# Improving rubber tread designs against heat build-up under cyclic loading using strain energy

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*Abstract: Heat generation in rubber is a complex phenomenon that occurs when a rubber component is being cyclically loaded. The development of this heat build-up comes from the viscoelastic nature of rubber compounds that occurs during the loading and unloading processes, and it is a difficult mechanism to quantify numerically. A lot of research on this particular and characteristic behavior of rubber has been done essentially since the invention of rubber. Over the course of the last decade or so, there have been numerous breakthroughs in the area of heat generation, and finite element codes are beginning to provide solutions to study this behavior. However, it is still a very complex parameter to measure and validate for practical purposes. As a result, an alternate way to devise a method to improve the designs of treads in our tracks against the development of heat build-up is to study the strain energy. The purpose of this research is to understand how we can use the strain energy generated under one full load cycle and utilize this to design a new and better generation of treads that can meet the constant increasing demands for performance in the world of rubber tracks.*

*Keywords: rubber, strain energy, cyclic loading, heat generation, heat build-up, blowout*

## 1 Introduction

Rubber has many great advantages as the material of choice for tires, and other forms of transportation such as belts and caterpillar-type tracks. It is a unique material that can provide very large elastic deformations with very little plastic or permanent deformation, consistently under very long cyclic conditions. This is because rubber has some very peculiar rheological properties that make it the ideal material for this type of applications.

However, it also has its range of shortcomings; for one, it will dissipate heat under cyclic loading conditions. So, let us learn more about how this heat is generated.

Unlike some other elastic materials, rubber is predominantly a viscoelastic material. This means that rubber will exhibit elastic properties as well as large viscous effects when undergoing deformation. The consequence of these viscous effects can easily be seen in the hysteresis formed in the stress-strain (or force-displacement) curve when the rubber material is being loaded and unloaded, as shown in Figure 1. The area under this curve corresponds to the dissipated energy created by the loss of energy, and this energy is transformed almost entirely into heat. The size of this area or in other words, how large the hysteresis is, will give way to how much heat is generated internally. As a consequence, some rubber compounds will inheritably be more prone to dissipated heat than others based on the processes and constituents which were used to manufacture them.

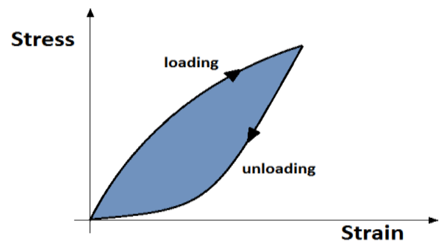


**Figure 1 – Stress-Strain behavior of elastomers in loading and unloading**

Additionally, rubber is a great thermal insulator which means it has very low thermal conductivity. A combination of heat generation with poor heat dissipation will give way to the term, that is commonly known in the rubber world, as “thermal blowout”.

A thermal blowout can typically happen in large tread-bars of rubber in tires or tracks when they undergo cyclic loading for extended periods of time. The following image (Figure 2) shows the case of a blowout in a tire tread.

**Figure 2 – Depiction of a thermal blowout in a tire tread**

This blowout phenomenon, as we just mentioned, is generally produced when the block is solicited cyclically and the heat generated internally is not dissipated well enough, or fast enough, and the temperature keeps rising until it reaches a critical point in which the rubber material cannot resist.

In a sense, the rubber is being slowly transformed into an entirely different material.

## *1.1.* Background information on rubber heat Build-Up and Blowout

Heat generation, as the name implies, is the temperature rise in the body of a material due to its internal effects (i.e. not taking into account the temperature influence from other external sources). Why is it important to study this phenomenon? The answer is simple. Over time, this heat build-up effect leads to material degradation which changes both the rubber physical and chemical properties. Additionally, this internal heating will accelerate the aging of the rubber and consequently make it stiffer, as well as reducing its damping properties. If unchecked, this internal heat generation of rubber will lead to internal melting and ultimately an explosive rupture, or blowout.

