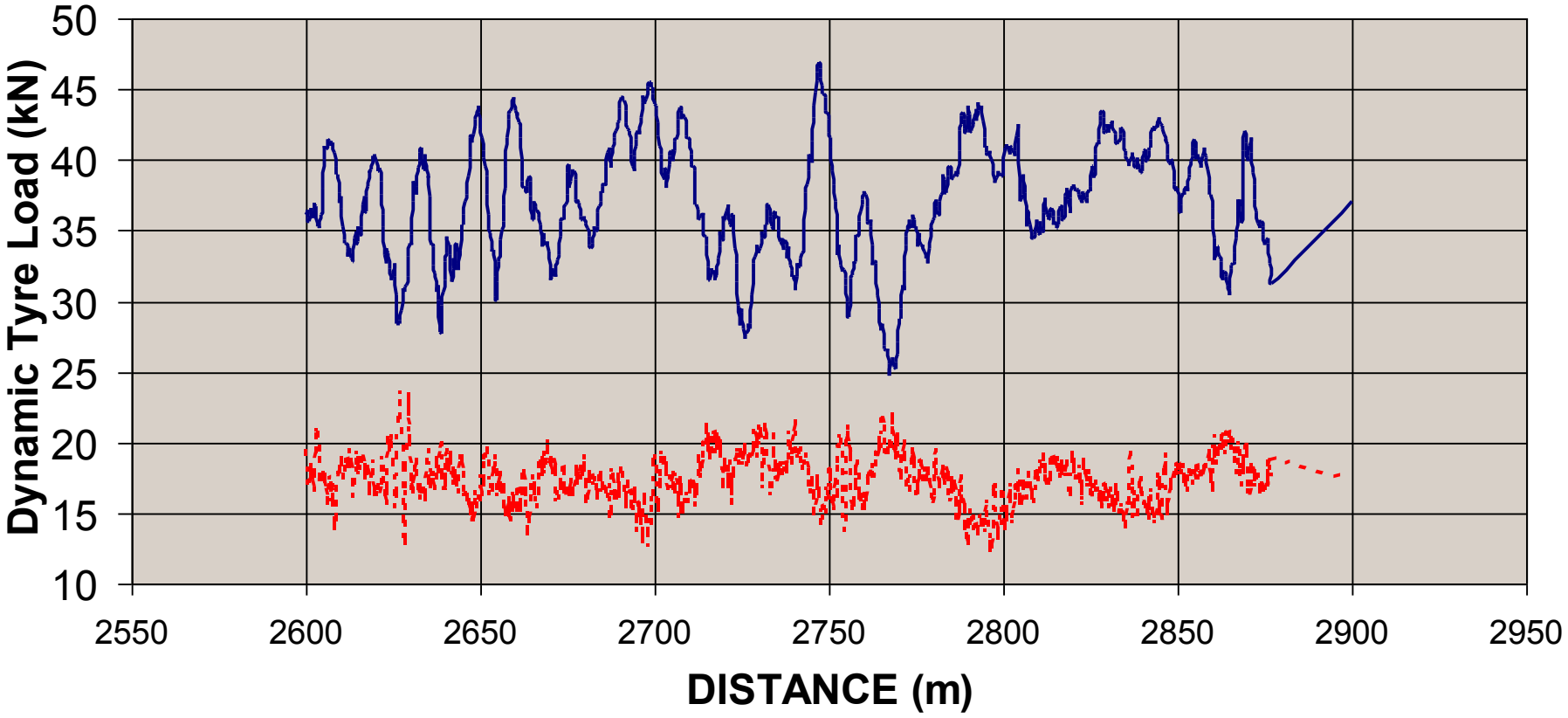
…to address understanding of pavement behaviour…

HVS - Moving Dynamic Load

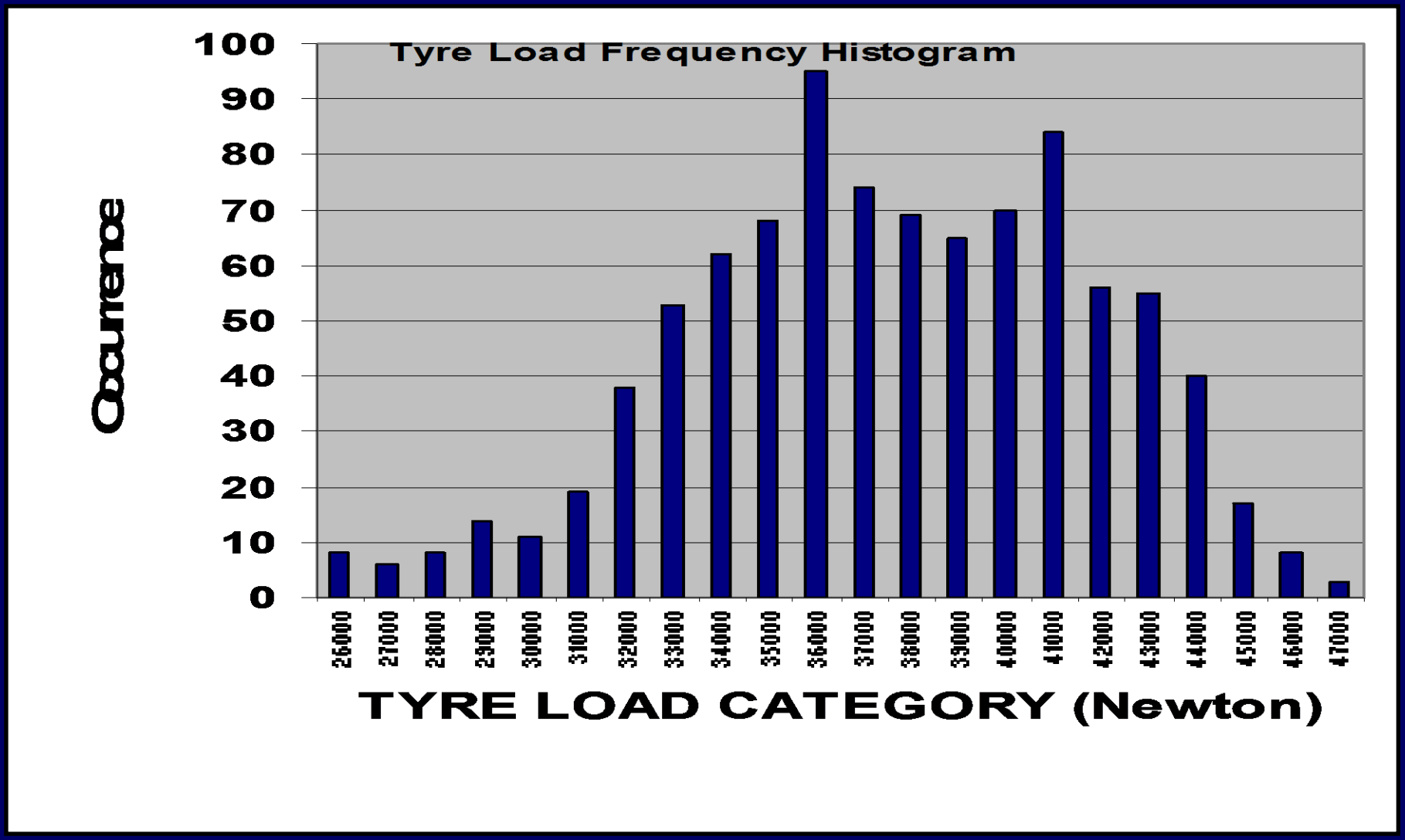
Road Profiles: HRI=3.1m/km



Computed Dynamic Loads (DADS):



Dynamic Loads converted to contact stress
DISTRIBUTIONS- VERTICAL LOAD:

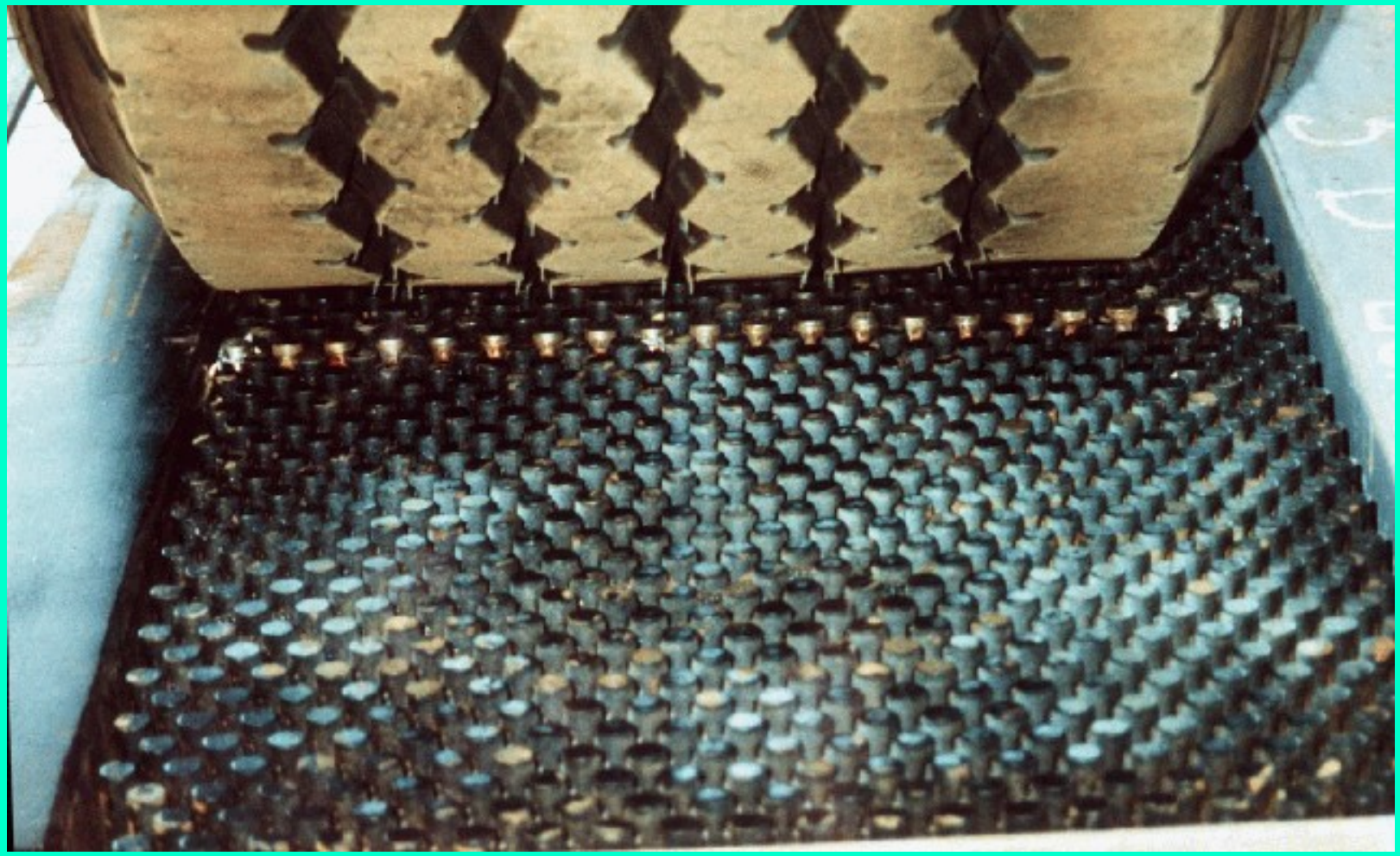



Vehicle-Tyre-Pavement Interaction:
STRESS-IN-MOTION (SIM)
Technology

Stress - In - Motion (SIM) - SIM Mk II:

CSIR Transportek: '93-'95:

315/80 HVS TYRE ON SIM Mk II SYSTEM

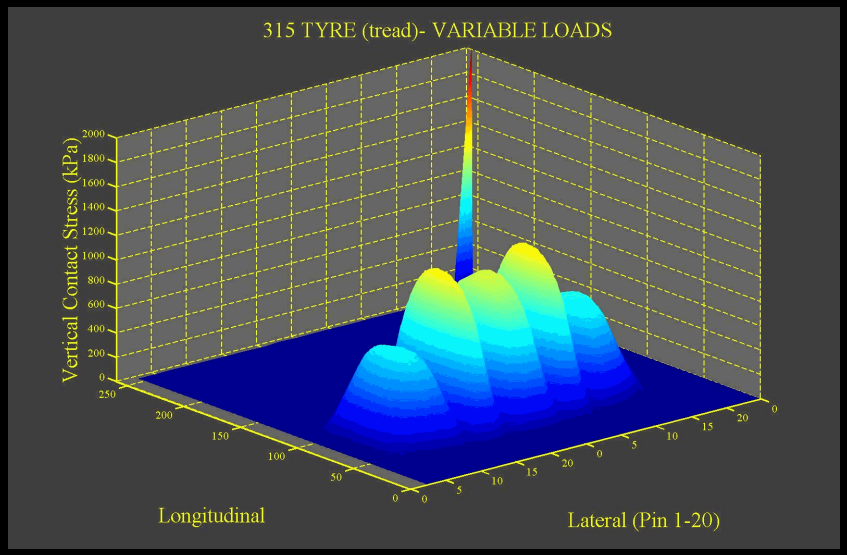


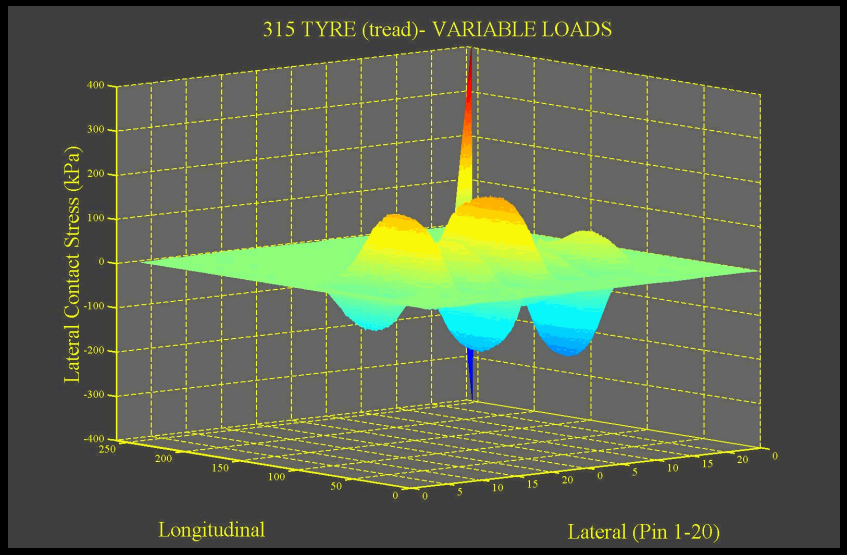
425 /65 R22.5 HVS Tyre ON SIM SYSTEM:

Single pad SIM system (Use with HVS)

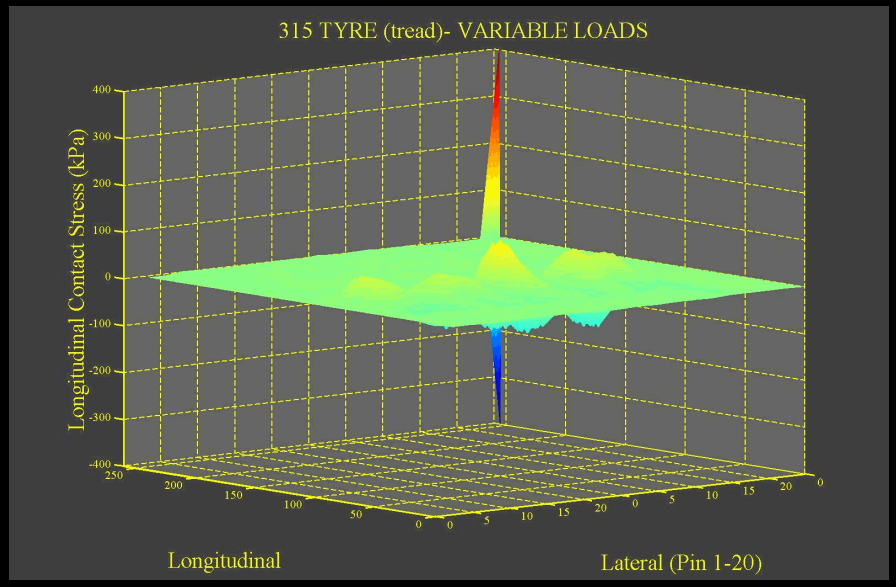
CSIR TRANSPORTEK

Typical SIM measured contact stress data sets:

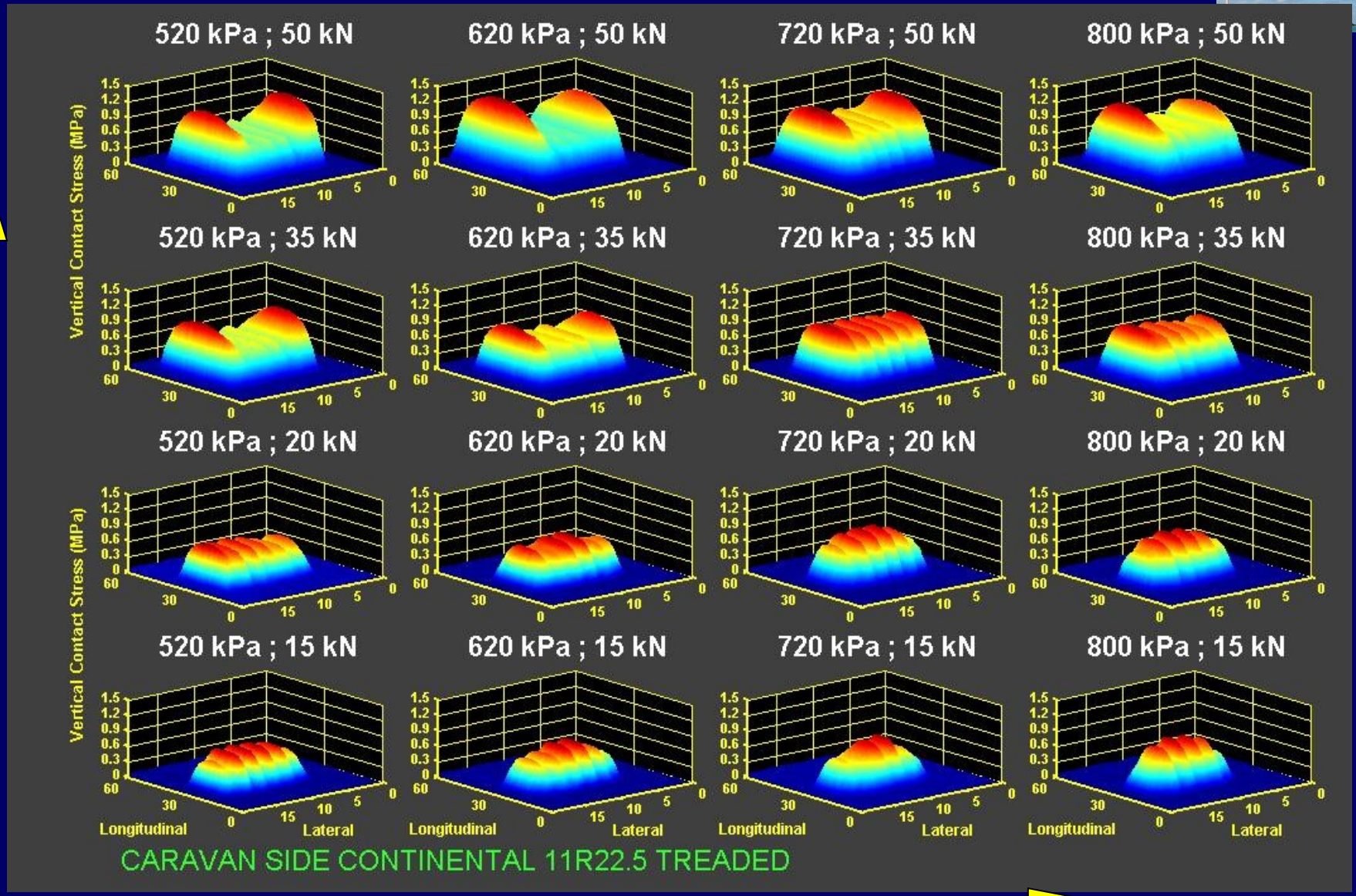




3D – Z,X,Y - Contact Stress: Variable loads: 315/80 R22.5 Tire



TYRE "FINGER PRINTING": (HVS : SIM : 11R22.5 TYRE)



LOAD

INFLATION PRESSURE

SIM Mk III on N1 (North): Mantsole TCC

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SIM Mk III on N1 (North)

