TOWARDS QUANTIFYING HORIZONTAL STRESSES OF FREE-ROLLING PNEUMATIC RUBBER TYRES ON ROAD SURFACINGS

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ABSTRACT

Multi-dimensional forces (and stresses) inside the contact patch of a free-rolling pneumatic rubber tyre generally occur as a direct result of a complex interaction between flexible rubber and a rigid test surface or road surface. These forces, transformed to stresses, were measured in three dimensions (3D) with the Stress-In-Motion (SIM) device on four (4) full-scale truck test tyres with the Heavy Vehicle Simulator (HVS), as well as on a 1/3rd scale test tyre using the Model Mobile Load Simulator (MMLS3). In this paper the focus is on the *tangential lateral* and *tangential longitudinal* stresses or, more simply referred to in this paper as horizontal stresses (X, Y - Stresses) within the contact patch. A limited number of tests were also carried out in which the horizontal stresses on a relatively *rough-textured (RT)* test surface were compared with those on a relatively *smooth (S)* test surface, representing nominal positive textured road surfaces and nominal smooth (zero texture) road surfaces, respectively. In this study the main characteristics and magnitudes of these X, Y – Stresses are described for the purpose of improving the engineering understanding of these. It is anticipated that better understanding of these stresses will lead to the development of improved and more rational mechanistic design of road surfacings including, for example, chip seals, asphalt overlays and asphalt surfacings with or without rolled-in chips.

It is important to note that the findings in this study relate solely to relatively slow-moving, free-rolling pneumatic rubber tyres on these two types of test surfaces. Further it is important to note at this stage that for especially those results from the “smooth” (S) surface testing and are meant to merely act as a *primer* for future research on the effect of surface texture and tyre tread patterns on contact stresses.

1. INTRODUCTION

1.1 Background

The pneumatic tyre engineering process, including its complex mechanical nature and its characteristics were described by Davisson (1969) as long ago as 1969. Also local interest in tyre contact stresses and its measurment was illustrated by Bonse and Kuhn back in 1959 (Bonse and Kuhn, 1959). In the foregoing research adequate reference is made to the importance of the proper understanding of tyre contact pressures (or stresses as they are referred to in this paper). The multi-dimensional forces (and stresses) inside the contact patch of a free-rolling pneumatic tyre generally occur as a direct result of a complex interaction between flexible rubber and a rigid test surface or road surface. These forces, transformed to stresses in this paper, were measured in three dimensions (3D), viz.

+ Z, +/- X and +/- Y with the Stress-In-Motion (SIM) device on four (4) full-scale truck test tyres with the Heavy Vehicle Simulator (HVS) as the loading device, as well as on a 1/3rd scale test tyre (Diamond Tyre (D-tyre), with a square tyre profile) using the Model Mobile Load Simulator (MMLS3) as the loading device. In this paper the focus is on the *tangential lateral* and *tangential longitudinal* stresses, more simply referred to here as horizontal stresses (i.e. X, Y – Stresses), within the contact patch for these tyres. The results are partly a reconsideration of the results from an earlier study (i.e. the main study) described elsewhere (De Beer *et al.*, 2006 and De Beer and Fisher, 2007). A limited number of tests were carried out in which the vertical and horizontal stresses on a relatively *rough-textured (RT)* test surface were compared with those on a *relatively smooth (S)* test surface, representing nominal textured road surfaces and nominal smooth road surfaces, respectively. It should be noted that previous studies reported on the Maximum Vertical Contact Stresses (MVCS, or Z – Stresses) of the full-scale and 1/3rd scale test tyres (De Beer *et al.,* 2005a; De Beer and Sadzik, 2007). In this paper, however, only the main characteristics of the *tangential* (horizontal) X, Y – Stresses determined during the main study are described. The results in this paper serve as a *primer* for further research on stresses within tyre contact patches on road surfaces with different texture characteristics. It is also anticipated that increased understanding could potentially lead to the development of an improved mechanistic design of road surfacings, i.e. of chip seals, asphalt overlays and asphalt surfacings with rolled-in chips, using a micro-mechanics approach. Similar research was already reported by Woodside *et al.*, (1997, 1999), and Douglas *et al.*, (2000, 2001, 2003). In addition, Milne *et al., (*2004) proposed the first multiple element seal Finite Element Method (FEM) model for seal design. Input forces (or stresses) discussed here could play an important role for the different tyres tested and could assist with an improvement in the current micro-mechanics FEM methodology as proposed by Milne *et al.,* (2004).

1.2 Problem statement, Aim and Scope

The problem investigated here is the quantification of only the *tangential* horizontal stresses (X, Y – Stresses) for 5 different types of pneumatic rubber tyres. As stated above these horizontal stresses were measured, together with vertical stresses (3D measurements) reported earlier (De Beer and Sadzik, 2007). The horizontal stresses produced by non-driven, free-rolling tyres at slow speed over a normal relatively "*rough-textured" (RT)* SIM surface were measured. Strictly speaking, the test surface of the SIM device can be described as one with "negative" texture, with a TRL Pendulum dry skid resistance value of 76 (representing an average dry asphalt pavement – see De Beer *et al.,* (1997). As stated earlier limited 3D SIM testing was also done on a simulated relatively "*smooth surface" (S)* with a thin (0.9 mm) aluminium plate (non-instrumented) between the test tyre and the surface of the SIM device. (See De Beer *et al*., 2006.) These 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 (RT)* test surface (De Beer *et al*., 1997), as well as on the relatively smooth (S) test surface. The aim and focus of this paper is to only summarize the measured *tangential* (horizontal) tests results found on four (4) different types of truck tyre, as well as on the 1/3rd scale test tyre of the MMLS3 during 3D SIM testring. The tyre types and test surfaces on the SIM device include:

- Single wide base 425/65 R22.5 tyre *(on RT surface);*
- Single 315/80 R22.5 full-scale tyre *(on RT and S surfaces);*
- Dual 12R22.5 full-scale tyres *(on RT and S surfaces);*

- Dual 11R22.5 full-scale tyres *(on RT surface),* and
- A 1/3rd scale MMLS3 Diamond Tyre (D-tyre), with a square tyre profile – *(on RT and S surfaces).*

It should be noted that the derived *tangential* (horizontal) stress results from the *"smooth" (S)* plate tests reported in this paper are only given as an indication of these stresses as measured, particularly under a thin flexible plate and should therefore be used with caution, until further research proves their validity or otherwise. As these stresses *cannot* be regarded as "true" *tangential* or horizontal stresses on relative smooth surfaces, further research is required in this regard. Further research to include the effects on tyres of, amongst other factors, tyre tread patterns, cornering and scuffing (or slippage), acceleration and deceleration of driving torque and braking on tyre contact stresses, is also warranted.

2. MEASURED CONTACT STRESSES AND EXCURSION CURVES

The basic 3D contact stresses that were measured with the SIM device are given in Figure 1, together with definitions of shapes. See A, B, C & D in Figure 1. In this paper only the *tangential* (horizontal) stresses (i.e. C & D, referred to in this paper as X, Y – Stresses) are discussed and are illustrated by way of excursion curves (ECs) shown in Figure 2, and which compare favourably with those shapes observed by Douglas *et al.,* (2003). It should be noted that the EC approach (also known as *Shear Excursions)* was first discussed by Douglas *et al.,* (2000, 2001, 2003), who also introduced the promising concept of "interface shear energy". The ECs illustrate the tangential movement (i.e. "screwing action", reported by Douglas *et al.,* 2000, 2003) of the measuring pin of the SIM device (simulating a coarse aggregate particle on the road surface) as a result of forces in a horizontal plane as it is influenced by the movement of the rolling tyre, starting at the centre (0,0) of the graph in Figure 2.

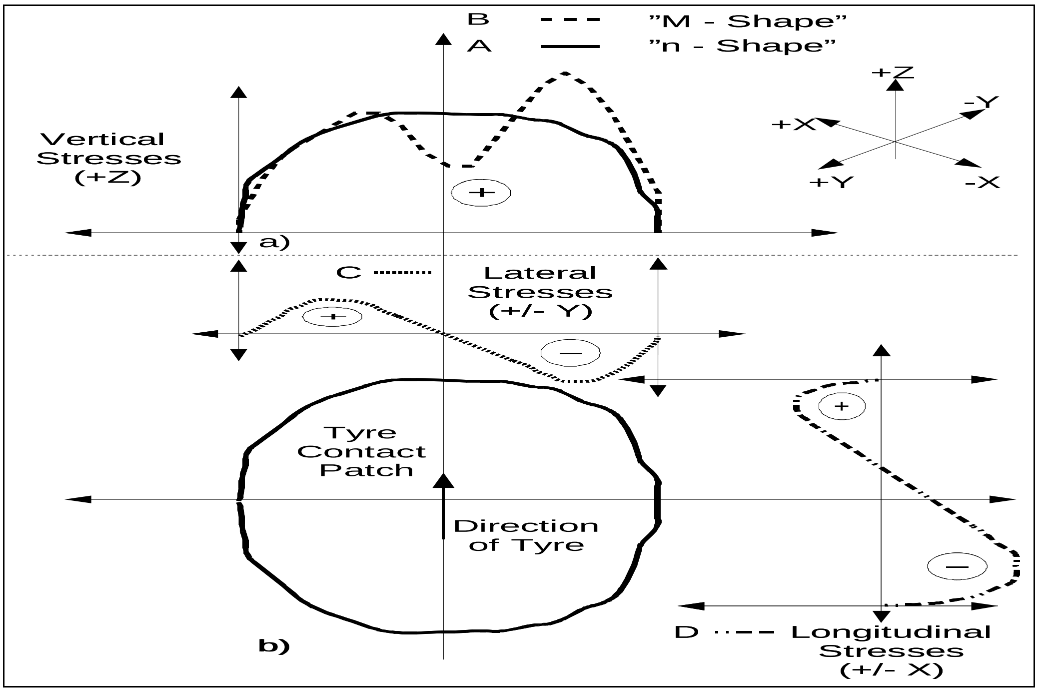
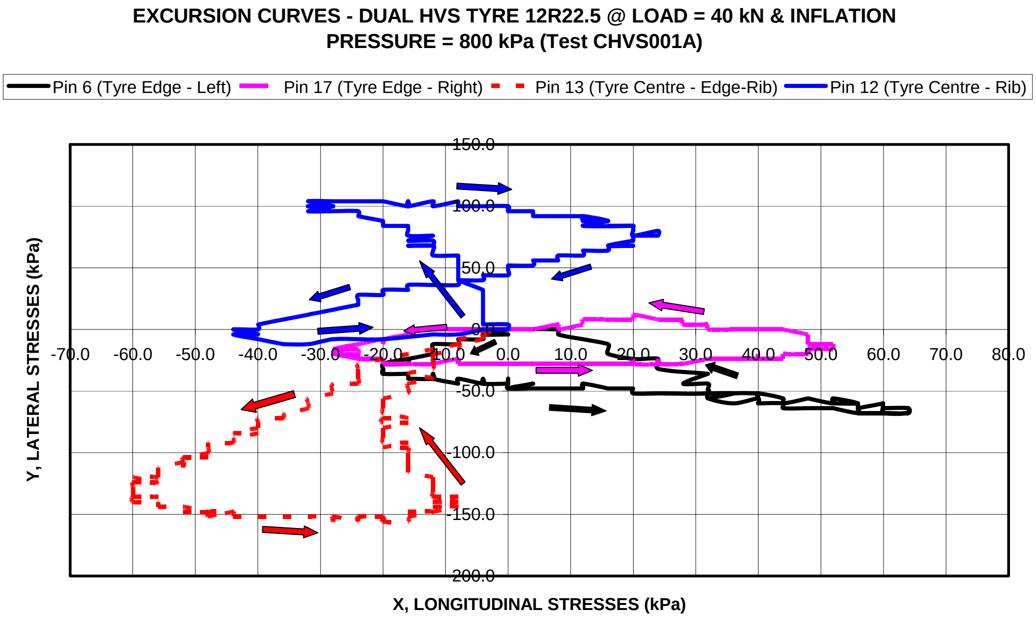


