



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

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South Africa



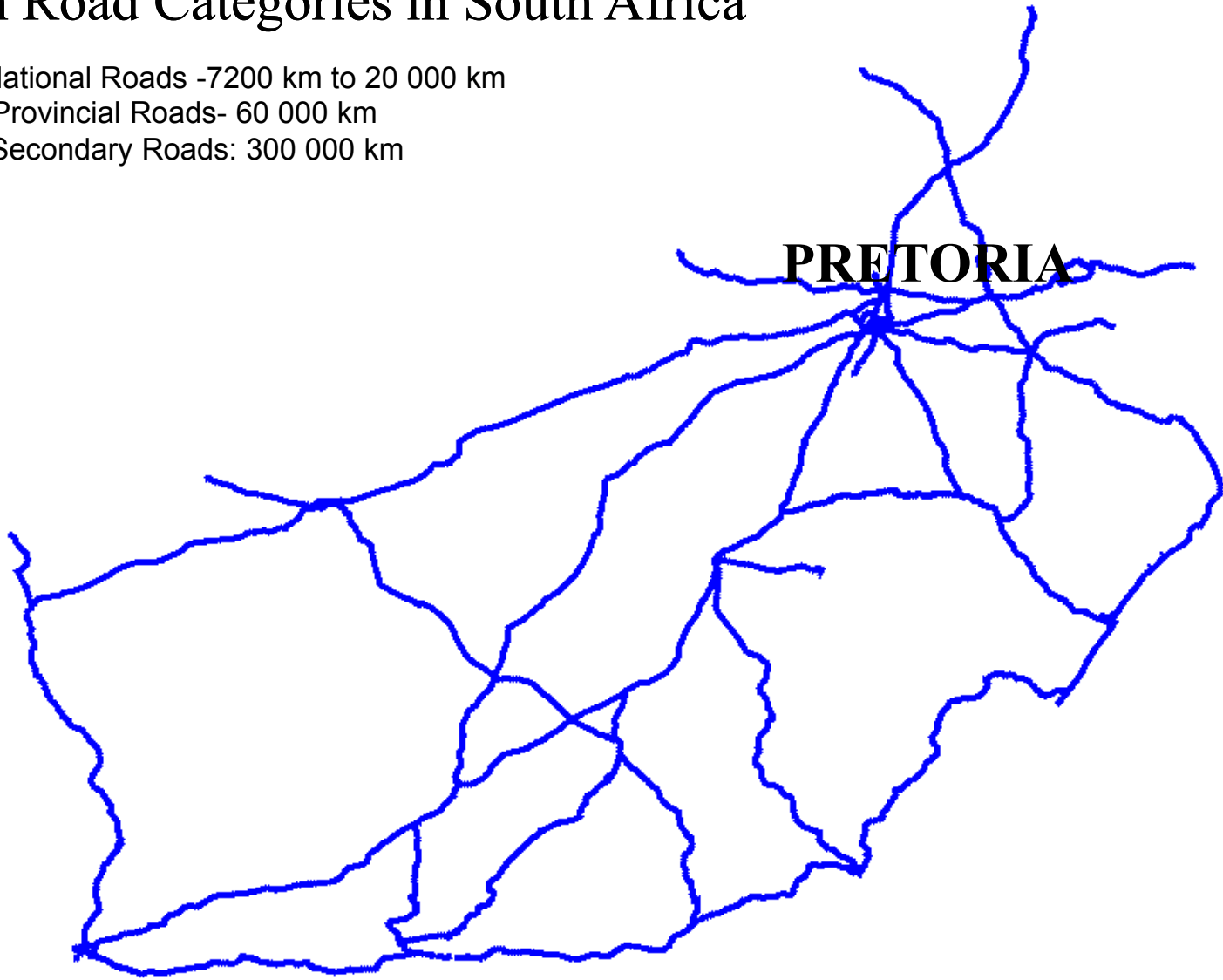


Layout of Presentation:

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



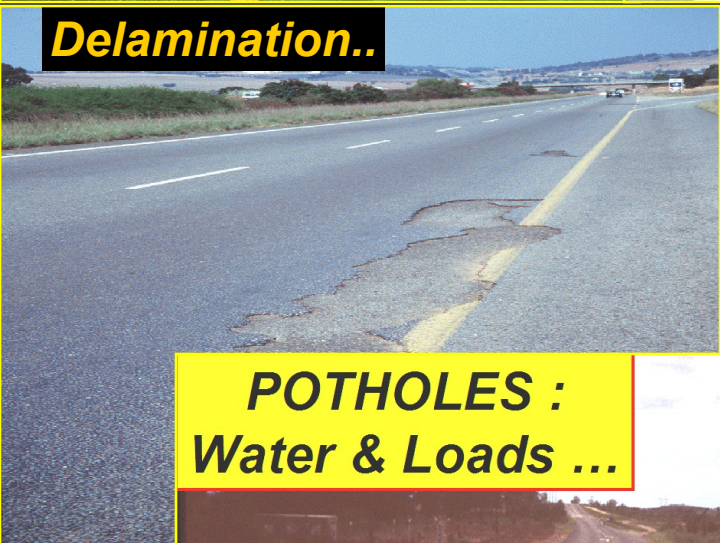
RUTTING



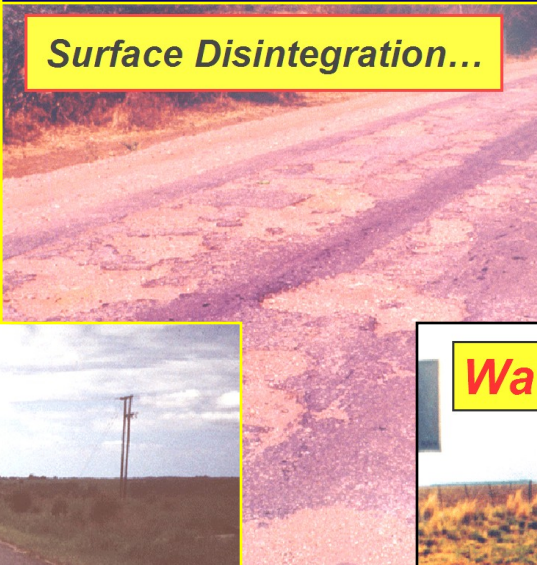
Longitudinal Flow of Asphalt



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...*

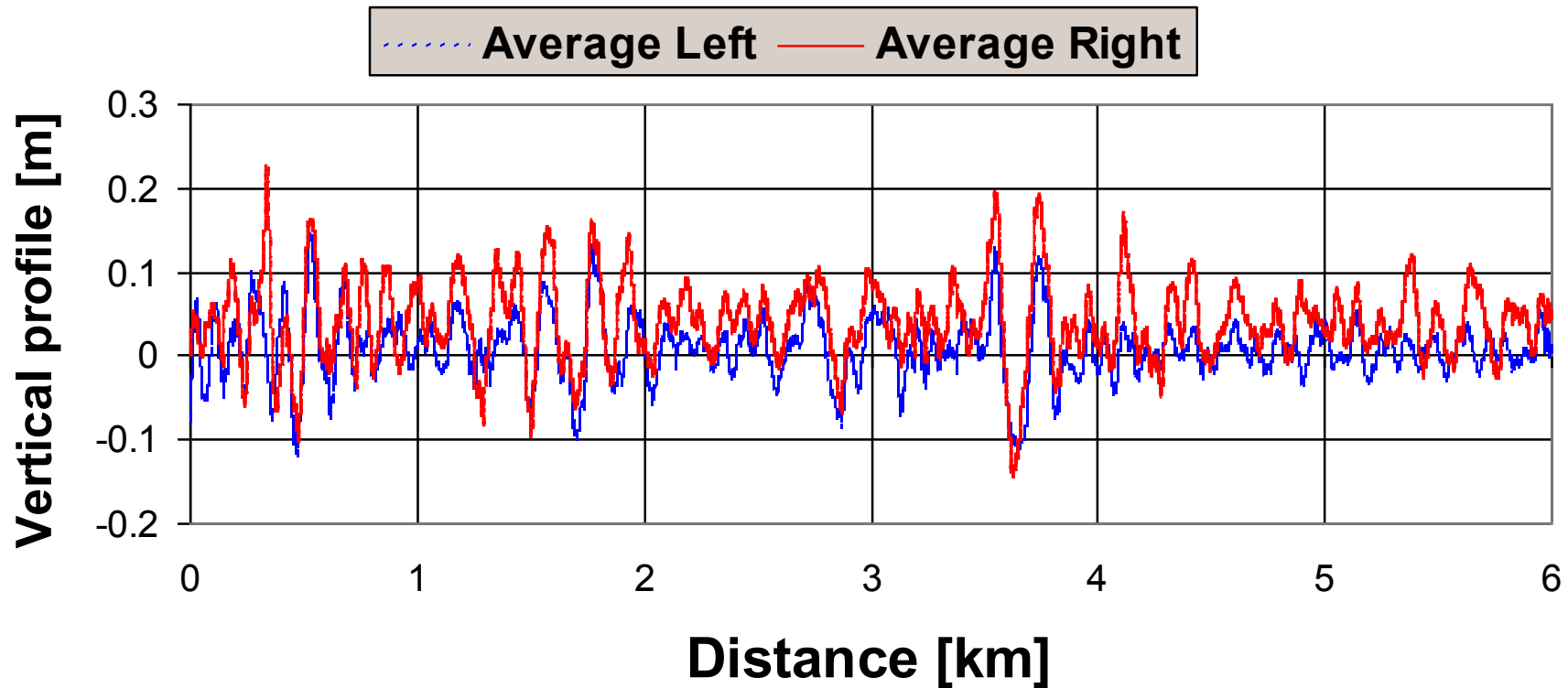


HVS - Moving Dynamic Load



Road Profiles: $HRI=3.1\text{m/km}$

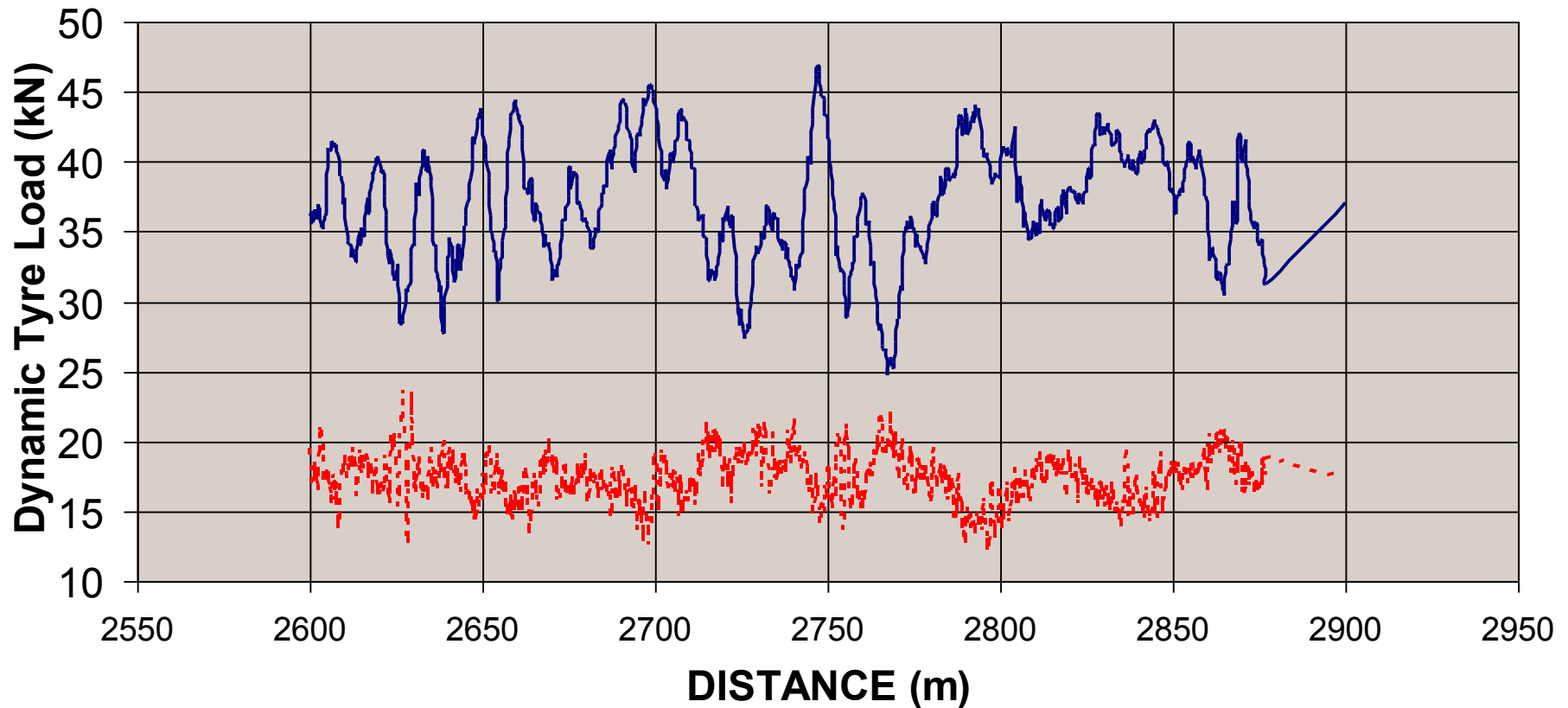
Pavement left and right profiles



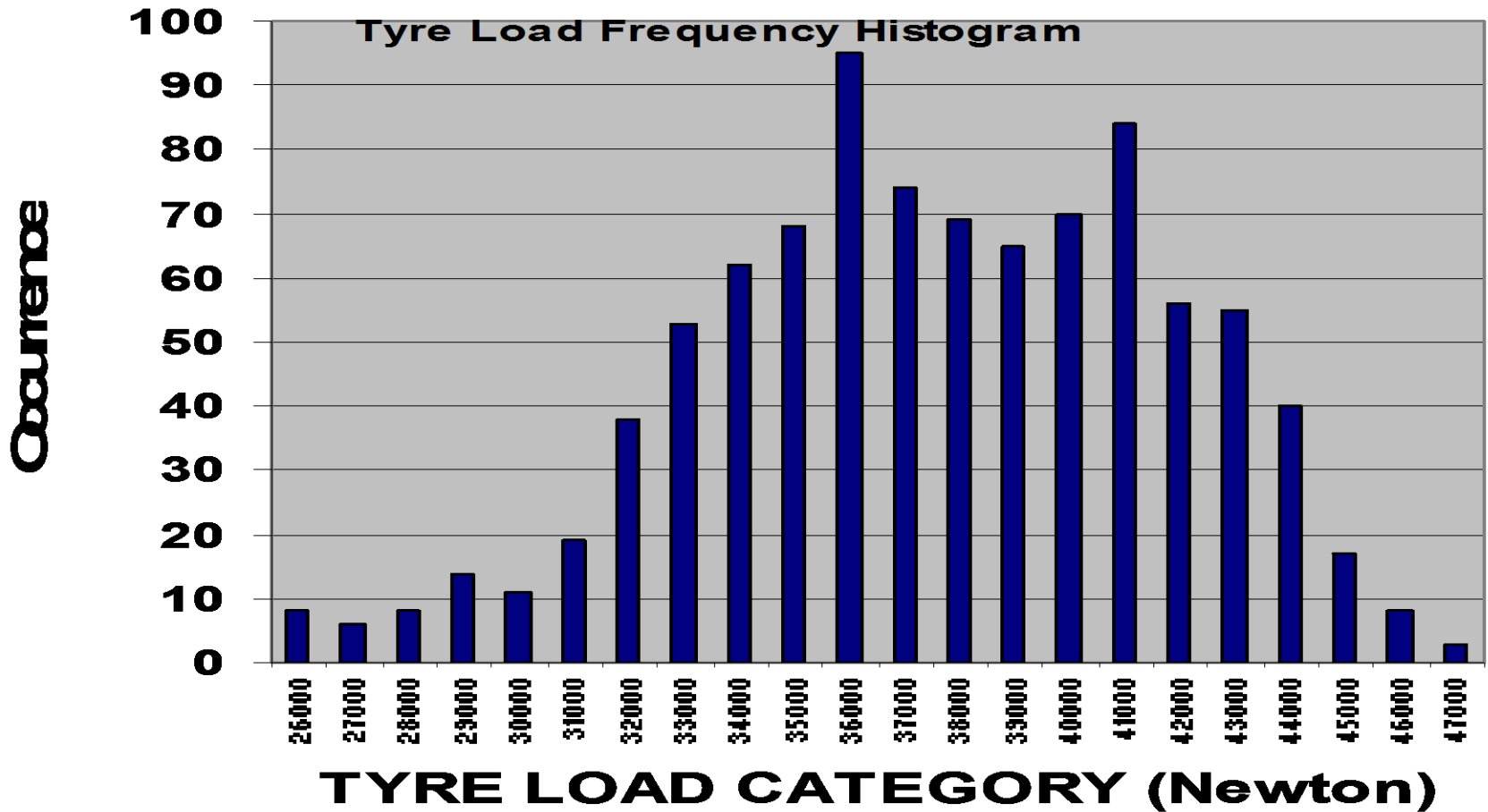
Computed Dynamic Loads (DADS):

1:2:2:2 Truck Tractor and Tandem-Tandem Semi-Trailor

— Steering tyre (Left) - - - Leader first axle- right outer tyre



Dynamic Loads converted to contact stress DISTRIBUTIONS- VERTICAL LOAD:



A photograph of a two-lane asphalt road stretching into the distance under a blue sky with light clouds. The road is flanked by tall, dry grass. In the distance, a white car is driving towards the viewer on the left side of the road, and a white truck is driving away on the right side. Utility poles are visible on the left side of the road.

Vehicle-Tyre-Pavement Interaction:

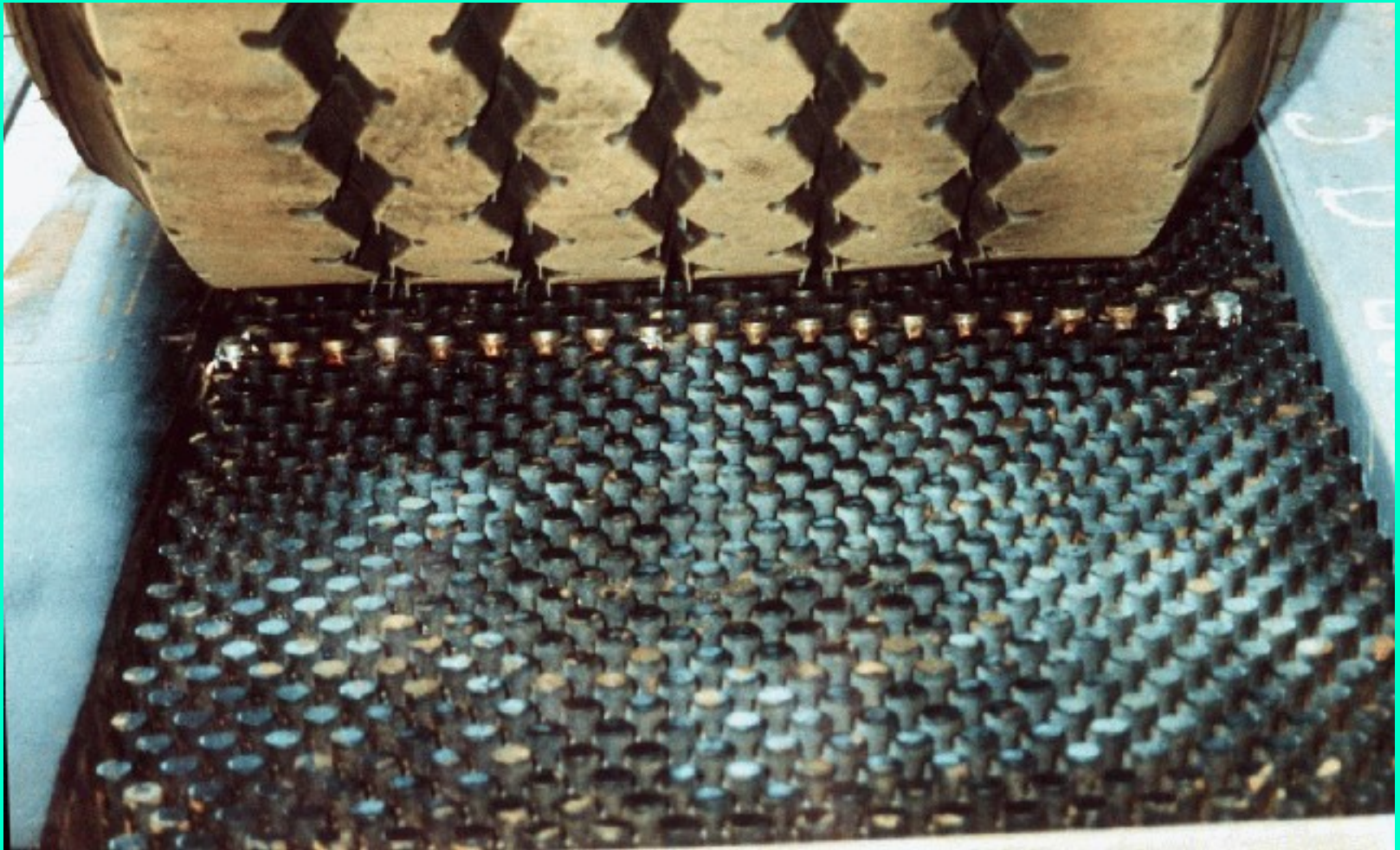
STRESS-IN-MOTION (SIM) Technology



Stress - In - Motion (SIM) - SIM Mk II: CSIR Transportek: '93-'95:



