Towards Quantifying Horizontal Stresses of Free Rolling Pneumatic Rubber Tyres on Road Surfacings

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ABSTRACT

Friction inside the contact patch of a pneumatic free-rolling rubber tyre generally occurs as a direct result of a complex configuration of generated contact loads and stresses. These stresses, referred to as horizontal stresses in this paper, were measured with the Stress-In-Motion (SIM) device on a range of four (4) full-scale truck test tyres, as well as on a 1/3rd scale test tyre. A limited number of tests were also made in which the horizontal stresses on a relatively *rough-textured* test surface were compared with those on a relatively *smooth* test surface, representing nominal textured road surfaces and nominal smooth road surfaces, respectively. In this study the main characteristics of these horizontal (X, Y) stresses are described for the purpose of a improving the engineering understanding of these contact stresses. It is anticipated that better understanding of these horizontal forces/stresses could lead to improved and more rational mechanistic design of road surfacings including e.g. seals, asphalt overlays, rolled-in chips.

It is important to note that the findings in this study strictly relate to relatively slow-moving free-rolling pneumatic tyres.

1. INTRODUCTION

1.1. Background

Friction forces inside the contact patch of a pneumatic free-rolling rubber tyre generally occurs as a direct result of a complex configuration of generated contact loads and stresses. These stresses, referred to as horizontal stresses in this paper, were measured with the Stress-In-Motion (SIM) device on a range of full-scale (truck) test tyres normally used for Heavy Vehicle Simulator (HVS) testing, as well as on a 1/3rd scale test tyre of the Model Mobile Load Simulator (MMLS3). A limited number of tests were also made in which the horizontal stresses on a relatively *rough-textured* test surface were compared with those on a *relatively smooth* test surface, representing nominal textured road surfaces and nominal smooth road surfaces, respectively. The main study summarised in this paper is described elsewhere (De Beer and Fisher, 2007). It is also worthwhile to note that the results of a previous study in which the maximum vertical contact stresses of the 1/3rd scale test tyres of the Model Mobile Load Simulator (MMLS3) were compared with those measured for three types of full-scale test tyres of the Heavy Vehicle Simulator (HVS) (De Beer and Sadzik, SATC 2007).

In this present study the main characteristics of only the horizontal (X, Y) stresses are described for the purpose of a improving the engineering understanding of these contact stresses. It is anticipated that better understanding could lead to improved mechanistic design of road surfacings, i.e. of seals, asphalt overlays, rolled-in chips.

1.2. Problem statement, Aim and Scope

The problem investigated with this study is to quantify horizontal stresses for 5 different pneumatic rubber tyre types. The mode of measurement was non-driven free-rolling at slow speed over the normal relatively rough-textured SIM surface. In addition, limited testing was done on a simulated relatively smooth surface with a thin (0.9 mm) aluminium plate between the test tyre and the surface of the SIM device. The comparative tests were done using the Stress-In-Motion (SIM) device designed to capture three-dimensional (3D) tyre-pavement contact stresses on a relatively rough-textured test surface. The aim of the paper is to summarize the measured horizontal tests results found on four (4) different truck tyre types, including a 1/3rd scale test tyre of the MMLS3. The tyre types and test surfaces include:

- Single wide base 425/65 R22.5 HVS tyre - rough-textured and smooth SIM surfaces;
- Single 315/80 R22.5 full-scale HVS tyre - rough-textured and smooth SIM surfaces;
- Dual 12R22.5 full-scale HVS tyres - rough-textured and smooth SIM surfaces;
- Dual 11R22.5 full-scale HVS tyres - rough-textured SIM surface, and a
- 1/3rd scale MMLS3 Diamond Tyre (D-tyre), with a square tyre profile - rough-textured SIM surface and smooth SIM surfaces;

The scope includes only the quantification of above tyre types, and further research is warranted to include effects of, amongst others: 1) Cornering and scuffing of tyres, and acceleration and deceleration of driving torque and braking on tyres.