The topic of heat generation in rubber has been extensively researched. There are many papers in literature regarding this peculiar material characteristic of rubber, such as the early work done by A. N. Gent and M. Hindi [1988], in which they studied the critical temperatures of rubber blocks in a series of rubber compounds. In such studies they conducted their analysis using cylindrical rubber specimens, which were cycled under compression. Other investigations like those conducted by A. I. Medali [1991], and K. K. Kar, and A. K. Bhowmick [1997] advanced further in this territory of heat generation to give us a better understanding of this rubber phenomena. An interesting research was conducted by Y-J. Lin and S-J. Hwang [2004], in which the authors used the hysteresis of the rubber to predict heat generation of rubber springs during fatigue tests. They employed FEA for their approach, and calculated the energy loss per cycle based on the hysteresis which they obtained experimentally. Similar work was also conducted by R. K. Luo et al [2005].

So, an important reasoning from this research is that heat generation of rubber materials can be associated with the hysteresis result of the material when conducting cyclic fatigue studies. L. Pesek et al [2007] developed a similar research using this notion when it was applied to the rubber blocks.

As mentioned earlier, the hysteresis of the rubber is one of the most commonly used values to define the viscoelastic response of rubbers. The viscoelastic property of the rubber has a great deal to do with the crystallinity structure of the rubber compounds, and it is highly dependent on the strain induced crystallization when it goes through deformation. This deformation and its response is very time dependent (i.e. cyclic frequency, strain-rate, etc…), so it is important to keep that in mind because we have to obtain the hysteresis properties at the conditions at which the rubber is solicited in the actual model.

In either case, the hysteresis of a material can be easily obtained by dividing the loss energy by its total energy. The total energy represents the total amount of internal energy, and the loss energy represents the dissipated energy of the rubber. As we said previously, it is this loss energy that is the cause of the temperature rise, or heat build-up in rubber. The hysteresis of any material can be calculated using DMA test (dynamic mechanical analysis), and with it one can fundamentally obtain both the storage modulus (E') and the loss modulus (E"). The total energy ($E^*$) of the material can thus be obtained using the following equation:

$$E^* = \sqrt{(E')^2 + (E'')^2} \tag{1}$$

If we combine this equation with the ratio of the energies to obtain the hysteresis we find the following equation:

$$H = \frac{Loss\ Modulus}{Total\ Energy} = \frac{E''}{E^*} \quad (2)$$

Subsequently, using these parameters we can obtain some fundamental knowledge on the heat generation of rubber material when they undergo some cyclic loading conditions. Furthermore, there are many research studies on how we can convert this loss energy, and efficiently calculate the heat build-up or temperatures, in a steady-state condition. As it was described on the works done by L. C. Yohan et al [2009], estimating the heat build-up, and in turn the temperature, can be solved using three different approaches to this thermo-mechanical problem. The assumption of course is that in all his research cases the temperature inside the rubber reaches an equilibrium; that is a steady-state condition.

More difficult, however, is to determine the blowout temperatures of rubber, and consequently how to predict it. Considerable less research work has been conducted for these more severe dynamic conditions, though blowout (critical) temperature remains a very important property for all rubber materials.

The blowout phenomenon is considered as a nucleation type problem. As the rubber is heated, it will cause the formation of small and volatile nuclei of air pockets in sections where temperatures reach a certain critical point. This is produced at the cellular level; therefore the constituents and the curing processes of the rubber will have an influence on the size, quantity and location of these pockets. If the temperature continues to increase, these regions will grow in size until they reach a thermal point that completely destabilizes the integrity of the compound and will make the rubber break or even explode. This can be seen in the following image, Figure 3, which shows the formation of these air pockets.