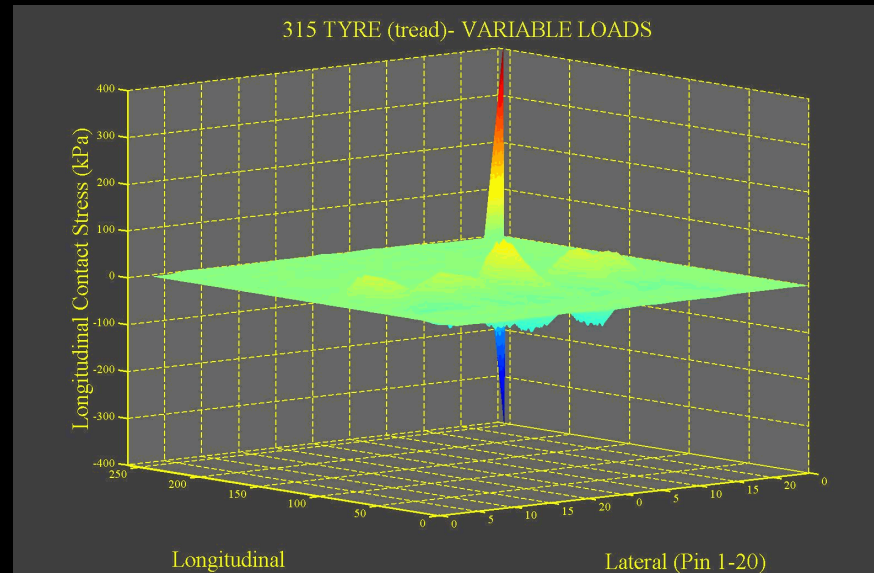
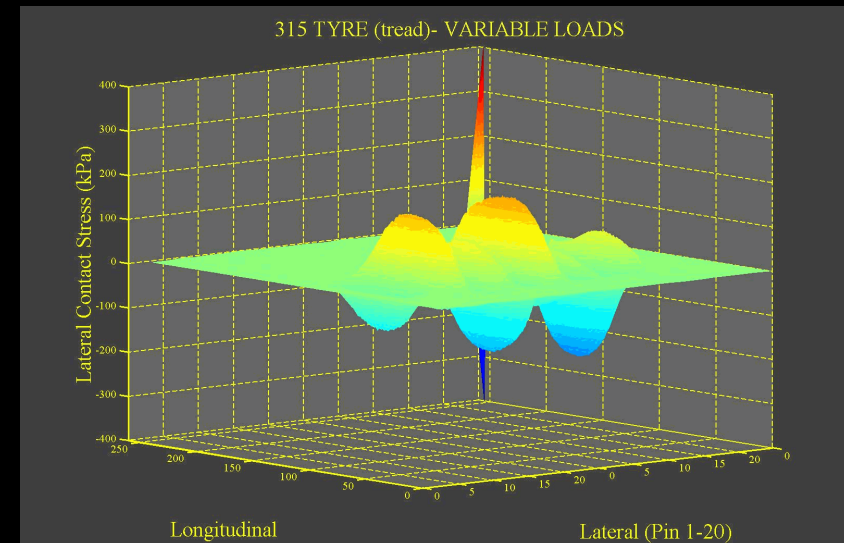
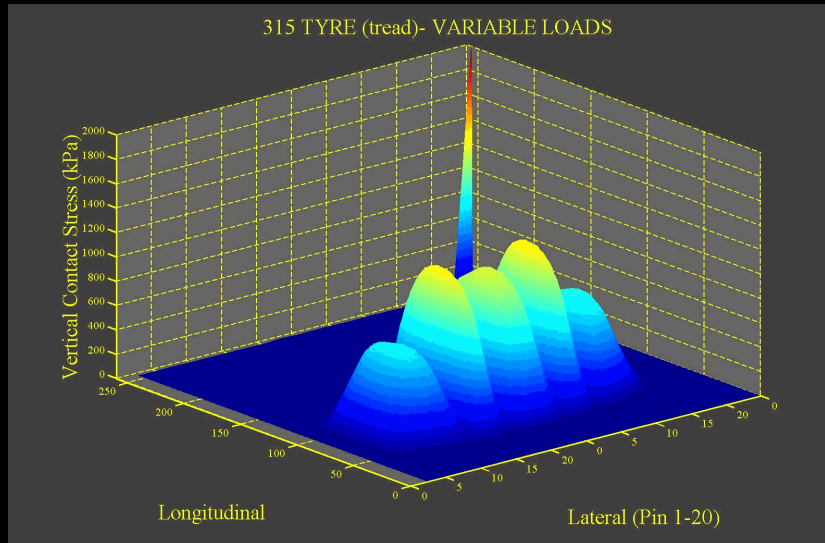
315/80 HVS TYRE ON SIM Mk II SYSTEM



425 /65 R22.5 HVS Tyre ON SIM SYSTEM:
Single pad SIM system (Use with HVS)



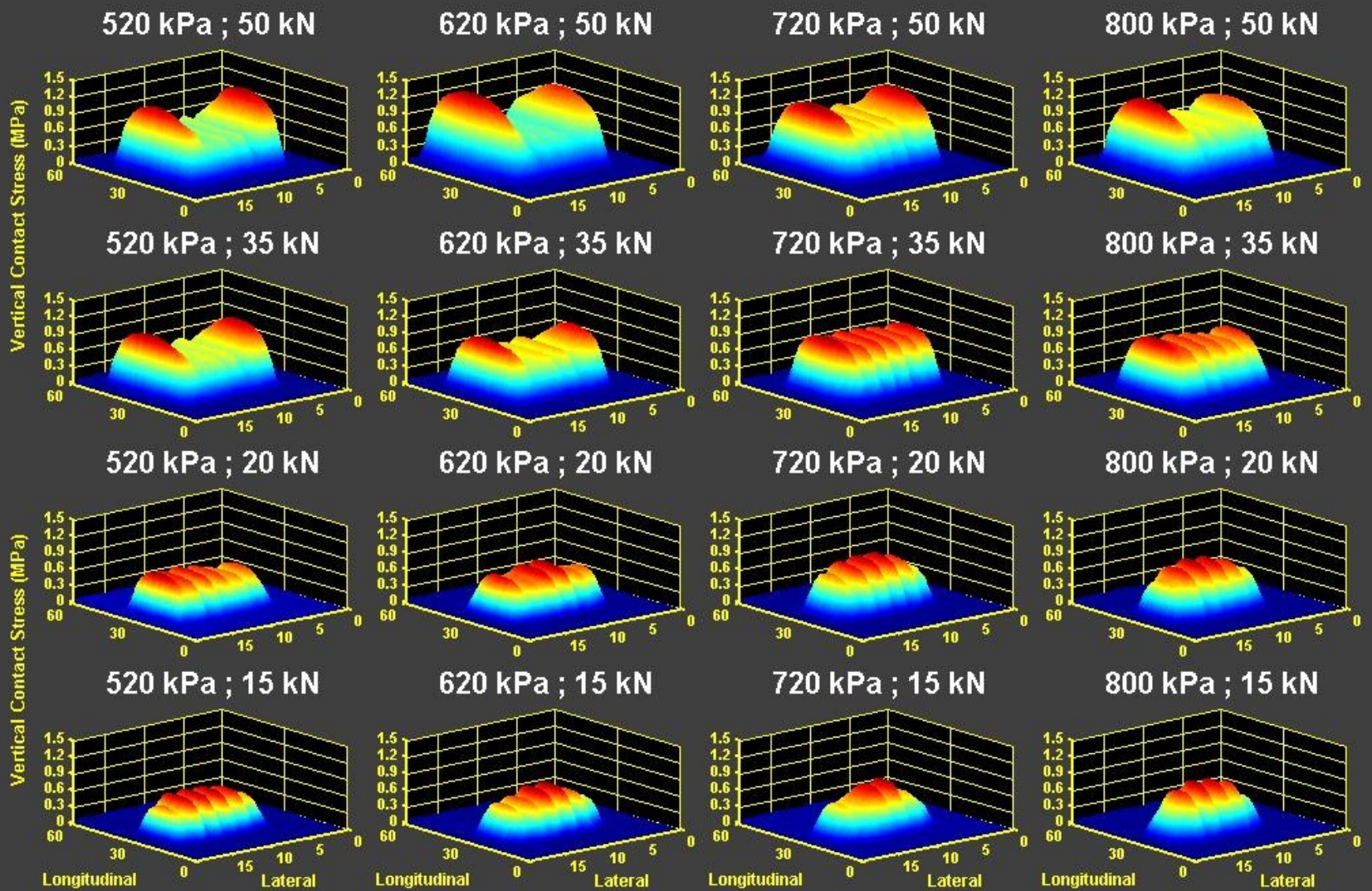
Typical SIM measured contact stress data sets:



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

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

LOAD



CARAVAN SIDE CONTINENTAL 11R22.5 TREADED

INFLATION PRESSURE

SIM Mk III on N1 (North): Mantsole TCC



SIM Mk III on N1 (North)





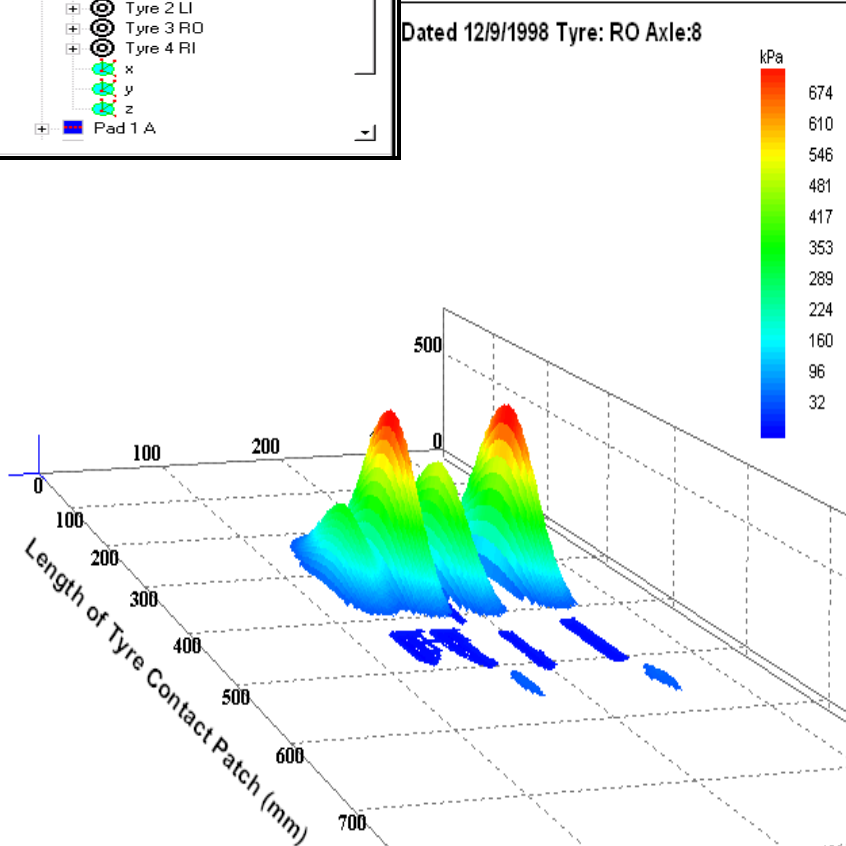
SIM DATA ORGANISATION :

Catalog

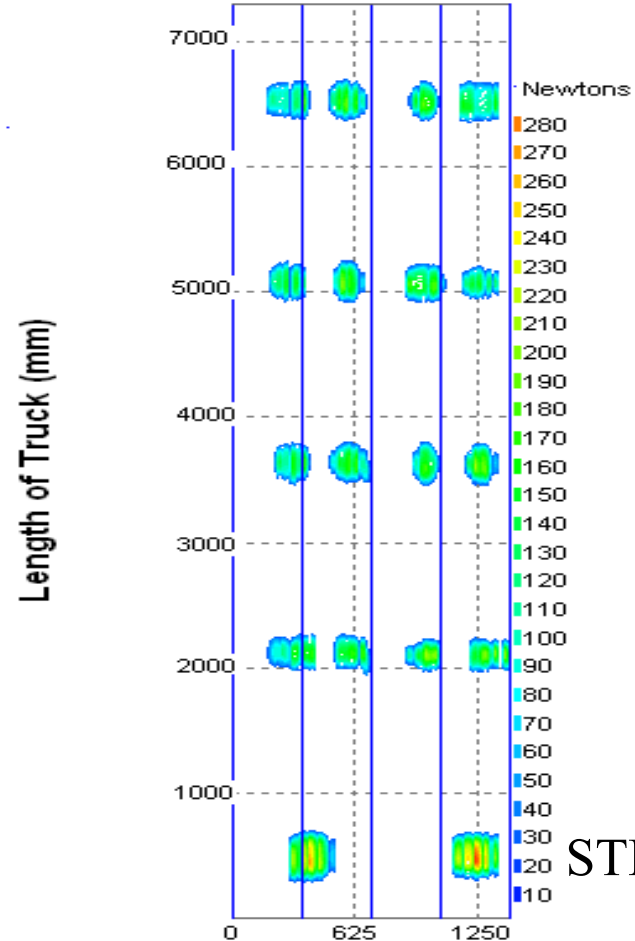
- + Test 001
- + Test 002
- + Test 003
- Test 012
 - + Axle 1
 - + Axle 2
 - + Axle 3
 - + Axle 4
 - + Axle 5
 - + Axle 6
 - + Axle 7
 - Tyre 1 LO
 - x
 - y
 - z
 - + Tyre 2 LI
 - + Tyre 3 RO
 - + Tyre 4 RI
 - x
 - y
 - z
 - + Pad 1 A

VIEW Z-Direction

Dated 12/9/1998 Tyre: RO Axle:8



Test 003 done at MANTSOLE Dated 12/9/1998



STEERING

Artificial Neural Networks (ANN) :

(ANN -
FHWA/
PENN
STATE)

Predicted

M DE BEER ET AL.

Measured

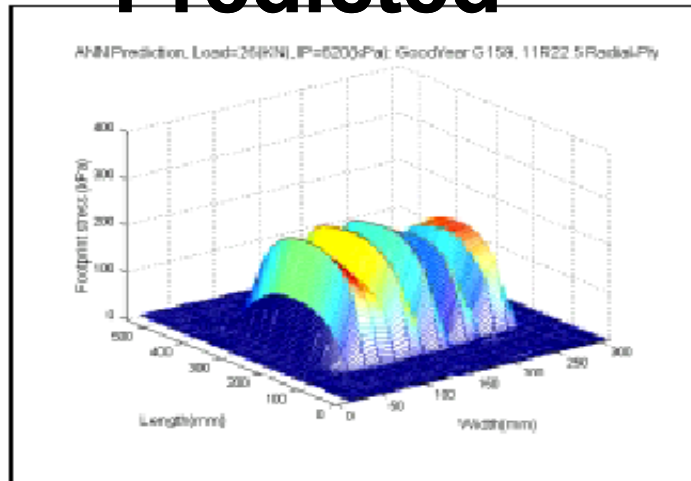


Figure 9. ANN prediction: Vertical contact stress

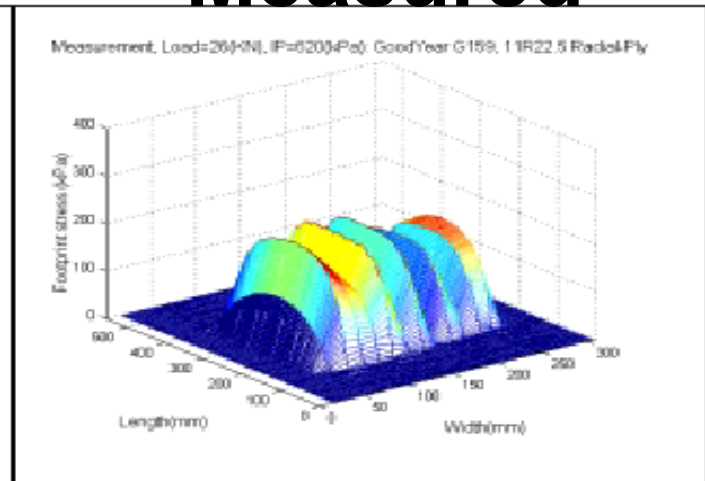


Figure 10. Measured vertical contact stress

Error

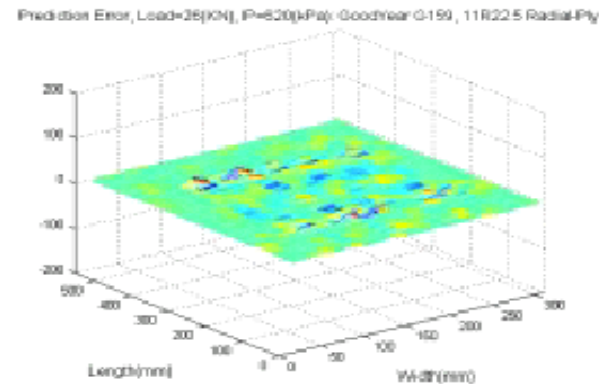
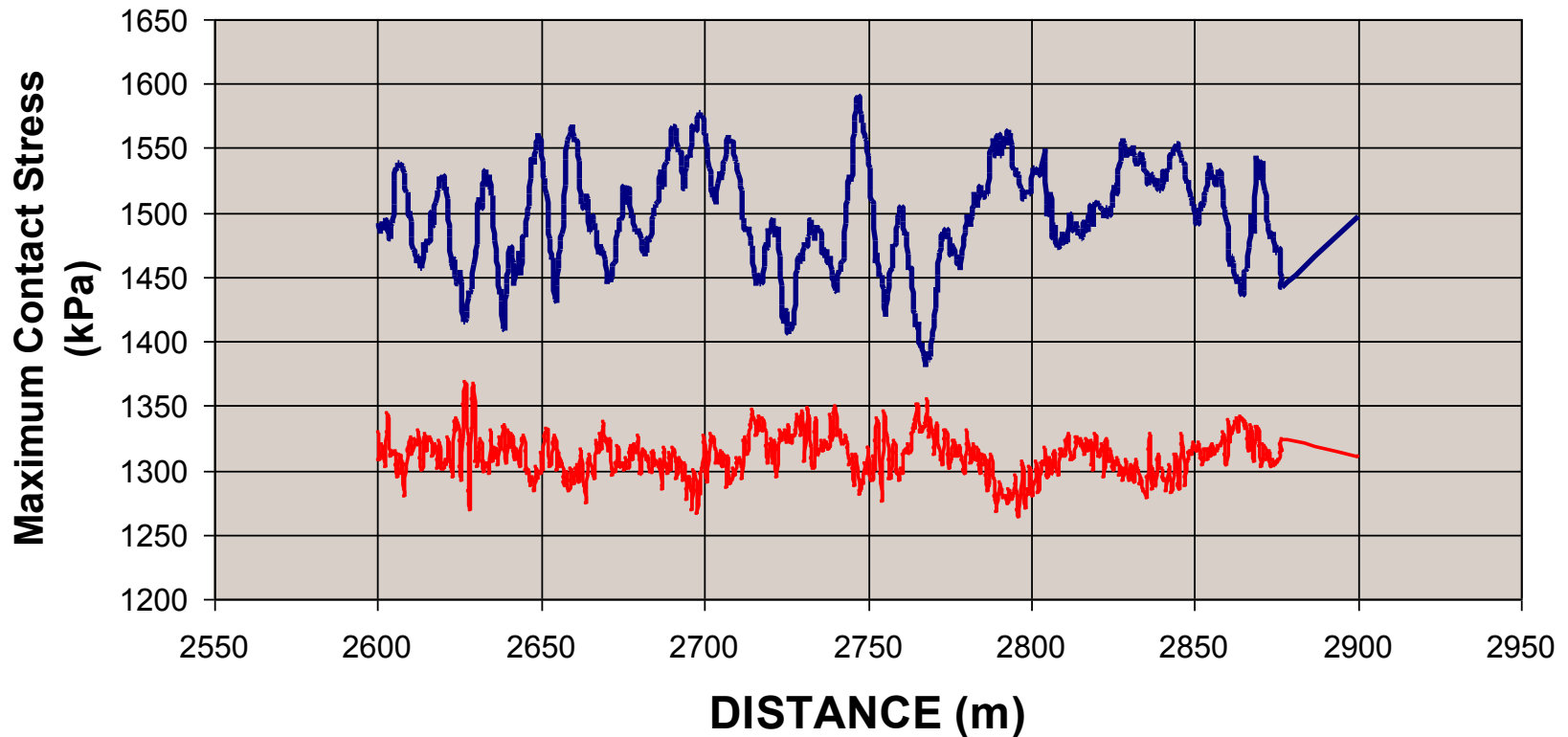


Figure 11. Prediction error: Difference between ANN prediction and measured vertical contact stress at a load of 26 kN, and inflation pressure of 620 kPa.