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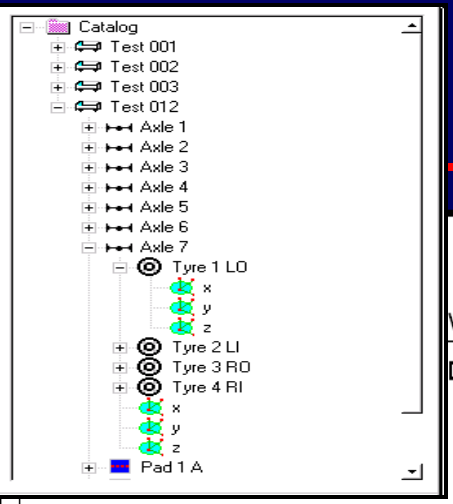
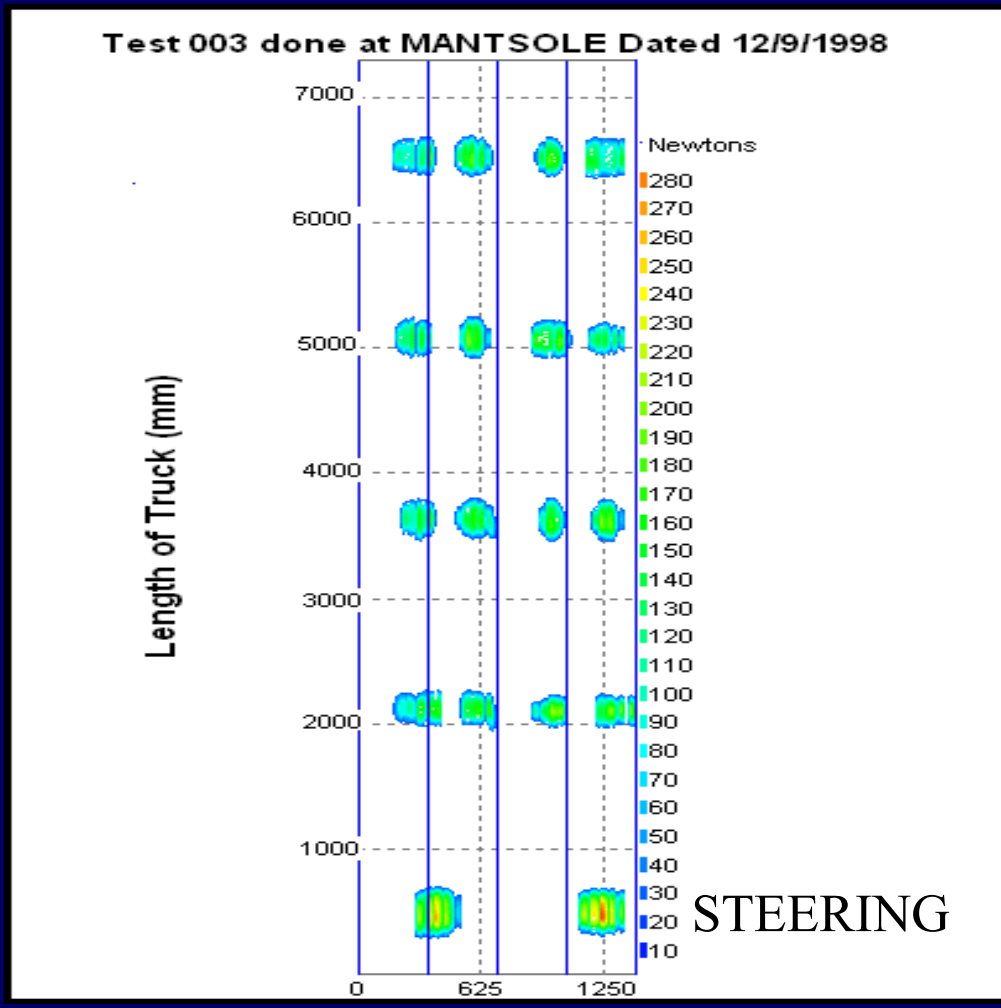
SIM DATA ORGANISATION :





STEERING

Artificial Neural Networks (ANN) :

(ANN - FHWA/ PENN STATE)

Predicted M DE BEER ET AL. **Measured**

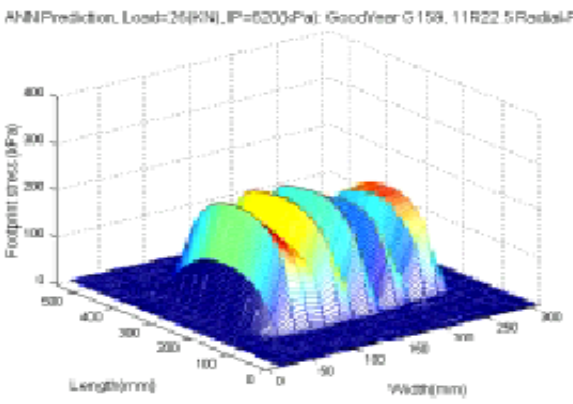


Figure 9. ANN prediction: Vertical contact stress

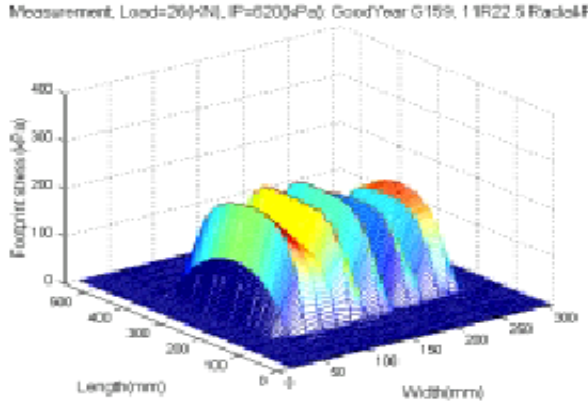


Figure 10. Measured vertical contact stress

Error

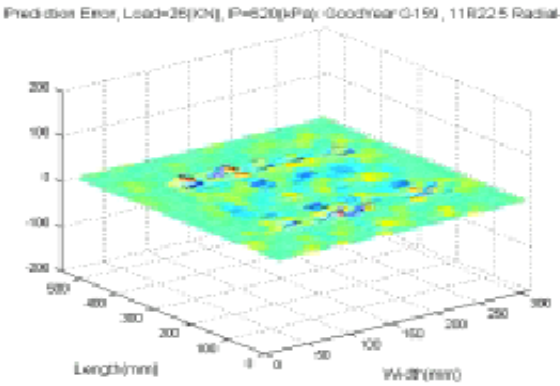
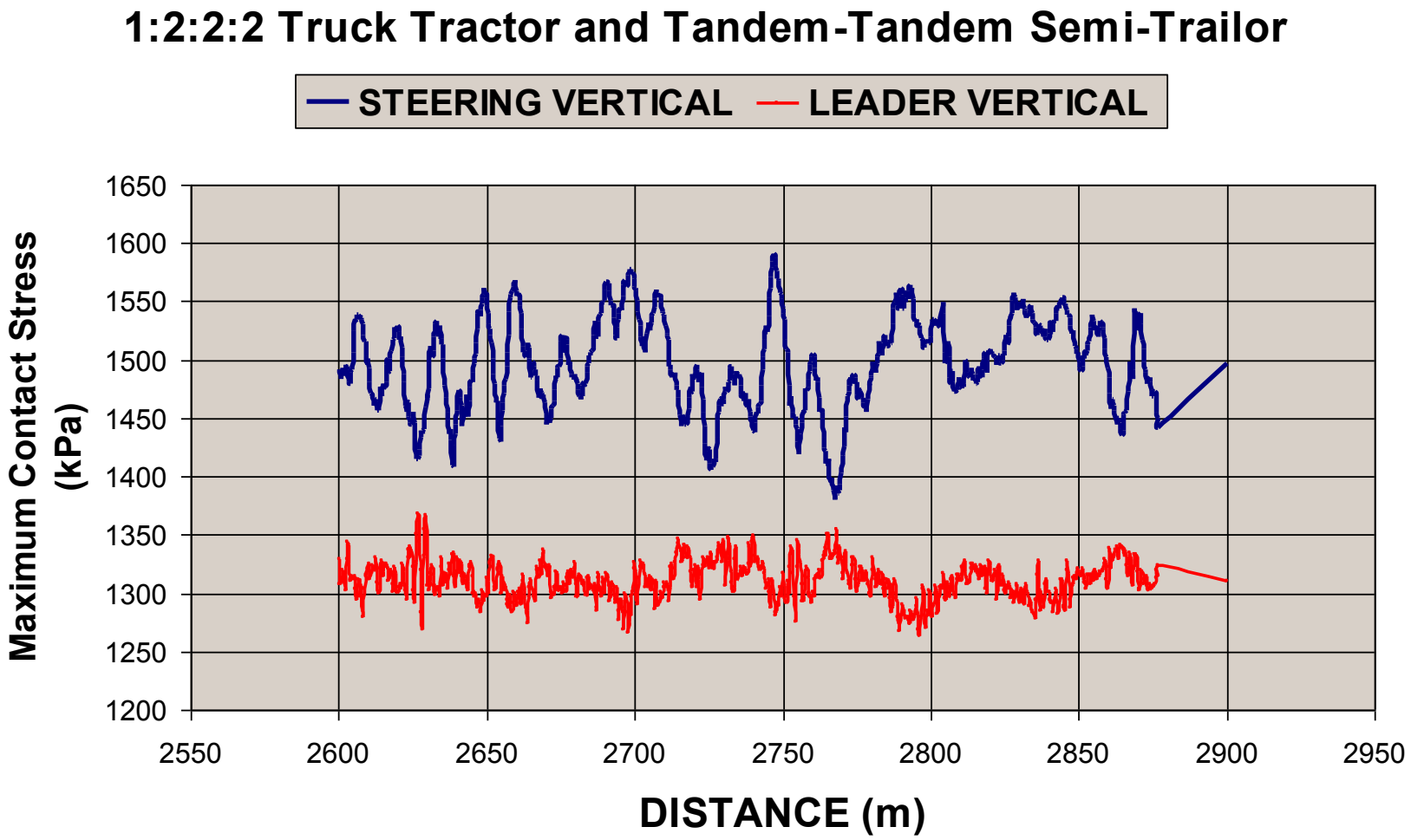
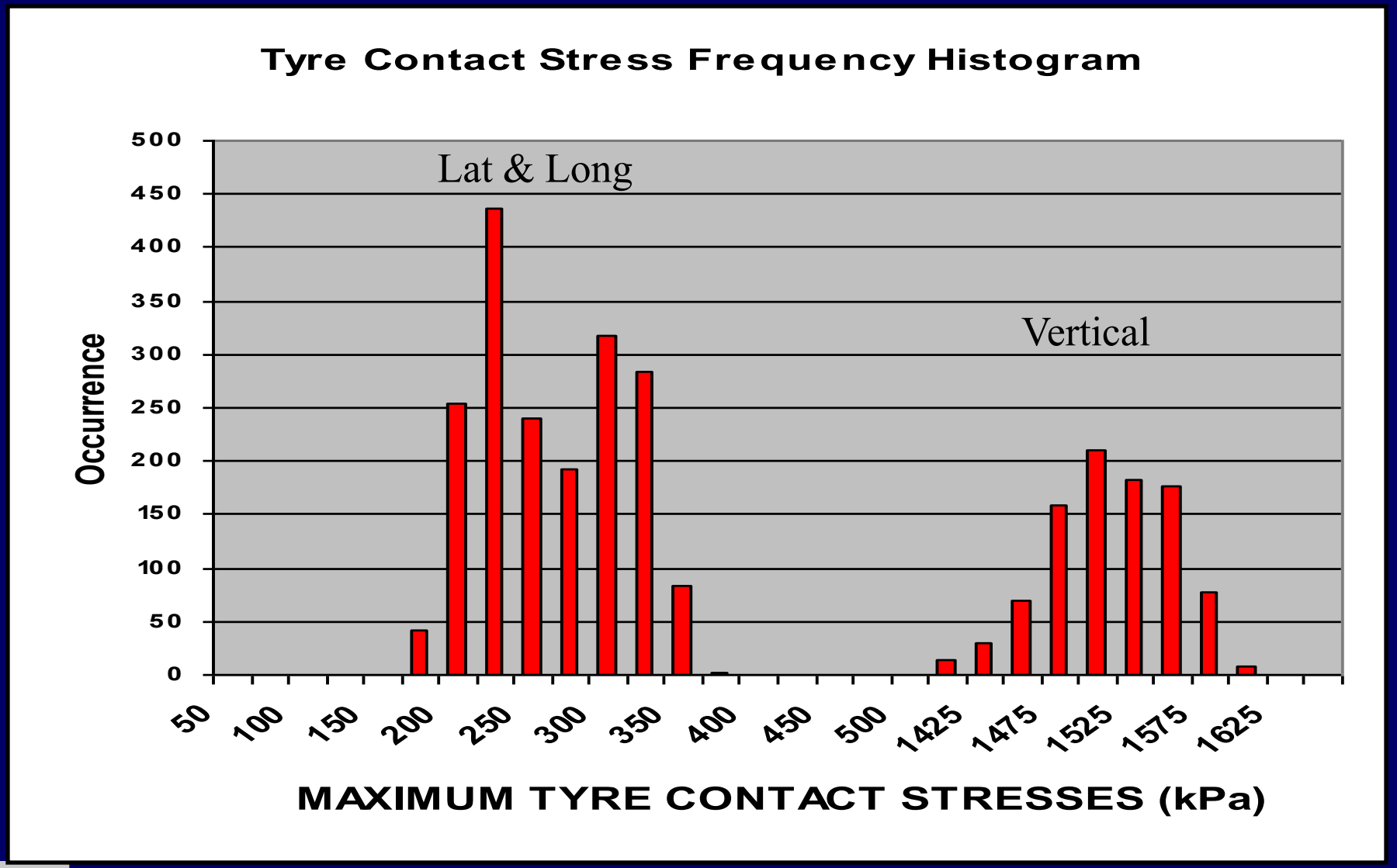


Figure 11. Prediction error: Difference between ANN prediction and measured vertical contact stress at a load of 26 kN, and inflation pressure of 620 kPa.

Dynamic Loads converted to contact stress (algorithms from ICAP 1997 paper):



Derived “dynamic” (max) contact stress distributions:



MODELED PAVEMENT STRUCTURE – LINEAR ELASTIC

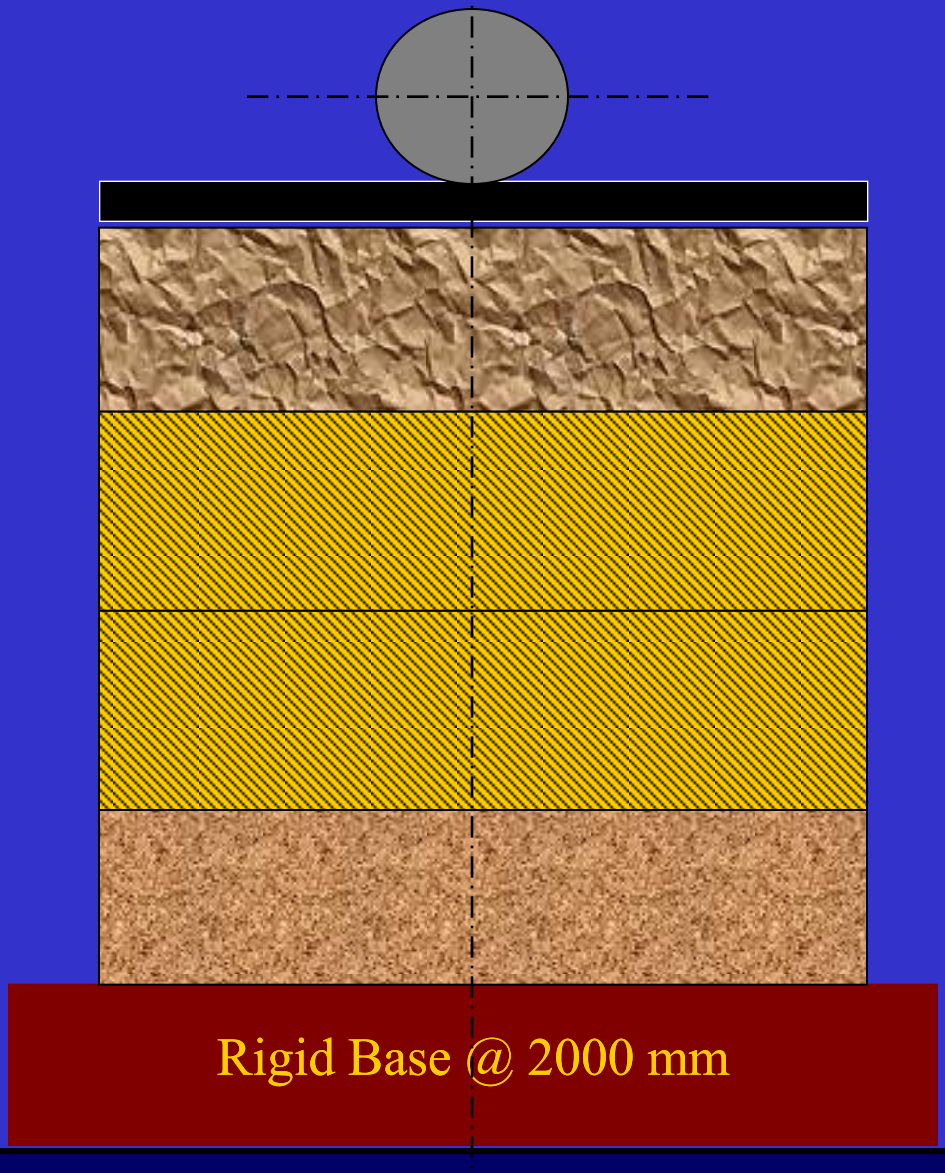
Thin Asphalt Surfacing: 40 mm
(E_1 = 5000 MPa, 1000, 200, ν_1 = 0.44);
(C = 2000 kPa, Φ = 43 deg, Yield = 1462 kPa, 585 kPa, 117 kPa)

Crushed Stone Base: 150 mm
(E_2 = 350 MPa, ν_2 = 0.35)

Cementitious Subbase-1: 150 mm
(E_3 = 1500 MPa, ν_3 = 0.35)

Cementitious Subbase-2: 150 mm
(E_4 = 1500 MPa, ν_4 = 0.35)

Soil Subgrade:2000 mm
(E_5 = 100 MPa, ν_5 = 0.35)



The six (6) response parameters selected for this study include:

1. Maximum Vertical Compressive Strain (ε_{zz});
2. Maximum Vertical Compressive Stress (σ_{zz});
3. Maximum First Invariant of Stress (I_1);
4. Maximum of the Second invariant of deviatoric strain (J'_2- Strain);
5. Maximum Second invariant of deviatoric stress (J'_2- Stress); and
6. Maximum Yield values for estimation of Mohr-Coulomb yield failure in the asphalt surfacing

LOAD CASE 1:
STANDARD LOAD CASE (SLC):
ASSUMTIONS:

- Circular;
- Load = 20 kN;
- Uniform Pressure: 520 kPa

Design Tyre:
20 kN, 520 kPa

Load Case 2:
MEASURED (SIM)
26 kN; 420 kPa:
Vertical Contact Stress
Distribution
and
Static Tyre print-
Overloaded-
Under
Inflated