2. MEASURED CONTACT STRESSES AND EXCURSION CURVES

The basic 3D contact stresses that were measured with the SIM are given in Figure 1, together with definitions of shapes. See A, B, C & D in Figure 1. For this paper only the horizontal stresses (i.e. C & D, generally referred to as X,Y Stresses in this paper) are discussed and is illustrated by way of excursion curves (ECs) shown in Figure 2. Figures 3 to 6 illustrate the measurement techniques used for the MMLS3 and the HVS tyres. The ECs illustrate the movement of the measuring pin of the SIM (representing a coarse aggregate on the road surface) in a horizontal path as it is pushed by the movement of the rolling tyre, starting at the centre (0,0) of the graph. For example, measuring Pin 13 near centre of tyre is pushed to a maximum lateral stress of 150 kPa and a maximum negative (backward) stress of 60 kPa. See Figure 2.

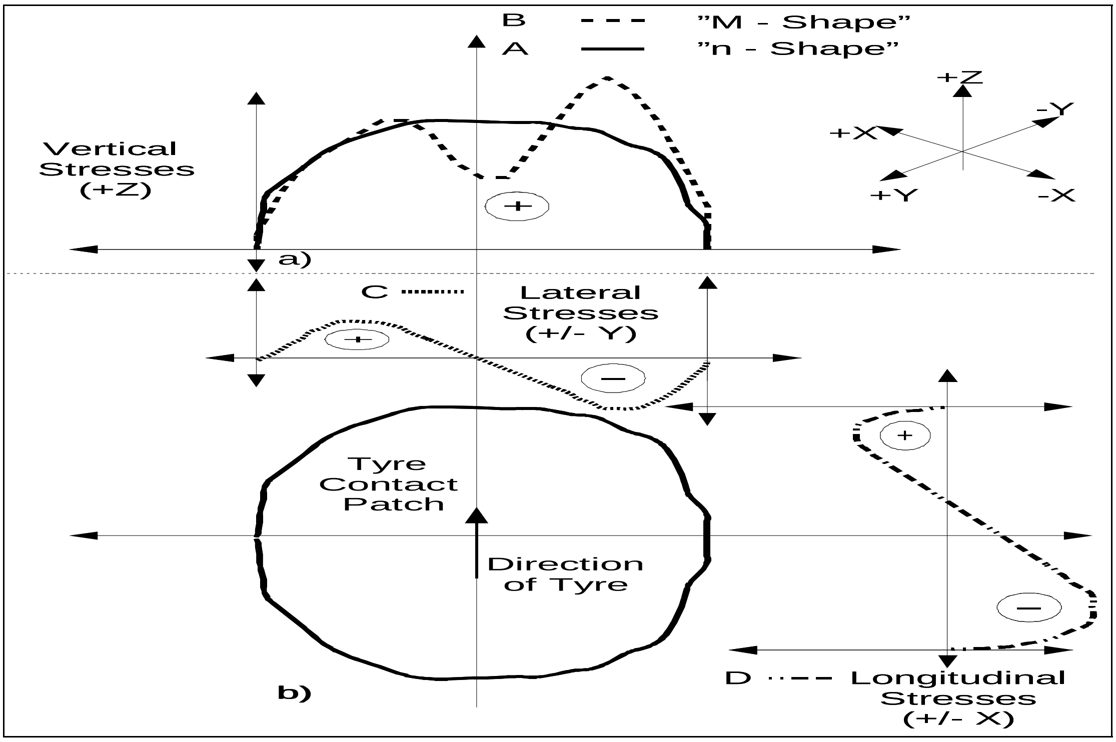


Figure 1. Basic 3D Contact Stresses and their shapes as measured with the Stress-In-Motion (SIM) device.