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

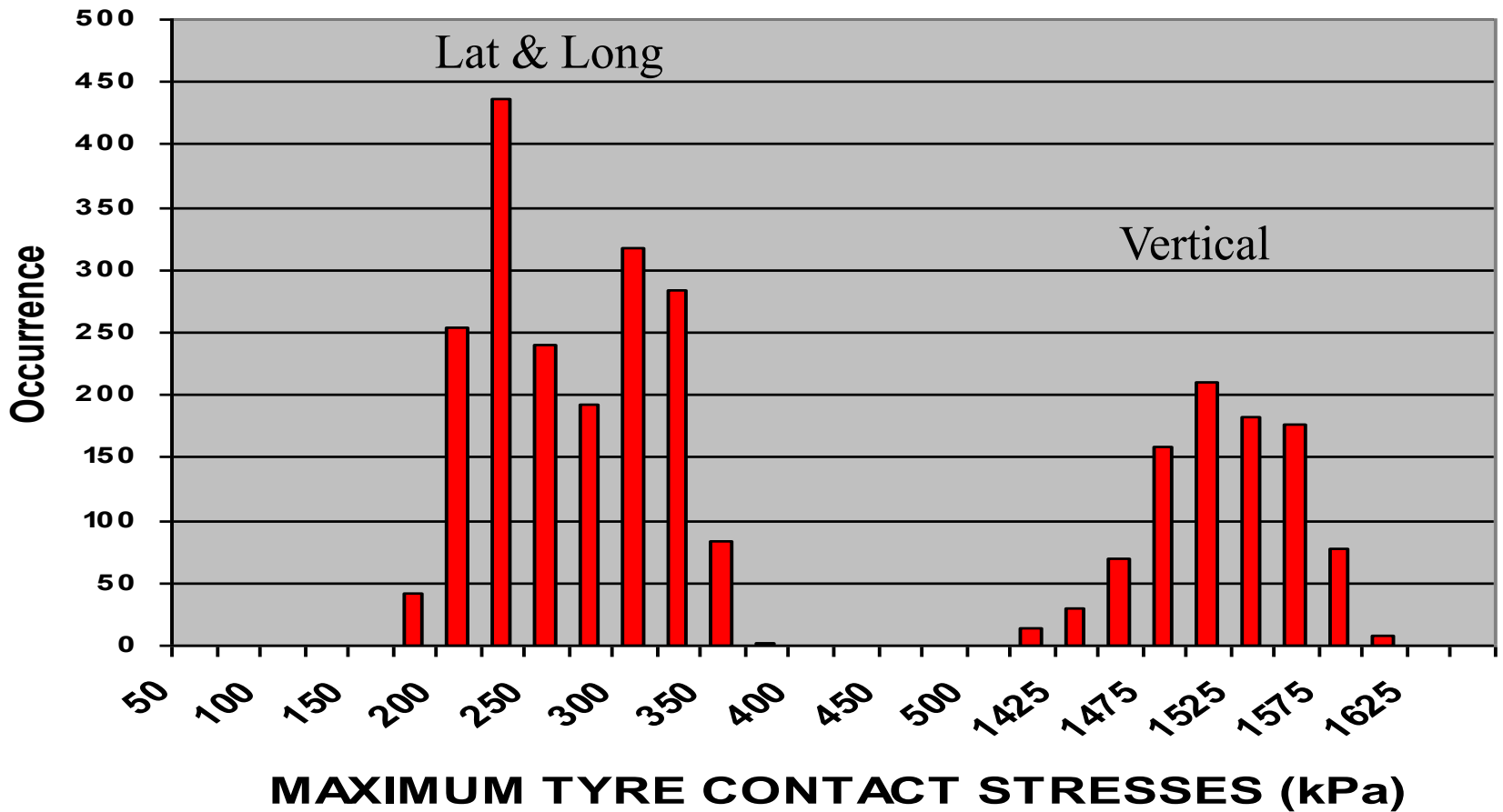
1:2:2:2 Truck Tractor and Tandem-Tandem Semi-Trailor

— STEERING VERTICAL — LEADER VERTICAL



Derived "dynamic" (max) contact stress distributions:

Tyre Contact Stress Frequency Histogram



MODELED PAVEMENT STRUCTURE – LINEAR ELASTIC

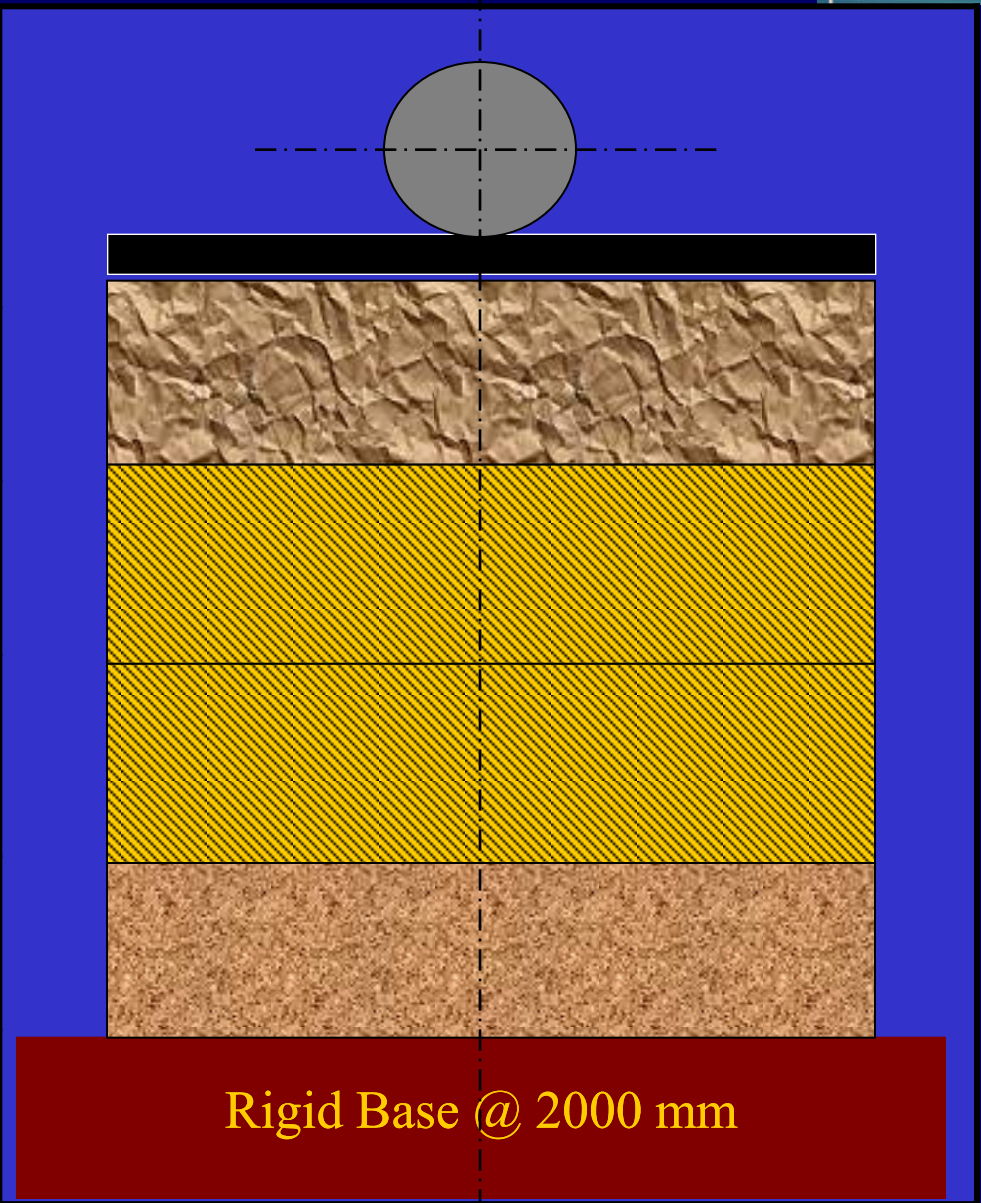
Thin Asphalt Surfacing: 40 mm
($E_1 = 5000$ MPa, 1000, 200, $\nu_1 = 0.44$);
($C = 2000$ kPa, $\Phi = 43$ deg, Yield =
1462 kPa, 585 kPa, 117 kPa)

Crushed Stone Base: 150 mm
($E_2 = 350$ MPa, $\nu_2 = 0.35$)

Cementitious Subbase-1: 150 mm
($E_3 = 1500$ MPa, $\nu_3 = 0.35$)

Cementitious Subbase-2: 150 mm
($E_4 = 1500$ MPa, $\nu_4 = 0.35$)

Soil Subgrade: 2000 mm
($E_5 = 100$ MPa, $\nu_5 = 0.35$)





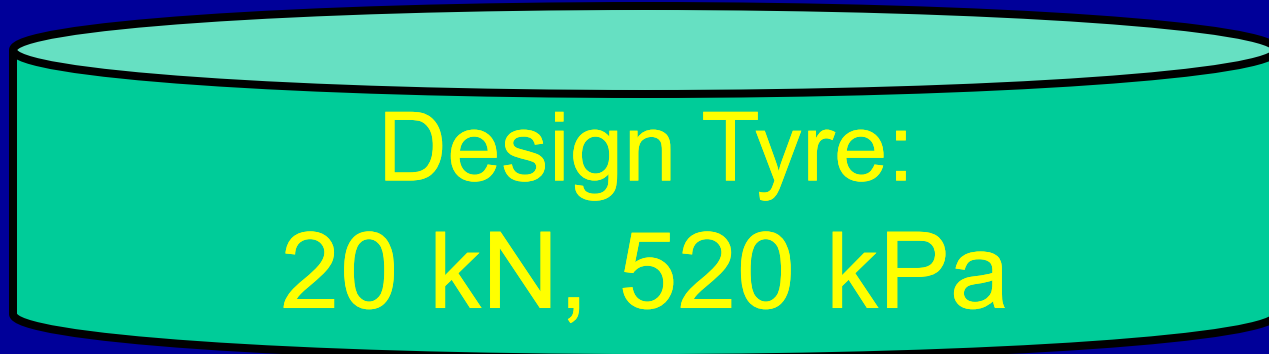
The six (6) response parameters selected for this study include:

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): ASSUMPTIONS:

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



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

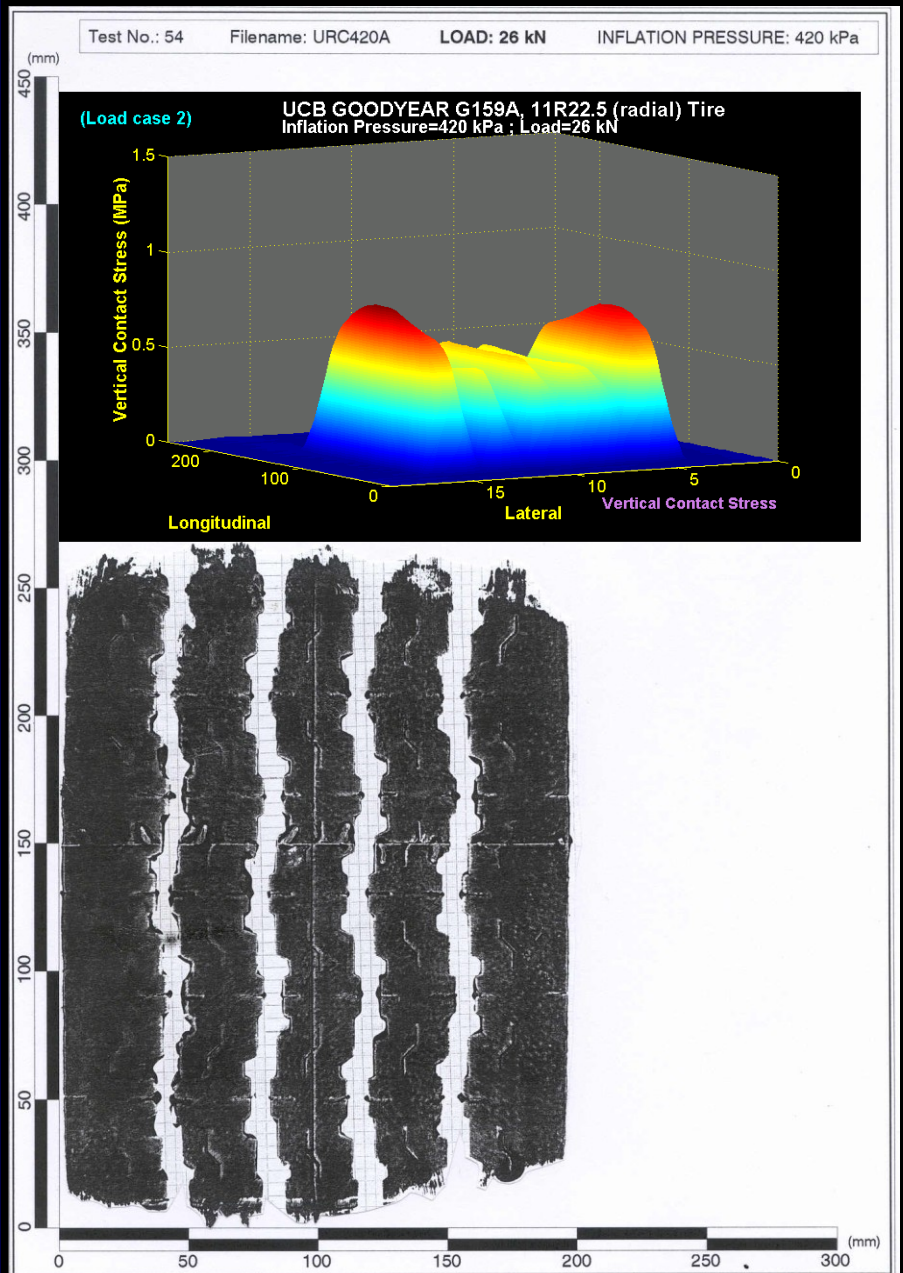
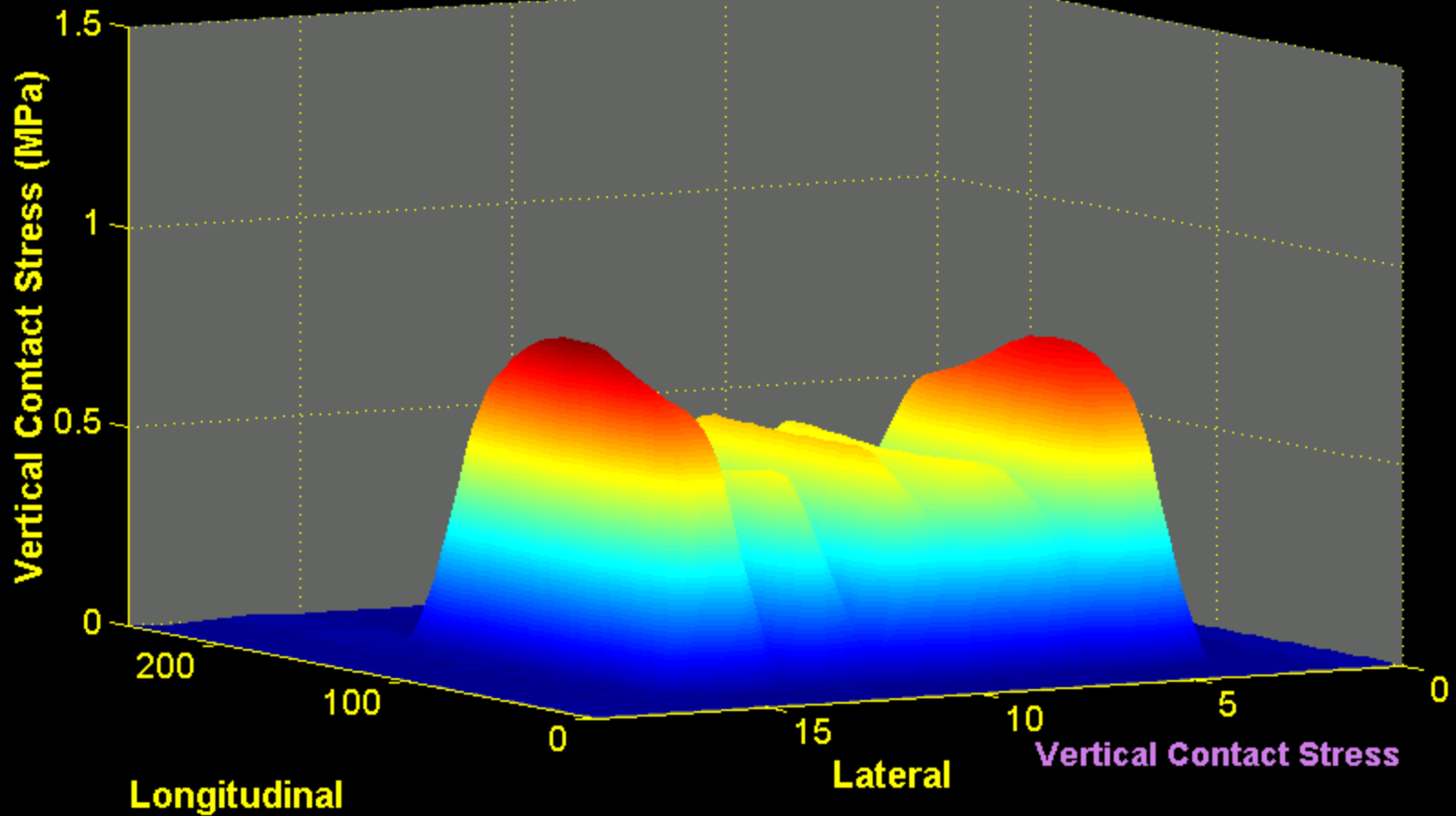


Figure D4
Goodyear, G159A, 11R22.5

VERTICAL STRESS:

(Load case 2)

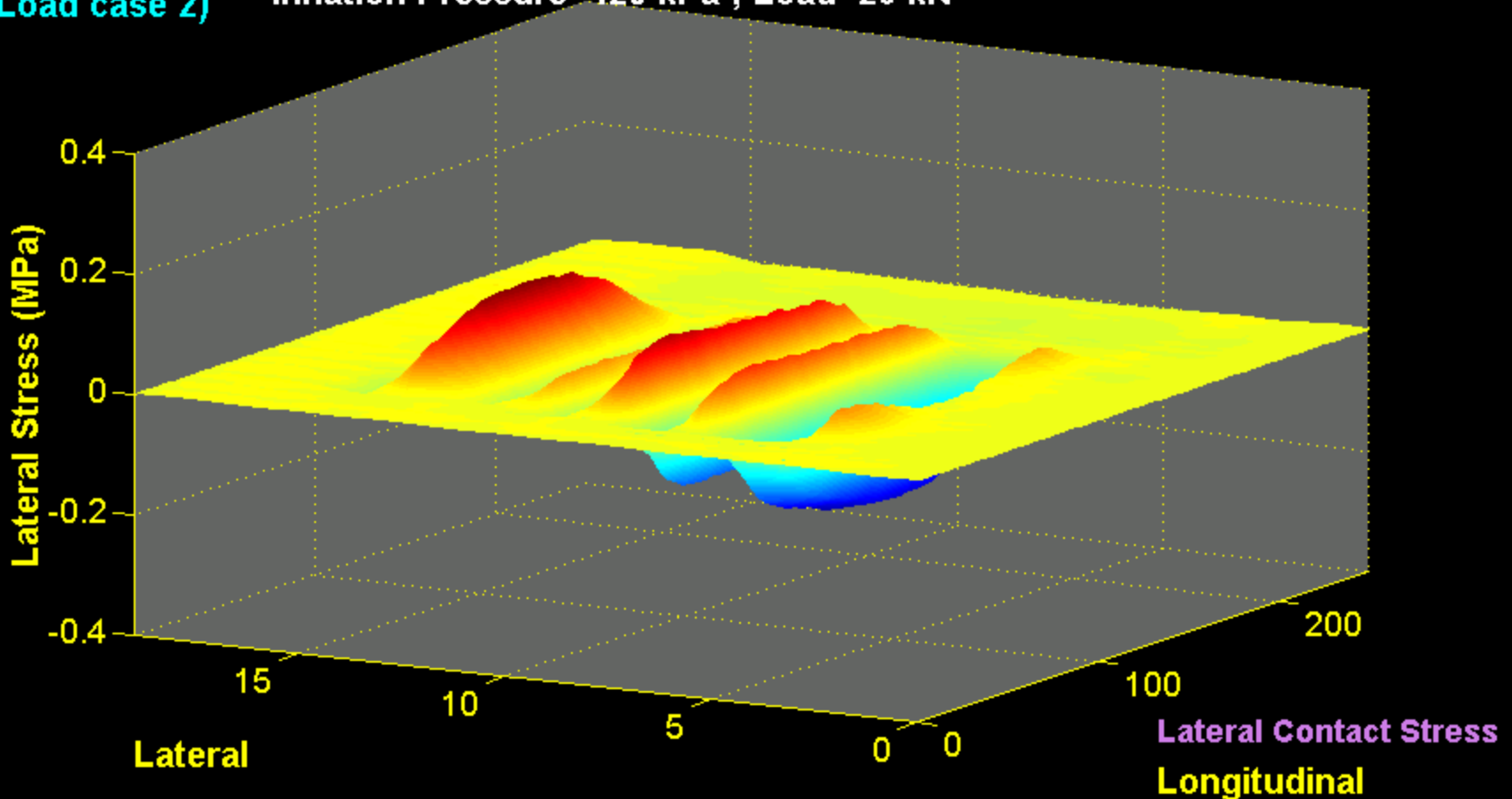
UCB GOODYEAR G159A, 11R22.5 (radial) Tire
Inflation Pressure=420 kPa ; Load=26 kN