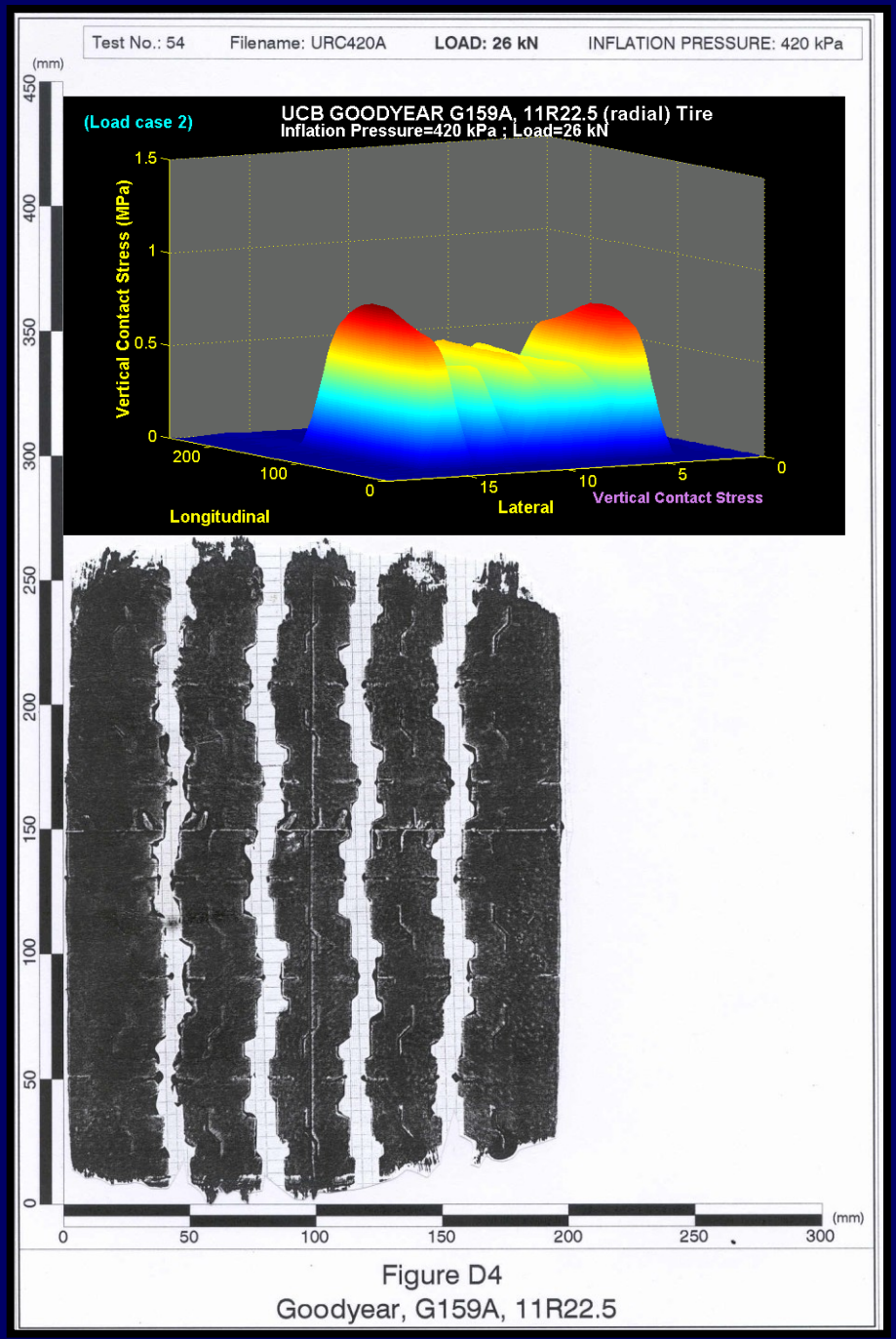
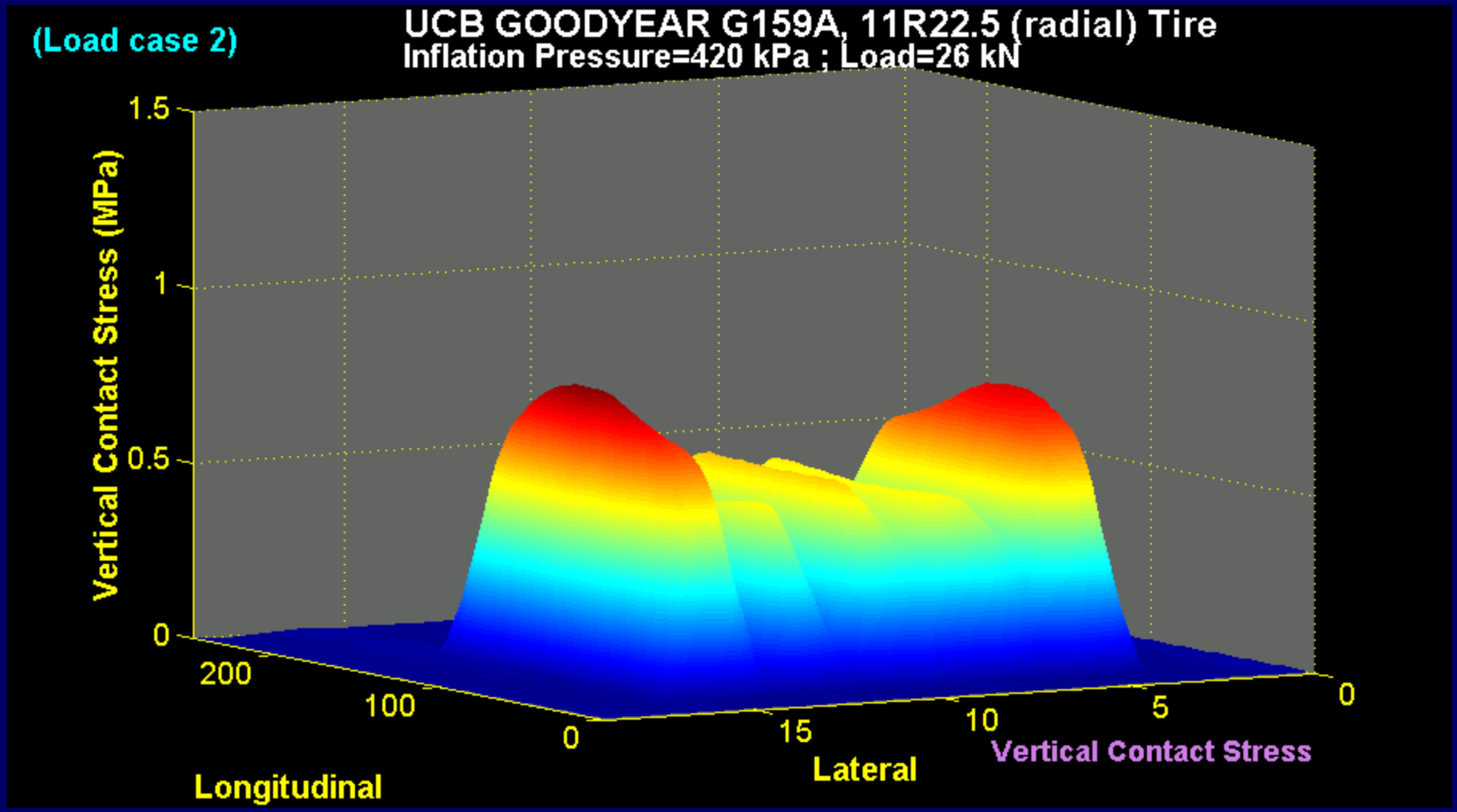
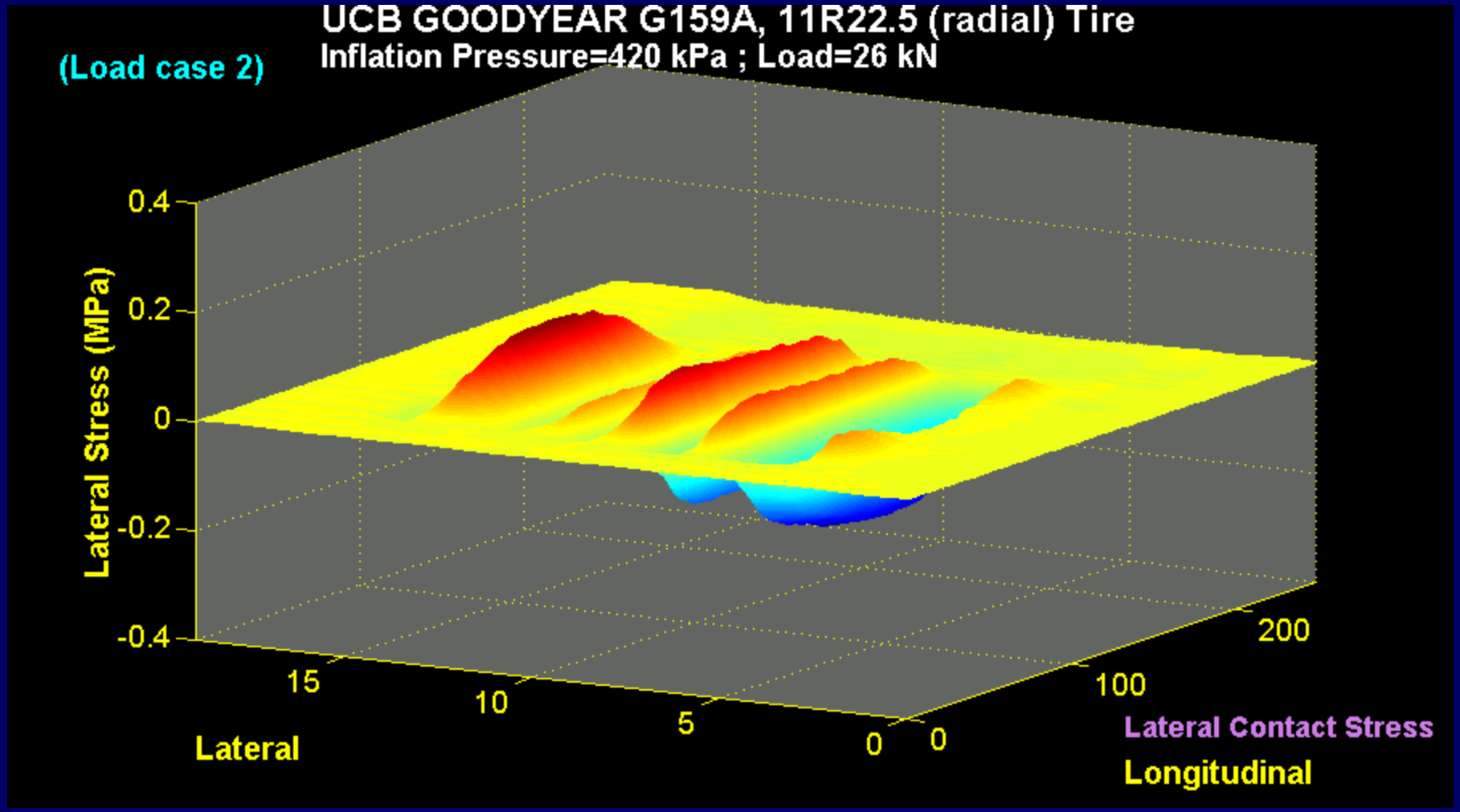


Figure D4
Goodyear, G159A, 11R22.5

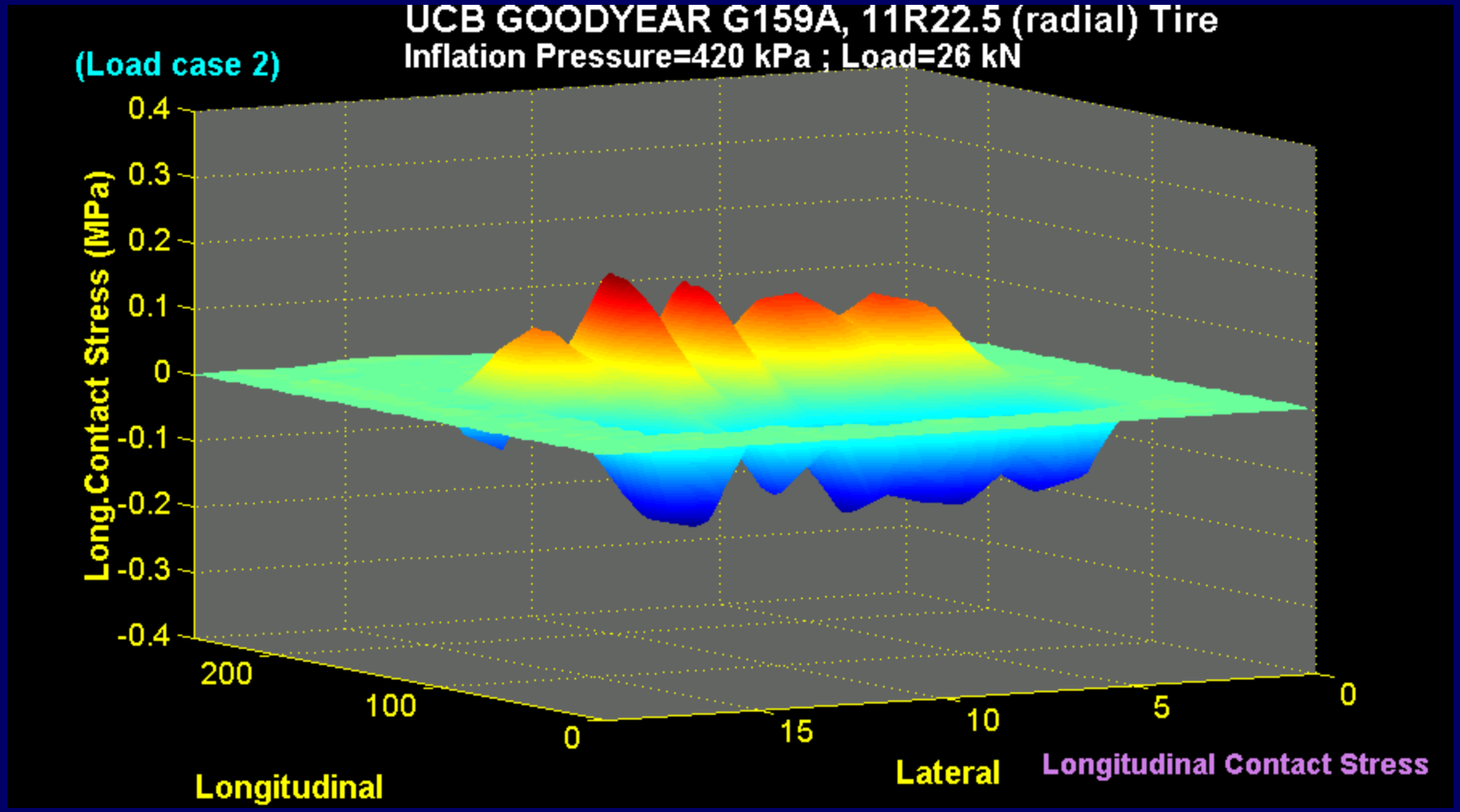
VERTICAL STRESS:



LATERAL STRESS:



LONGITUDINAL STRESS:



Load Case 3:
MEASURED (SIM)
26 kN; 690 kPa:
Vertical Contact Stress
Distribution
and
Static Tyre print:

Rated Loading for tyre

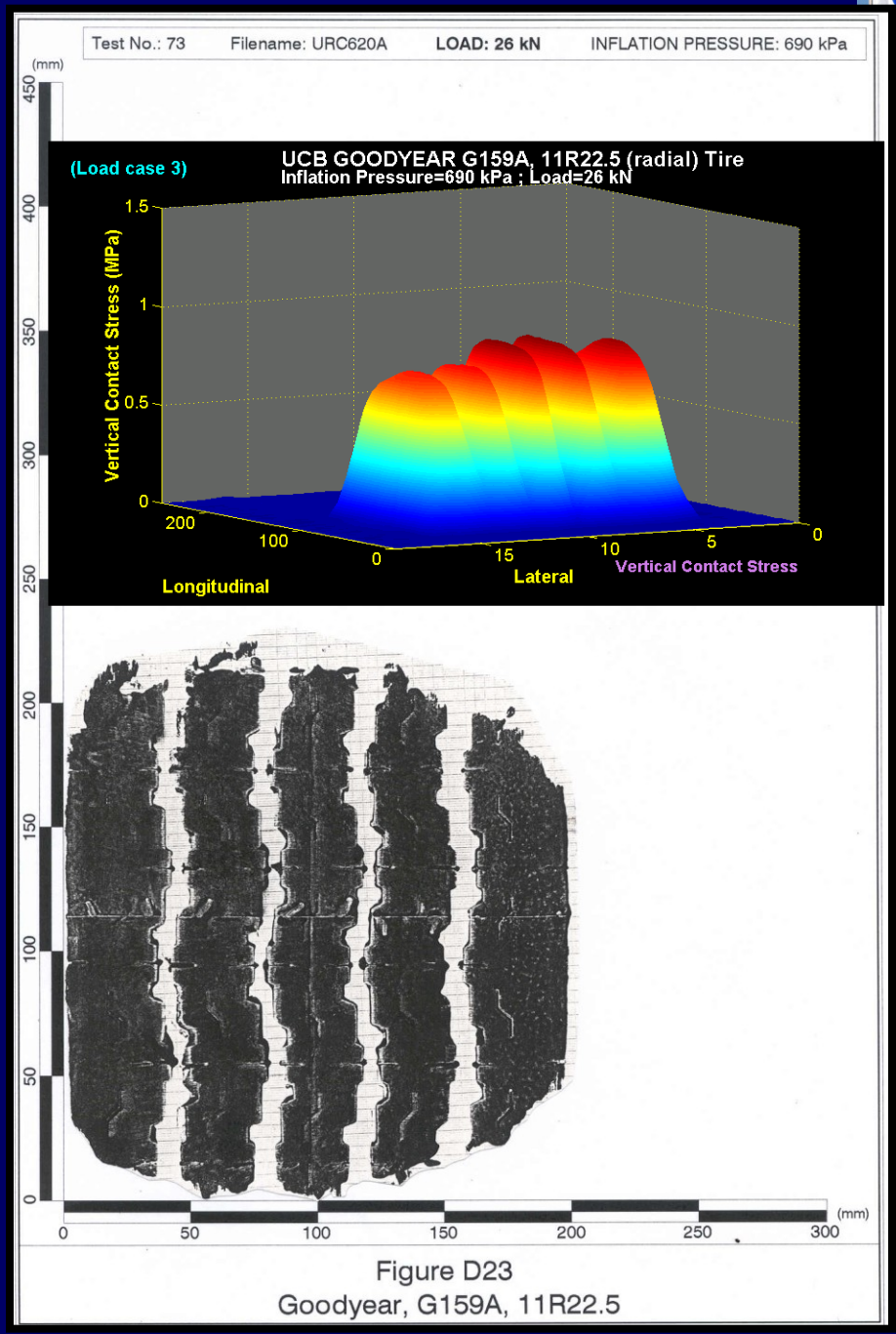
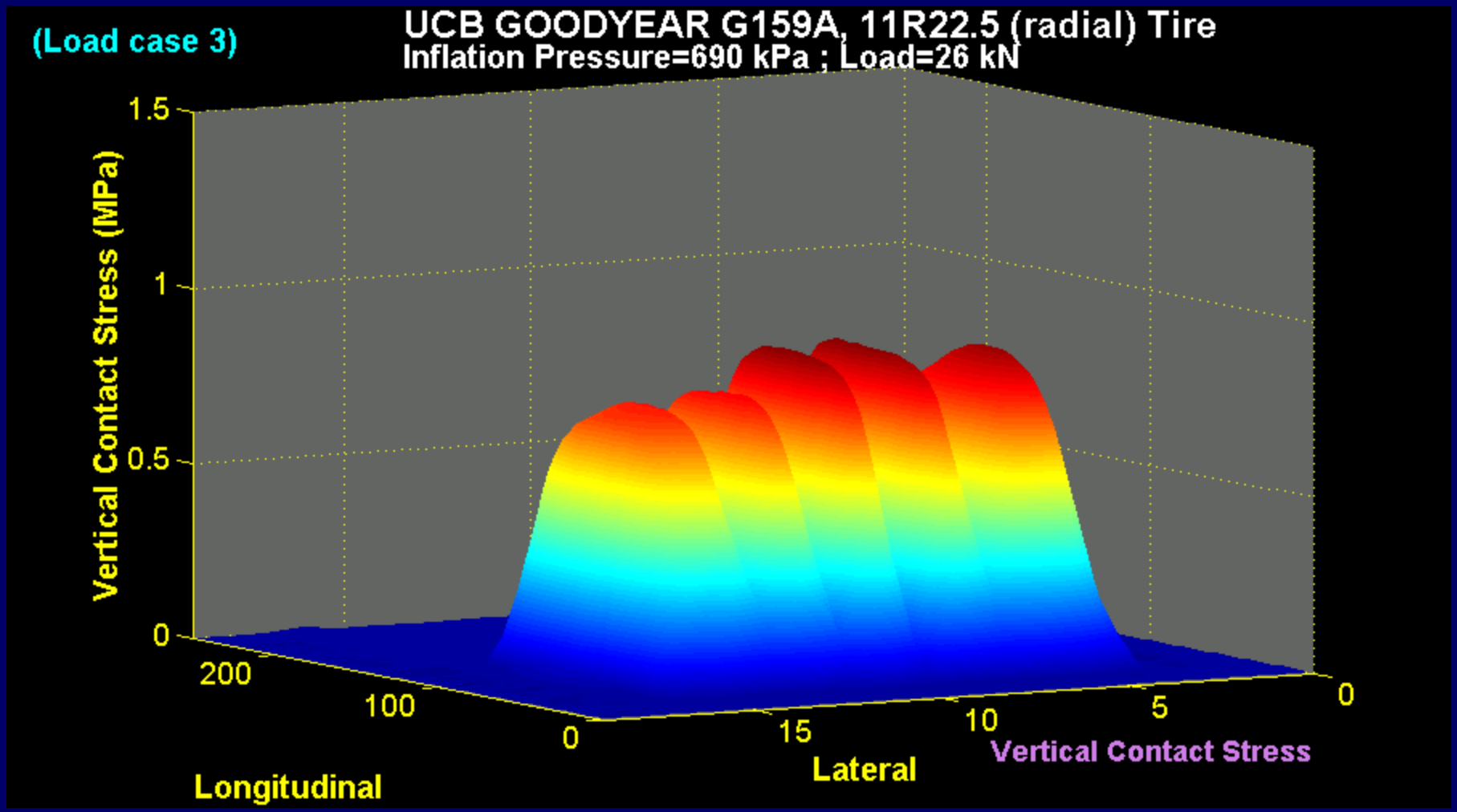
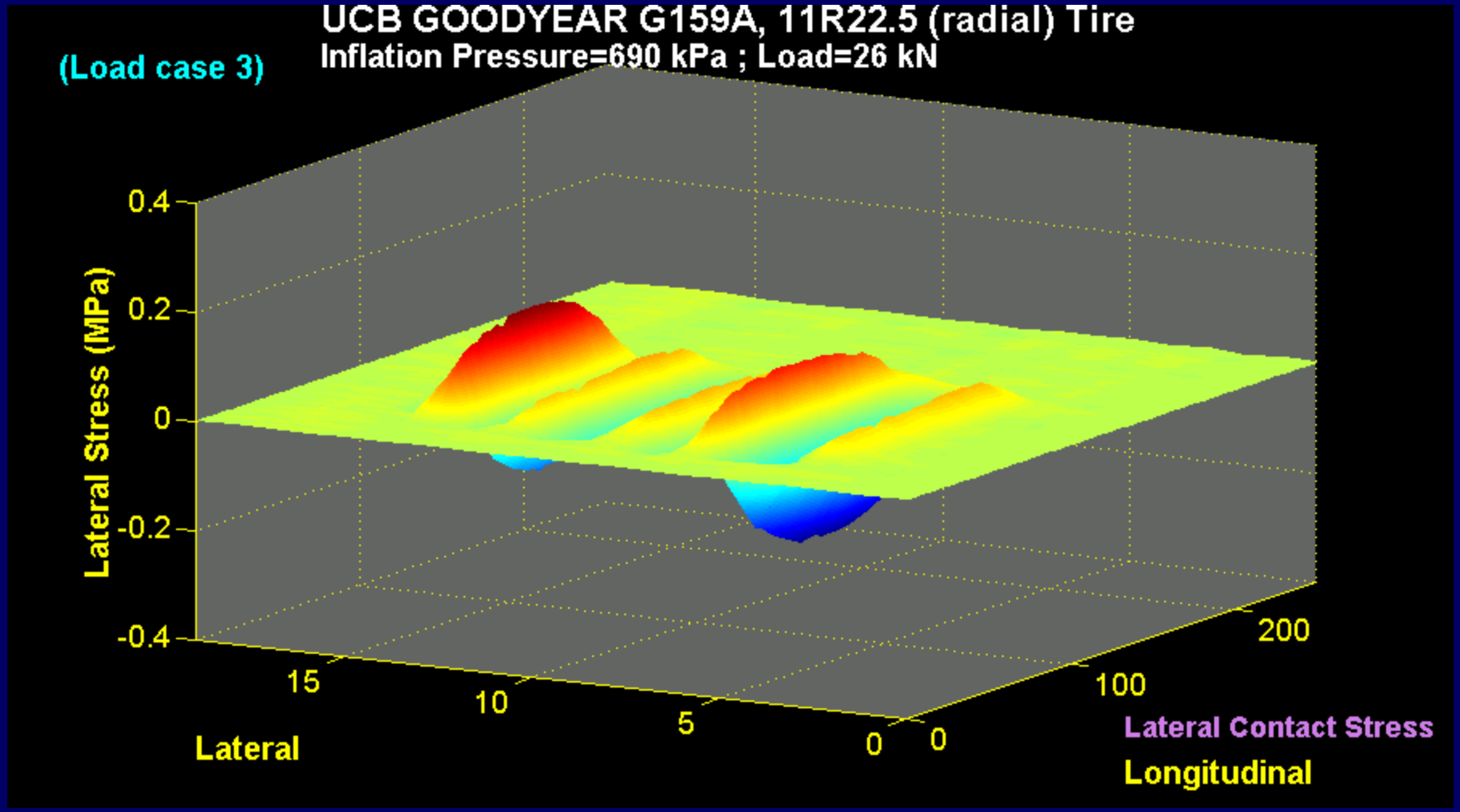