Figure 1 Basic 3D Contact Stresses and their basic shapes as observed with the Stress-In-Motion (SIM) device

Figure 2 Example of Excursion Curves (ECs) from horizontal X-Y contact stress data of four measuring pins across the tyre width from recent SIM measurements. [The tyre moved in the +X – direction.] Note that origin (0, 0) is in the centre of the figure. In this example the <u>average</u> X – Stress Ranges between approximately - 60 and + 60 kPa (i.e. max. range of +/- 60 kPa) and Y – Stress ranges between - 150 and + 100 kPa (i.e. max. Range of +/- 125 kPa). The arrows indicate the direction of forces resulting in the loops and "figure-of-eight" patterns. Note the difference between results of the centre and edge ribs in this example.

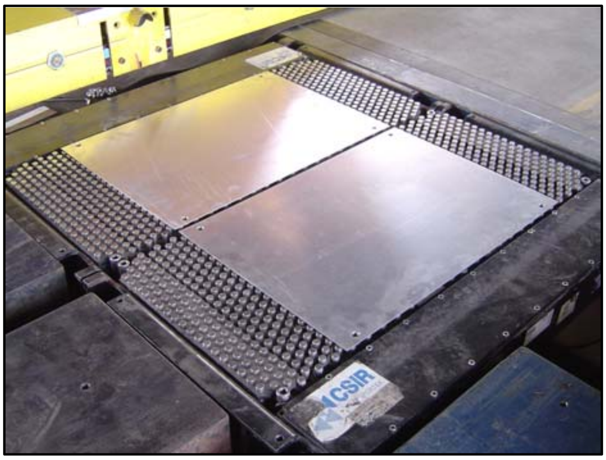


For example, measuring Pin 13, near the centre of the tyre, is pushed to an absolute maximum lateral Y – Stress of 150 kPa and an absolute maximum negative (backward) X – Stress of 60 kPa. See Figure 2. The data in Figure 2 further indicate relatively higher *tangential lateral stresss* near the tyre centre, and relatively higher *tangential longitudinal stresses* at the tyre edges. See Figure 2. More complete ECs for all the cases investigated are given in De Beer and Fisher, (2007). (Note that *load vectors* are measured directly by the SIM device in Newton units, which are then converted to stress units in MPa (see De Beer *et al.,* 1997)). It should, however, be noted that Douglas *et al.,* (2003) reported that the contact stresses given in their work are not considered as "true stresses" but those measured directly on the top of the contact force sensor which was *1 mm above* the surface of the test bed on their Tracker apparatus. Therefore the contact force sensor pretrudes directly into the rubber of the tyre during measurement. It is thus preferred to rather report "forces" and not "stresses" according to Douglas *et al.,* (2003) in their case. In the case of the SIM device however, the sensor pins and supporting pins all have the same height and are in a fixed geometric configuration (see De Beer *et al.,* 1997) and also that forces are measured directly as stated above which during post processing are transformed to "average" stress units by dividing the force per sensor pin by a geometric constant area of 250.28 mm^2. This eara is so defined that it continiously cover a 14.7224 mm wide strip of "tyre tread" for all the active sensors (see De Beer *et al.,* 1997). Since the sensor pins of the SIM device do not extend above the measuring surface as is the case with Douglas *et al.,* (2003) it is considered acceptable to report average contact stresses, and not contact forces. These forces, however, can directly be obtained by multiplying any of the given contact stress values of the SIM device by the constant area given above, if needed.

Figures 3 to 6 illustrate the measurement techniques used for the MMLS3 and the HVS tyres.

2.1 Approximate ranges of measured *tangential* (horizontal) X, Y – Stresses

The approximate measured ranges of average *tangential* (horizontal) X, Y – Stresses for the five types of tyre and associated test surface conditions are summarized in Table 1. The +/- X, +/- Y - Stress ranges are similar to those obtained from the Excursion Curves (ECs) illustrated in Figure 2. Table 1 indicates the type of tyre, loading ranges, inflation pressure ranges, Z – Stresses and X, Y – Stresses for the different surface conditions, i.e. *rough-textured (RT)* (i.e. normal SIM surface) as shown in Figures 4 and 5, and the simulated *smooth (S)* surface shown in Figure 6. (*Note: Ranges of associated Maximum Vertical Contact Stresses (i.e. MVCS or Z –Stresses) are given together with the X, Y – Stresses in Table 1 for completeness and are not further discussed in detail here.)* In this paper, the data under consideration are clustered into groups for a relatively low test loading range (< 50 kN), a higher test loading range (> 50 kN) and for two types of test surface, i.e. *RT* or *S*.