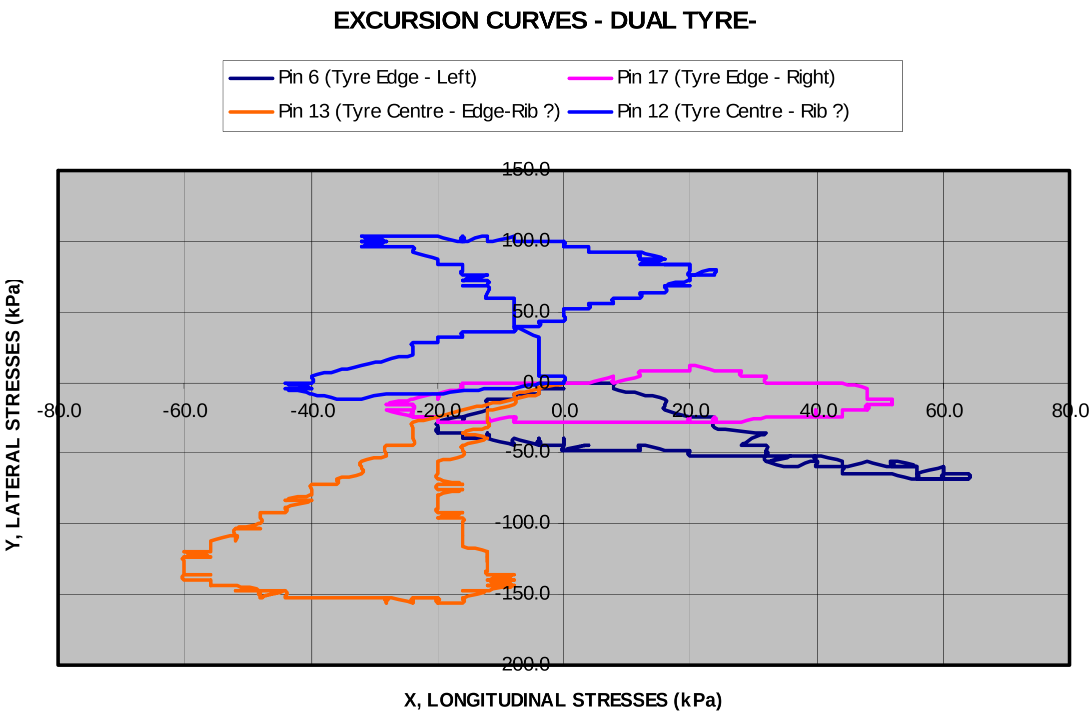
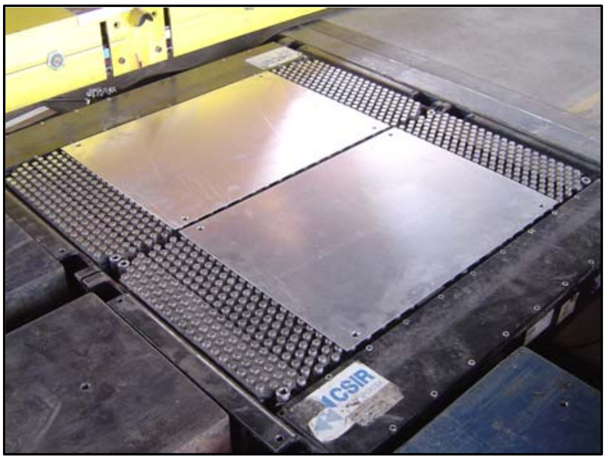


Figure 2. Example of Excursion Curves (ECs) from horizontal X-Y contact stress data of four measuring pins across the tyre width from the recent SIM measurements [The tyre moved in the +X - direction]. Note that origin (0, 0) is in the centre of figure. On this examlpe the X - Stress Range is approximately +/- 60 kPa, and Y - Stress range +/-125 kPa.

	
Figure 3. MMLS3 on the SIM pad at GDPTRW, Koedoespoort facility.	**Figure 4.** Close-up: 1/3rd scale D-tyre of MMLS3 on the *rough-textured* SIM surface (pad).
	
Figure 5. HVS full-scaled dual tyres on the *rough-textured* SIM surface.	**Figure 6.** Artificial smooth plate on the SIM surface, before full-scale testing.

2.1. <u>Approximate ranges of measured horizontal X, Y Stresses</u>

In Table 1 a summary is given of the approximate measured ranges of average X,Y -Stresses for the five tyre types and associated test surface conditions. The stress ranges are similar to those for the Excursion Curves (EC) as illustrated in Figure 2. The table indicates the tyre type, loading ranges, inflation pressure ranges and X, Y –Stresses for the different surface conditions, i.e. rough-textured (normal SIM surface) as shown in Figures 4 and 5, and the simulated smooth surface shown in Figure 6. In this paper, the data are clustered into groups for relatively lower test loading range (< 50 kN), higher test loading range (> 50 kN) and type of test surface, i.e. rough or smooth. The idea is to study for trends in X, Y – Stresses between tyre types, i.e. single or dual, as well as tyre size - full scale vs MMLS3 1/3rd scale on the two test surfaces. For this reason the various data groups are illustrated in Figures 7 to 12. Figure 7 illustrates the X, Y –Stresses for the full scale test tyres on a rough-textured test surface of the SIM for the loading range lower than 50 kN (< 50 kN), and Figure 8 for the higher than 50 kN (> 50 kN) case. In terms of trends the following can be noted:

- The smaller the tyre width the lower the stresses, especially at very high tyre loading;
- The horizontal X, Y - Stresses vary between 87 kPa to 277 kPa with Coefficient of Variance (CoV) between 12 and 22 per cent;
- For all loading cases the lateral Y - Stresses are generally higher than the longitudinal X - Stresses by 30 to 50 per cent;
- Of importance are the stresses obtained for the 315/80 R22.5 and 12R22.5 full scale tyres, since these are the most popular truck tyres used currently in South Africa. The 315/80 R22.5 are the most popular steering tyre and the associated X, Y – Stresses are 1.3 to 2 times higher than those obtained for the 12R22.5 tyres[1]. This suggests the 315/80 R22.5 tyre to be the critical design tyre – It is also noteworthy to mention that the maximum vertical contact stress (MVCS) for this tyre was almost equal or higher than those for the 12R22.5 tyre (De Beer et al, 2006), which re-enforces the preceding statement on "critical design tyre" for pavement analysis in SA;
- The highest horizontal X, Y – Stresses were obtained for the wide base 425/65 R22.5 tyre under high loading (> 50 kN), but this tyre is apparently out of production and not used regularly in SA anymore;
- The lowest stresses were obtained for the smallest full scale tyre, i.e. 11R22.5 under lower loading conditions (< 50 kN).

Figure 9 illustrates the X, Y –Stresses for two full scale test tyres on the simulated smooth test surface of the SIM for the loading range lower than 50 kN (< 50 kN), and Figure 10 for the higher than 50 kN (> 50 kN) case. In terms of trends the following can be noted:

- Again the lateral Y - Stresses are also higher than the X – Stresses by approximately 38 per cent in this case;
- Also higher X, Y - Stresses were obtained for the single 315/80 R22.5 tyre compared to the dual 12R22.5 tyre for both loading conditions;

2.2. Approximate ranges of measured X, Y - Stresses of 1/3rd scale MMLS3 tyres

[1] Both the single 315/80 R22.5 tyre and the 12R22.5 are used on steering axles of trucks. During a 2004 study showed that 47 per cent of the steering tyres were of the 315/80 R22.5 size and 40 per cent the 12R22.5 tyre size (De Beer et al, 24th SATC 2005). Important to note that the loading on the 12R22.5 tyres reported here are for a dual tyre set.

For the load range of 1.8 to 2.7 kN and simulated speed ranges of 3 km/h, 13 km/h and 26 km/h, the X, Y - Stresses of the MMLS3 tyre ranged between 37 kPa and 53 kPa on the rough-textured surface (CoV approximately 20 per cent probably due to load and speed variances). The MMLS3 load was set at one load level of 2.7 kN for the tests on the smooth surface at all three speeds of the MMLS3, and the associated values were 16 kPa and 31 kPa with CoV between 11 and 15 per cent. (The CoV in this case probably mainly due to speed range used, since load was kept constant at 2.7 kN). See Table 1.

2.3. Rough-Textured test surface vs Smooth test surface

2.3.1. Full Scale HVS test tyres

The X, Y - Stress data showing a trend of generally lower values obtained on the simulated smooth test surface. Of significance is the comparison found at the higher loading values (i.e. > 50 kN) where approximately 40 per cent lower values were measured on the smooth surface for the 12R22.5 full scale HVS test tyres, and 40 to 55 per cent lower for the MMLS3 tyre.

2.3.2. MMLS3 test tyre – 1/3rd scale

Interestingly, the MMLS3 X,Y - Stresses on a rough-textured surface are approximately three times (3.3 to 3.4 – see Table 1 and Figure 11) smaller (i.e. approx. 1/3rd) compared to those found for all the full scale HVS test tyres. It is however important to note that this ratio increased under the higher loading range to approximately 4.5, and as high as 8 on the simulated smooth test surface.