Figure D23
Goodyear, G159A, 11R22.5

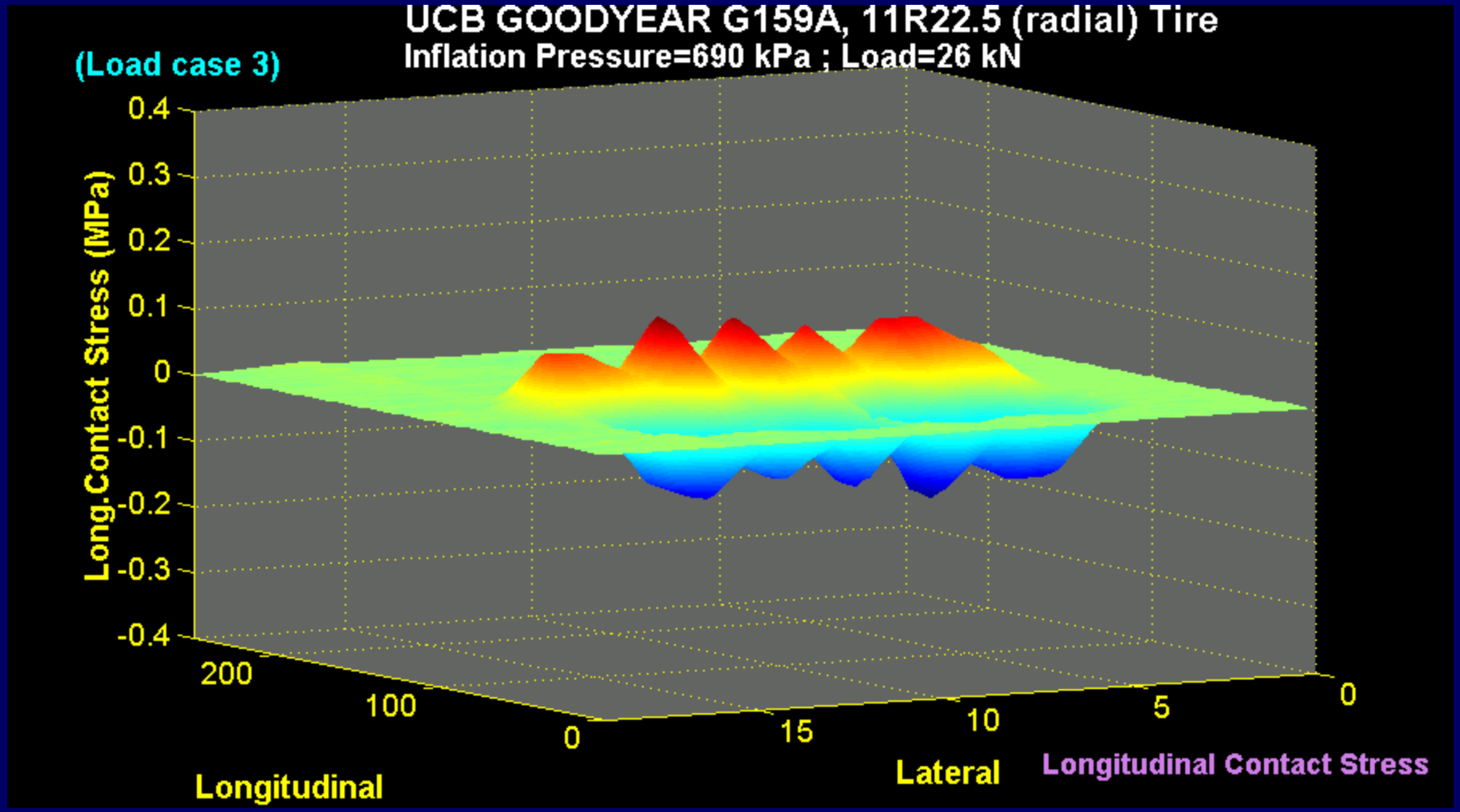
VERTICAL STRESS:



LATERAL STRESS:



LONGITUDINAL STRESS:



Load Case 4:
MEASURED (SIM)
31 kN; 690 kPa:
Vertical Contact Stress
Distribution
and
Static Tyre print:

High loading with
High inflation
Pressure

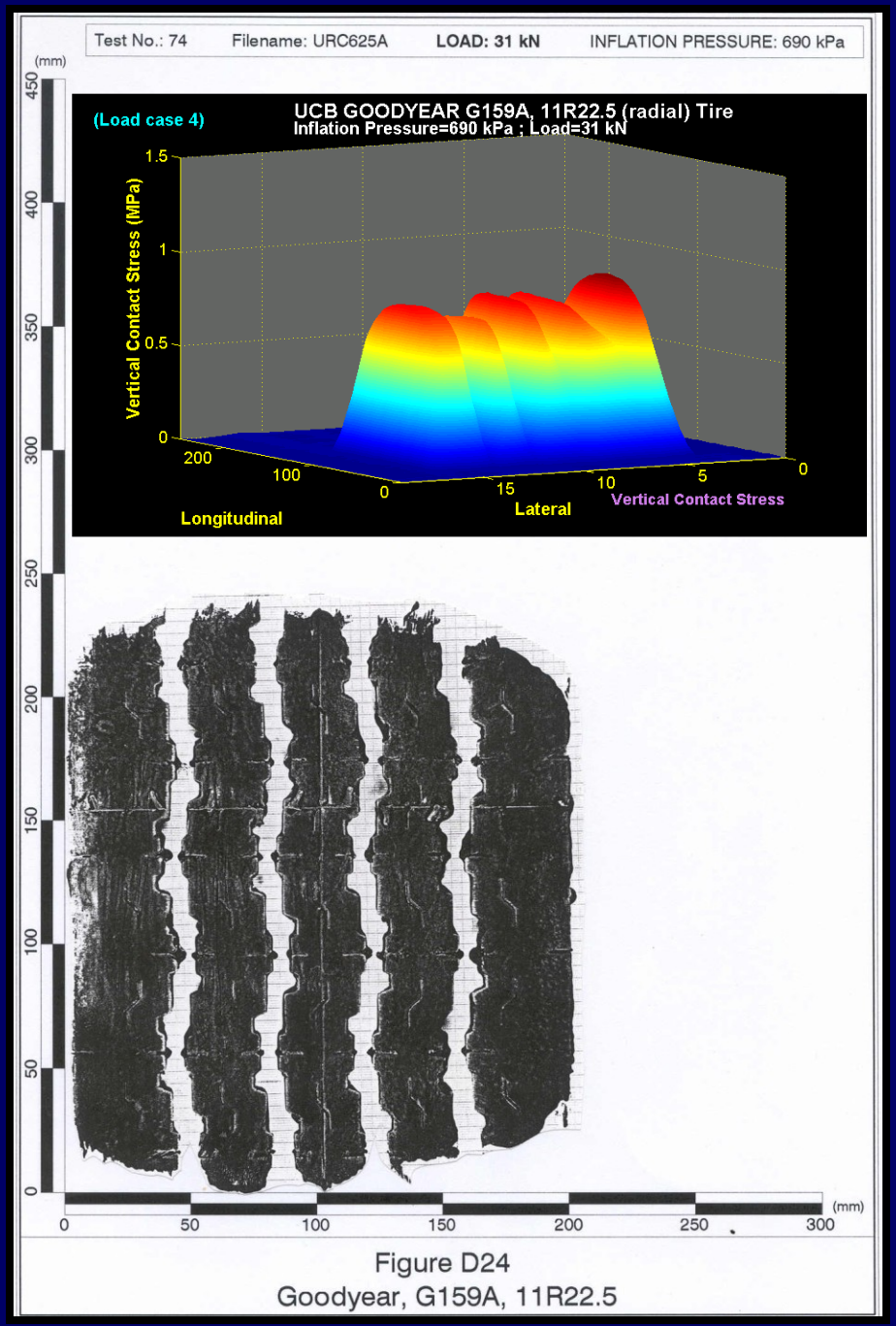
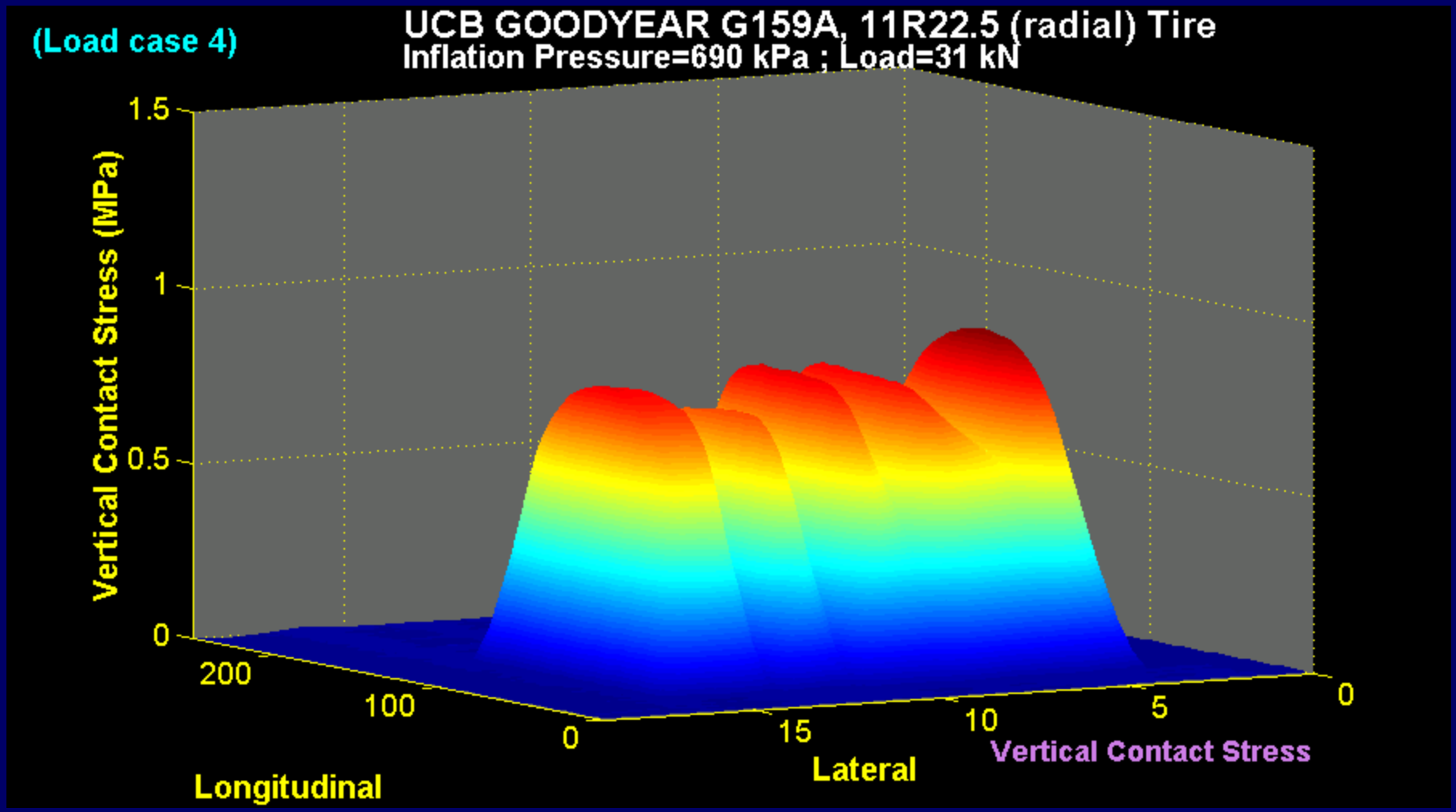
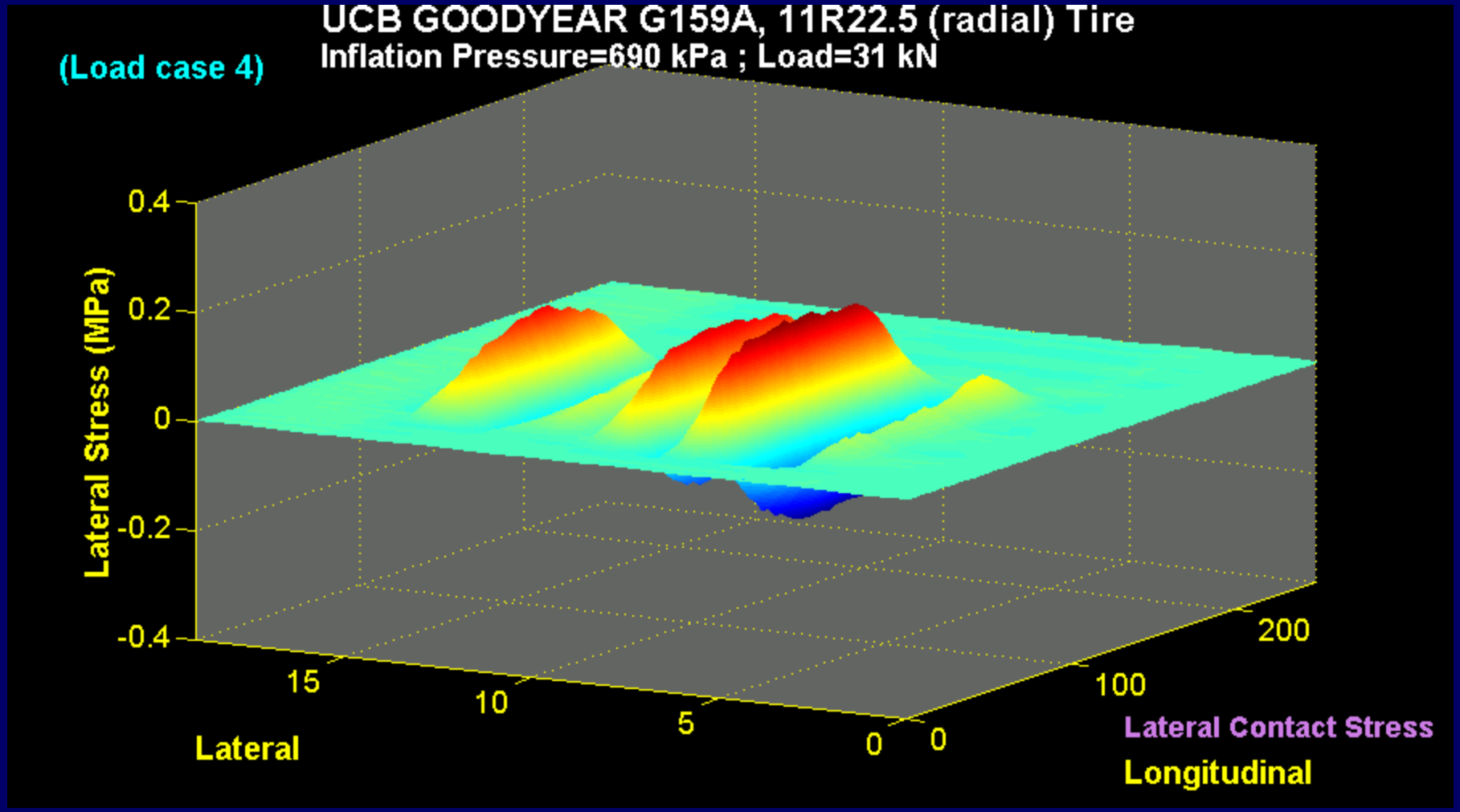


Figure D24
Goodyear, G159A, 11R22.5

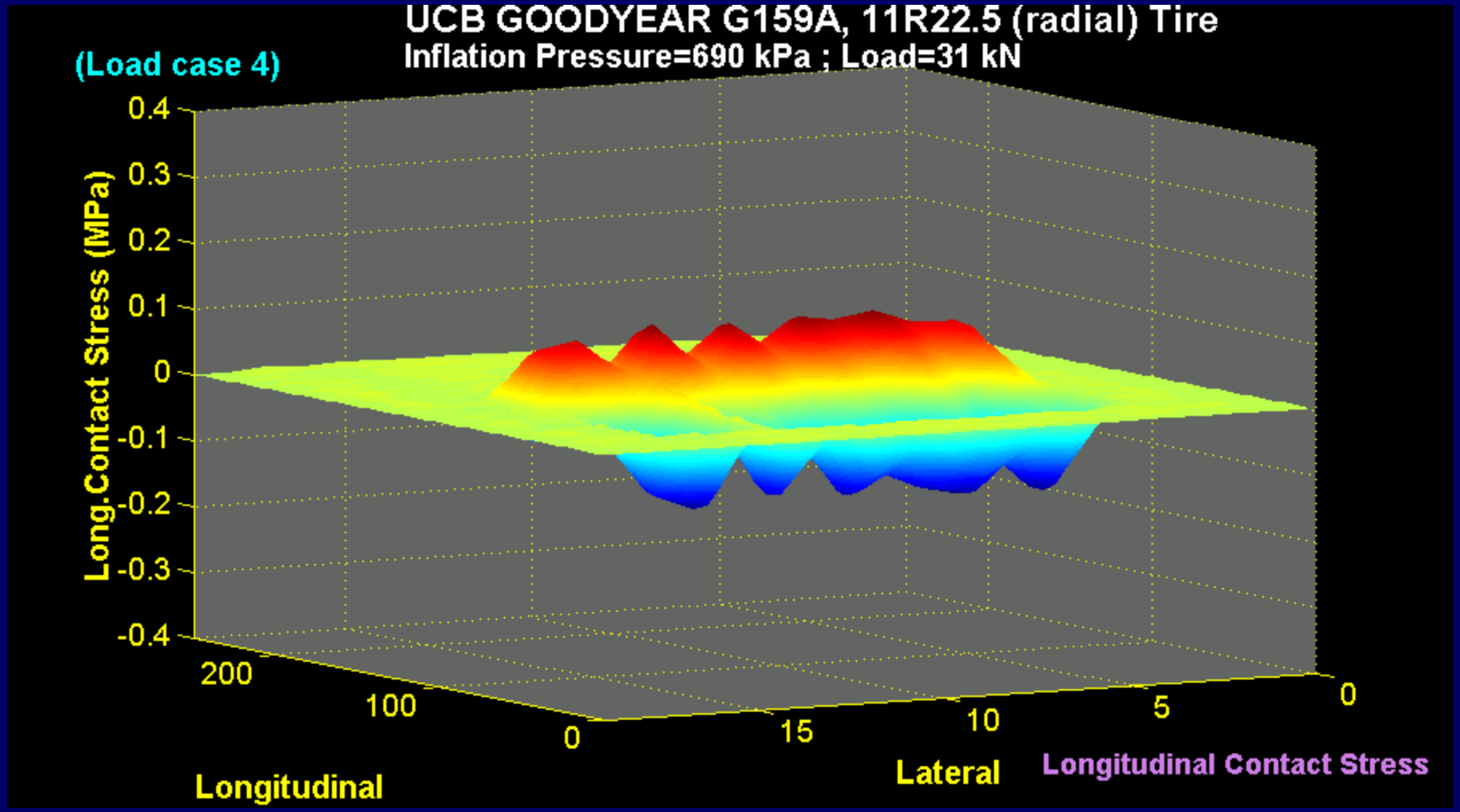
VERTICAL STRESS:



LATERAL STRESS:



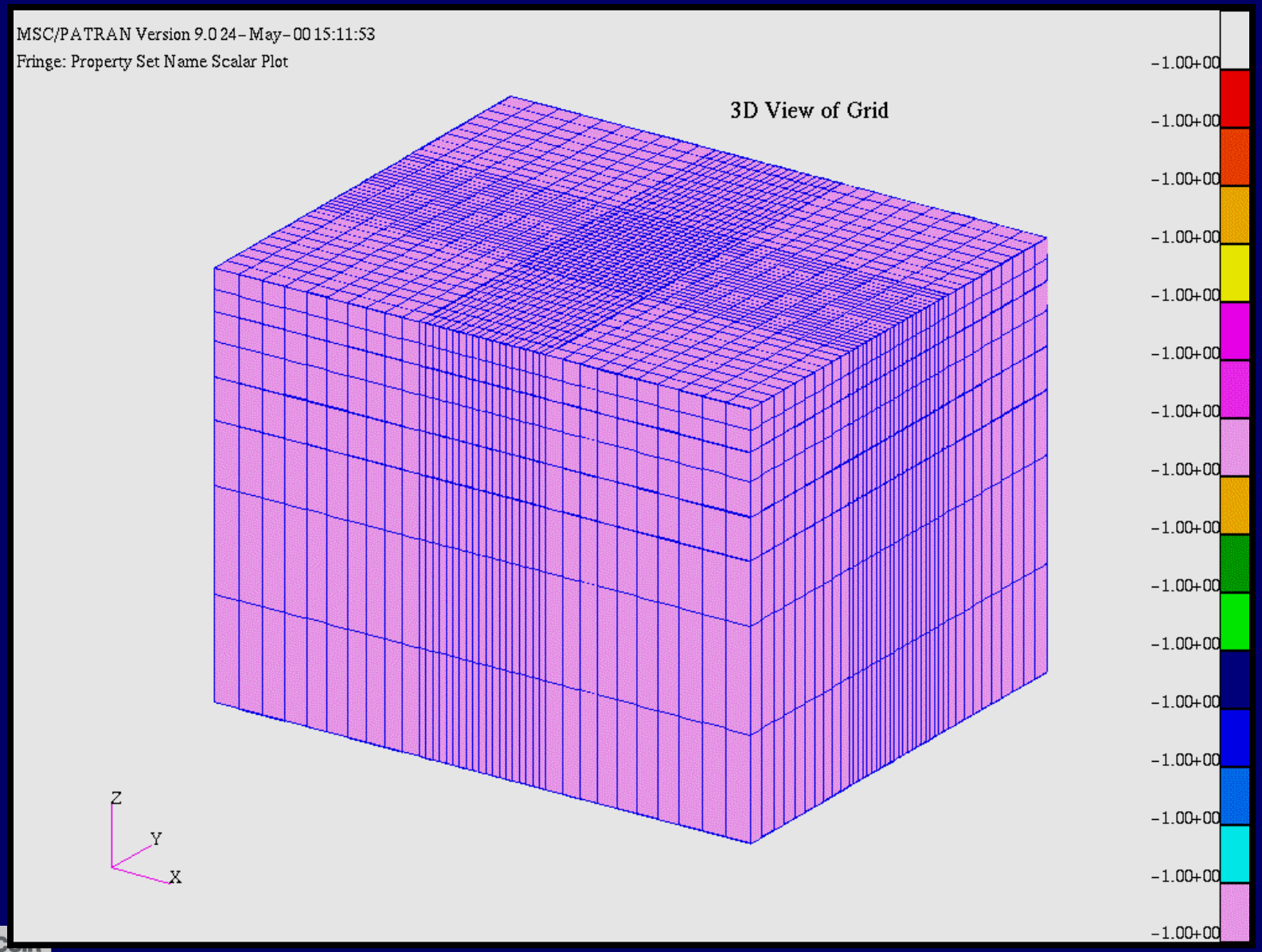
LONGITUDINAL STRESS:



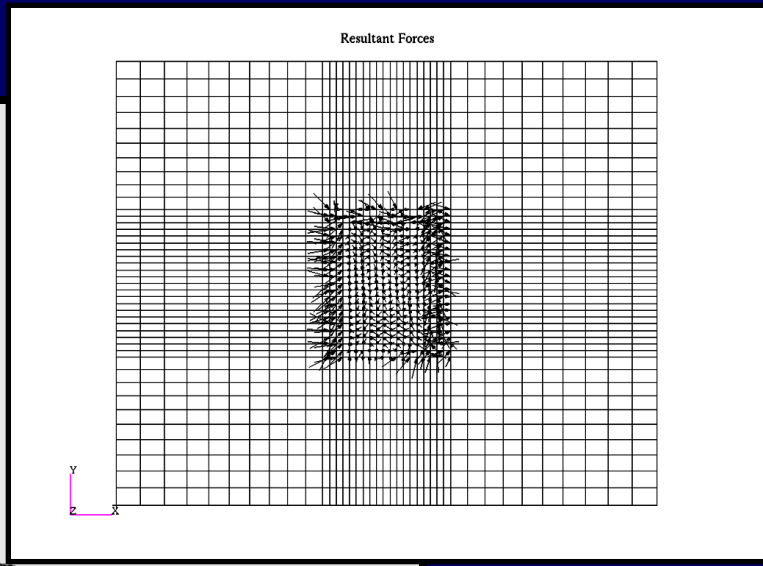
FEM LOAD APPLICATION:

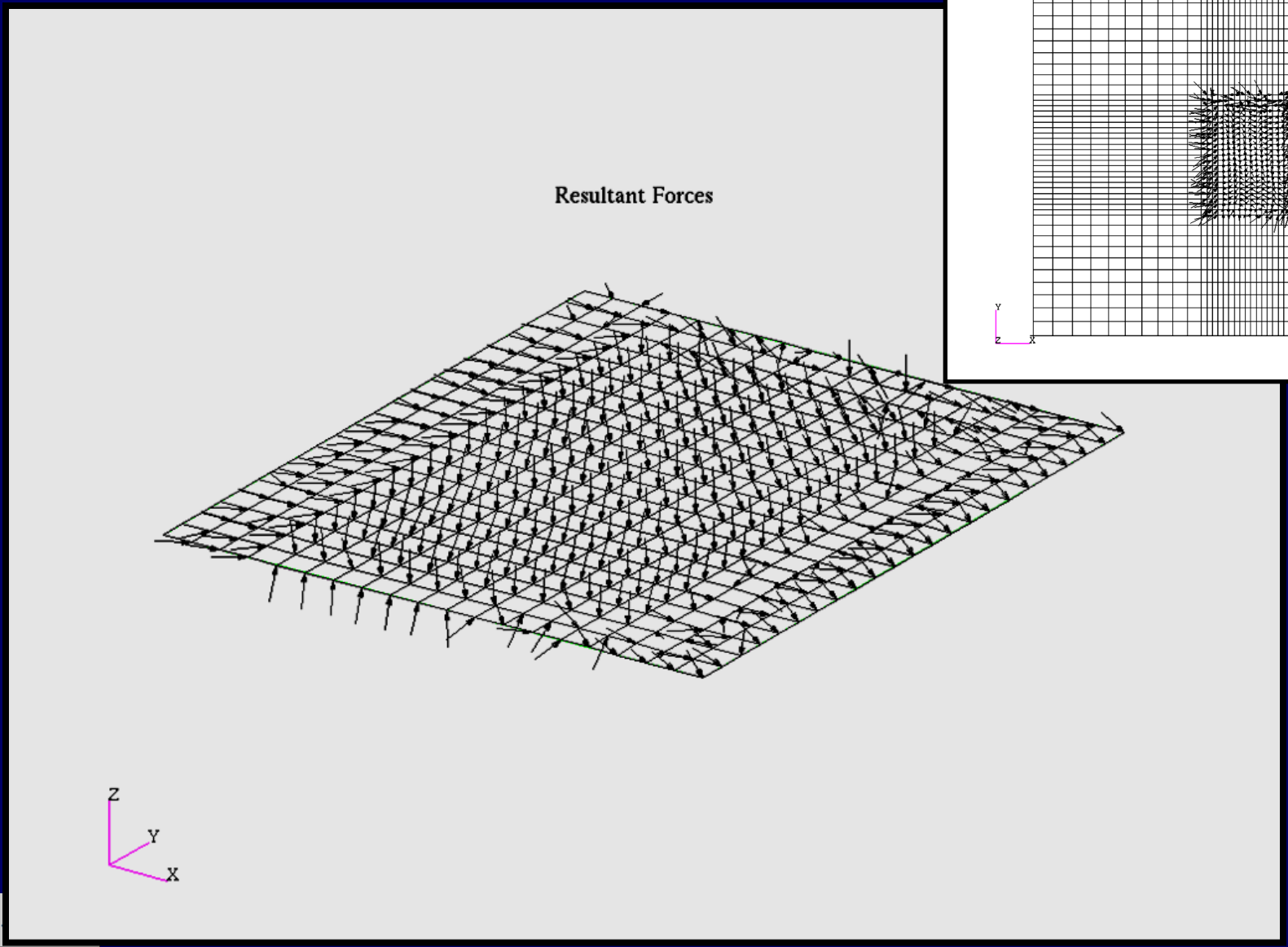
1. Full 3-D SIM loading: X, Y and Z;
2. Separate Component loads: X - only, Y - only and Z - only;
3. All SIM loads defined by approximately 400 to 460 individual discrete loads/forces on the FEM node points;

FEM (NASTRAN) PAVEMENT MODEL

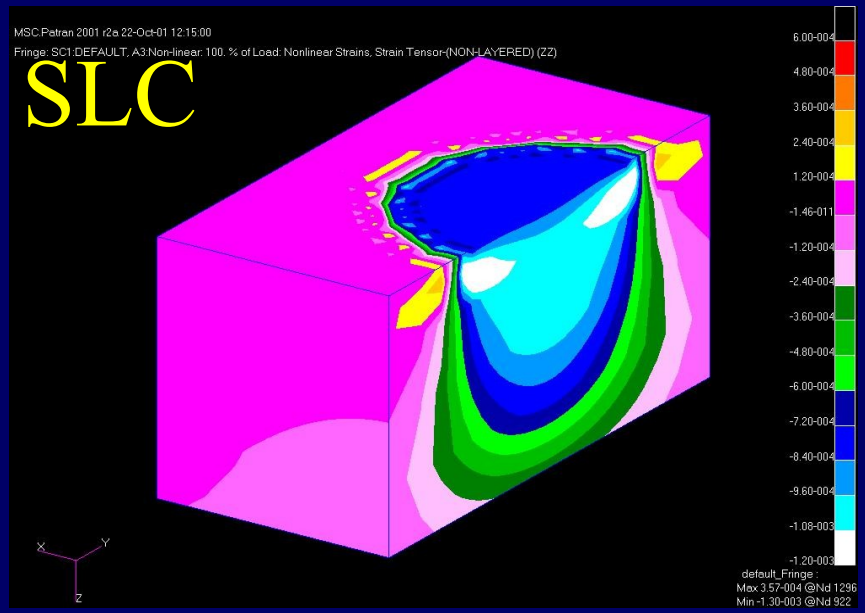


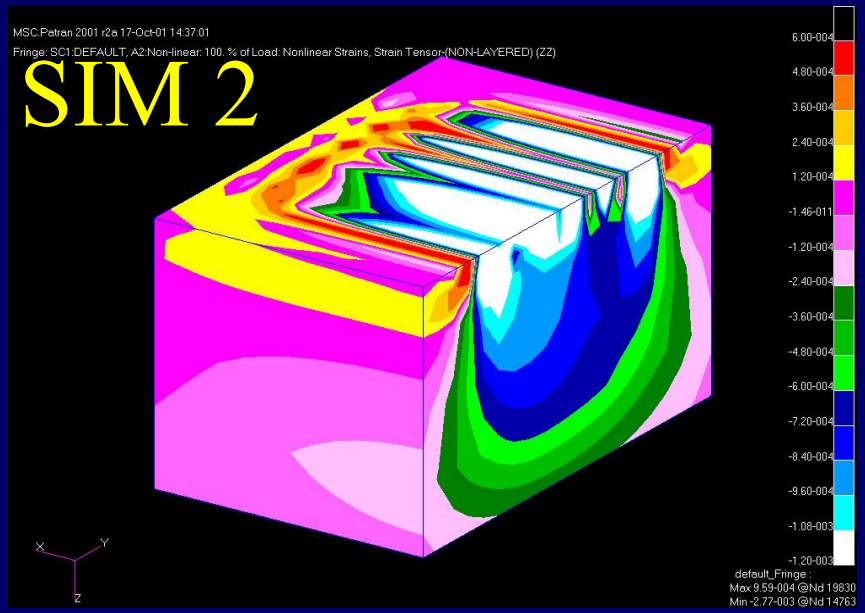
3-D SIM RESULTANT FORCES ON PAVEMENT

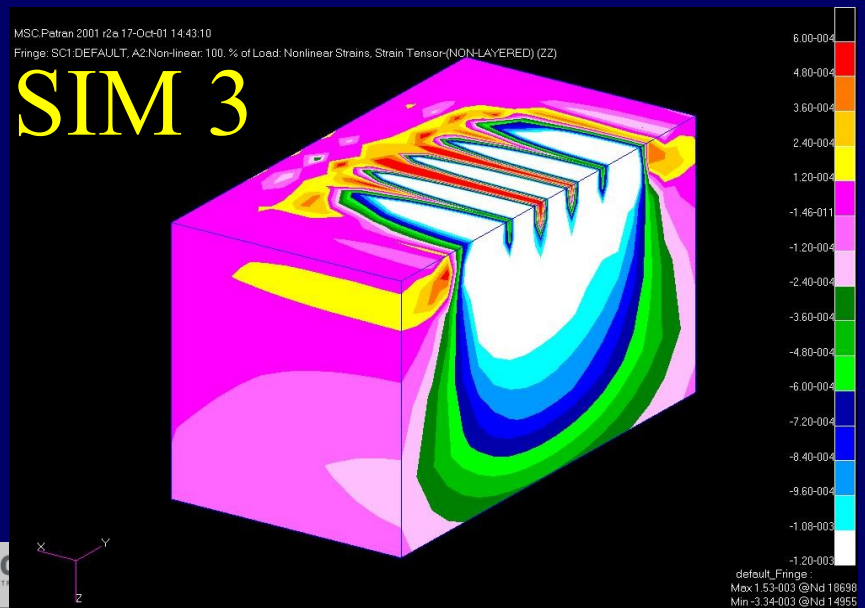


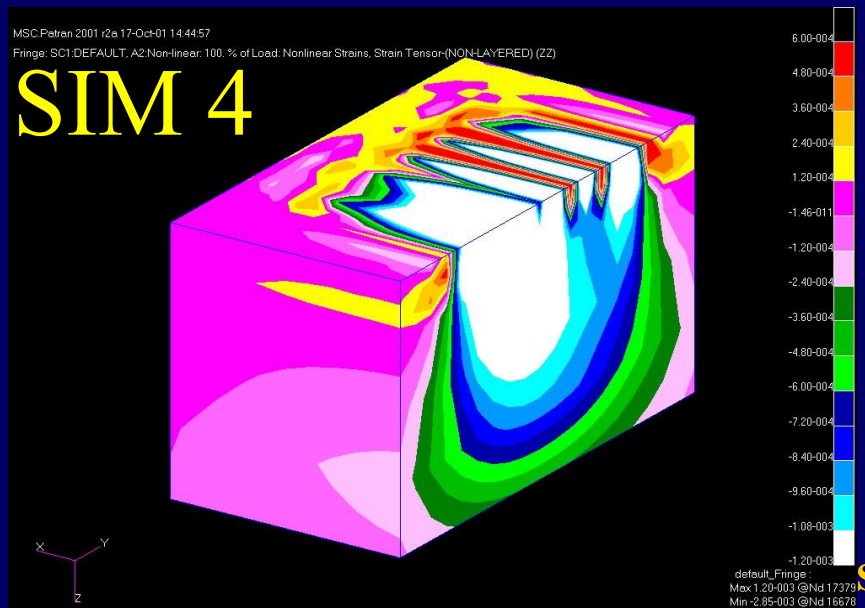


VERTICAL COMPRESSIVE STRAINS (HOT CASE)