 	
Figure 3 Model Mobile Load Simulator (MMLS3) on the SIM device at Gauteng Department of Public Transport, Roads and Works (GDPTRW) Koedoespoort facility.	**Figure 4 Close-up: 1/3rd scale square profile (D-tyre) of MMLS3 on the *rough-textured (RT)* SIM surface.**
	
Figure 5 Heavy Vehicle Simulator (HVS) full-scale dual tyres on the *rough-textured (RT)* SIM surface.	**Figure 6 Artificial *smooth (S)* test surface showing the aluminium plate (0.9 mm) fixed on the corners of the SIM surface, before full-scale tyre testing.**

It is also important to note that the tested loadings for the full-scale tyres reported here represent *extremely* high tyre loadings, mainly to inform on conditions during accelerated pavement testing (APT) where “higher-than-normal” prescribed tyre test loadings are used in order to *accelerate* the testing. APT is normally carried out by equipment such as (amongst many others) the Heavy Vehicle Simulator (HVS) shown in Figure 5, the Accelerated Loading Facility (ALF) and the Mobile Load Simulator (MLS), to name but a few. For more information on APT devices and associated test findings see synthesis reports NCHRP 235 (1996) and NCHRP 325 (2004).

The purpose of this paper is to identify the main trends in X, Y – Stresses for the different types of tyre, i.e. single or dual, as well as for tyre sizes – full-scale vs. MMLS3 1/3rd scale tyre on the two types of test surfaces. For this reason the various X, Y - Stresses are summarised in Table 1 and also illustrated in Figures 7 to 12, in a comparative way.

2.1.1 Results on the rough-textured (RT) Surface

The X, Y – Stresses for the full-scale test tyres on the *RT* test surface of the SIM device for the < 50 kN loading range are illustrated in Figure 7, and those for the > 50 kN loading range are illustrated in Figure 8. In terms of magnitude and trends on a *rough-textured (RT)* surface the following can be noted from Table 1:

- The *average* horizontal X, Y – Stresses vary between 134 kPa and 222 kPa with Coefficients of Variance (CoV) between 12 and 22 per cent, and associated average Maximum Vertical Contact Stresses (MVCS) of between 824 kPa and 1770 kPa, (CoV between 15 and 18 per cent) depending on loading level;

- For all tyres and loading cases the average lateral Y – Stresses are generally 36 to 47 per cent *higher* than the average longitudinal X – Stresses;

- Of importance are the stresses obtained for the single 315/80 R22.5 and dual 12R22.5 full-scale tyres, since these are the most popular truck tyres currently used in South Africa. The 315/80 R22.5 tyre is the most commonly used steering tyre in South Africa and its associated X, Y – Stresses are 1.2 to 1.8 times *higher* than those measured for the dual 12R22.5 tyre for all loading conditions. *(Note: Both the single 315/80 R22.5 tyre and the 12R22.5 tyre are used on the steering axles of trucks. During a study conducted in 2004 it was found that 47 per cent of the steering tyres were of the 315/80 R22.5 size and 40 per cent were 12R22.5 tyres (De Beer et al., 2005). It is important to note that the loading on the 12R22.5 tyres reported here is for a dual tyre configuration, which may explain the lower X, Y - Stresses obtained for this type of tyre.)* This suggests that the 315/80 R22.5 tyre can potentially be viewed as a critical design tyre for pavement surfaces. It is also worth mentioning that the Maximum Vertical Contact Stress (MVCS, or Z – Stress) for this tyre was almost 20 to 25 per cent *higher* than that for the 12R22.5 tyre, which reinforces the preceding statement on the possibility of a critical design tyre. (For further information on the MVCS of these tyres see De Beer *et al.*, 2005a, 2005b). It is noted that further work is needed for a direct comparison between the contact stress results of a *single* 12R22.5 tyre and a *single* 315/80 R22.5 tyre (when used on the steering axle) in order to identify the most damaging tyre in this context. This however, is outside the scope of this paper.

- In this study the highest horizontal X, Y – Stresses were obtained for the wide base 425/65 R22.5 tyre under *extremely* high loading (> 50 kN). However this tyre is apparently no longer in production and is no longer used regularly in SA (see Figure 7); and

- The lowest X, Y – Stresses were obtained for the smallest full-scale tyre used here, i.e. 11R22.5 under relatively low loading conditions (< 50 kN). For the higher loading range (> 50 kN) the lowest stresses were obtained for the popular 12R22.5 truck tyres. See Figures 7 and 8.

2.1.2 Results on the smooth (S) test surface

The X, Y – Stresses for two full-scale test tyres on the simulated *smooth* (S) test surface are illustrated in Figures 9 and 10. The following can be noted:

- The lateral Y – Stresses are also approximately 30 per cent *higher* than the X – Stresses in this case; and

- Higher X, Y – Stresses were also obtained for the single 315/80 R22.5 tyre than for the dual 12R22.5 tyre under both tyre loading conditions (i.e. < 50 *and* > 50 kN).