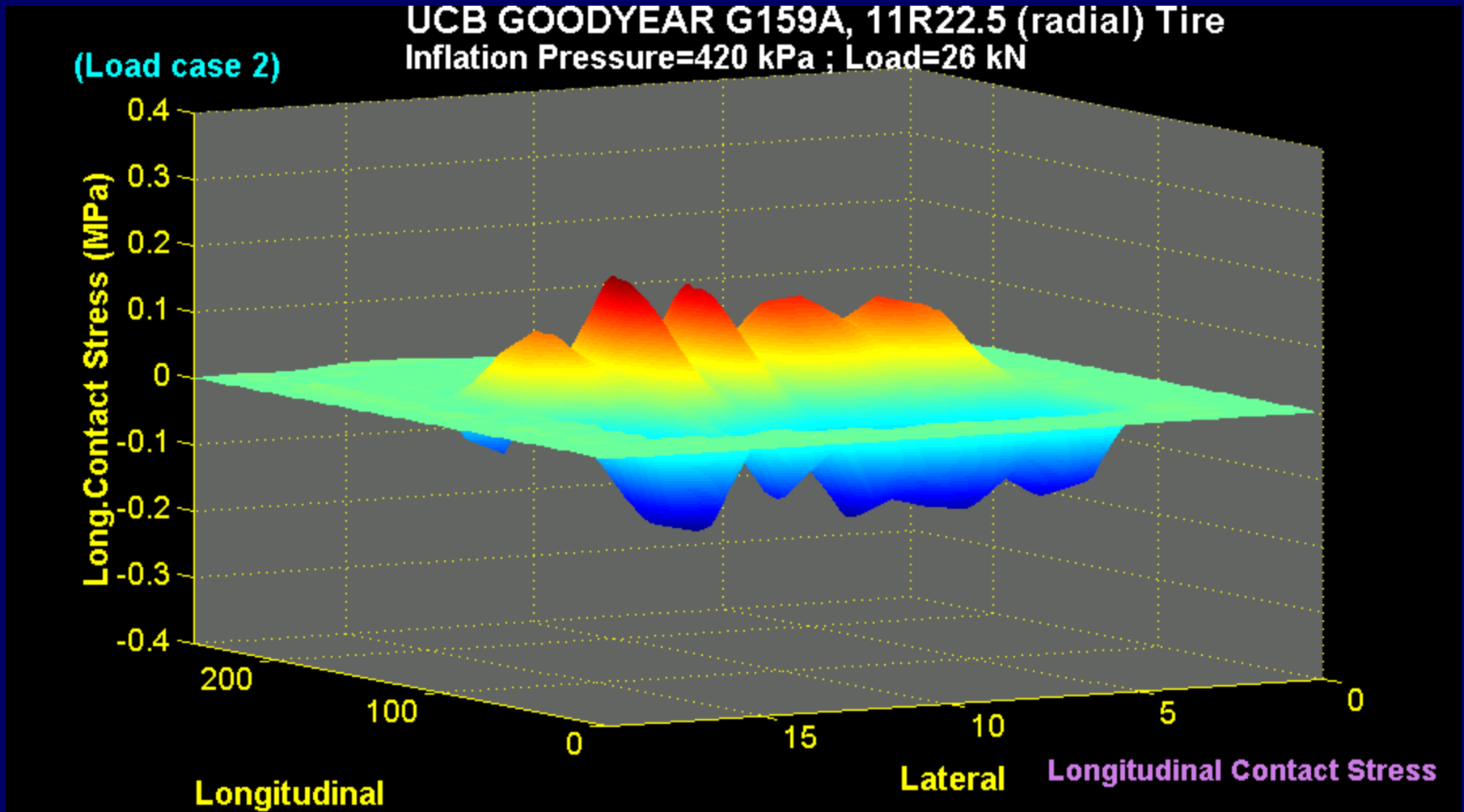
LATERAL STRESS:

UCB GOODYEAR G159A, 11R22.5 (radial) Tire
Inflation Pressure=420 kPa ; Load=26 kN

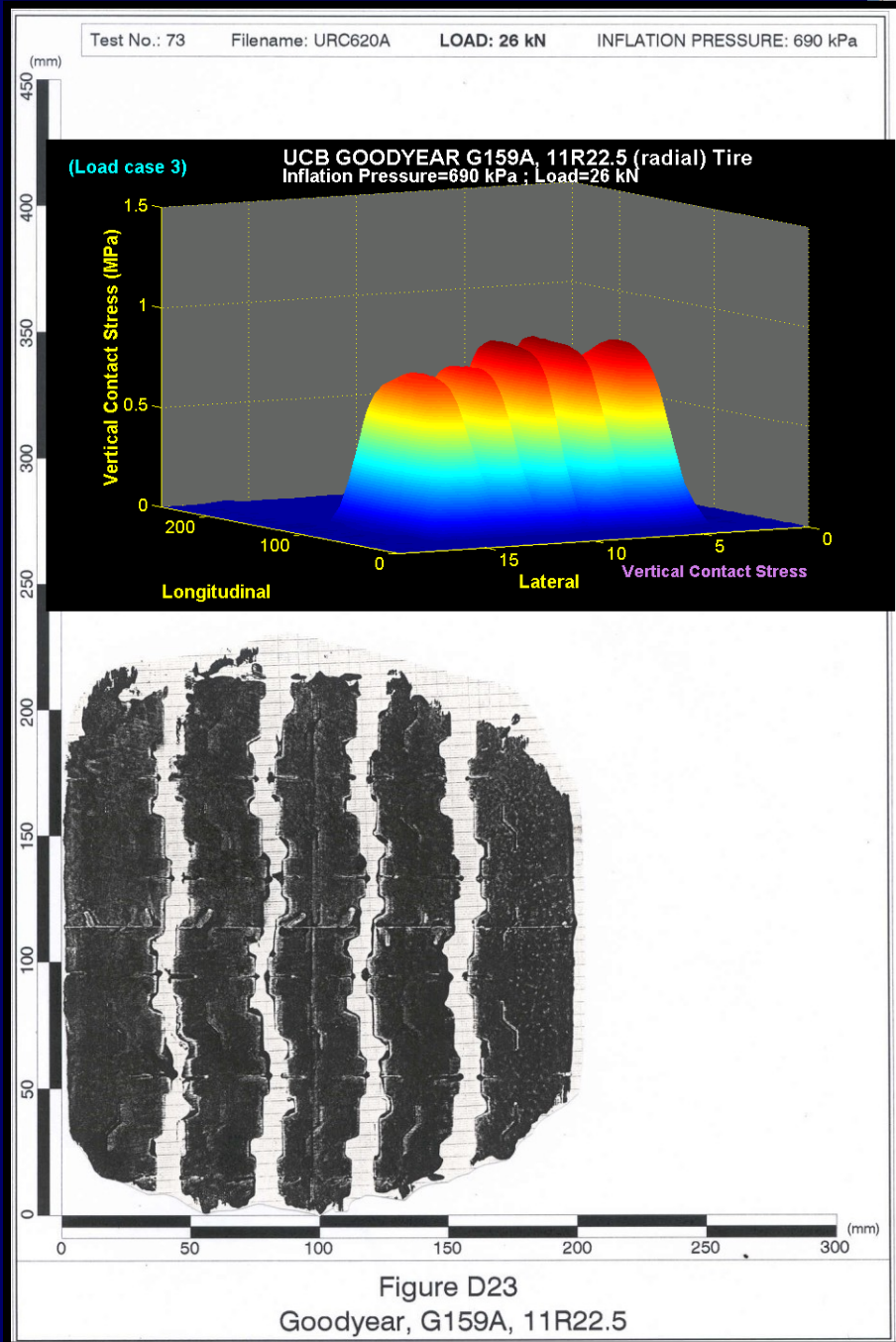
(Load case 2)



LONGITUDINAL STRESS:



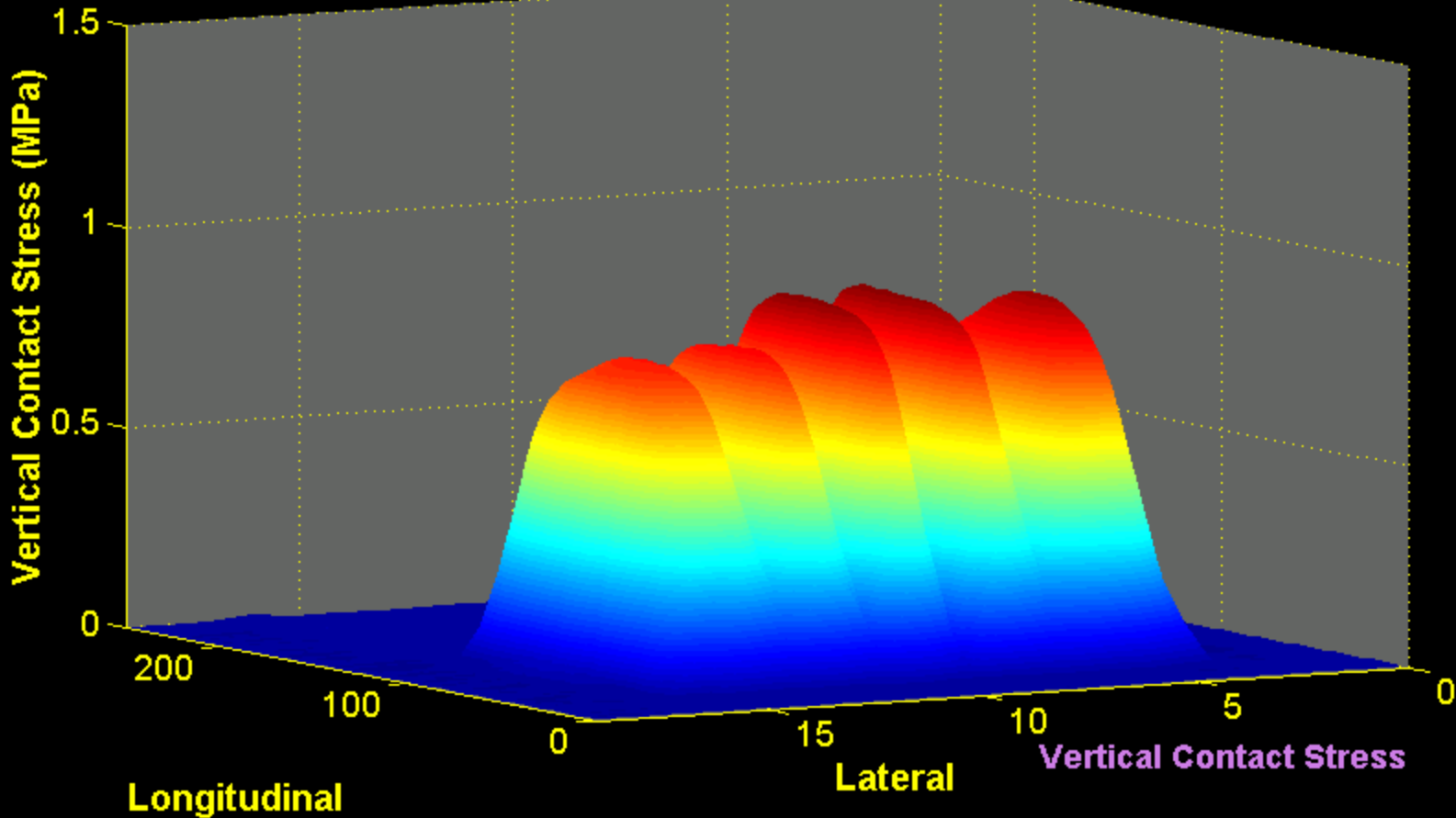
Load Case 3:
MEASURED (SIM)
26 kN; 690 kPa:
Vertical Contact Stress
Distribution
and
Static Tyre print:
Rated Loading for tyre



VERTICAL STRESS:

(Load case 3)

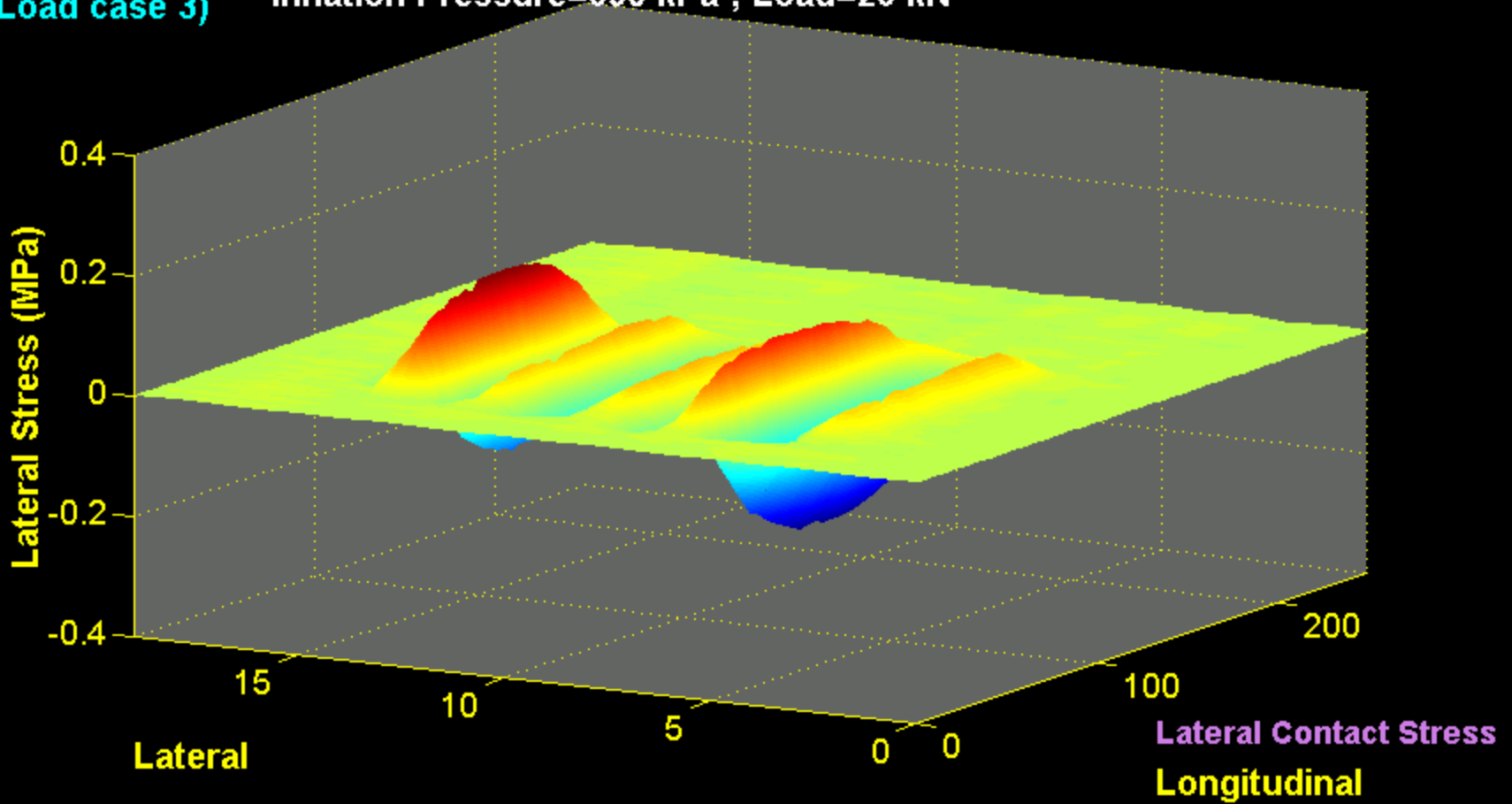
UCB GOODYEAR G159A, 11R22.5 (radial) Tire
Inflation Pressure=690 kPa ; Load=26 kN



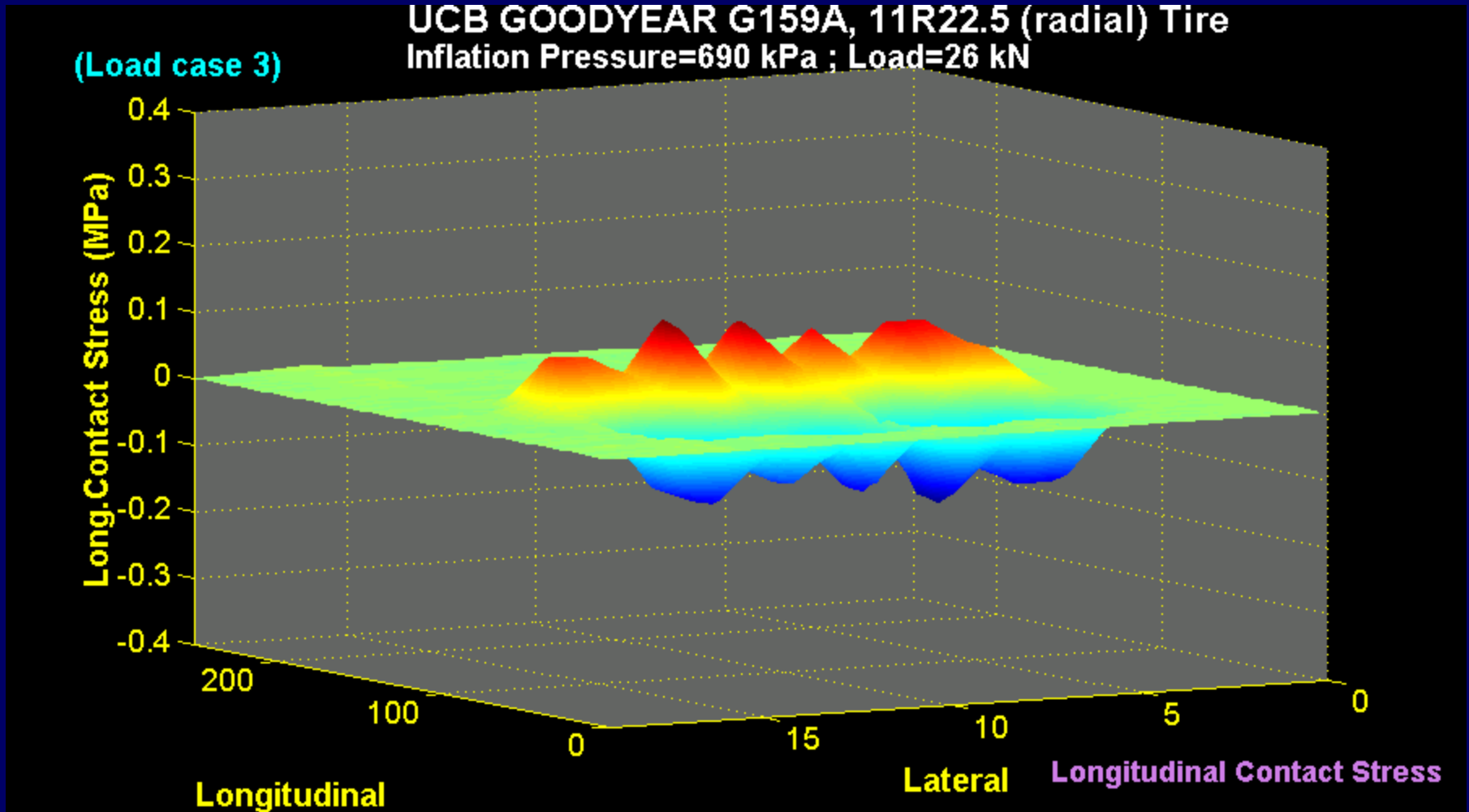
LATERAL STRESS:

UCB GOODYEAR G159A, 11R22.5 (radial) Tire
Inflation Pressure=690 kPa ; Load=26 kN

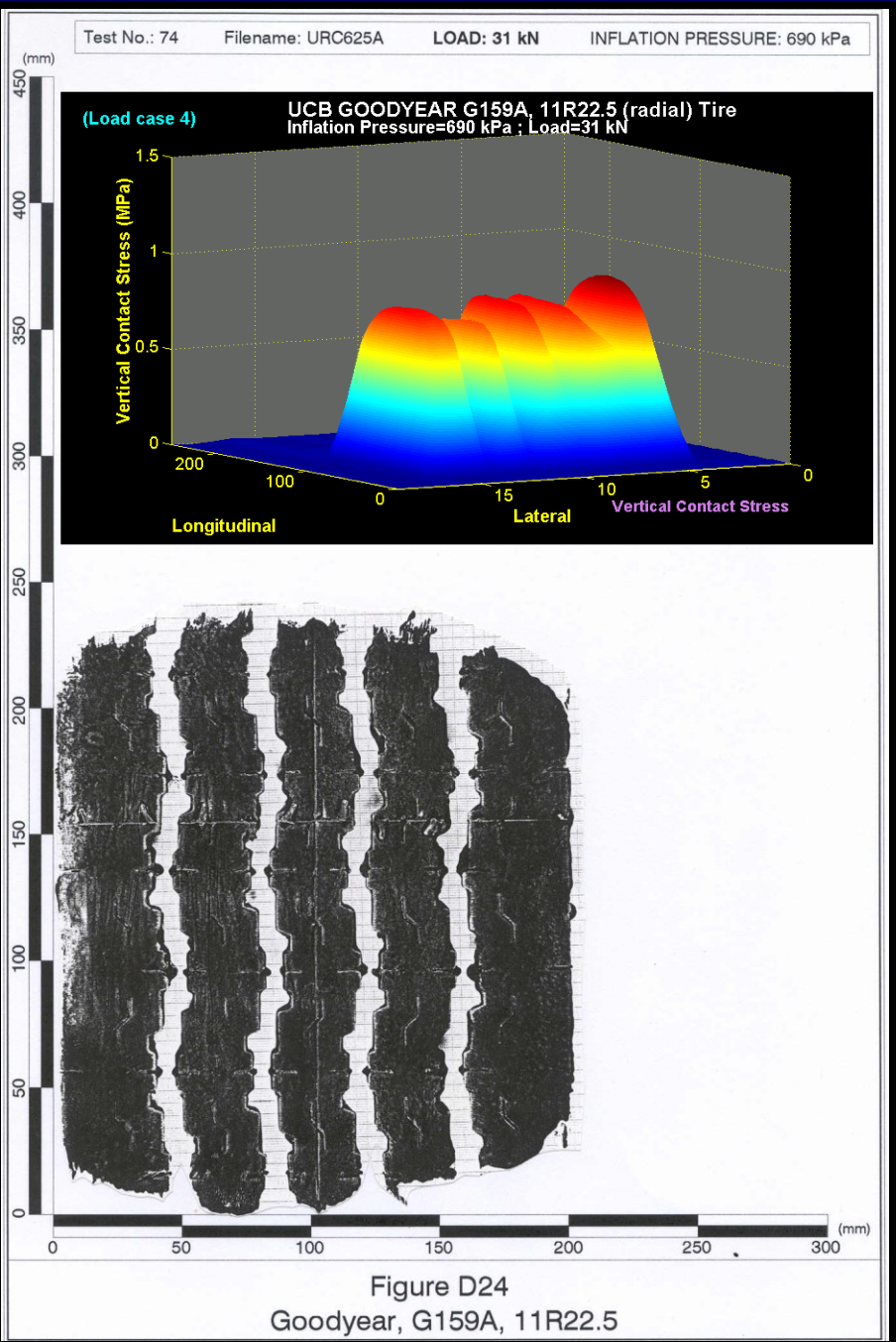
(Load case 3)