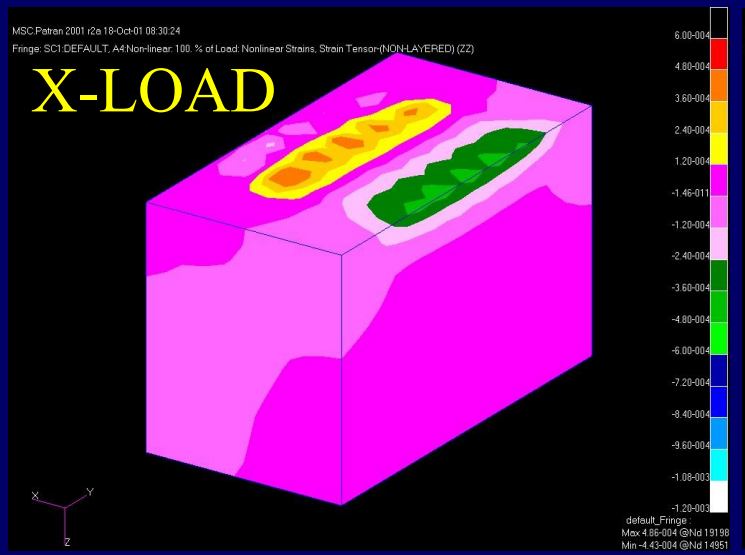


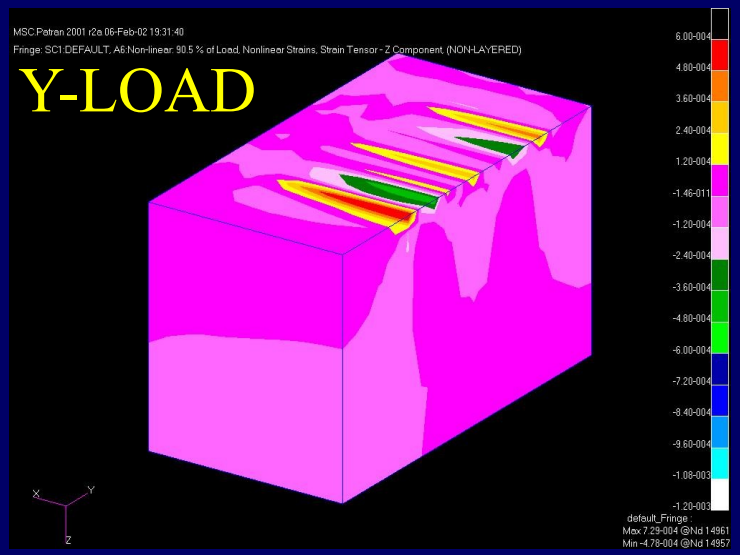


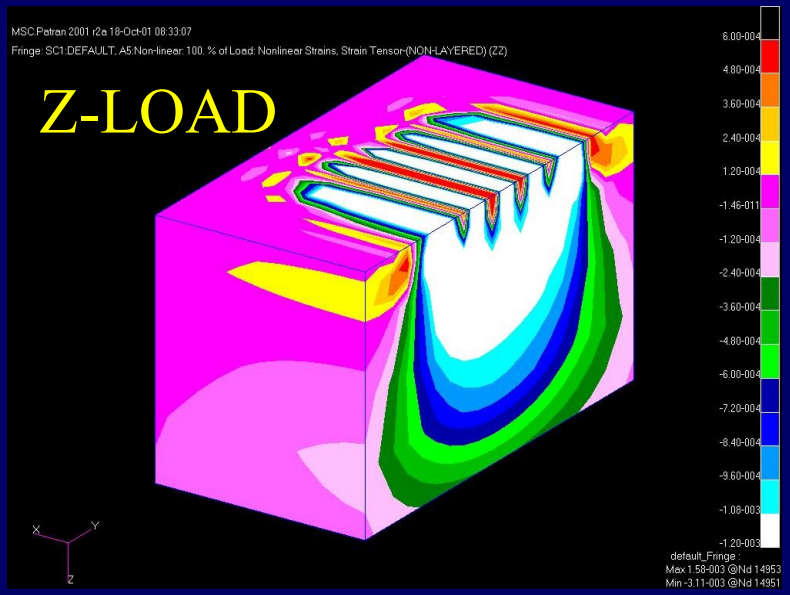




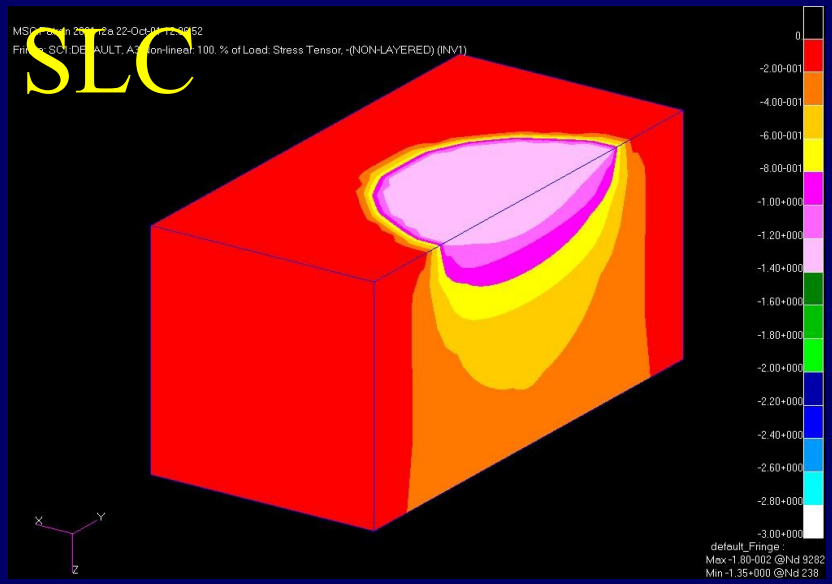
VERTICAL COMPRESSIVE STRAINS (HOT CASE)- X,Y,Z - COMPONENT LOADS

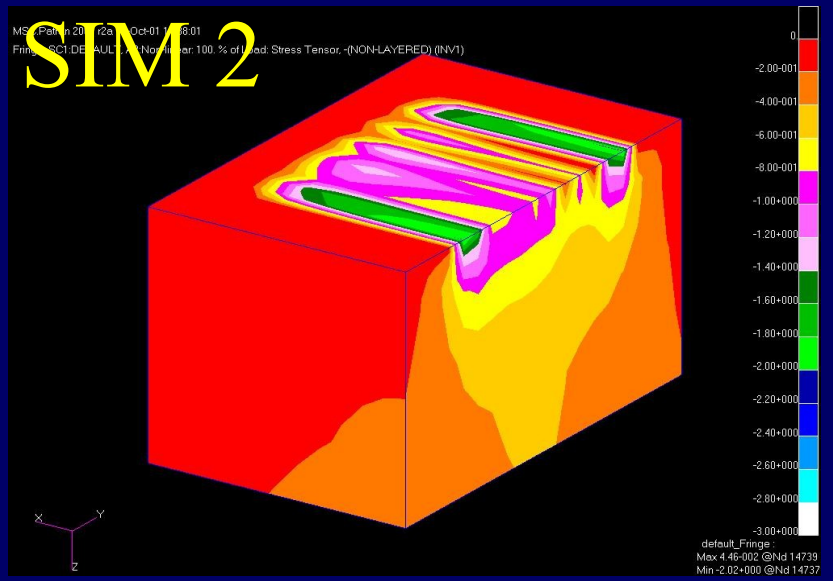


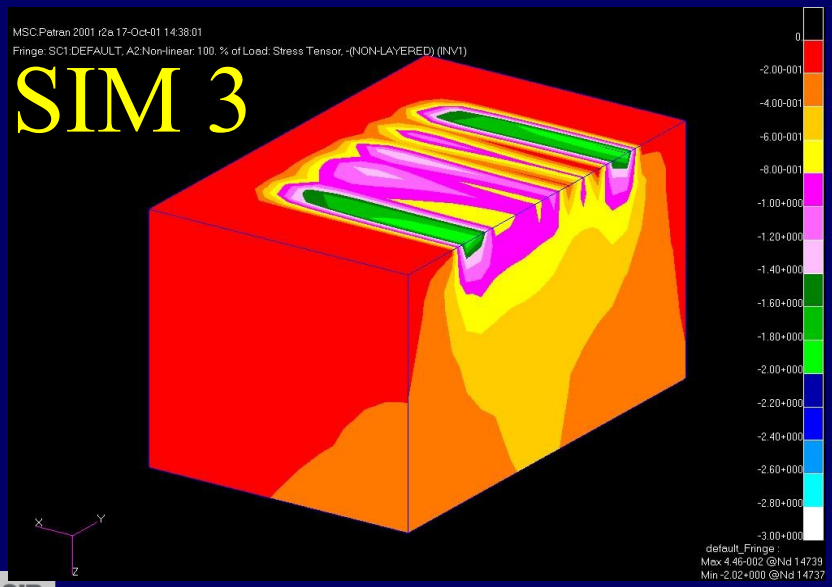


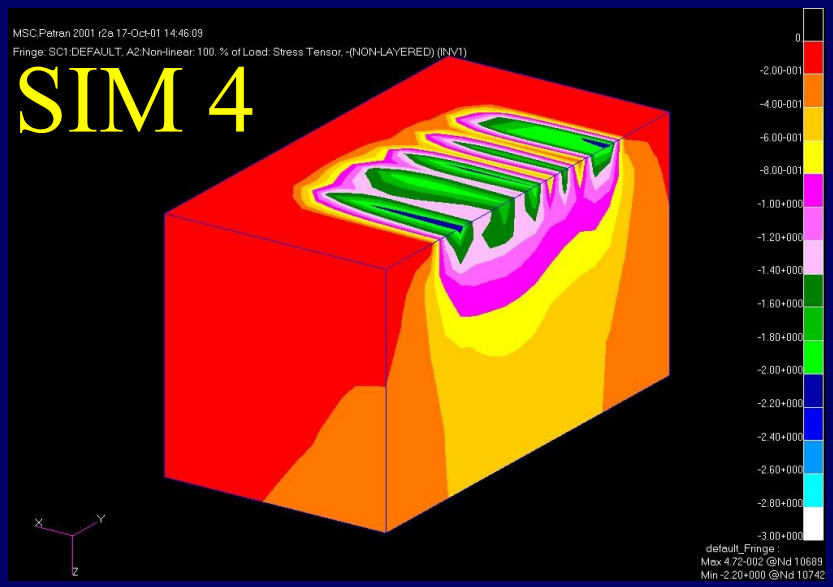


1ST INVARIANT OF STRESS (I_1): HOT CASE

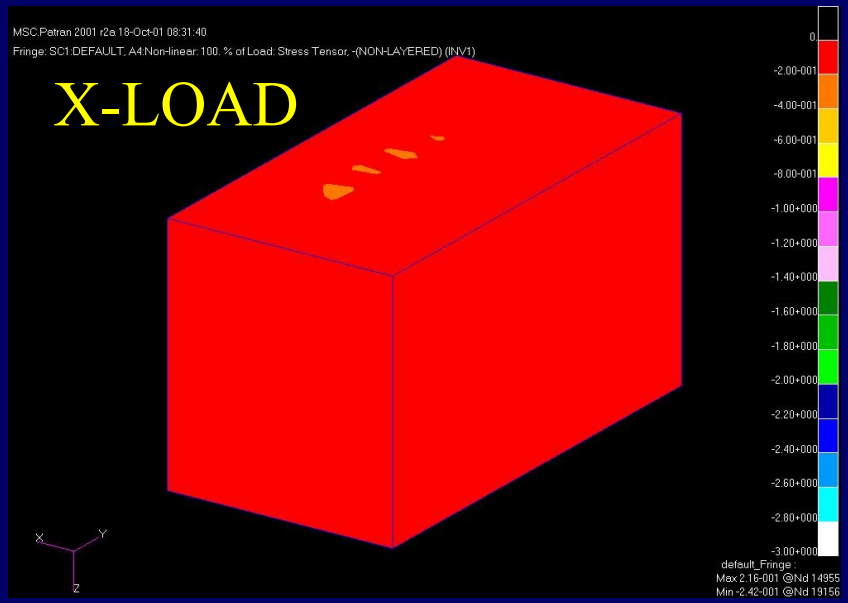


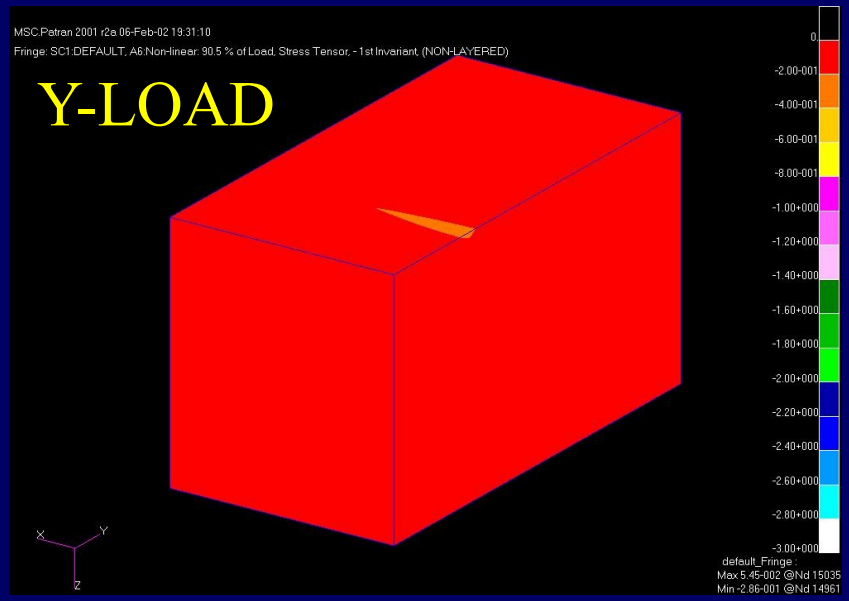


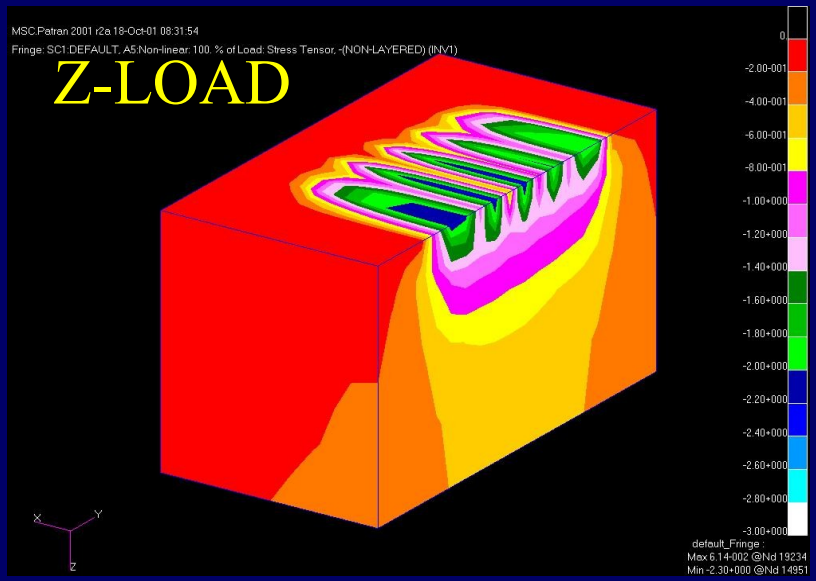




1ST INVARIANT OF STRESS (I_1): (HOT CASE)- X,Y,Z - COMPONENT LOADS



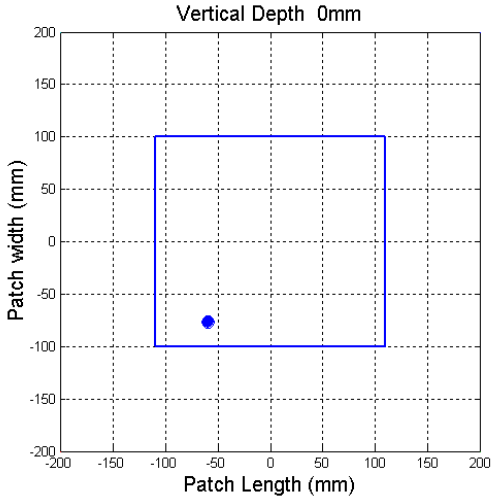


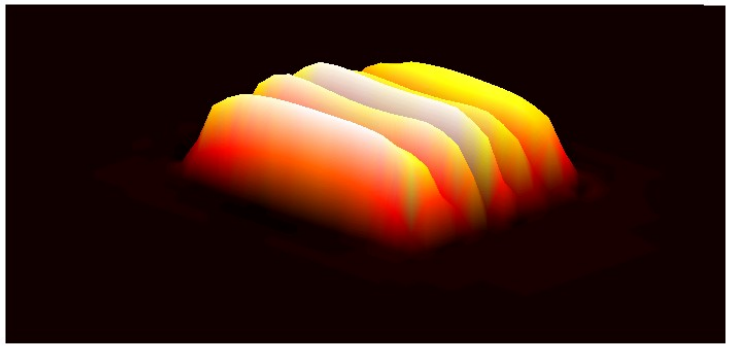


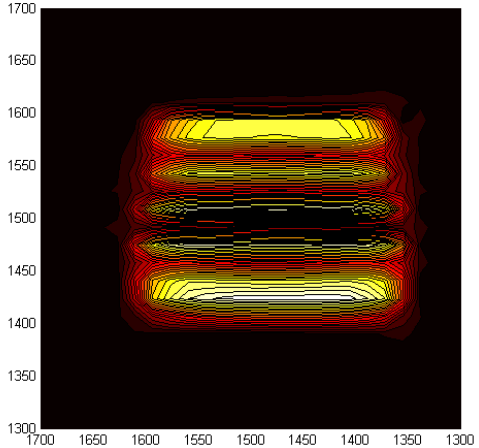
Case 3: SIM: Load 26kN; 690kPa (Nastran)

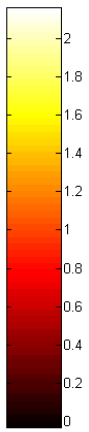
Invariants J1 – Stress Plot (MPa)

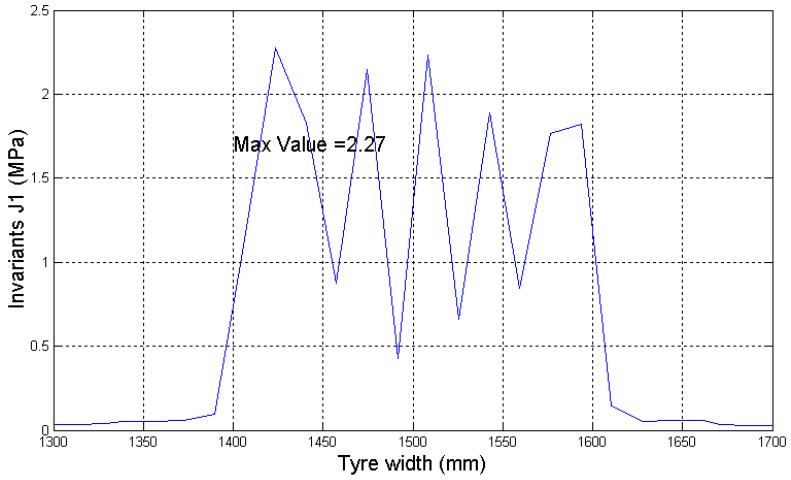
HOT







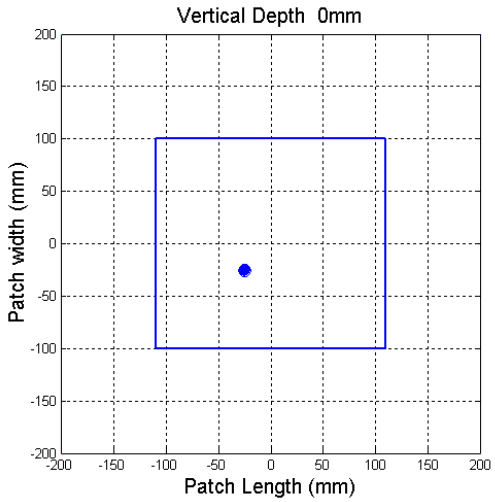


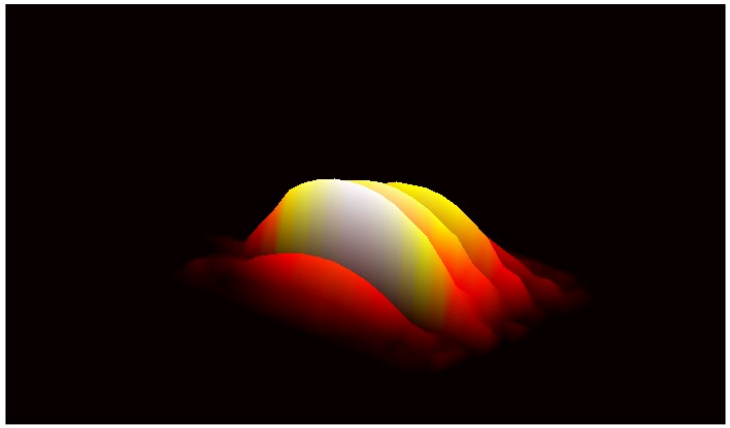


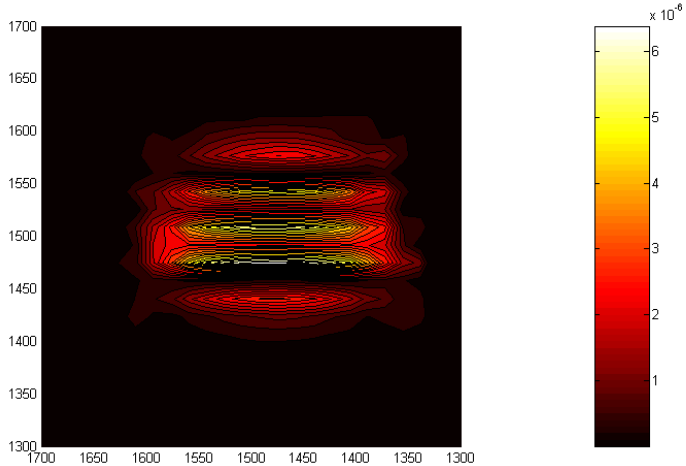
Case 3: SIM: Load 26kN; 690kPa(Nastran)

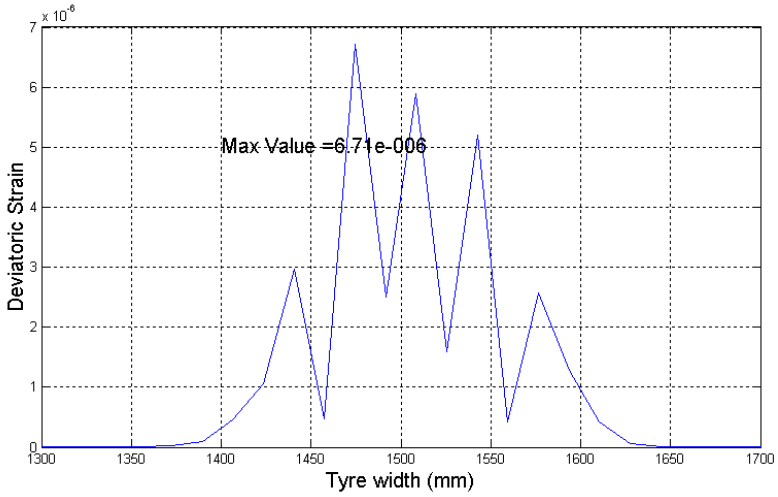
Invariants J2' – Strain Plot (MPa)

HOT





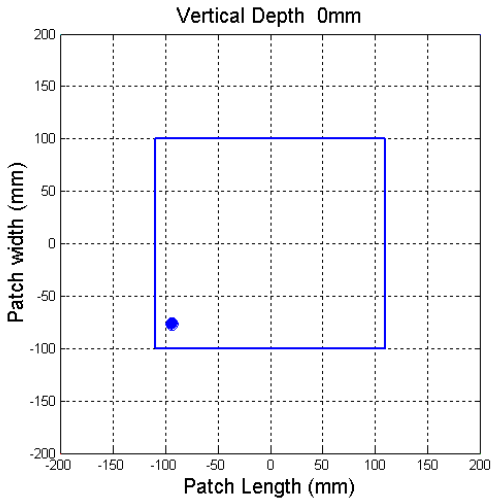


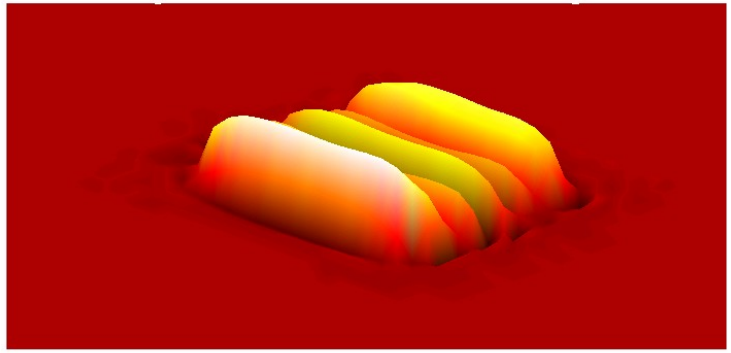


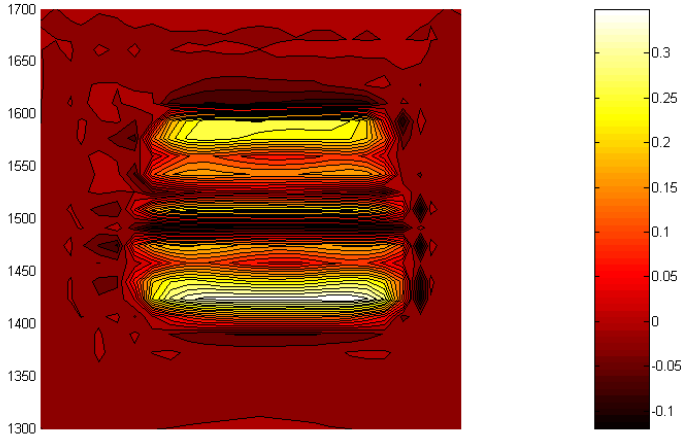
Case 3: SIM: Load 26kN; 690kPa (Nastran)

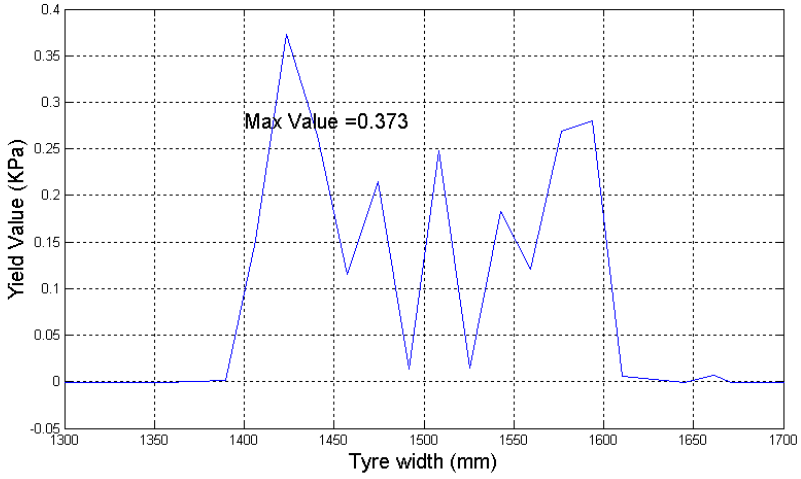
Yield Value Plot (KPa)