2.2 Ranges of measured X, Y – Stresses of 1/3rd scale MMLS3 tyres

As in the case of the full-scale HVS test tyres, the Y – Stresses for the MMLS3 1/3rd scale tyre were also found to be between 58 and 105 per cent *higher* than the X – Stresses. Under loads ranging from 1.8 to 2.7 kN and at simulated speeds of 3 km/h, 13 km/h and 26 km/h, the X, Y – Stresses of the MMLS3 tyre ranged between 40 kPa and 63 kPa on the *RT* surface (with a CoV of approximately 22 per cent - probably due to variations in load and speed). The load on the MMLS3 was set at 2.7 kN for the tests on the *smooth (S)* surface at all three speeds of the MMLS3. The associated values were 19 kPa and 39 kPa with CoV of between 13 and 16 per cent. (The CoV in this case was probably mainly due to the speeds used, since the load was kept constant at 2.7 kN). See Figure 11 and Table 1.

2.3 *Rough-Textured (RT)* test surface vs. *Smooth (S)* test surface – Discussion

2.3.1 Simulation of smooth (S) surface

The use of a thin (0.9 mm) flexible smooth aluminium plate on top of the textured surface of the SIM device (i.e. corner-fixed on top of the “diamond-patterned” pin configurations to prevent tangential plate slippage), (see Figure 6). This plate provided for a test surface with a relatively “smooth” texture, albeit that the plate was not instrumented. The bottom of the plate was not fixed on the measuring pins, allowing each of the measuring sensor pins to maintain its 5 degrees of freedom (+Z, +/- Y, +/- X) for capturing the 3D load/force vectors “indirectly” within the limits determined by the corner-fixed thin aluminium plate and the associated boundary conditions. The main purpose of these tests was to study the effect of surface texture on vertical loads and stresses, indirectly. It was, however, observed that the vertical stresses on the *smooth (S)* surface were as much as 30 per cent *greater* than those on a *rough-textured (RT)* surface as reported earlier by De Beer *et al*., (2006) and De Beer and Sadzik, (2007). However, further inspection of the 3D data also indicated that significant *tangential lateral* and *tangential longitudinal* (horizontal) loads were also captured (albeit indirectly) under the thin plate with the SIM device. It is these loads (or stresses) that are also discussed in this paper which, as stated before, could act as a *primer* for future research on the effect of surface texture (and tyre tread pattern) on 3D tyre contact stresses. It is, however, acknowledged that this test configuration with the fixed smooth plate is a rather crude way of simulating a relatively *smooth (S)* road surface, as fixing the plates at the corners would affect the vertical and *tangential* (horizontal) forces to some extent. As no slippage of the plate was allowed, the horizontal forces are directly influenced by the deformation/flexure of the fixed plate under the tyre contact force and the prevailing boundary conditions. The results on the *“smooth (S)* surface” are therefore presented as a “first approximation” of these rather “indirect horizontal forces” and need to be treated with caution until further research with improved equipment proves their validity or otherwise. It should also be noted that, in the main study, grooves were also added to some of the the plates. However, the results of this part of the study are not discussed in this paper as it is seen as prematurely for reasons given above. The reported methodology and associated results on the *smooth (S)* test surface should therefore be viewed at this stage as merely being of academic value which may be used to further inform on future studies of similar nature.

2.3.2 Full-scale HVS test tyres

The X, Y – Stress data show that, under < 50 kN loading on the simulated *RT* test surface, the horizontal stresses for the 315/80 R22.5 tyre and the 12R22.5 tyre were generally 16 to 32 per cent higher than those on the *smooth (S)* surface. See Figures 7 and 9. Under the higher loading conditions this trend was less clear, with some of these stresses being 10 to 20 per cent higher on the smooth (S) surface. See Figures 8 and 10.

2.3.3 MMLS3 test tyre – 1/3rd scale

For the MMLS3 tyre the X, Y – Stress data on the smooth (S) surface were approximately 38 to 53 per cent *lower* than those on the *rough-textured (RT)* surface. See Figure 11. Interestingly, the X, Y – Stresses for the MMLS3 tyre on a *RT* surface are approximately 1/3rd of those for all the full-scale HVS test tyres for < 50 kN tyre loading range (the ratio of the stresses for the full-scale test tyres to those of the MMLS3 tyre being 3.0 to 3.4 – see Table 1). It is, however, important to note that under the higher loading range this ratio increased to approximately 3.5 on the RT surface and to as much as 4.8 on the simulated *smooth* (*S)* test surface. (Note that the ratios reported above differ from the "Stress-Ratios" defined and reported earlier by De Beer *et al.,* 1997, 2006).

2.3.4 Comparison of all measured horizontal X, Y – Stress data

The average results from all the different data sets used in this study are illustrated for comparison purposes in Figure 12. The Y – Stresses are generally *higher* than the X – Stresses (as previously discussed). It is postulated that this is probably due to the tyre stiffness in the lateral Y – direction, which is normally higher than the stiffness in the longitudinal X – direction. Earlier test results indicated that, with increased loading, the length of the contact patch increases much more than the width, indicating a greater resistance to deformation in the Y – direction (i.e. across tyre width). Davisson (1969) reported a ratio of approximately 1:8 between the elongation in lateral contact width and elongation in the longitudinal direction (contact length) of a commercial tyre under the same vertical deflection range when loaded. See also De Beer *et al.,* (2005b) in this regard. In addition, the X, Y – Stresses on the *RT* surface are generally higher than those measured on the simulated *S* test surface. This is especially true in the case of the > 50 kN tests on the full-scale HVS test tyres and for the MMLS3 1/3rd scale test tyre.