LONGITUDINAL STRESS:



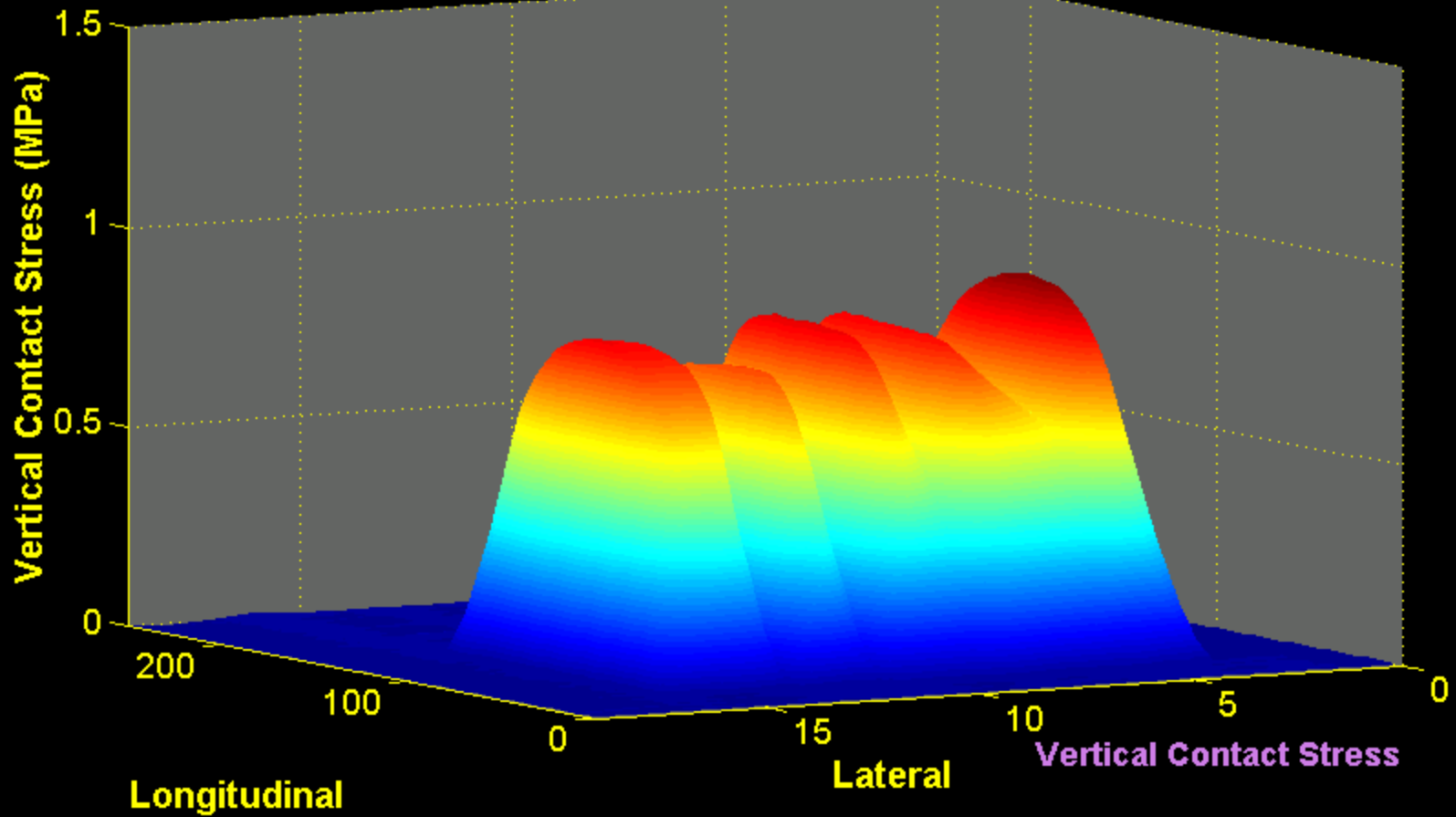
Load Case 4:
MEASURED (SIM)
31 kN; 690 kPa:
Vertical Contact Stress
Distribution
and
Static Tyre print:
High loading with
High inflation
Pressure



VERTICAL STRESS:

(Load case 4)

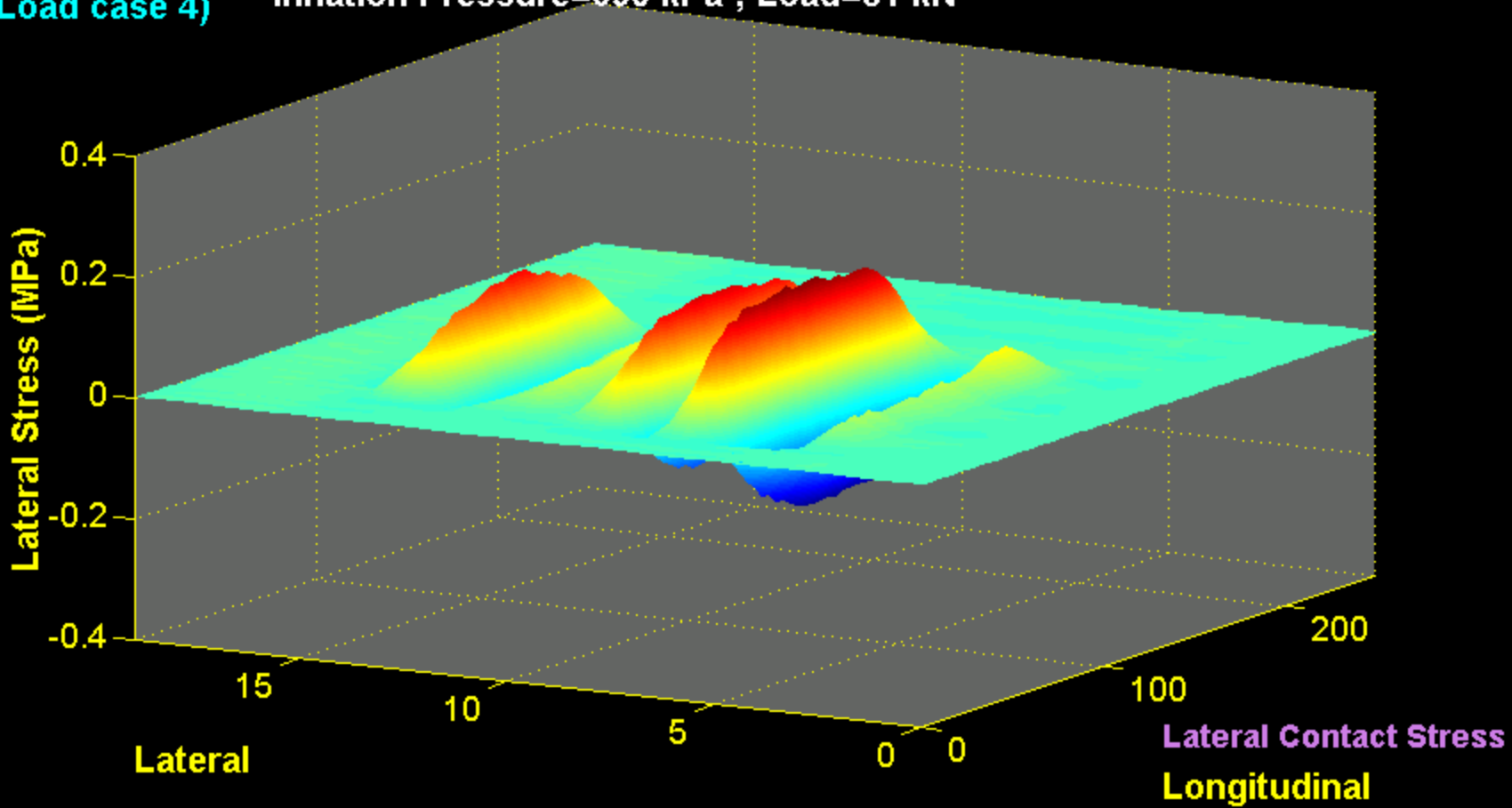
UCB GOODYEAR G159A, 11R22.5 (radial) Tire
Inflation Pressure=690 kPa ; Load=31 kN



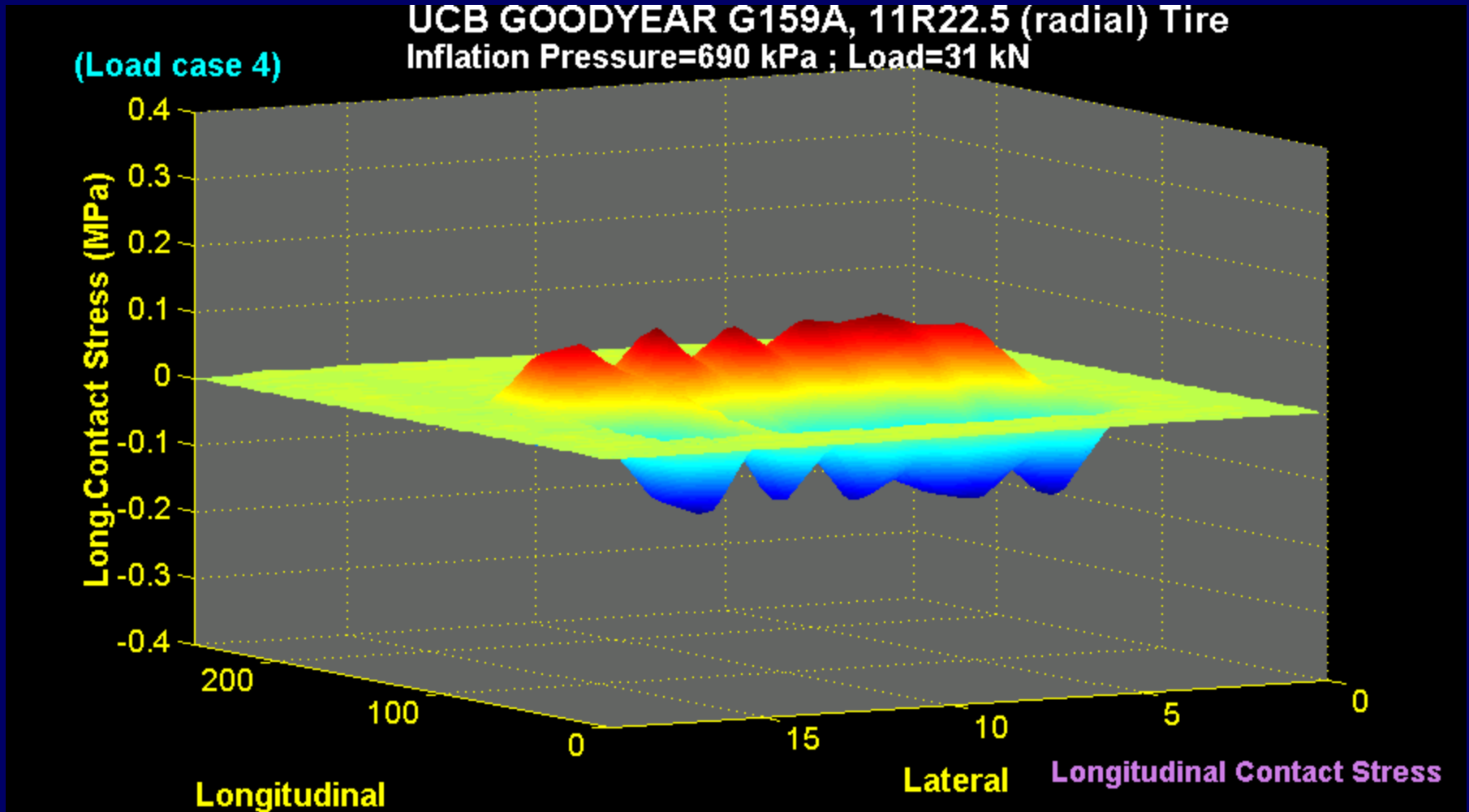
LATERAL STRESS:

UCB GOODYEAR G159A, 11R22.5 (radial) Tire
Inflation Pressure=690 kPa ; Load=31 kN

(Load case 4)



LONGITUDINAL STRESS:





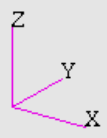
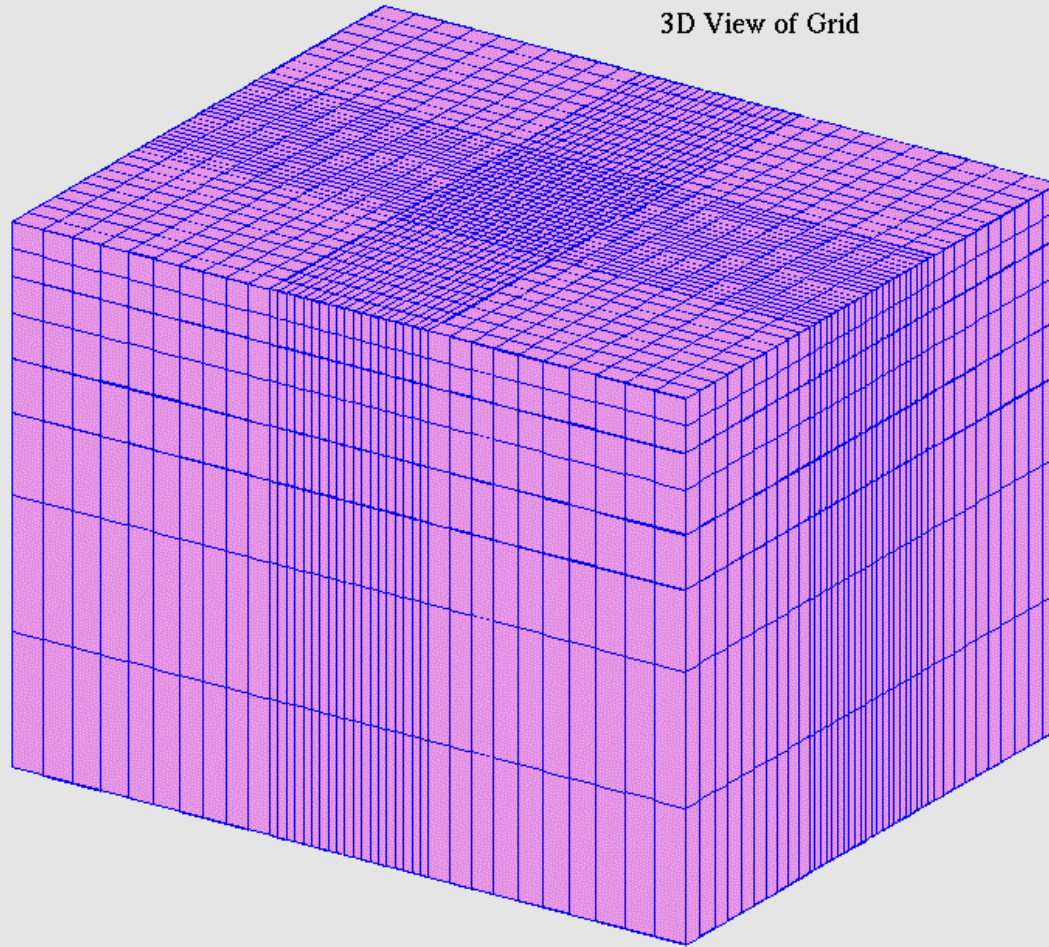
FEM LOAD APPLICATION:

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;