HOT









SUMMARY OF RESPONSE DATA

LOAD CASE	Vertical Compressive Strain (ε_{zz})		
	COLD	WARM	HOT
1 (SLC)	802	990	1 297
2 (SIM)	780	861	2 770
3 (SIM)	952	1 117	3 346
4 (SIM)	1 030	1 218	2 932
X-Component			***444 (34 % SLC)***
Y-Component			***478 (37 % SLC)***
Z-Component			***3 119 (2.4 X SLC)***

SUMMARY OF RESPONSE DATA

LOAD CASE	Maximum Second Invariant of Deviatoric Strain (J'_2 - Strain) (Shear Potential ?)		
	COLD	WARM	HOT
1 (SLC)	0.349	0.539	1.046
2 (SIM)	0.316	0.390	5.360
3 (SIM)	0.483	0.674	6.710
4 (SIM)	0.564	0.833	5.159
X-Component			***0.451 (40 % SLC)***
Y-Component			***0.712 (70 % SLC)***
Z-Component			***6.110 (5.8 X SLC)***

Mohr-Coulomb Yield Criterion

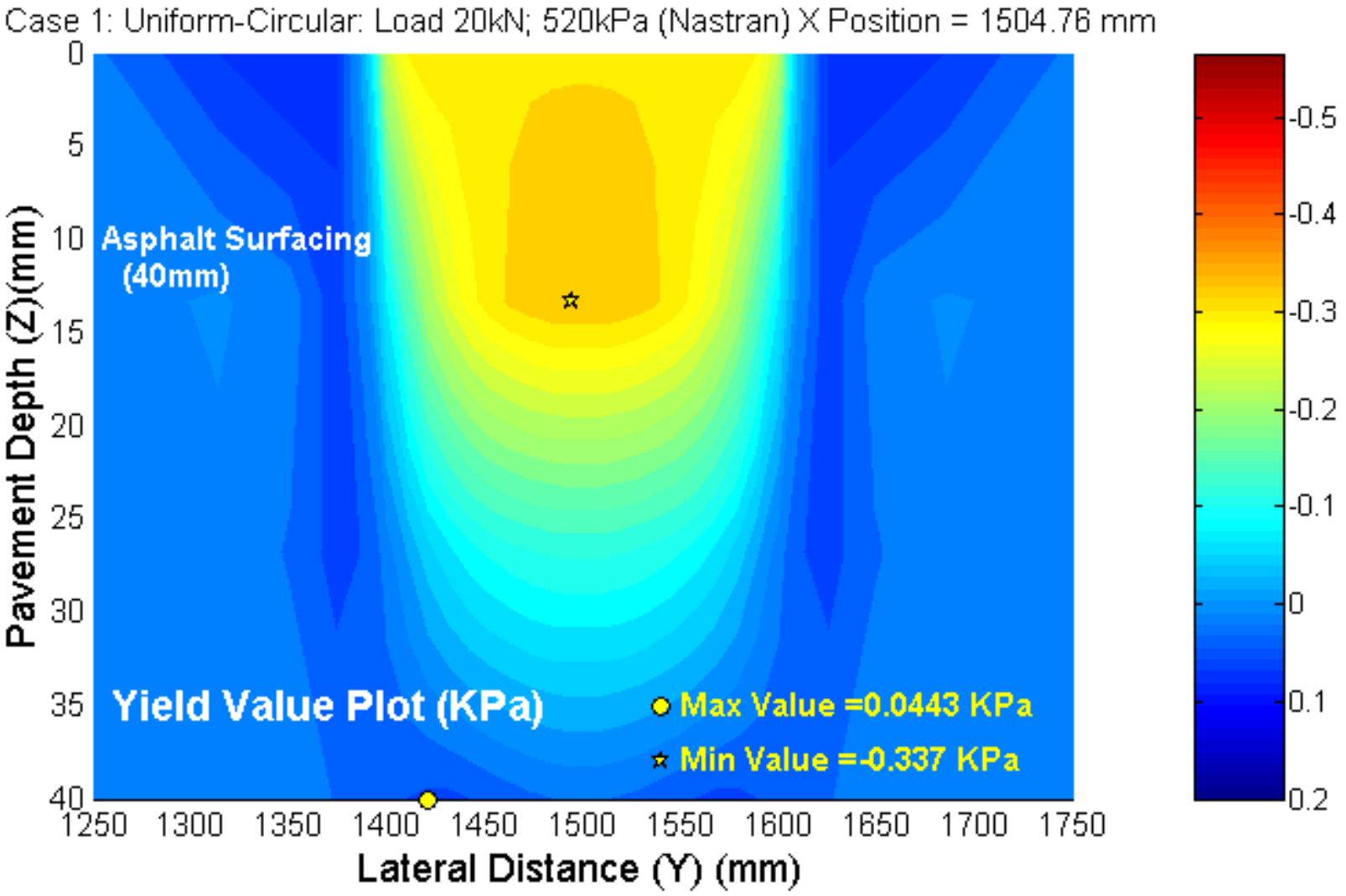
$$s = c + \sigma \tan\phi$$

$$\frac{1}{3} J_1 \sin\phi - \sqrt{J_2'} \left(\cos\theta - \frac{1}{\sqrt{3}} \sin\theta \sin\phi \right) = c \cos\phi$$

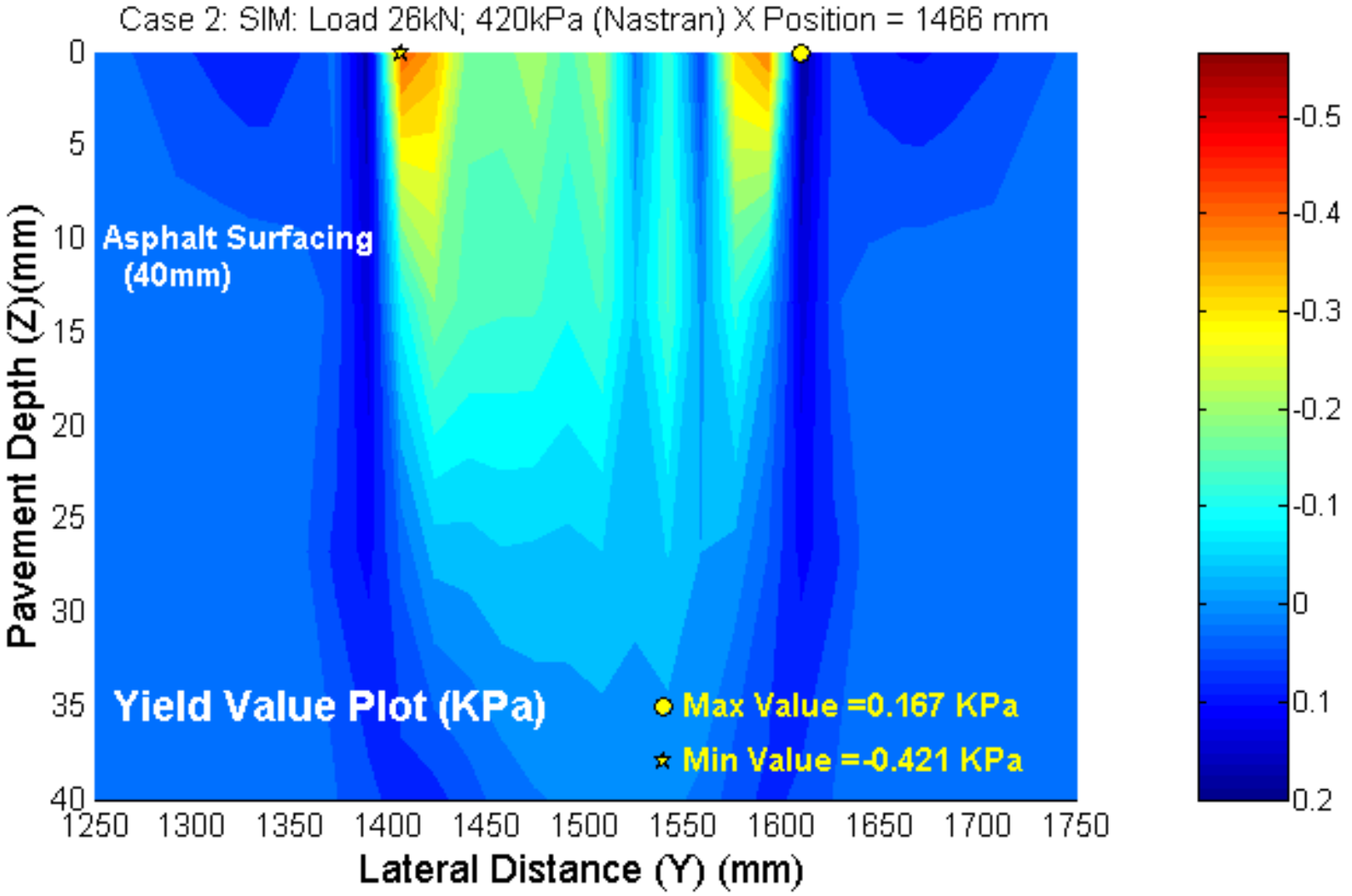
$$\sin 3\theta = -\frac{\sqrt{3}}{2} \frac{J_3'}{\left(J_2' \right)^{\frac{3}{2}}}$$

J'_i = the 1st, 2nd and 3rd stress invariants;

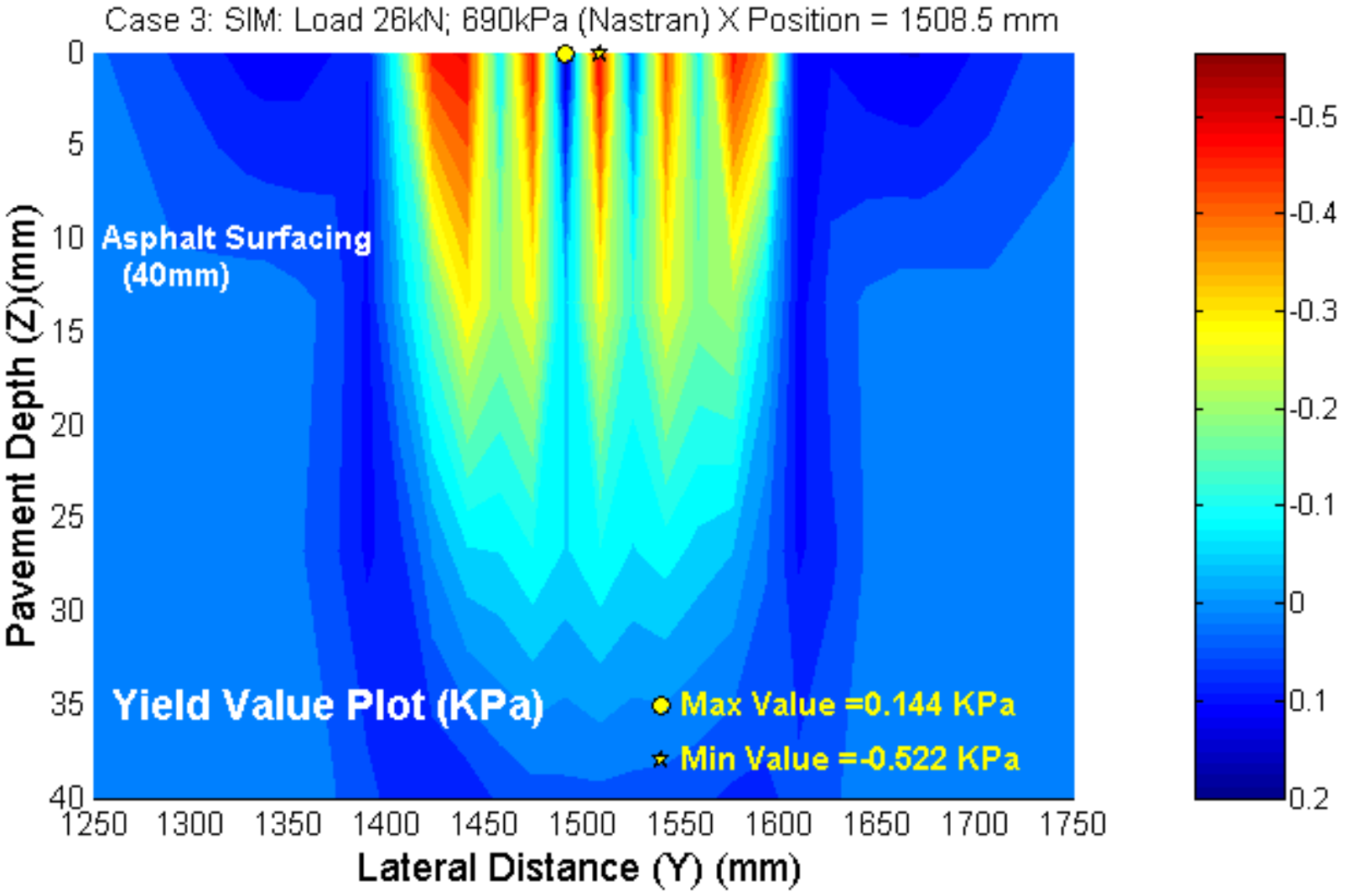
Yield Value Case 1: SLC



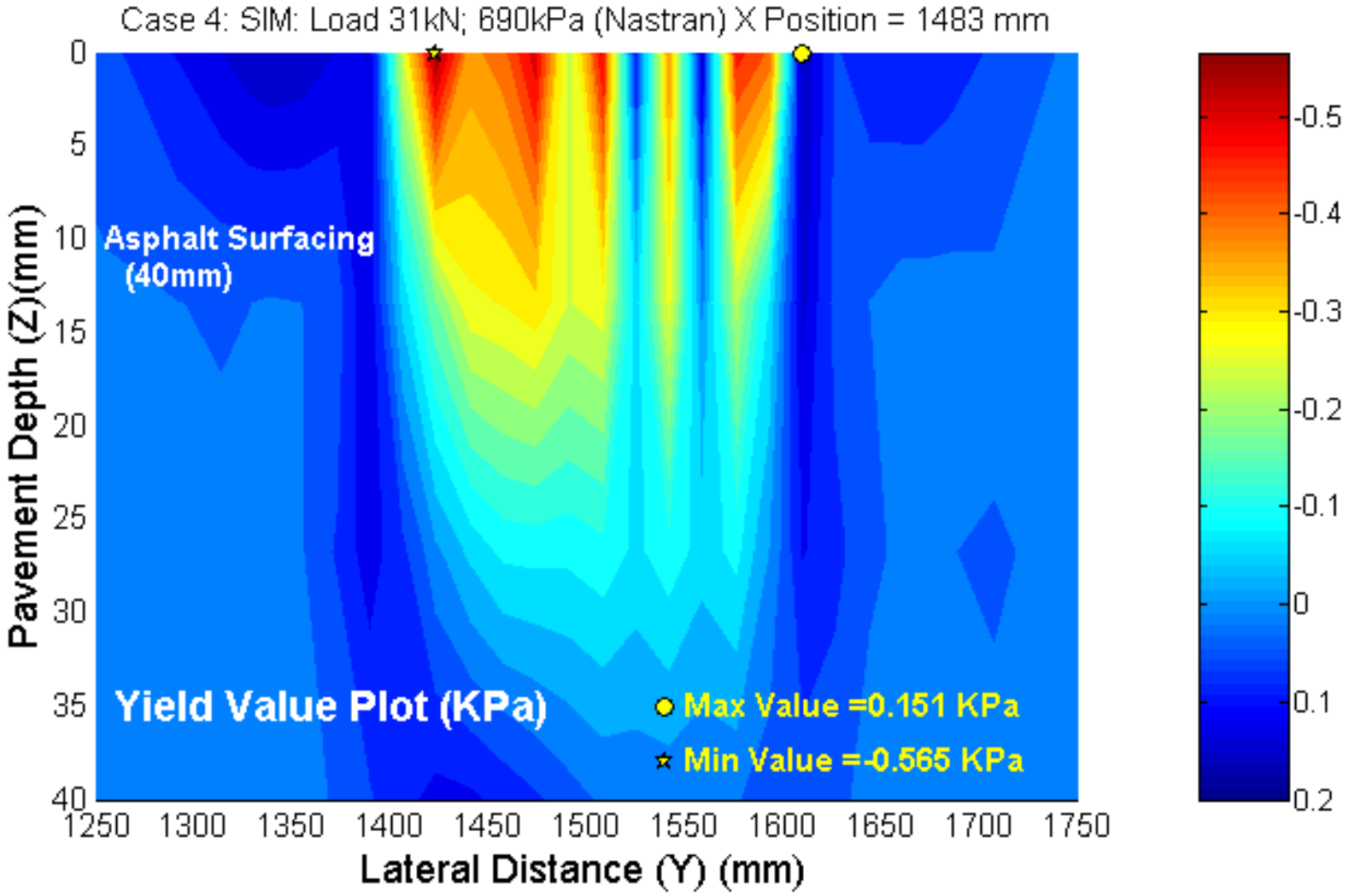
Yield Value Case 2: Low pressure



Yield Value Case 3: Correct loading/pressure



Yield Value Case 4: High loading/High pressure



SUMMARY OF RESPONSE DATA

LOAD CASE	CALCULATED YIELD POTENTIAL		
	COLD	WARM	HOT
1 (SLC)	555 (38 %)	337 (58 %)	267 (228 %)
2 (SIM)	461 (32 %)	421 (72 %)	305 (261 %)
3 (SIM)	600 (41 %)	522 (89 %)	373 (319 %)
4 (SIM)	710 (49 %)	565 (97 %)	369 (315 %)
X-Component			***132 (113 %)***
Y-Component			***56 (48 %)***
Z-Component			***384 (328 %)***

( ) = Percentage Yield

COMPARISONS BETWEEN LOAD CASES *(HOT CASE SIM LOAD relative to SLC):*

- Vertical Strain: 2.1 to 2.6 times higher;
- Vertical Stress: 1.7 to 2.1 times higher;
- Bulk Stress: 1.5 to 1.7 times higher;
- J'_2 - Strain: 5.1 to 6.4 times higher;
- J'_2 - Stress: 2.9 to 6.3 times higher;
- Potential Yield: 1.14 to 1.4 times higher.

CONTRIBUTIONS FROM X,Y,Z COMPONENT LOADS: *(HOT CASE SIM LOAD relative to SLC):*

- Vertical Strain: X and Y: 34 to 37 per cent, 250 per cent for Z;
- Vertical Stress: X and Y: 5 to 7 per cent, 220 per cent for Z;
- Bulk Stress (I_1): X and Y: 18 to 21 per cent, 170 per cent for Z;
- J'_2 – Strain: X and Y: 40 to 70 per cent, 580 per cent for Z;
- J'_2 - Stress: X and Y: 28 to 39 per cent, 300 per cent for Z;
- Potential Yield: X and Y: 21 to 49 per cent, 150 per cent for Z.

PART 1: CONCLUSIONS ON 6 RESPONSE PARAMETERS:

- Calculated Stress and Strain response reflects non-uniformity of the applied load inputs;
- All six response parameters – sensitive to shape and distribution of loading;
- Sensitivity increase with lower AC modulus (i.e. hot conditions);
- Strain parameters seem to be more sensitive to load shape & distribution than stress parameters;
- Sensitivity increase closer to the load application;
- Elastic "Strain-based" transfer functions for damage ?