2.4 General Discussion of Results

An interesting finding was that, for all the tyres tested (including the 1/3rd scale tyre), the Y – Stresses were generally 30 per cent to 50 per cent *higher* than the X – Stresses. In the case of the 1/3rd scale MMLS3 tyre the corresponding stress range was found to be 58 to 105 per cent higher. It should be noted that the above findings relate strictly to free-rolling pneumatic rubber tyres, which implies that, for driven or braking tyres, the X – Stresses *(tangential longitudinal)* in particular might change considerably, depending on tyre torque in the rolling direction. On the other hand, the Y – Stresses *(tangential lateral)* might also change considerably when the tyre "scuffs" (or slip) or is in a turning mode, as was also indicated by Davisson (1969). The results of limited testing in 1997 suggest that there is approximately a 30 kPa increase in X – Stresses per degree of turning (scuffing *or* slip) of the rolling pneumatic rubber tyre (De Beer *et al.,* 1997). This finding, however, needs to be critically evaluated further in the laboratory with the SIM device, the MMLS3 and the full-scale tyres on the HVS. (However, in order to do the foregoing, the current equipment would have to be adapted for the controlled application of horizontal forces (i.e. steering, acceleration or deceleration) on the test tyres.)

The above findings (see also Table 1) suggest that the X, Y - Stresses of the 1/3rd scale MMLS3 tyre are approximately 1/3rd of those of full-scale tyres on the *RT* surface, but reduce to approximately 1/5th when the relatively *smooth (S)* surface is tested with the same square-profile MMLS3 tyre (D-tyre). The foregoing probably suggests that *greater vertical rutting* takes place on a relatively *smooth (S)* surface than on a relatively *rough-textured (RT)* surface for the same number of load (stress) repetitions, all else being equal. This finding, however, should be critically evaluated in the laboratory with the MMLS3, as well as with the HVS for the full-scale tyres, under different loading levels, inflation pressures, different surface texture conditions, including different tyre types and tyre tread patterns.

3. SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

3.1 Summary and Conclusions

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

- For free-rolling pneumatic rubber tyres the *tangential lateral* and *tangential longitudinal* (horizontal) contact stresses were measured with the Stress-In-Motion (SIM) device (in addition to the vertical stresses). This allows for the relative quantification as well as for comparative studies of the horizontal loading/stress regimes generated from the different types of tyres studied here on two different test surfaces - until future research proves otherwise;

- The Excursion Curve (EC) methodology used here allows for improved visual understanding of the interaction between the *tangential* (horizontal) X and Y – Stresses of free-rolling rubber tyres;

- The lateral Y – Stresses are generally *higher* than the longitudinal X – Stresses (approximately 30 to 50 per cent higher);

- The X, Y – Stresses on a *relatively rough-textured (RT)* pavement surface appear to be approximately 16 per cent to 32 per cent *higher* than those found on a *relatively smooth (S) surface*. [However, the results from the *smooth (S)* surface testing should be treated with care owing to associated complexities with such a measurement configuration];

- Depending on loading levels, the X, Y – Stresses produced by the 1/3rd scale MMLS3 tyre (Diamond, square profile) are, on average, only approximately *one quarter to one third* of those produced by full-scale tyres on a *relatively rough-textured (RT)* test surface; and

- The X, Y – Stresses produced by the 1/3rd scale MMLS3 tyre (Diamond, square profile) on the *smooth (S)* surface are, on average, between 38 per cent and 53 per cent *lower* than those produced by the same tyre on the *relatively rough-textured (RT)* SIM surface.

- Although not discussed in detail in this paper it is worthwhile to mention that the Z – Stress data sets given in Table 1 suggest that for the MMLS3 1/3rd scale test tyre the MVCS (Z – Stresses) compares favourable with those of both full scale test tyres reported here on the *smooth (S)* surface. In the case of the *RT* surface, however, these stresses approximate only 40 to 63 per cent of those obtained for the full scale tyres. See Table 1. If results of the 1/3rd scale tyre are compared to the 12R22.5 tyre only, the corresponding percentages are approximately 56 and 80.

3.2 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, depending on need;
- Further studies on the effect of road texture on the tyre contact stresses with *improved measuring equipment*, when this becomes available;
- Planning of potential APT (i.e. HVS and MMLS3 tests) to evaluate *comparative* vertical rutting (i.e. plastic deformation) development on *different* surface texture conditions, i.e. relatively rough vs. relatively smooth surfaces – including highly textured surfaces vs. low texture and zero texture surfaces, as well as those with negative textures such as porous asphalt;
- As the current concept in TRH 3 (TRH 3, 2007) of converting Equivalent Light Vehicle (ELV) to traffic loading on seals could be challenged, it is recommended that this concept be re-examined and possibly be replaced by a more rational approach informed on the type of findings of this study. See also comments by Milne *et al.,* (2004) in this regard;
- Use of the X, Y - Stress data in this paper towards the improved micro-mechanic modelling of road surfacings in southern Africa, including Interface Shear Energy – similar to the approach discussed by Woodside *et al.,* (1997), Douglas *et al.,* (2000, 2001, 2003) and Milne *et al.,* (2004); and
- Study and quantification of the effects of tyre tread pattern, tyre torque, i.e. acceleration (driven), deceleration (braking) and cornering (turning, scuffing (or slippage) on all the generated stresses/forces and associated *tangential* (horizontal) stresses for potential inclusion in a more rationale *mechanistic* road surface design methodology based on micro-mechanics.