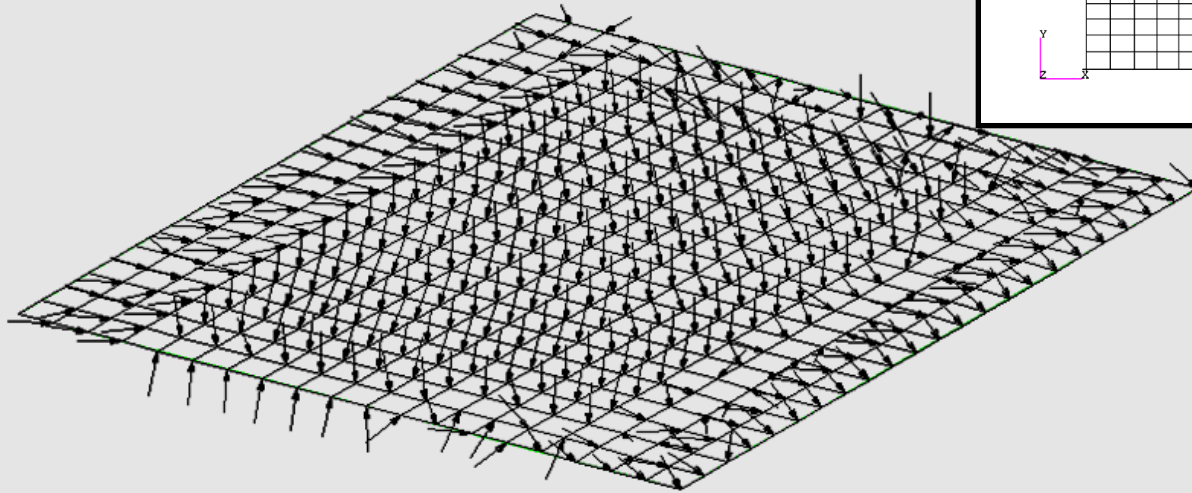
FEM (NASTRAN) PAVEMENT MODEL

MSC/PATRAN Version 9.0 24-May-00 15:11:53
Fringe: Property Set Name Scalar Plot

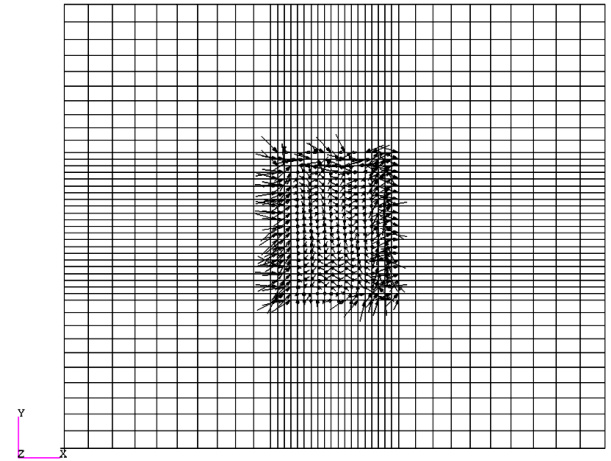


3-D SIM RESULTANT FORCES ON PAVEMENT

Resultant Forces

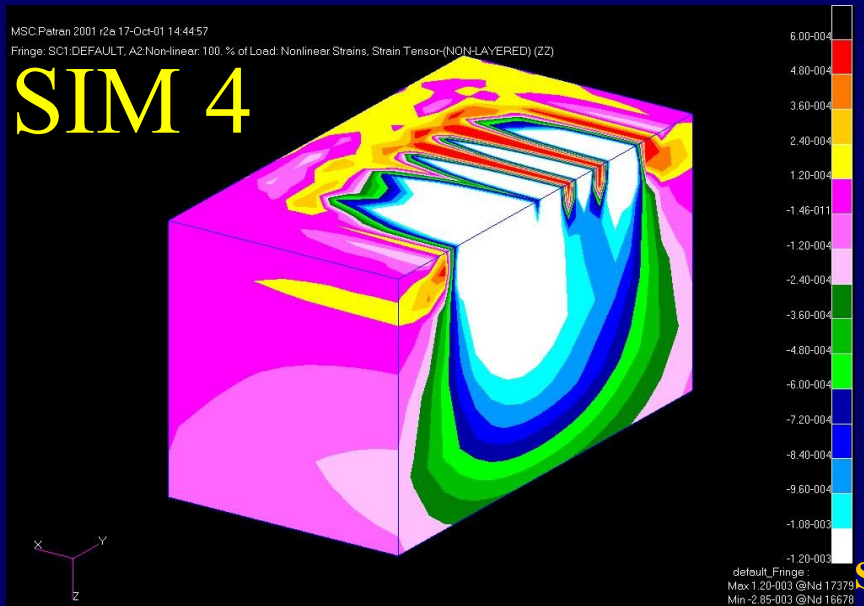
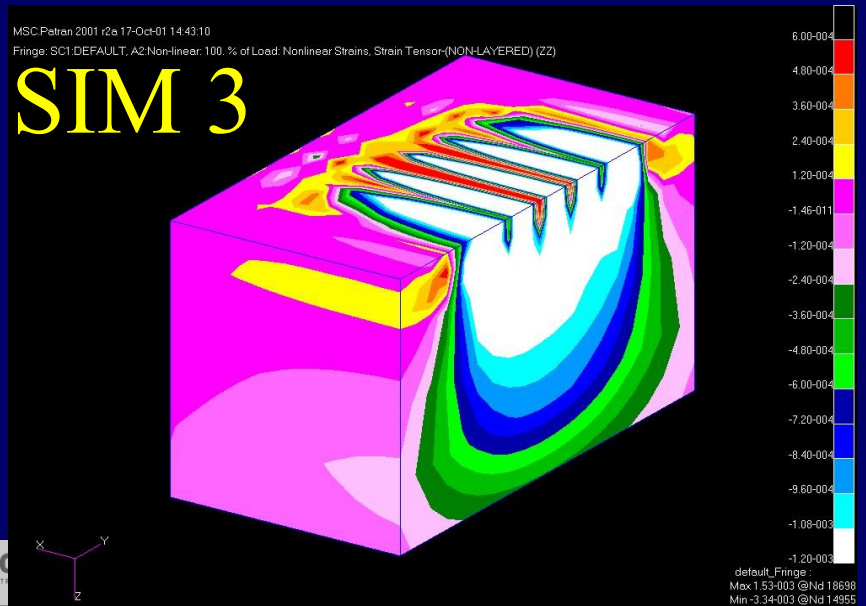
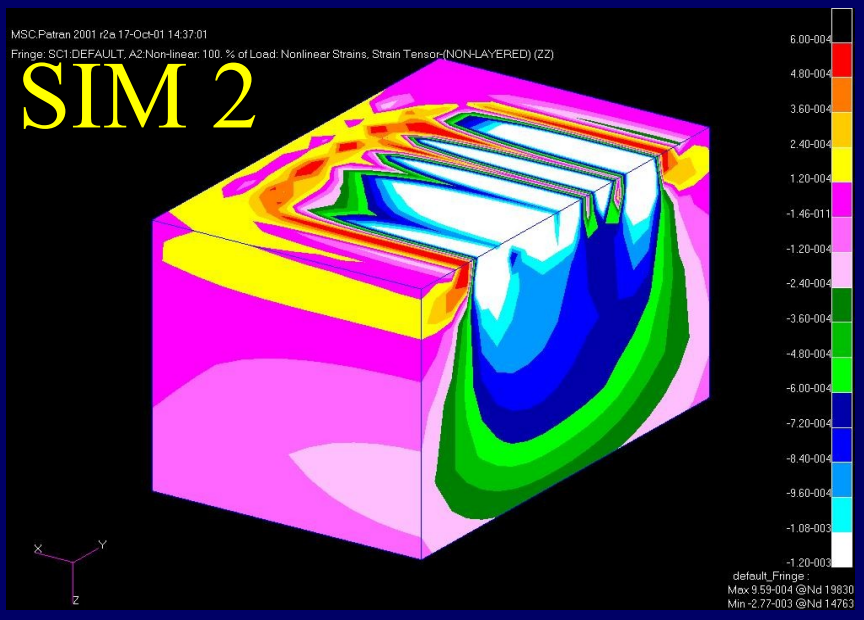
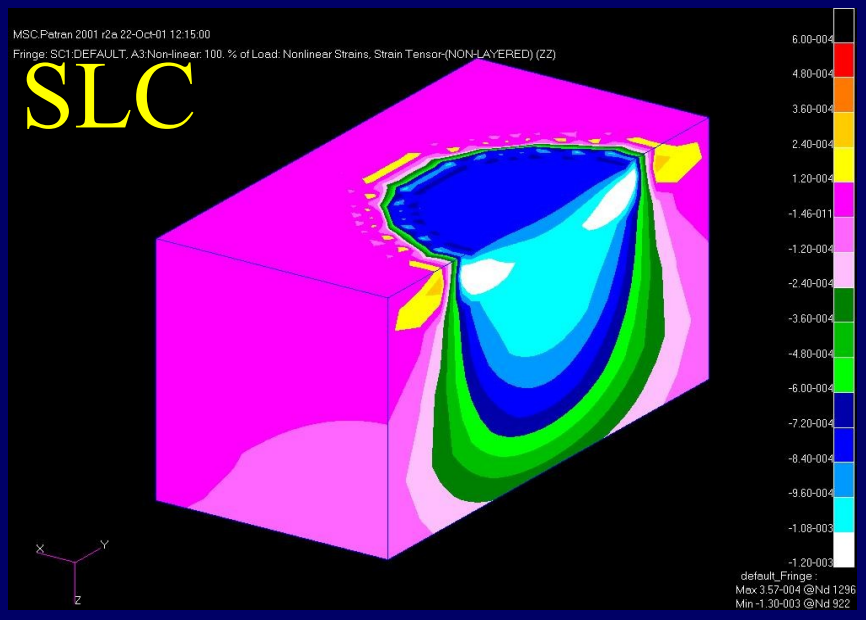


Resultant Forces

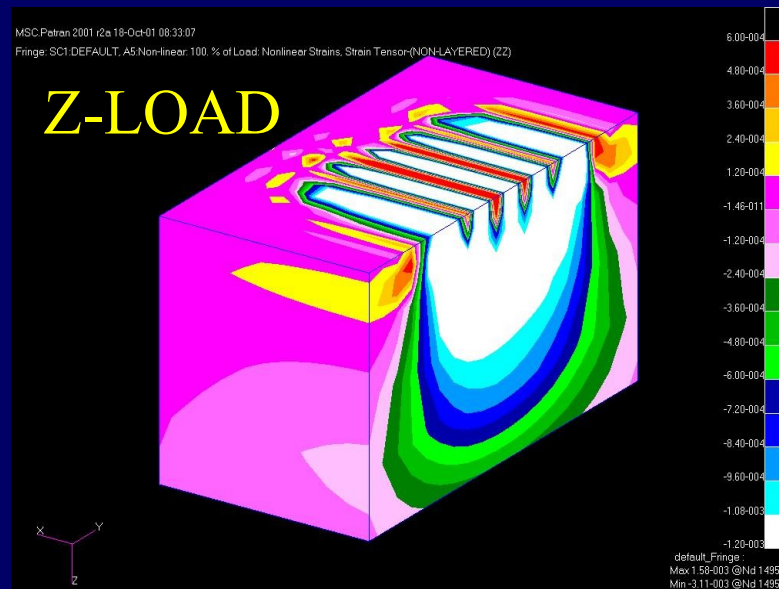
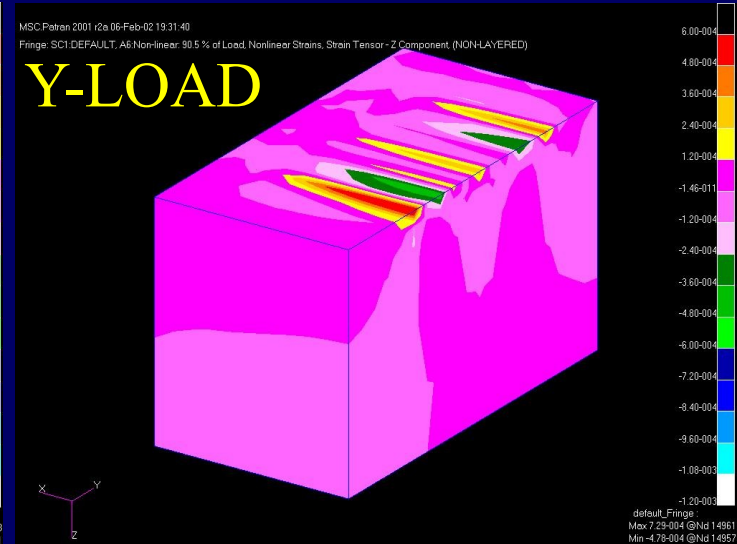
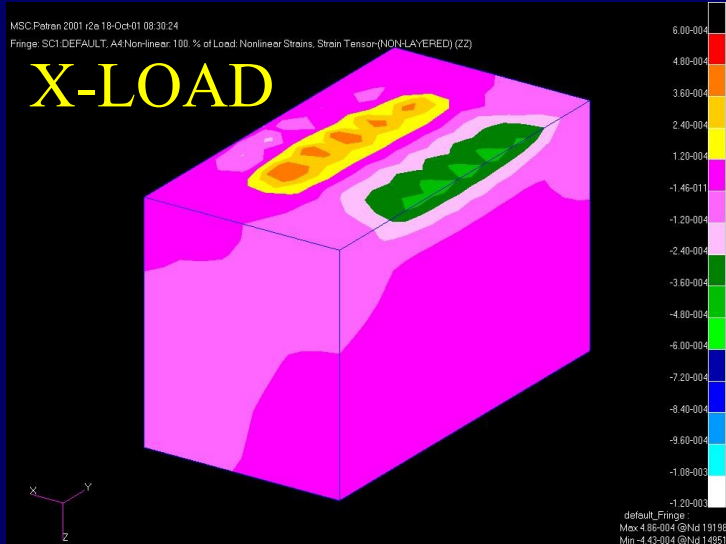




VERTICAL COMPRESSIVE STRAINS (HOT CASE)

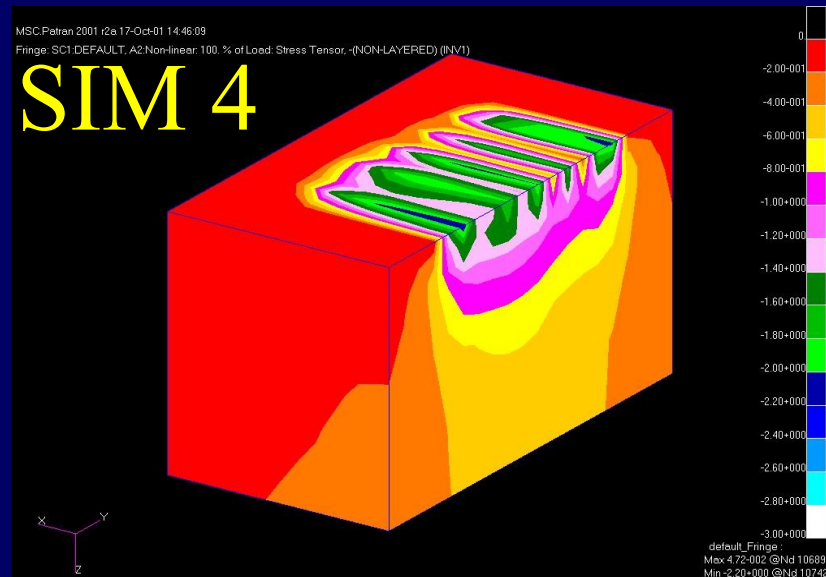
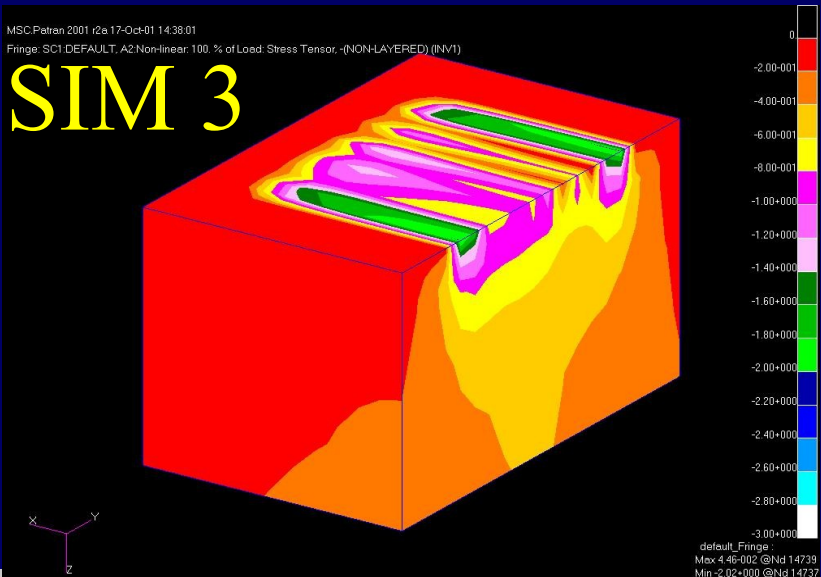
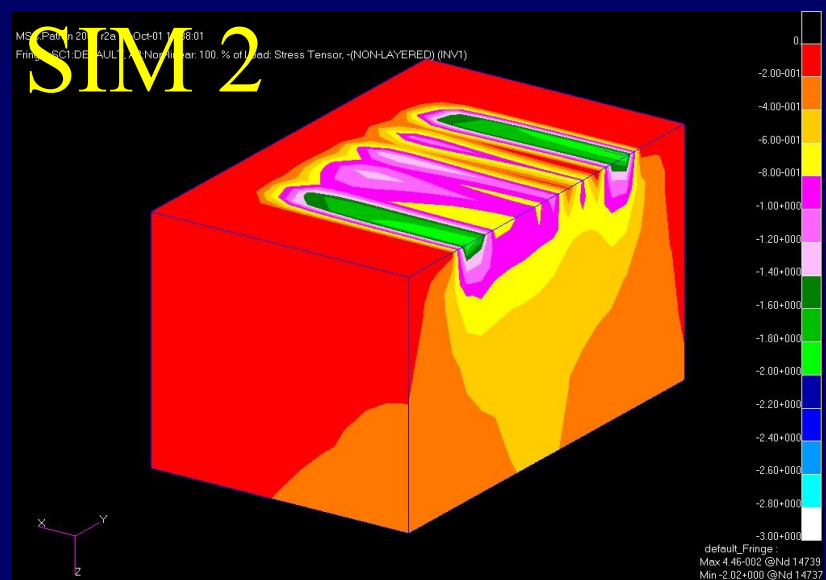
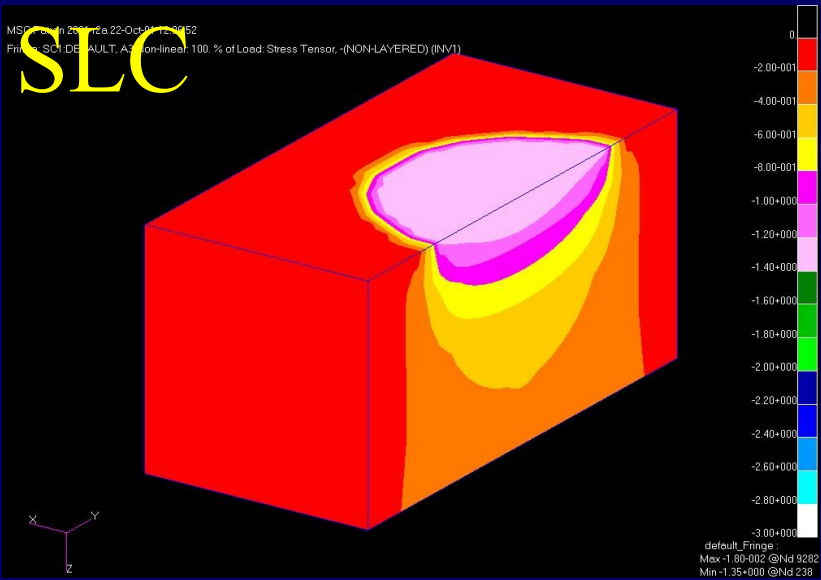


VERTICAL COMPRESSIVE STRAINS (HOT CASE)- X,Y,Z - COMPONENT LOADS





1ST INVARIANT OF STRESS (I_1): HOT CASE



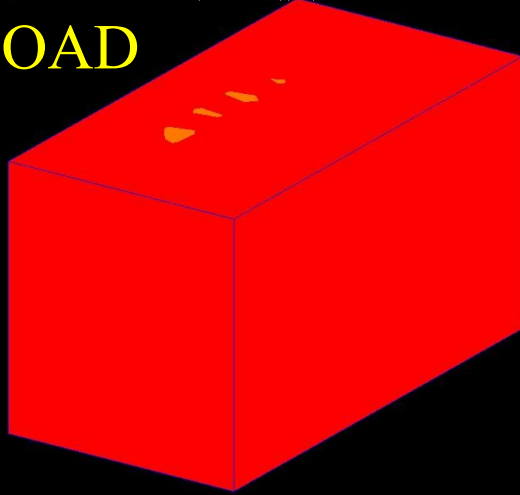


1ST INVARIANT OF STRESS (I_1): (HOT CASE)- X,Y,Z - COMPONENT LOADS

MSC Patran 2001 r2a 18-Oct-01 08:31:40

Fringe: SC1.DEFAULT,A4 Non-linear: 100. % of Load, Stress Tensor, -(NON-LAYERED) (INV1)

X-LOAD

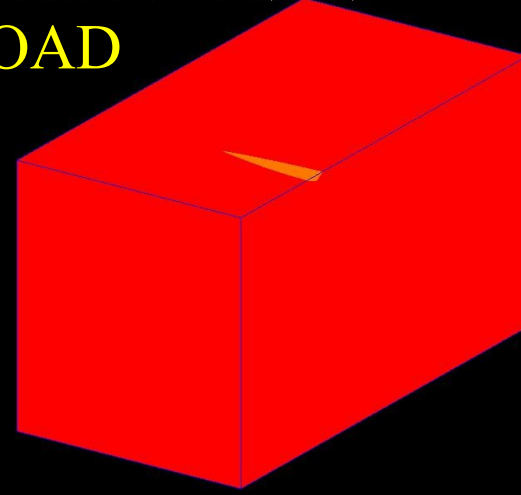


default_Fringe :
Max 2.16-001 @Nd 14955
Min -2.42-001 @Nd 19156

MSC Patran 2001 r2a 06-Feb-02 19:31:10

Fringe: SC1.DEFAULT,A6 Non-linear: 90.5 % of Load, Stress Tensor, - 1st Invariant, (NON-LAYERED)

Y-LOAD

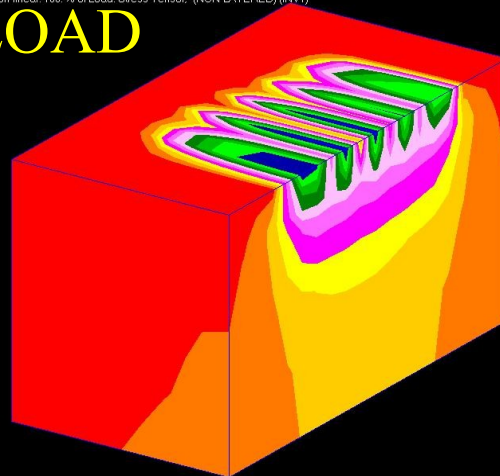


default_Fringe :
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MSC Patran 2001 r2a 18-Oct-01 08:31:54

Fringe: SC1.DEFAULT,A5 Non-linear: 100. % of Load, Stress Tensor, -(NON-LAYERED) (INV1)

Z-LOAD

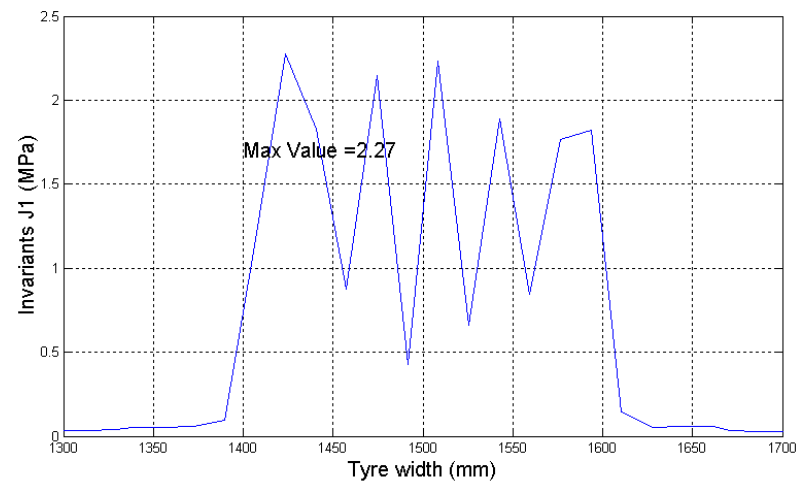
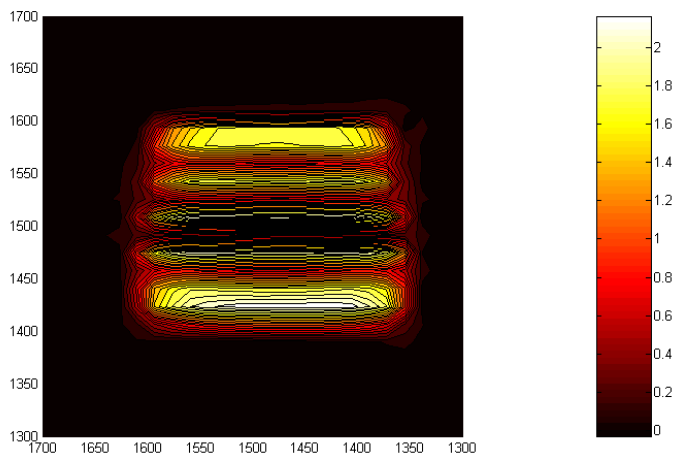
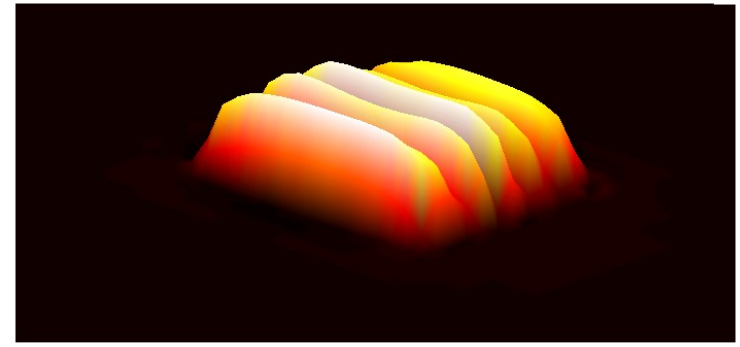
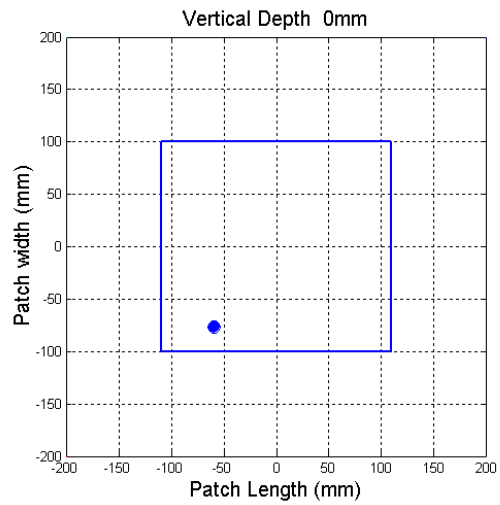


default_Fringe :
Max 6.14-002 @Nd 19234
Min -2.30+000 @Nd 14951

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

Invariants J1 – Stress Plot (MPa)