2.3.3. Comparison of all measured horizontal X, Y – Stress data

In Figure 12 a comparison based on average of average of the different data sets from this study are illustrated. In general the Y – Stresses are higher than the X- Stresses (as previously discussed), and further the X, Y - Stresses on the rough-textured surface are generally higher compared to those measured on the simulated smooth test surface. This is especially true for the higher load cases of the full scale HVS test tyres, and the 1/3rd scale MMLS3 test tyre.

2.4. Discussion of results

An interesting finding was that for all tyres tested (including the 1/3rd scale tyre), that the Y - Stresses (i.e. across the tyre patch) were generally 30 per cent to 50 per cent *higher* compared with the X - Stresses (i.e. longitudinal direction along tyre contact patch). For the 1/3rd scale MMLS3 tyre the percentage range was found to be 43 to 93 per cent. It should be noted that the foregoing is strictly for free-rolling rubber tyres, which implicate for driven tyres (or breaking tyres) that especially the X – Stresses might change considerably, depending on tyre torque in the rolling direction. On the other hand, the X – Stresses might also change considerably when the tyre “scuffs” or is in a turning mode. Limited testing in 1997 (De Beer et al, 1997) suggested a 30 kPa increase in X- Stresses per degree of turning (or scuffing) of the rolling pneumatic rubber tyre. Again, this finding, however, needs to be critically evaluated in the laboratory with the SIM, MMLS3, and also for the full scale tyres on the HVS (Note that in order to do the foregoing, the current equipment need to be adapted for the controlled application of horizontal forces (i.e. steering, acceleration or deceleration) on the test tyres). The findings above further suggests that the X,Y horizontal stresses of the 1/3rd scale MMLS3 tyre approximates a 1/3rd on a rough-textured surface, but increases drastically when a relatively smooth surface is tested with the same square profile MMLS3 tyre. For this MMLS3 tyre in itself, the foregoing probably suggests *higher vertical rutting* on a smooth surface compared to a rough-textured surface for the same number of load (stress) repetitions, and every thing else the same. This finding, however, needs to be critically evaluated in the laboratory with the MMLS3, and also for the full scale tyres on the HVS.

3. SUMMARY, CONCLUSIONS AND RECOMMENDATIONS[2]

From this work, the following important aspects are summarised and concluded:

- For free-rolling pneumatic rubber tyres the horizontal contact stresses were measured successfully with the Stress-In-Motion (SIM) device. This allows for the relative quantification as well as comparative studies of the horizontal loading/stress regimes generated from the different tyre types studied here;
- The Excursion Curve (EC) methodology used here allows for the improved visual understanding of the interaction between the X - Stresses and the Y – Stresses;
- Generally the lateral Y – Stresses are <u>higher</u> than the longitudinal X – Stresses;
- The X, Y - Stresses on a *relatively* <u>*rough-textured*</u> pavement surface appear to be higher than those on a *relatively* <u>*smooth surface*</u>, especially under the higher tyre loading used in this study;
- The X, Y - Stresses of the full-scale 12R22.5 tyres are on average approximately similar under the lower loading range of 30 to 40 kN on a *relatively* <u>*smooth surface*</u>, *but are approximately 40 per cent lower* under the higher loading range (> 50 kN) at the same inflation pressure range, by comparison with those obtained on the normal *relatively* <u>*rough-textured*</u> SIM surface. This is considered important, especially for Accelerated Pavement Testing (APT) using the higher loading ranges for the "acceleration" of testing in the field on road surfaces;
- The X, Y - Stresses of the 1/3rd scale MMLS3 tyre (Diamond, square profile) are, on average, only approximately *one third* of those for full-scale tyres on a *relatively* <u>*rough-textured*</u> test surface; and
- The X, Y - Stresses of the 1/3rd scale MMLS3 tyre (Diamond, square profile) are, on average, between *40 per cent and 60 per cent* lower than those measured on the *relatively* <u>*rough- textured*</u> SIM surface.

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[2] A more complete list of Summary, Conclusions and Recommendations from this study is available in De Beer and Fisher (2007).

Table 1. Summary of the measured X,Y Stresses (approximate ranges) found for the different full scale HVS tyre types and surface conditions (i.e. “rough-textured” and “smooth”) on the SIM device, including the 1/3rd scale MMLS3 test tyre.