4. ACKNOWLEDGEMENTS

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Table 1 Summary of the measured Z, X and Y - Stresses over various loading and inflation pressure ranges and test conditions for the different full-scale HVS tyre types and surface conditions (i.e. *“rough-textured” (RT)* and *“smooth” (S)* on the SIM device, including the 1/3rd scale MMLS3 test tyre.

TYPE OF TYRE TESTED	**TYRE LOADING RANGE (kN) - (HVS @ 1.22 km/h)**	**INFLATION PRESSURE RANGE (kPa)**	**Maximum Vertical Contact Stress (MVCS)**				**+/- X-Stresses (Ave. Max Range)**		**+/- Y-Stresses (Ave. Max. Range)**		**Difference of Y-Stress relative to X-Stress (%)**	**Surface (SIM) and Number of Tests ***
			Max Z Stress - min. of range (kPa)	**Max Z Stress - max. of range (kPa)**	**Z Max. Ave. Stress (kPa)**	***CoV (%)***	**Average Max. (kPa)**	***CoV (%)***	**Average Max. (kPa)**	***CoV (%)***		
LOWER LOADS & ROUGH-TEXTURED (RT) SIM TEST SURFACE:												
Wide Base Single: 425/65 R22.5	25 to 50	500 to 1000	978	1843	1409	16	121	33	226	15	86.7	*RT (12x3)*
Single: 315/80 R22.5	20 to 35	520 to 1000	759	1994	1244	31	208	29	238	17	14.2	*RT (8x3)*
Dual: 12R22.5	30 to 40	520 to 1000	799	1207	1041	13	113	12	184	7	62.3	*RT (9x3)*
Dual: 11R22.5	30 to 40	420 to 800	759	1016	898	12	95	16	119	11	25.3	*RT (20x3)*
		Average:	***823.8***	***1515.0***	***1147.8***	***17.9***	***134.3***	***22.4***	***191.4***	***12.4***	***47.1***	
1/3rd Scale MMLS3 (@3 to 26 km/h)	1.8 to 2.7	520 to 860	455	967	722	16	40	21	63	24	57.5	*RT (681)*
		RATIO: FULL SCALE/MMLS3	***1.8***	***1.6***	***1.6***	***1.1***	***3.4***	***1.1***	***3.0***	***0.5***	***0.8***	
HIGHER LOADS & ROUGH-TEXTURED (RT) SIM TEST SURFACE:												
Wide Base Single: 425/65 R22.5	75 to 100	500 to 1000	1663	2204	1953	9	203	19	287	11	41.4	*RT (11x3)*
Single: 315/80 R22.5	50 to 100	520 to 1000	863	1994	1375	27	191	38	214	32	12.3	*RT (8x3)*
Dual: 12R22.5	50 to 100	520 to 1000	803	1398	1097	13	111	12	179	12	62.2	*RT (16x3)*
Dual: 11R22.5	70 to 100	420 to 800	1118	1485	1289	13	163	16	209	24	27.9	*RT (20x3)*
		Average:	***1111.8***	***1770.3***	***1428.3***	***15.4***	***166.8***	***21.3***	***222.2***	***19.7***	***36.0***	
1/3rd Scale MMLS3 (@3 to 26 km/h)	1.8 to 2.7	520 to 860	455	967	722	16	40	21	63	24	57.5	*RT (681)*
		RATIO: FULL SCALE/MMLS3	***2.4***	***1.8***	***2.0***	***1.0***	***4.2***	***1.0***	***3.5***	***0.8***	***0.6***	
LOWER LOADS & SMOOTH (S) SIM TEST SURFACE:												
Single: 315/80 R22.5	50 to 100	520 to 1000	863	2465	1495	35	141	33	204	31	44	*S (8x3)*
Dual: 12R22.5	50 to 100	520 to 1000	935	1586	1313	15	95	17	135	9	42	*S (8x3)*
		Average:	***600.1***	***1350.9***	***936.6***	***17.0***	***80.1***	***16.8***	***114.1***	***13.6***	***29.1***	
1/3rd Scale MMLS3 (@3 to 26 km/h)	2.7	700 to 860	727	1187	937	11	19	16	39	13	105	*S (178)*
		RATIO: MMLS3/FULL SCALE	***0.8***	***1.1***	***1.0***	***1.5***	***4.2***	***1.1***	***2.9***	***1.0***	***0.3***	
HIGHER LOADS & SMOOTH (S) SIM TEST SURFACE:												
Single: 315/80 R22.5	50 to 100	520 to 1000	1426	2561	1979	24	150	32	257	20	71	*S (8x3)*
Dual: 12R22.5	50 to 100	520 to 1000	1127	1926	1493	16	122	5	140	7	15	*S (8x3)*
		Average:	***851.3***	***1496.0***	***1157.5***	***14.1***	***92.1***	***12.6***	***133.1***	***9.5***	***28.6***	
1/3rd Scale MMLS3 (@3 to 26 km/h)	2.7	700 to 860	727	1187	937	11	19	16	39	13	105	*S (178)*
		RATIO: FULL SCALE/MMLS3	***1.2***	***1.3***	***1.2***	***1.3***	***4.8***	***0.8***	***3.4***	***0.7***	***0.3***	

* Legend: RT = Rough-Textured SIM test surface, and S = Smooth SIM test surface. Note:The given "Z Stress" represents the Maximum Vertical Contact Stress (MVCS) for each case. RT (Number of tests), S (Number of tests)