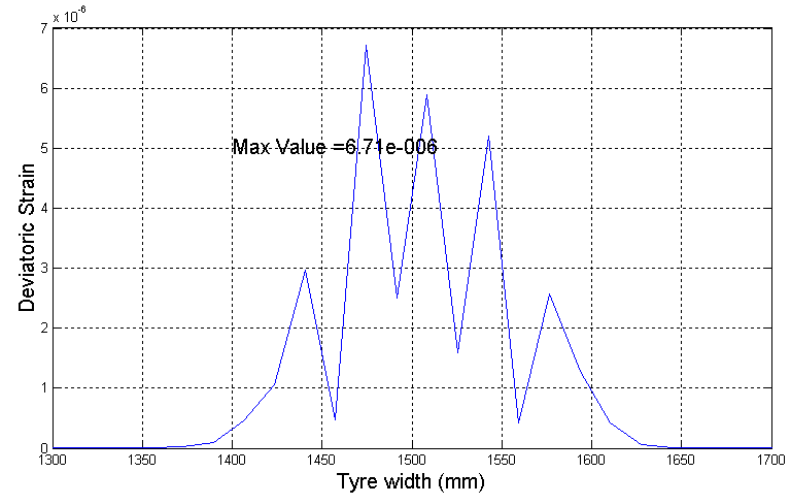
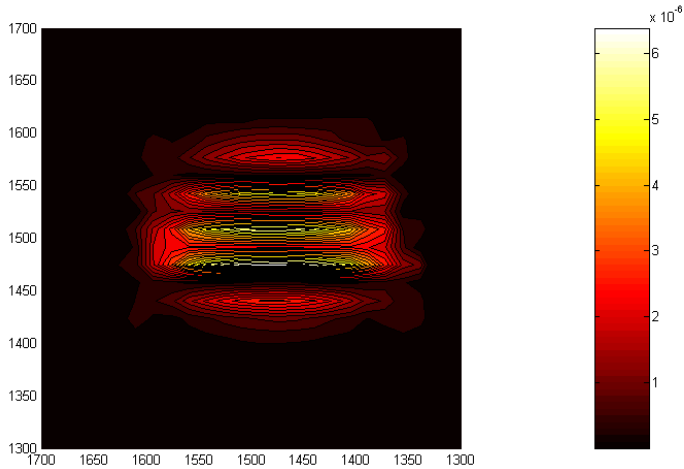
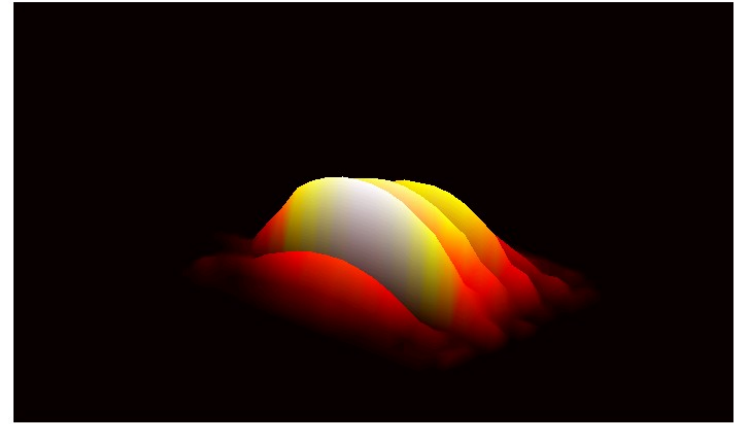
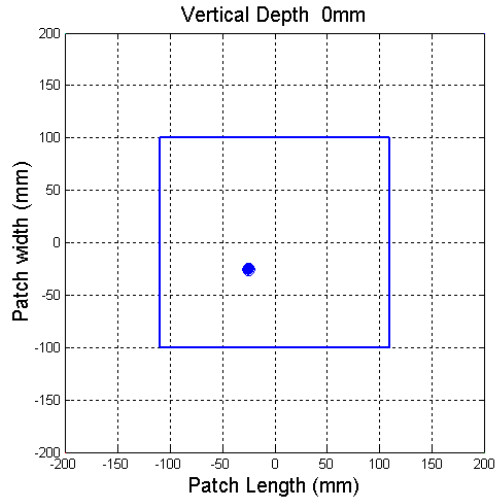
HOT



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

Invariants J2' – Strain Plot (MPa)

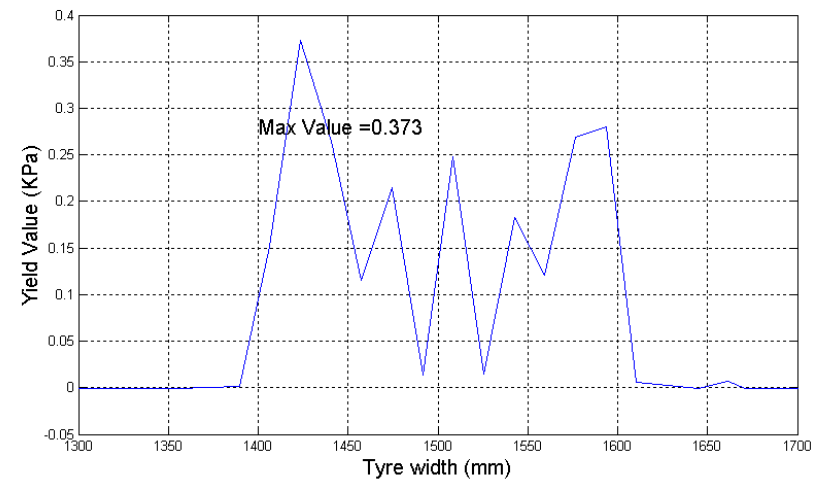
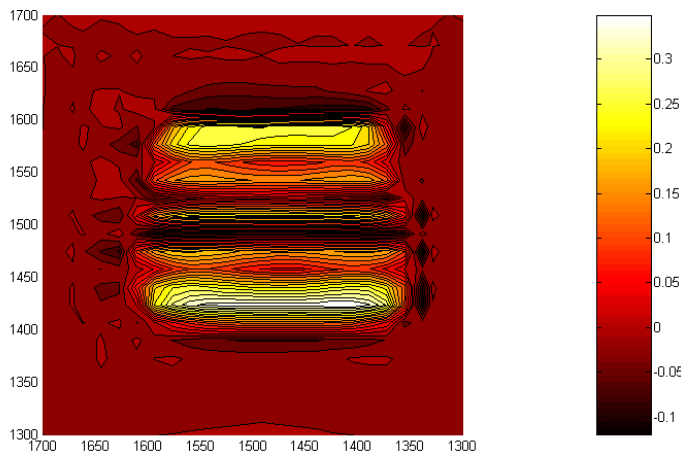
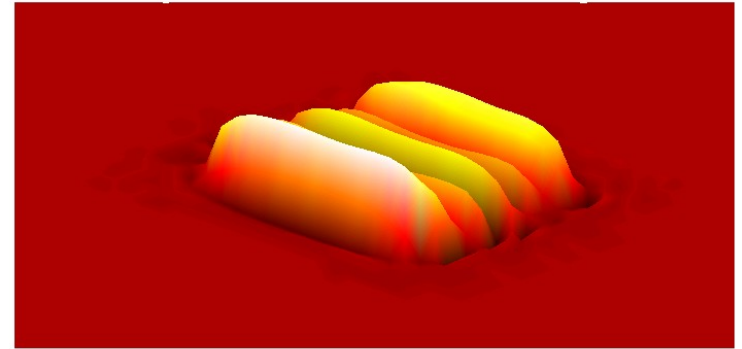
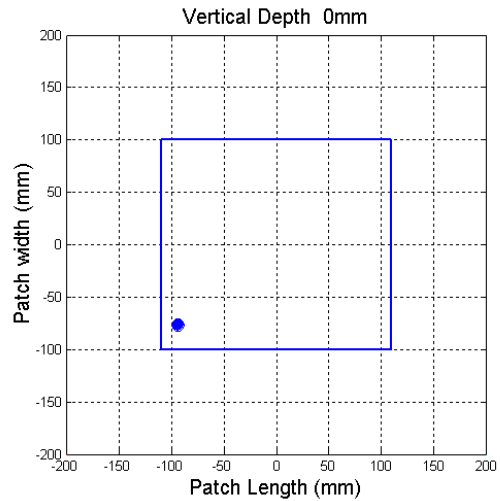
HOT



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
<i>X-Component</i>			444 (34 % SLC)
<i>Y-Component</i>			478 (37 % SLC)
<i>Z-Component</i>			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
<i>X-Component</i>			<i>0.451 (40 % SLC)</i>
<i>Y-Component</i>			<i>0.712 (70 % SLC)</i>
<i>Z-Component</i>			<i>6.110 (5.8 X SLC)</i>



Mohr-Coulomb Yield Criterion

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

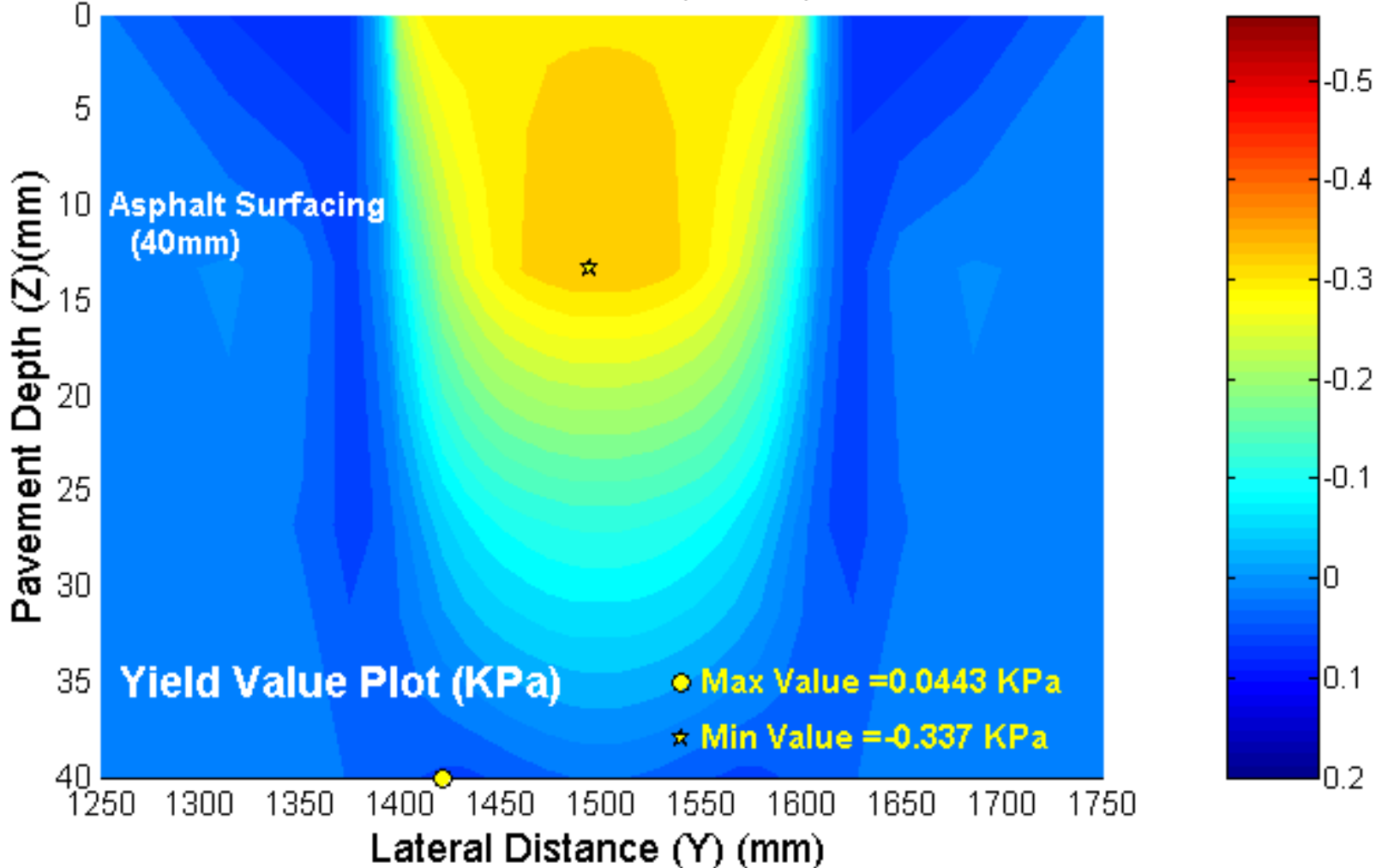
$$\frac{1}{3} J_1 \sin \phi - \sqrt{J_2'} \cos \theta - \frac{1}{\sqrt{3}} \sin \theta \sin \phi = c \cos \phi$$

$$\sin 3\theta = - \frac{\sqrt{3}}{2} \frac{J_3'}{J_2'^{3/2}}$$

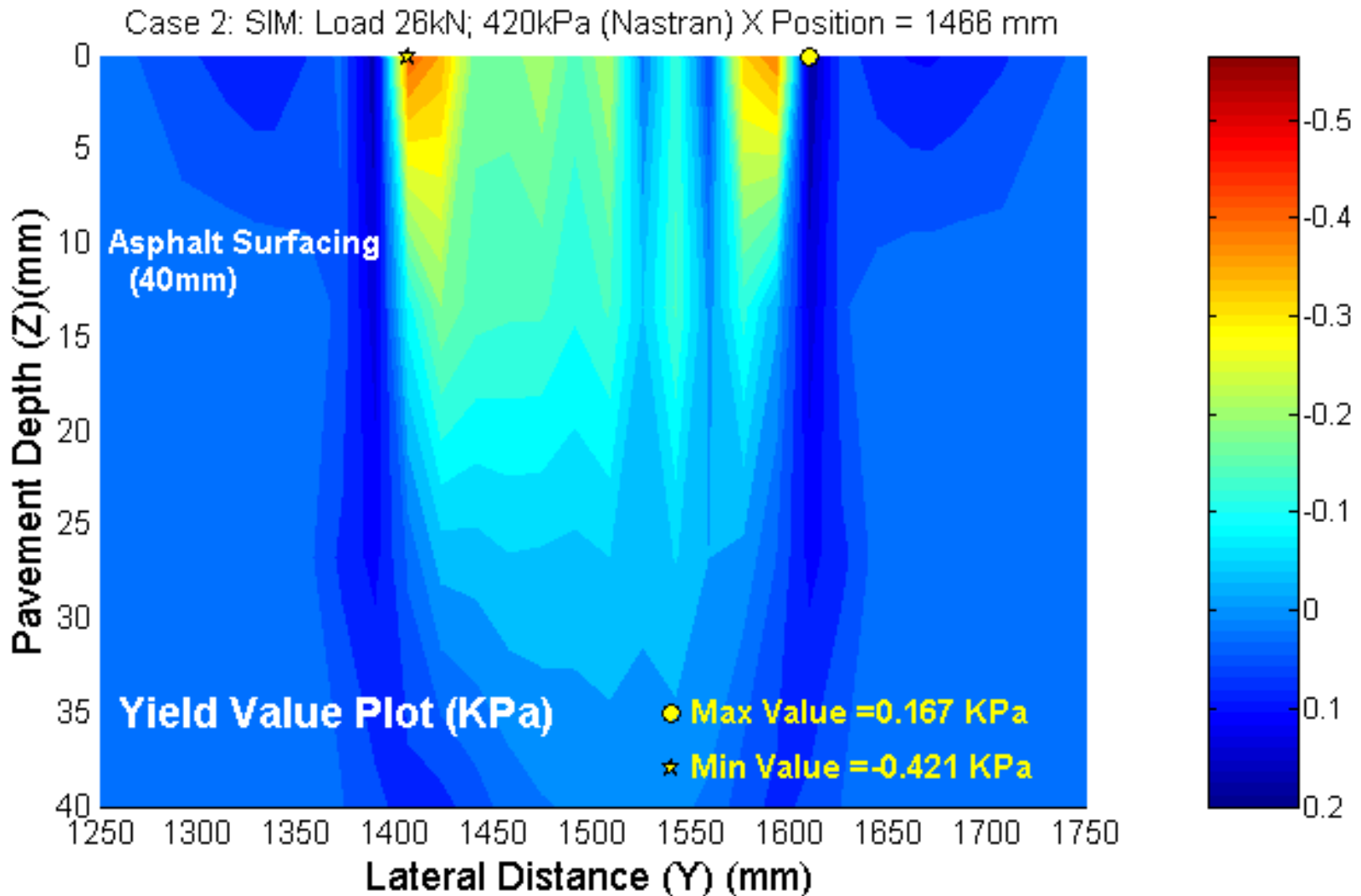
J'_i = the 1st, 2nd and 3rd stress invariants;

Yield Value Case 1: SLC

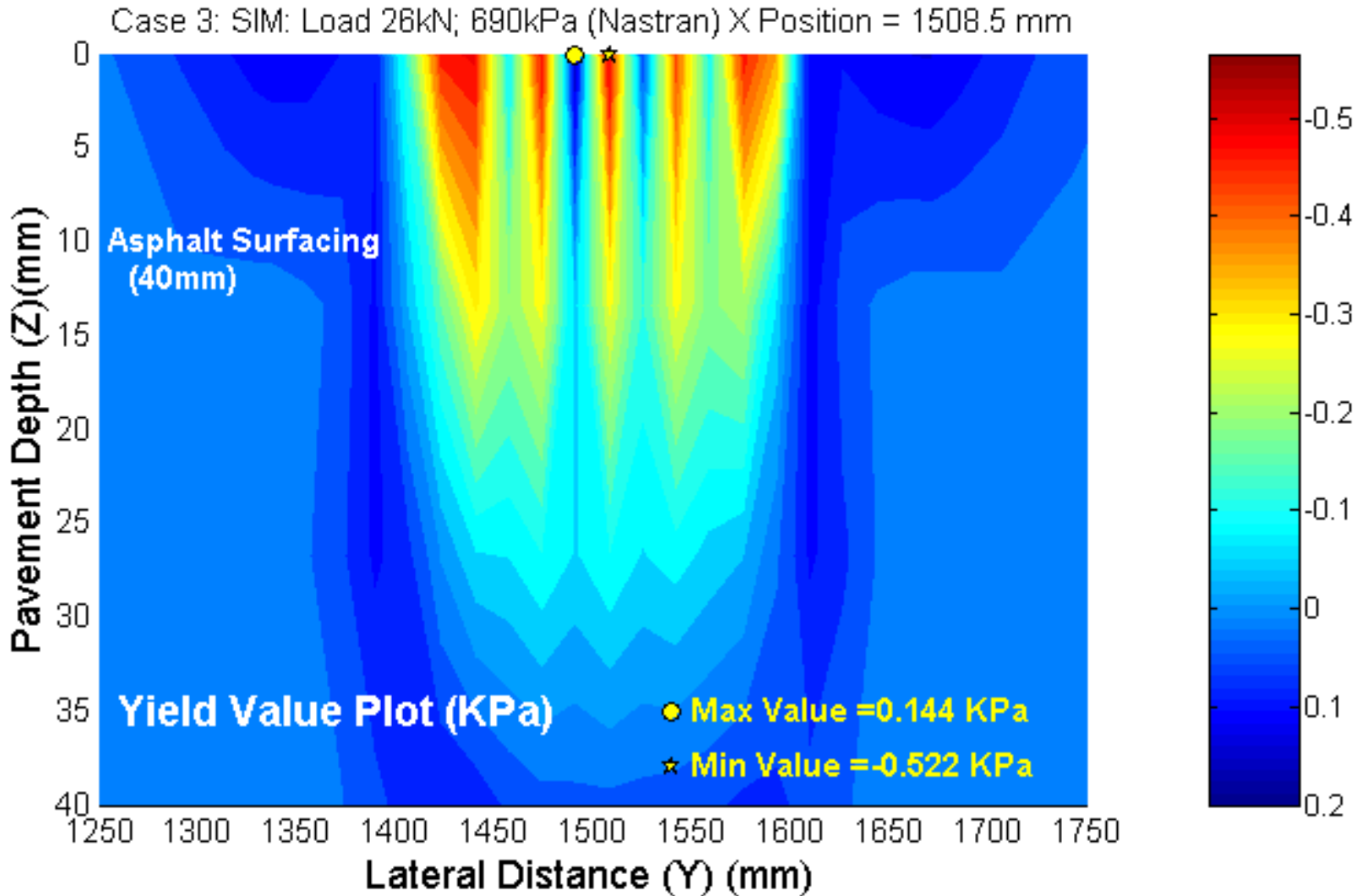
Case 1: Uniform-Circular: Load 20kN; 520kPa (Nastran) X Position = 1504.76 mm