LOWER LOADS & ROUGH-TEXTURED SIM TEST SURFACE:								
TYRE TYPE TESTED	**TYRE LOADING RANGE (kN) - (HVS @ 1.22 km/h)**	**INFLATION PRESSURE RANGE (kPa)**	**+/- X-Stresses (Rough)**		**+/- Y-Stresses (Rough)**		**Surface Condition (SIM)**	**Difference of Y-Stress relative to X-Stress (%)**
			Average (kPa)	***CoV (%)***	**Average (kPa)**	***CoV (%)***		
Wide Base Single: 425/65 R22.5	25 to 50	500 to 1000	120	*33*	216	*16*	*Rough-Textured*	80.0
Single: 315/80 R22.5	20 to 35	520 to 1000	182	*29*	231	*16*	*Rough-Textured*	26.9
Dual: 12R22.5	30 to 40	520 to 1000	93	*8*	163	*17*	*Rough-Textured*	75.3
Dual: 11R22.5	30 to 40	420 to 800	87	*16*	120	*10*	*Rough-Textured*	37.9
		AVERAGE OF AVERAGE:	***120.5***	***21.5***	***182.5***	***14.8***		**51.5**
		MMLS3/FULL SCALE	***3.3***		***3.4***			
1/3rd Scale MMLS3 (@ 3 to 26 km/h)	1.8 to 2.7	520 to 860	37	*20*	53	*20*	*Rough-Textured*	**43.2**
HIGHER LOADS & ROUGH-TEXTURED SIM TEST SURFACE:								
TYRE TYPE TESTED	**TYRE LOADING RANGE (kN) - (HVS @ 1.22 km/h)**	**INFLATION PRESSURE RANGE (kPa)**	**+/- X-Stresses (Rough)**		**+/- Y-Stresses (Rough)**		**Surface Condition (SIM)**	**Difference of Y-Stress relative to X-Stress (%)**
			Average (kPa)	***CoV (%)***	**Average (kPa)**	***CoV (%)***		
Wide Base Single: 425/65 R22.5	75 to 100	500 to 1000	203	*20*	277	*11*	*Rough-Textured*	36.5
Single: 315/80 R22.5	50 to 100	520 to 1000	213	*27*	251	*19*	*Rough-Textured*	17.8
Dual: 12R22.5	50 to 100	520 to 1000	134	*19*	192	*14*	*Rough-Textured*	43.3
Dual: 11R22.5	70 to 100	420 to 800	165	*8*	201	*5*	*Rough-Textured*	21.8
		AVERAGE OF AVERAGE:	***178.8***	***18.5***	***230.3***	***12.3***		**28.8**
		MMLS3/FULL SCALE	***4.8***		***4.3***			
1/3rd Scale MMLS3 (@ 3 to 26 km/h)	1.8 to 2.7	520 to 860	37	*20*	53	*20*	*Rough-Textured*	**43.2**
LOWER LOADS & SMOOTH SIM TEST SURFACE:								
TYRE TYPE TESTED	**TYRE LOADING RANGE (kN) - (HVS @ 1.22 km/h)**	**INFLATION PRESSURE RANGE (kPa)**	**+/- X-Stresses (Smooth)**		**+/- Y-Stresses (Smooth)**		**Surface Condition (SIM)**	**Difference of Y-Stress relative to X-Stress (%)**
			Average (kPa)	***CoV (%)***	**Average (kPa)**	***CoV (%)***		
Single: 315/80 R22.5	20 to 35	520 to 1000	176	*19*	220	*11*	*Smooth*	25.0
Dual: 12R22.5	30 to 40	520 to 1000	106	*13*	149	*13*	*Smooth*	40.6
		AVERAGE OF AVERAGE:	***141.0***	***16.0***	***184.5***	***12.0***		**30.9**
		MMLS3/FULL SCALE	***8.8***		***6.0***			
1/3rd Scale MMLS3 (@ 3 to 26 km/h)	2.7	520 to 860	16	*15*	31	*11*	*Smooth*	**93.8**
HIGHER LOADS & SMOOTH SIM TEST SURFACE:								
TYRE TYPE TESTED	**TYRE LOADING RANGE (kN) - (HVS @ 1.22 km/h)**	**INFLATION PRESSURE RANGE (kPa)**	**+/- X-Stresses (Smooth)**		**+/- Y-Stresses (Smooth)**		**Surface Condition (SIM)**	**Difference of Y-Stress relative to X-Stress (%)**
			Average (kPa)	***CoV (%)***	**Average (kPa)**	***CoV (%)***		
Single: 315/80 R22.5	50 to 100	520 to 1000	172	*21*	255	*20*	*Smooth*	48.3
Dual: 12R22.5	50 to 100	520 to 1000	82	*28*	112	*22*	*Smooth*	36.6
		AVERAGE OF AVERAGE:	***127.0***	***24.5***	***183.5***	***21.0***		**44.5**
		MMLS3/FULL SCALE	***7.9***		***5.9***			
1/3rd Scale MMLS3 (@ 3 to 26 km/h)	2.7	520 to 860	16	*15*	31	*11*	*Smooth*	**93.8**