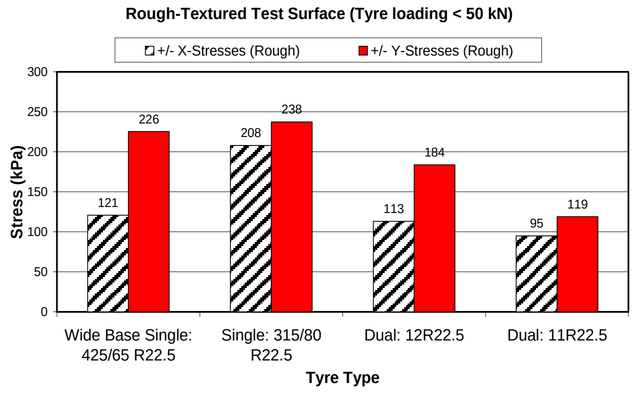

Figure 7 X, Y – Stresses on the *rough-textured (RT)* surface - Full-scale tyres (< 50 kN).

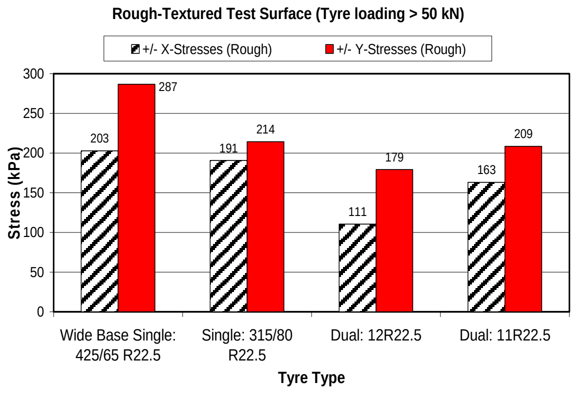

Figure 8 X, Y – Stresses on the *rough-textured (RT)* surface - Full-scale tyres (> 50 kN).

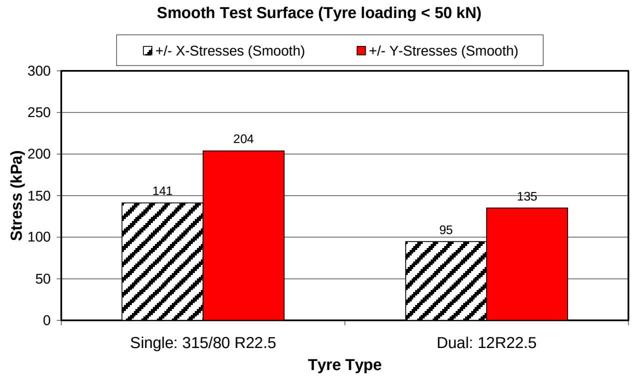

Figure 9 X, Y – Stresses on the *smooth (S)* surface - Full-scale tyres (< 50 kN).

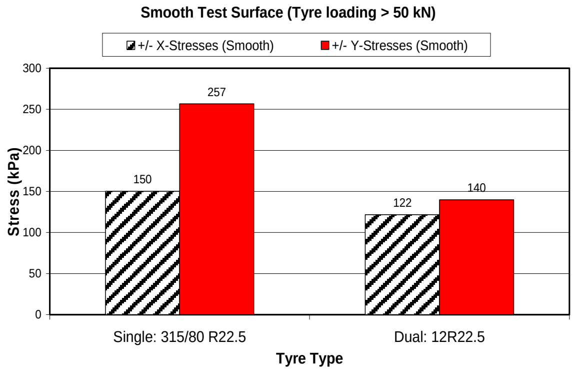

Figure 10 X, Y – Stresses on the *smooth (S)* surface - Full-scale tyres (> 50 kN).

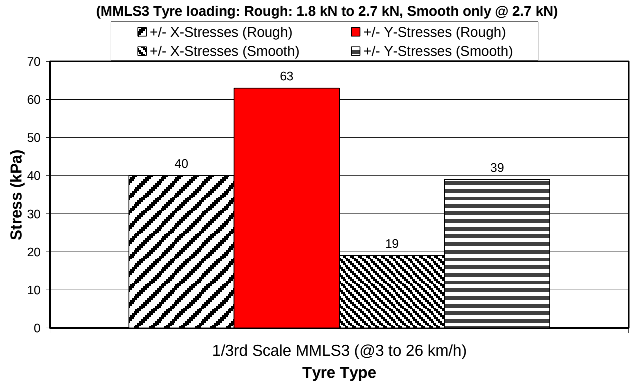

Figure 11 X, Y – Stresses from the MMLS3 tyre – both *rough (RT)* and *smooth (S)* surfaces.

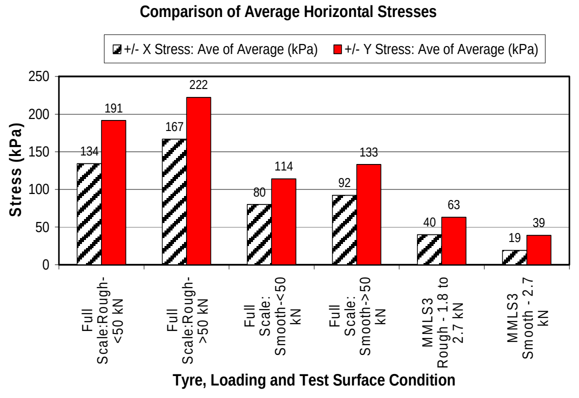

Figure 12 Average X, Y – Stresses – all tyres, loading and test surface conditions – this study.