MODELED PAVEMENT STRUCTURE – Semi-Analytical-FEM

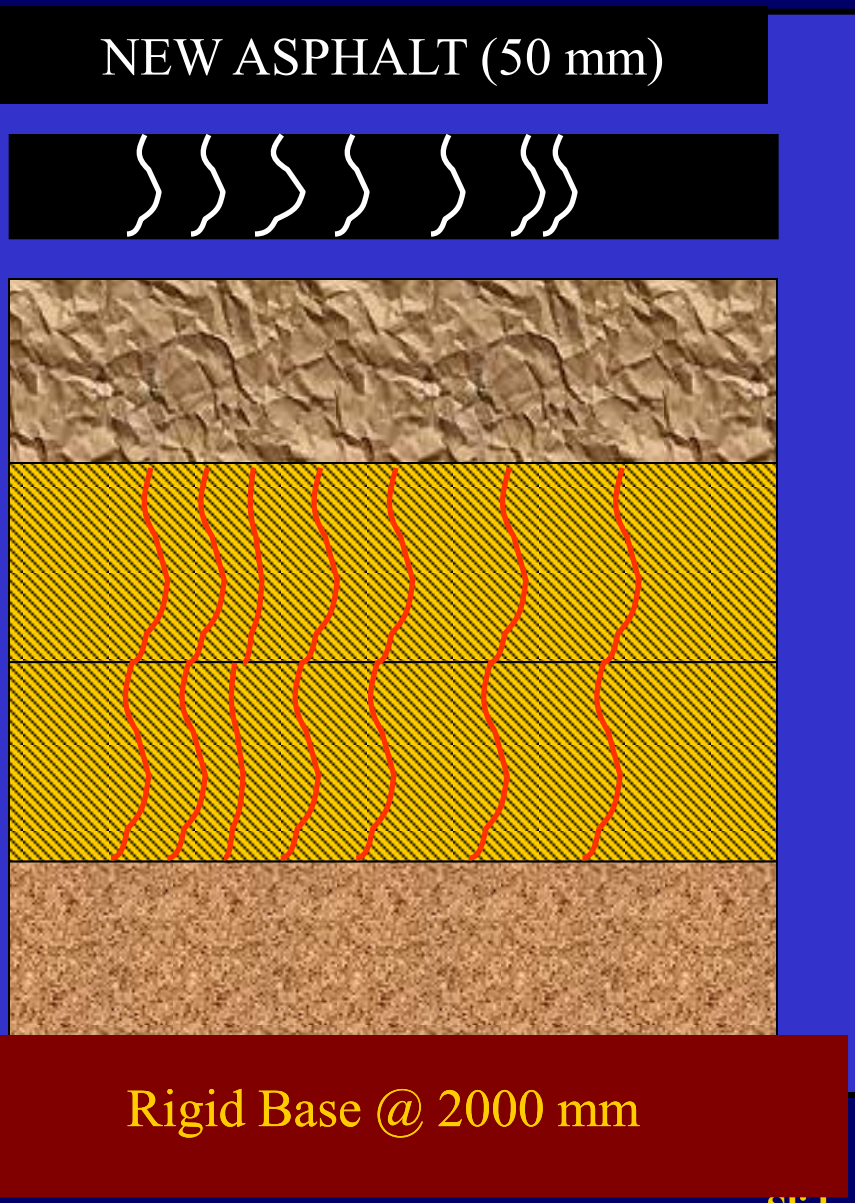
New Asphalt Surfacing: 50 mm
(E_1 = 2500 MPa, ν_1 = 0.44);

Old Cracked Asphalt: 50 mm
(E_2 = 3000 MPa, ν_2 = 0.44);

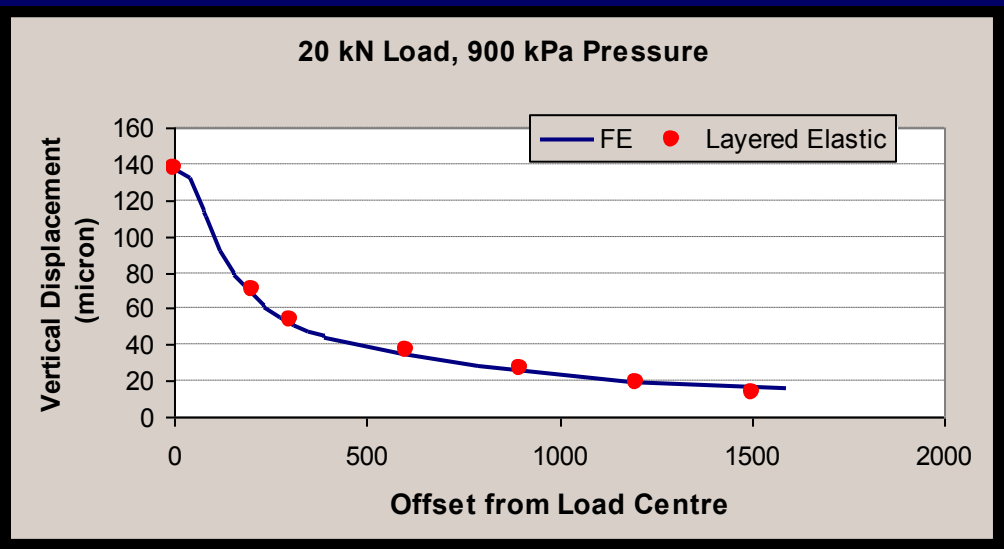
Crushed Stone Base: 150 mm
-NON-LINEAR (Witczak & Uzan, 1988);

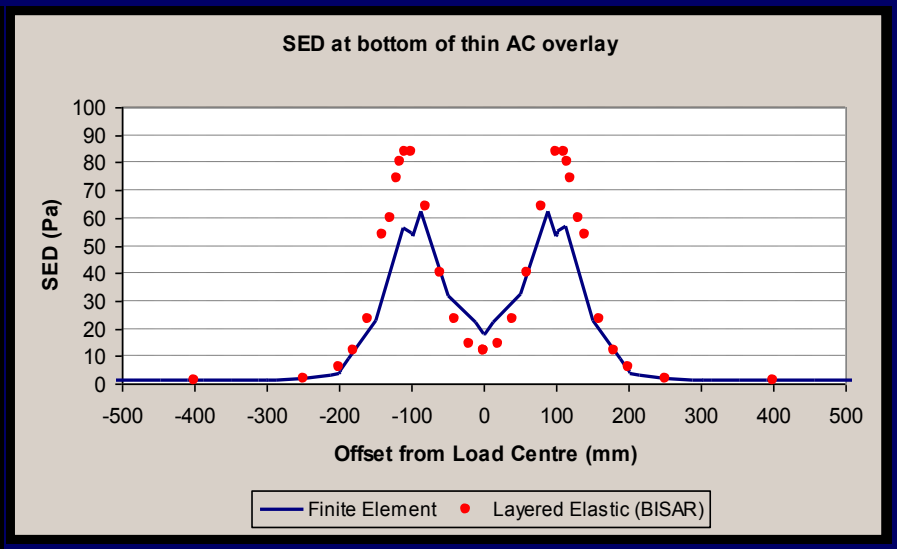
Cementitious Subbase-1: 2 x150 mm
(E_4 = 1800 MPa, ν_4 = 0.35)

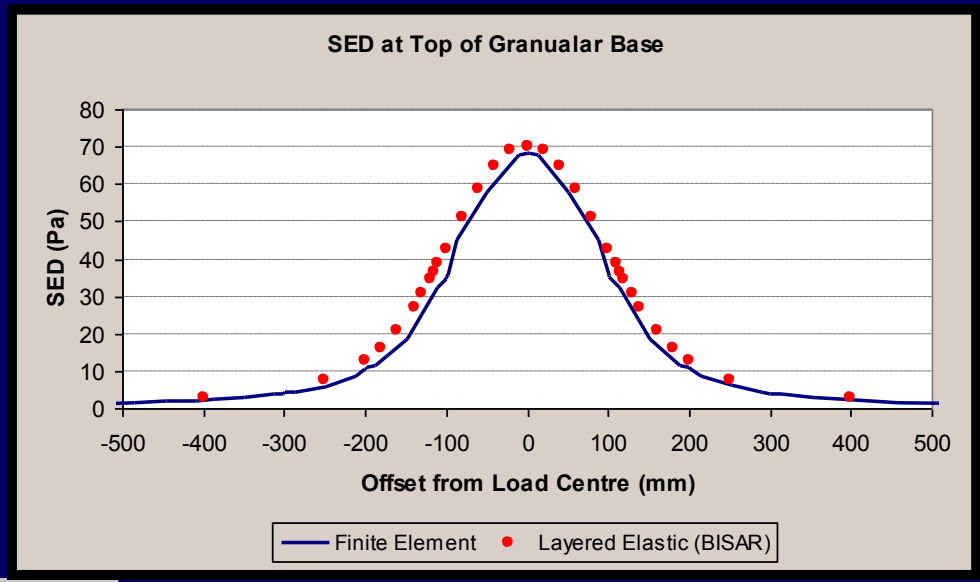
Soil Subgrade: 2000 mm
(E_5 = 100 MPa, ν_5 = 0.35)

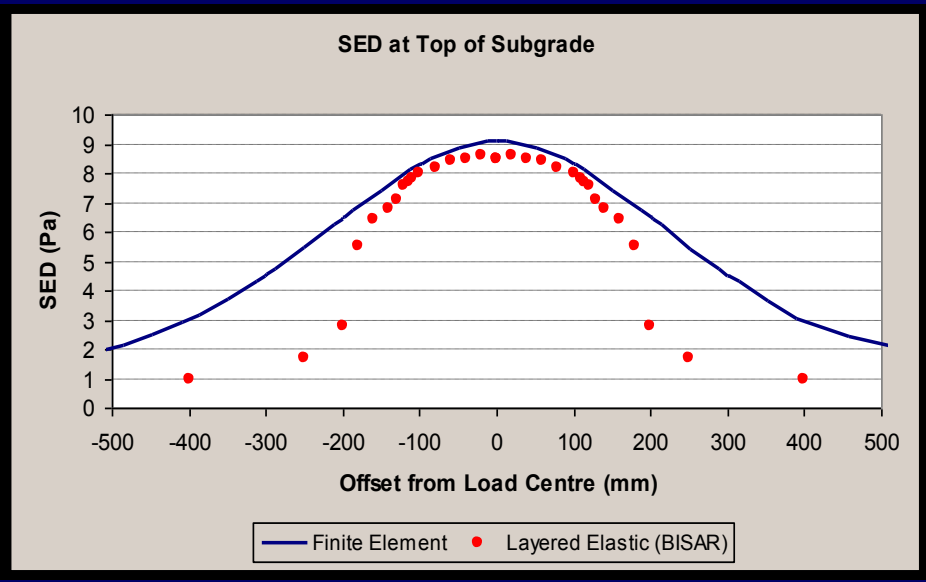


Benchmark- Semi-Analytical FEM-MLE

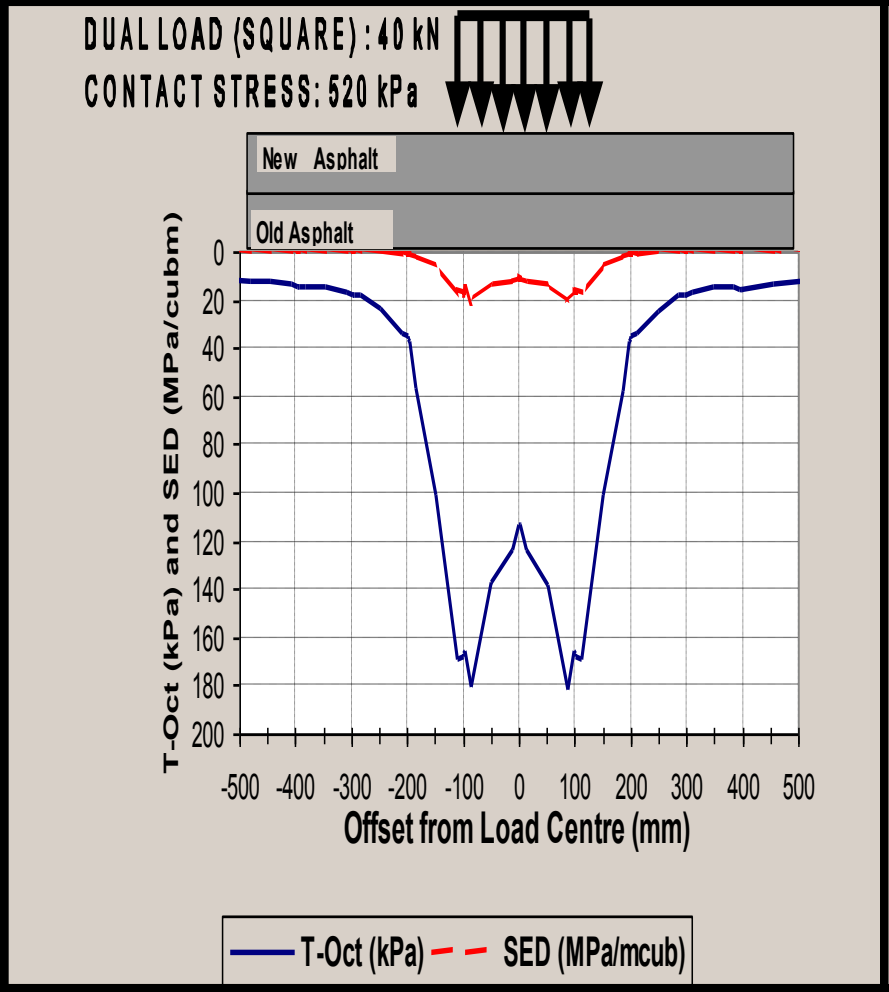


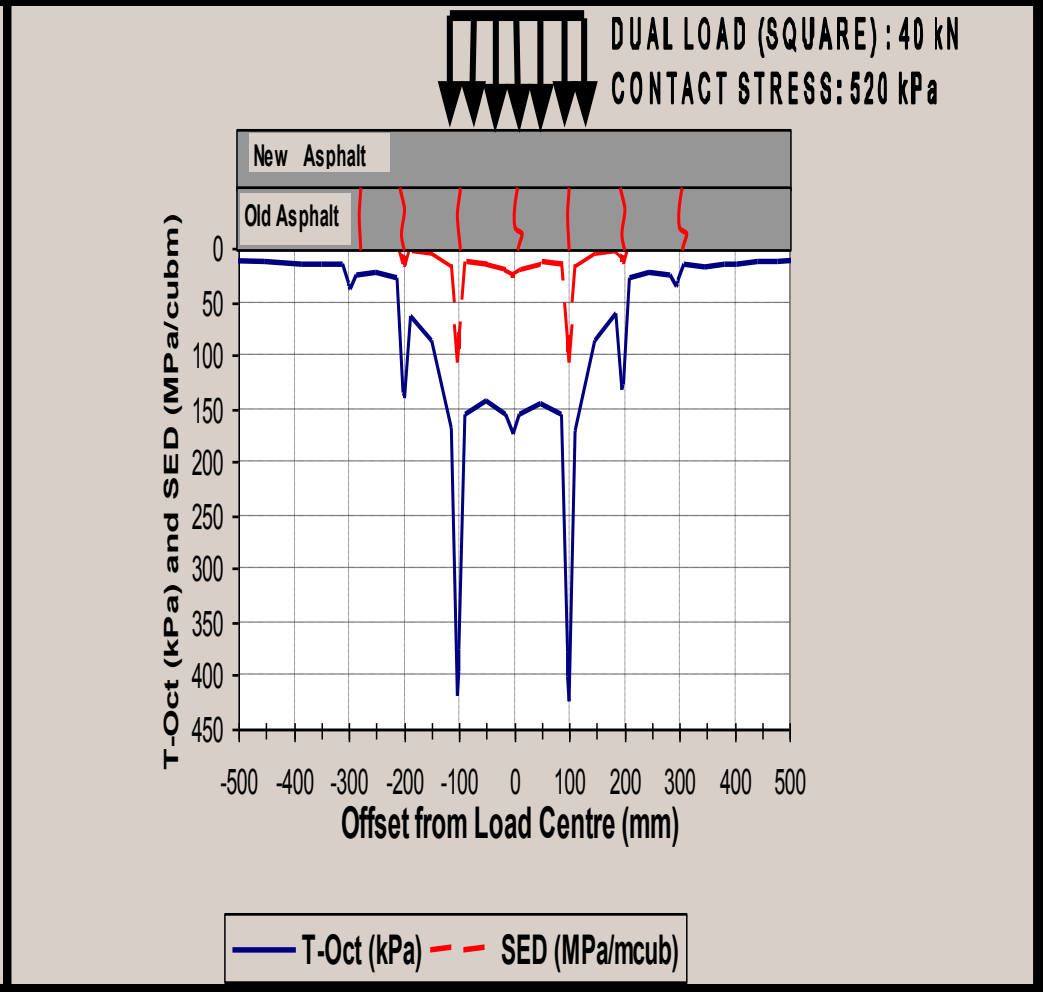


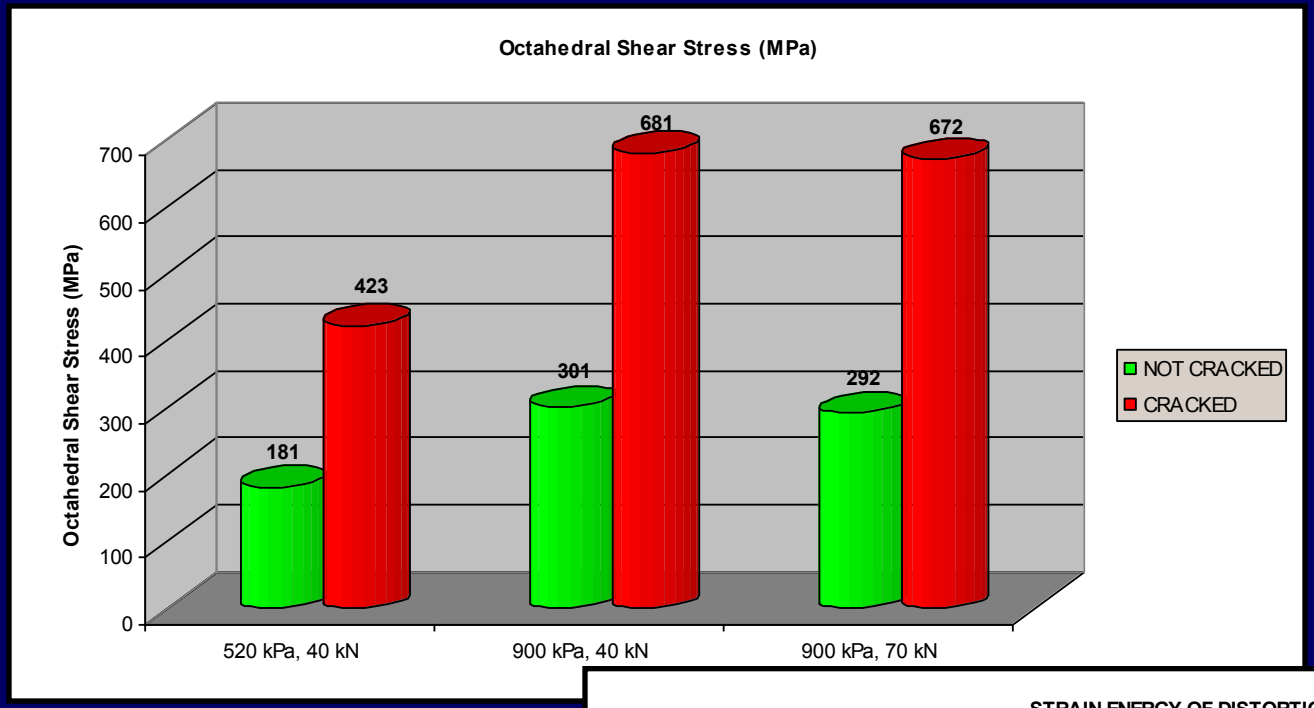




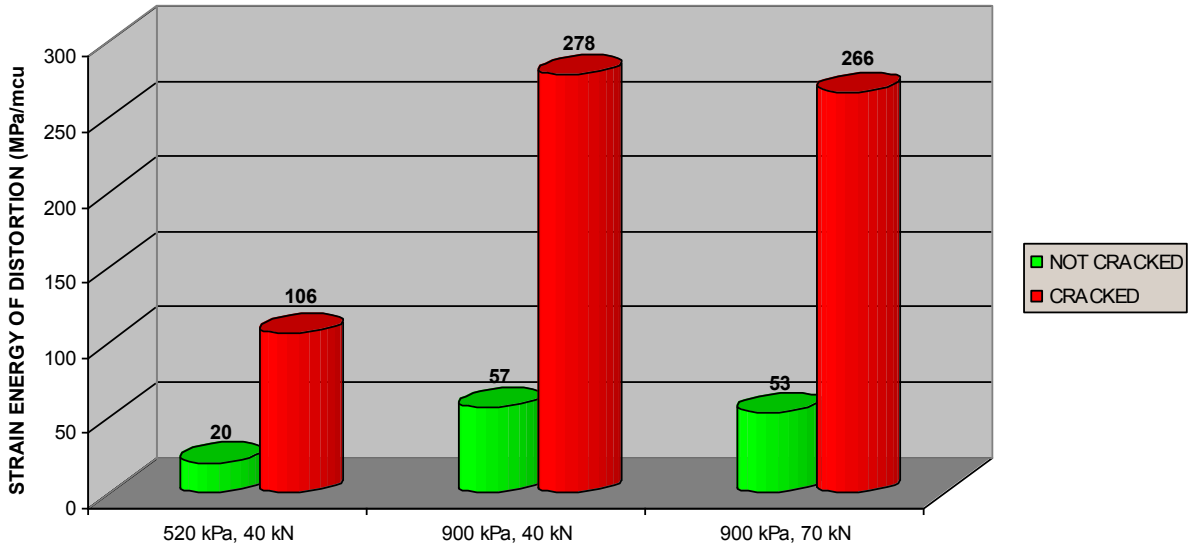
SA-FEM RESULTS: UNCRACKED vs CRACKED PAVEMENT







SA-FEM RESULTS: Un-Cracked vs Cracked



FINAL CONCLUSIONS and RECOMMENDATIONS:

- Calculated Stress and Strain response reflects applied load inputs - shape and distribution NB !;
- Sensitivity increase with lower AC modulus (i.e. hot conditions);
- Strain parameters seem to be *more sensitive* than Stress parameters;
- Elastic "Strain-based " transfer functions for damage ?
- Circular vs Square loading: Important differences noted in response parameters (SED and Octahedral shear stress);
- Cracked pavements: effects can be studied using SA-FEM using Oct.Stress and SED @ bottom of new thin AC layer.

RECOMMENDATIONS:

- More rational use of 3D tyre-pavement contact stresses in the design of flexible pavements;
- Effects of lateral contact stresses important for thin AC pavements - hot conditions;
- Influence of speed and tyre torque on 3D contact stresses to be quantified;
- Develop appropriate " transfer functions" for AC damage ?
- Tyre contact stress data to be managed well;
- AC Laboratory test methods to be "calibrated" for contact stress regimes obtained from real trucks tyres.

Thank You for your attention !