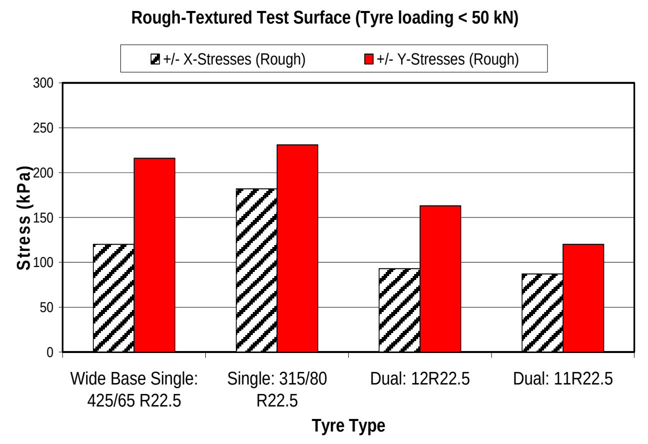

Figure 7. X, Y Stresses on the rough-textured surface - Full Scale tyres (< 50 kN).

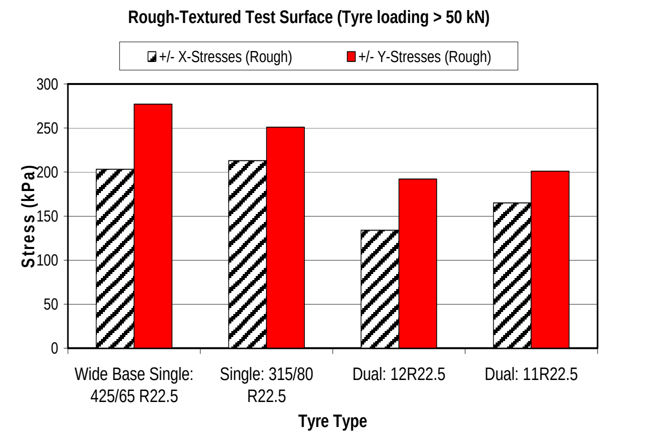

Figure 8. X, Y Stresses on the rough-textured surface - Full Scale tyres (> 50 kN).

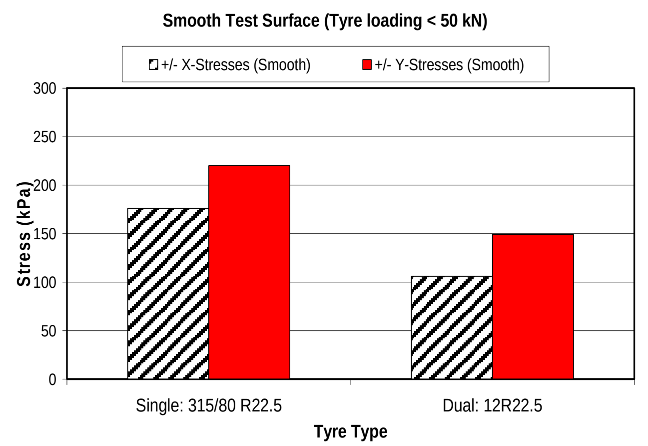

Figure 9. X, Y Stresses on the smooth surface - Full Scale tyres (< 50 kN).