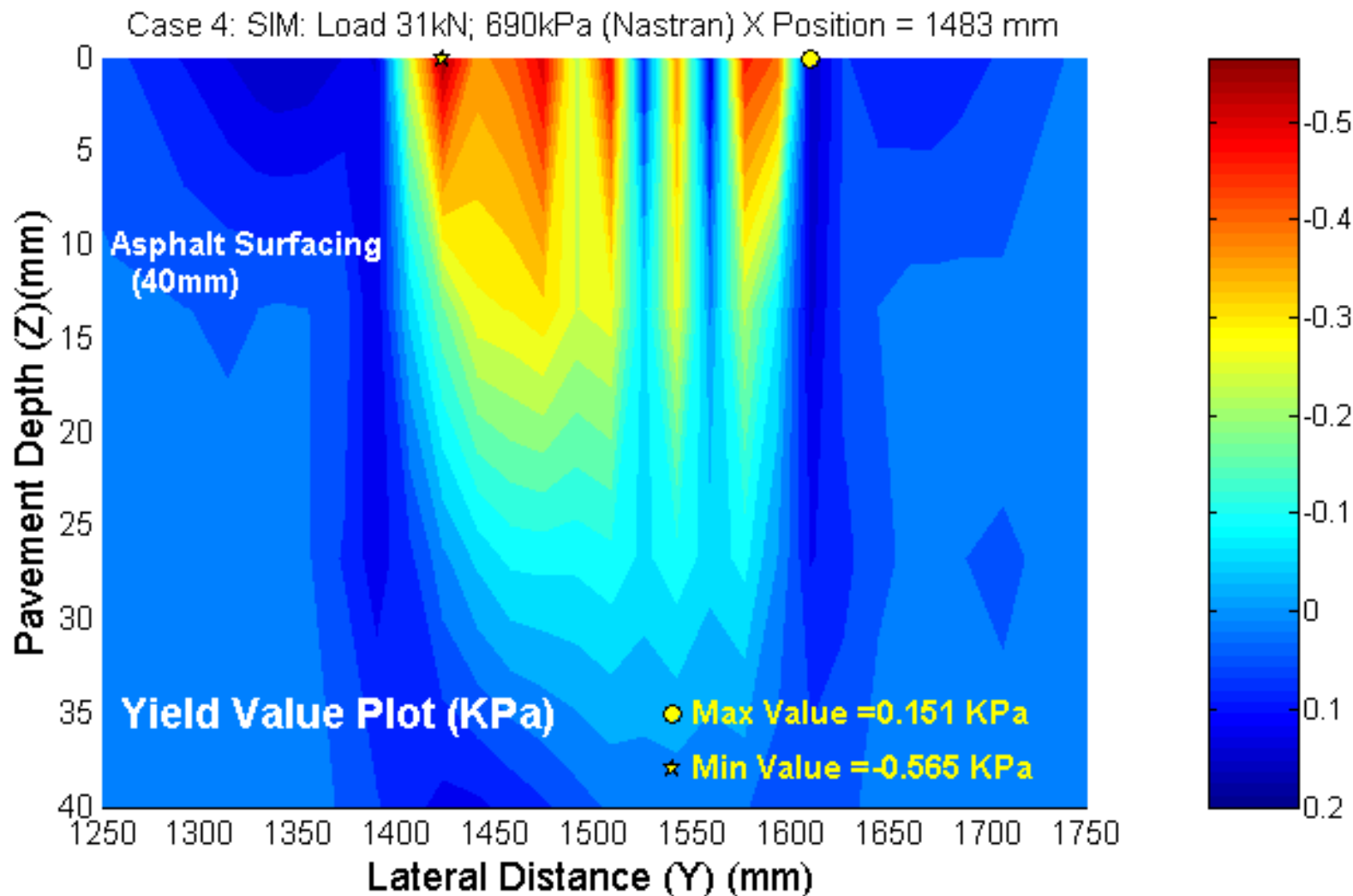
Yield Value Case 2: Low pressure



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 %)
<i>X-Component</i>			<i>132 (113 %)</i>
<i>Y-Component</i>			<i>56 (48 %)</i>
<i>Z-Component</i>			<i>384 (328 %)</i>

() = 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*):

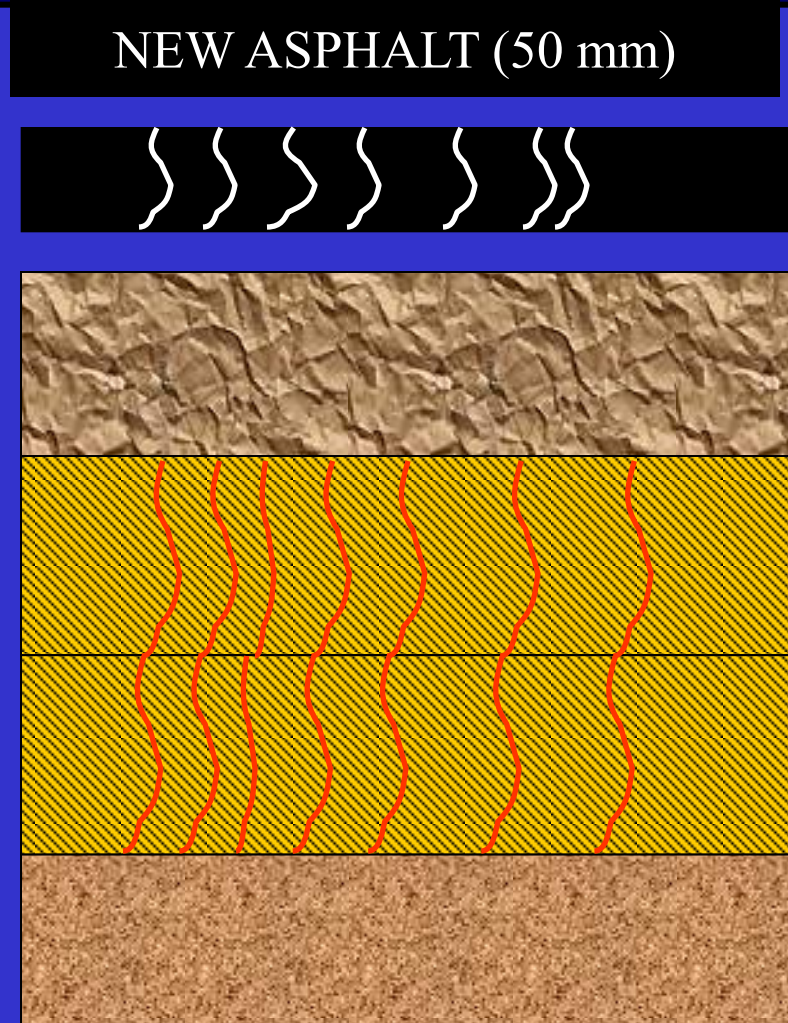
- Vertical Strain: X and Y: 34 to 37 per cent, 250 per cent for Z;
- Vertical Stress: X and Y: 5 to 7 per cent, 220 per cent for Z;
- Bulk Stress (I_1): X and Y: 18 to 21 per cent, 170 per cent for Z;
- J'_2 - Strain: X and Y: 40 to 70 per cent, 580 per cent for Z;
- J'_2 - Stress: X and Y: 28 to 39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

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

MODELED PAVEMENT STRUCTURE – Semi-Analytical-FEM

- New Asphalt Surfacing: 50 mm
($E_1 = 2500$ MPa, $\nu_1 = 0.44$);
- Old Cracked Asphalt: 50 mm
($E_2 = 3000$ MPa, $\nu_2 = 0.44$);
- Crushed Stone Base: 150 mm
-NON-LINEAR (Witczak & Uzan, 1988);
- Cementitious Subbase-1: 2 x 150 mm
($E_4 = 1800$ MPa, $\nu_4 = 0.35$)
- Soil Subgrade: 2000 mm
($E_5 = 100$ MPa, $\nu_5 = 0.35$)

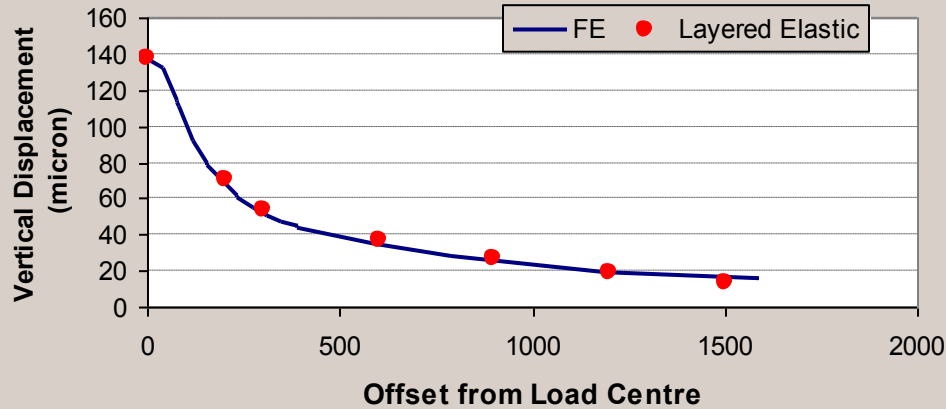


Rigid Base @ 2000 mm

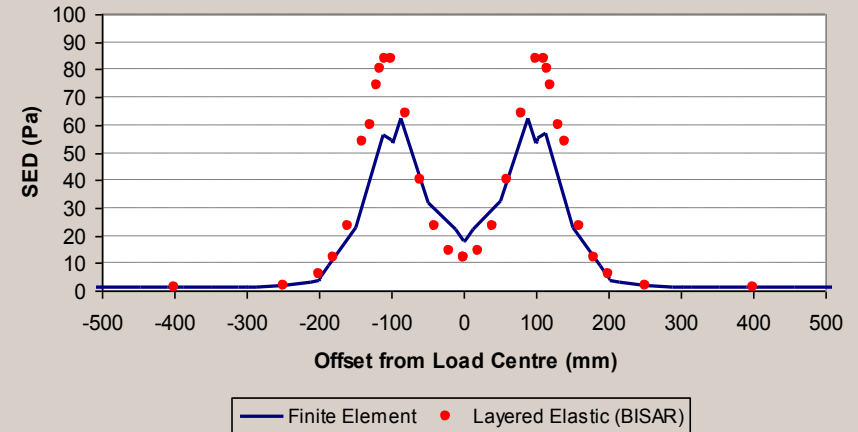


Benchmark- Semi-Analytical FEM-MLE

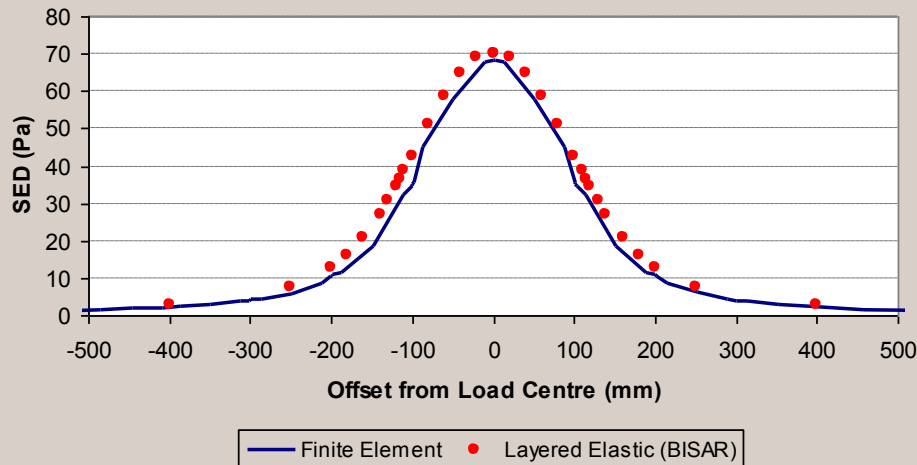
20 kN Load, 900 kPa Pressure



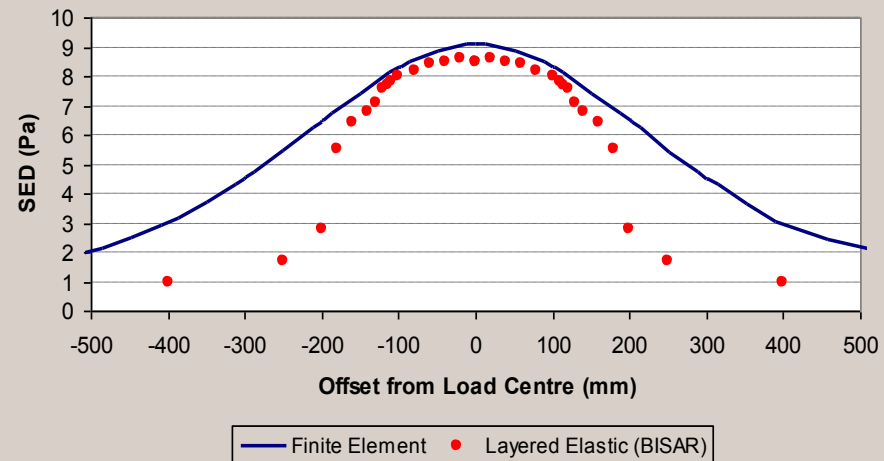
SED at bottom of thin AC overlay



SED at Top of Granular Base



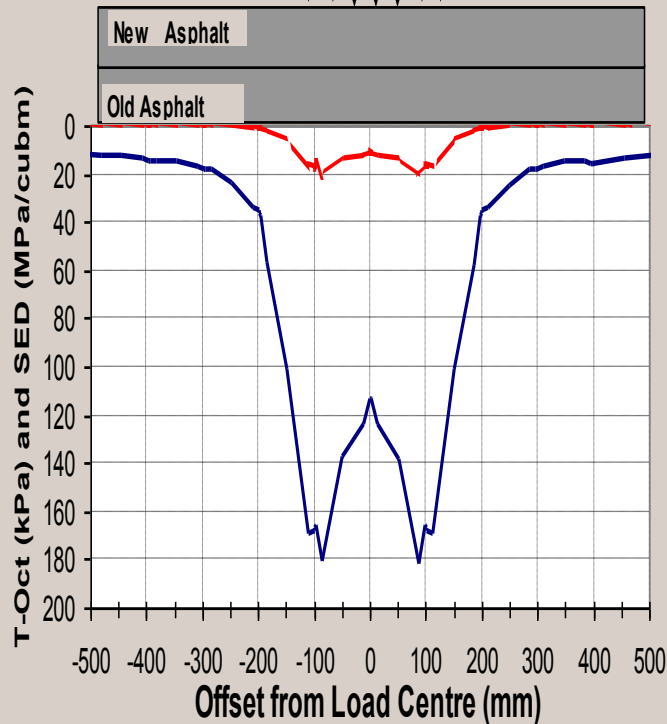
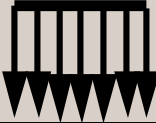
SED at Top of Subgrade





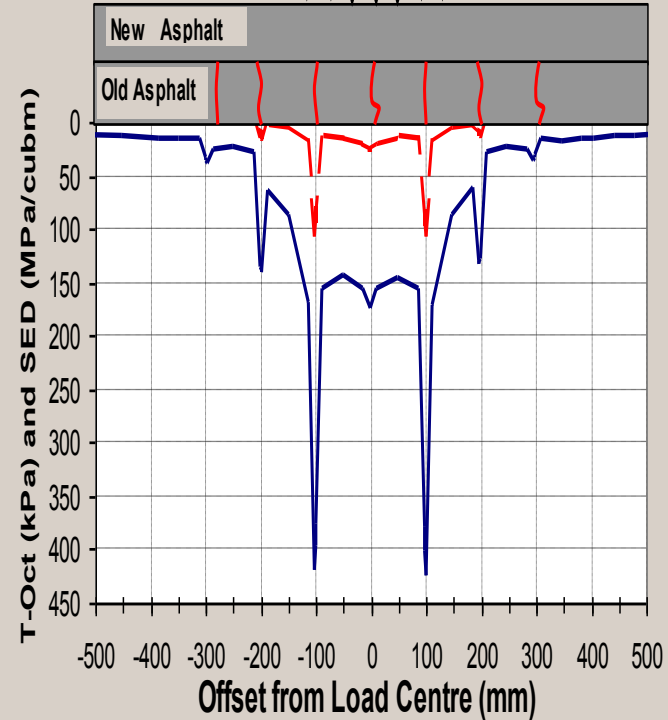
SA-FEM RESULTS: UNCRACKED vs CRACKED PAVEMENT

DUAL LOAD (SQUARE) : 40 kN
CONTACT STRESS: 520 kPa



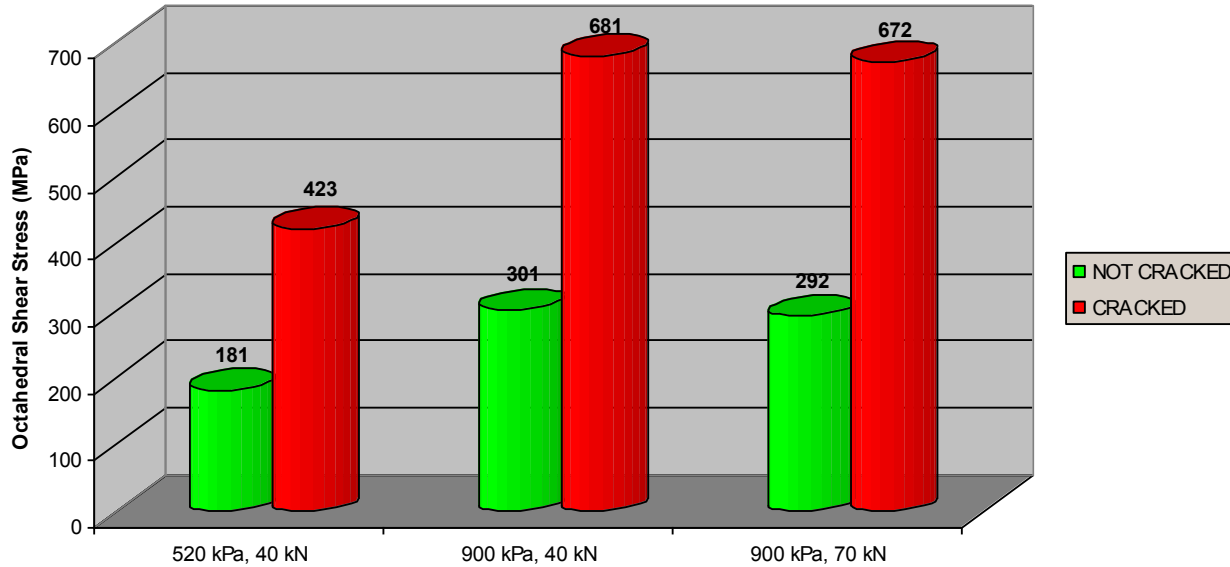
— T-Oct (kPa) - - SED (MPa/mcub)

DUAL LOAD (SQUARE) : 40 kN
CONTACT STRESS: 520 kPa



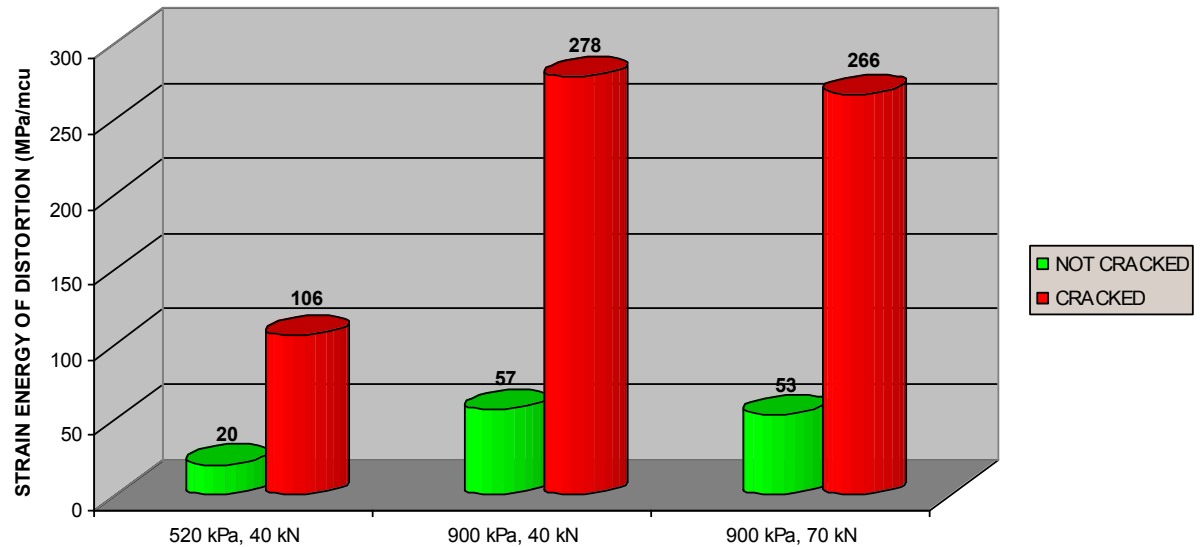
— T-Oct (kPa) - - SED (MPa/mcub)

Octahedral Shear Stress (MPa)



SA-FEM RESULTS: Un-Cracked vs Cracked

STRAIN ENERGY OF DISTORTION (SED)



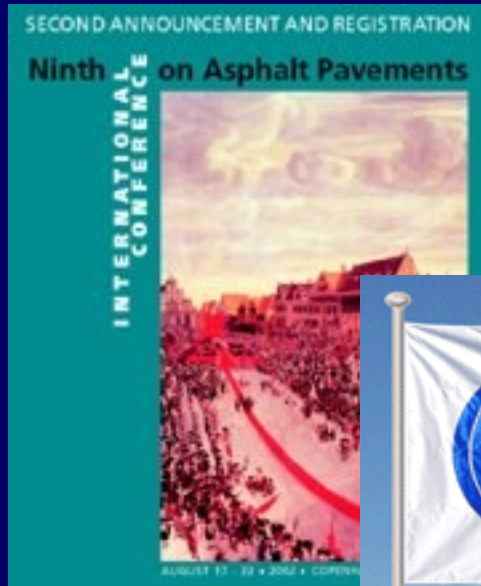


FINAL CONCLUSIONS and RECOMMENDATIONS:

- 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:

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



Thank You for
your attention !