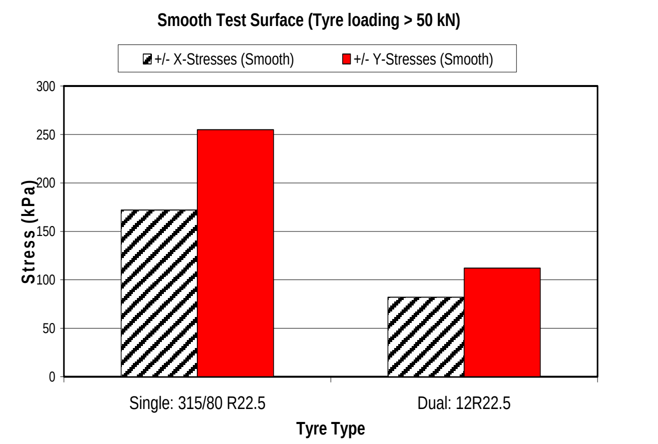

Figure 10. X, Y Stresses on the smooth surface - Full Scale tyres (> 50 kN).

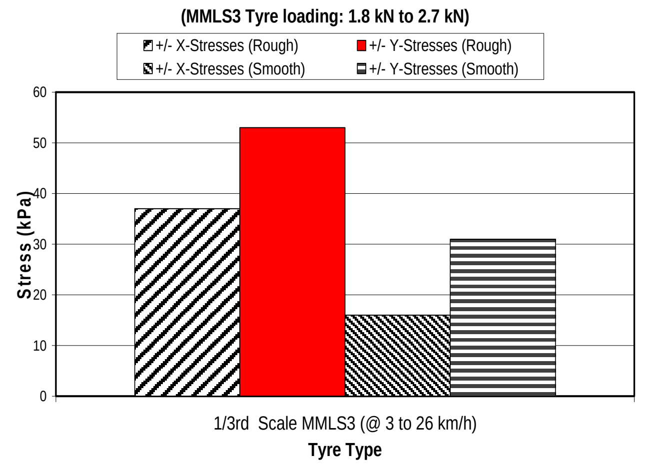

Figure 11. X, Y Stresses from the MMLS3 tyre – both rough and smooth surfaces.

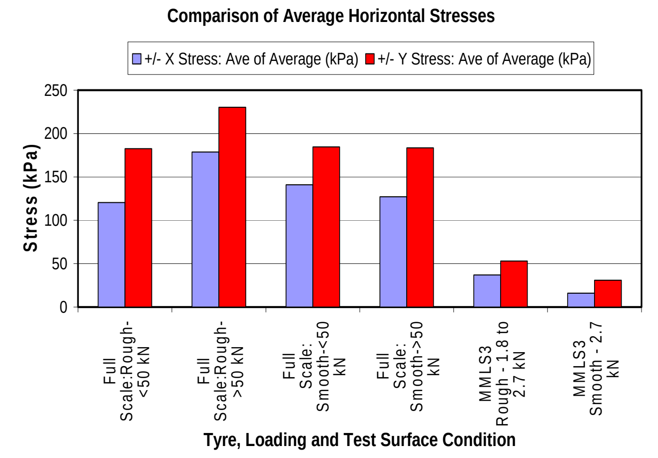

Figure 12. Average of average X, Y Stresses – all tyres, loading and test surface conditions.

3.1. Some Recommendations

The following areas for further exploration are recommended:

- A study of unclustered SIM data sets of all tyres studied here, i.e. separation of the influences of loading level, inflation pressure level and tyre speed for each tyre in the current data sets;
- Planning of HVS (APT) tests (and potential MMLS3 tests) to test the hypotheses that the vertical rutting (i.e. plastic deformation) on the surface of the pavement under the same tyre loading, inflation pressure and test conditions are a strong function of the texture characteristics, specifically that the expected rutting levels on a pavement with a relatively coarse textured surface *are measurably less* than those for a pavement with a relatively smooth surface;
- The current issue of Equivalent Light Vehicle (ELV) concept to convert traffic loading on seals in TRH 3 (TRH 3, 2007) could be challenged, and potentially be replaced with a more rational approach;
- Study and quantification of the effects of tyre torque, i.e. acceleration (driven), deceleration (braking) and cornering (turning) forces and associated horizontal stresses for potential inclusion in road surfacing design;
- Evaluation of the effects of horizontal stresses on tyre life and type of road surfaces - incorporated into updated chapter of a future TRH 3 (TRH 3, 2007); and
- Recommendations for the way forward.

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5. REFERENCES

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