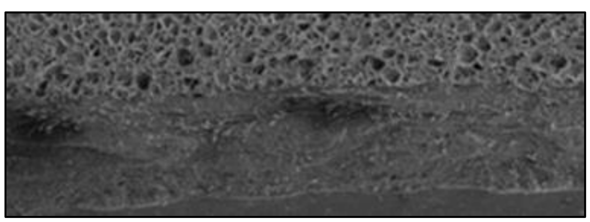

**Figure 3 – Depiction of areas of air pocket nucleation due to heating**

## *1.2.* Research objective: Tread design analysis using strain energy function

The main goal for this research was to determine a way to predict if any particular design of our tread bars will be prone to the development of heat build-up. Consequently, the objective of this study was not to obtain a method to predict temperatures during the heat build-up process, but rather use a parameter in our FEA code which is directly proportional to self-heat generation in elastomers.

So given this clarification in our objectives, it is decided to focus on the study of the total strain energy, which can be easily obtained in our FEA code (ABAQUS). Using the strain energy generated at the tread bars per cycle, would give us a good prediction of the dissipated energy during the cyclic loading. It is assumed quite reasonably that the energy loss per cycle of the rubber block, under fixed dynamic amplitude, will not depend on the loading frequency. This is to say that the hysteresis under one cycle can be used to get an estimate on the impact of the tread design in our dissipated energy.

The dissipated energy can be obtained as a product of the obtained hysteresis (from DMA tests) and the total strain energy of the material (from our FEA analysis). The following equation, which represents the material hysteresis, can also be defined in terms of energy.

$$H = \frac{Loss\ Energy}{Total\ Energy} = \frac{U_{diss.}}{U_{Total}} \quad (3)$$

Where, $U_{Total}$ represents the total strain energy obtained per cycle. And if it is solved for the heat generation rate $\dot{H}_G$, per cycle analysis, it is really a simple product of the total strain energy with H and *f*, which is the loading frequency.

$$U_{diss.} = H * U_{Total} \quad (4)$$

$$\dot{H}_G = U_{diss.} * f = H * f * U_{Total} = C * U_{Total} \quad (5)$$

Where, C is just a constant of the product of the two parameters of the hysteresis ratio and the loading frequency.

Consequently, in case of a steady-state or static simulation of one loading cycle for one of our rubber tread bars, the $U_{Total}$ is a sufficient parameter for analyzing the geometric and material impact of a tread bar design in terms of heat build-up. This will not provide us with an indication of whether a blowout incident will take place since the heat build-up impact at one cycle is analyzed. Further calculation would need to take place to determine this critical temperature. Another method would need to be conducted in which at each cycle both the heat generation rate obtained with the current temperature field are iterated. This method of course, can be done both as coupled and un-coupled thermo-mechanical analyses.

In order to obtain the temperature profile of the rubber, temperature equation obtained by A. N. Gent and J. D. Walter [2005] can be used in which the maximum temperature that is reached in the center of a rubber block can be obtained with the following formula. Note, this equation is also used in the works done by A. N. Gent and M. Hindi [1988].

$$T_m = T_o + f * U_{diss.} * \frac{H^2}{8\,K} = T_o + \dot{H}_G * \frac{H^2}{8\,K} \quad (6)$$

Where, K is the coefficient of thermal conductivity of rubber. However, this blow-out study is beyond the scope of this research. It is important to note that this equation was obtained for a thin rubber block, thus it might not be a valid model for the case of thick rubber blocks.

## 2 FEA Modeling of the Tread Design study

The product chosen for our research is the typical tread bar that can be found in any rubber caterpillar-type track, such as those found on agriculture or construction vehicles. The concept for FEA modeling for these tread bars consisted of constructing the necessary environment requirements for obtaining the conditions corresponding to one loading cycle. This means that the FEA model should replicate, sufficiently and accurately enough, the multiple and complex mechanisms that lead into the deformations causing the heat build-up.

Instead of modeling an entire track with all its subassembly of undercarriage components, it was decided to model just a section of the track. This simplification was done obviously to reduce computational time. However, by doing so the reduced track section should indeed behave as it would do in a full track. To do so, the boundary conditions on both ends of the track were created in a way that it replicates the real test conditions.

As mentioned, the goal of this research is to obtain a design tool by which the self-heat generation due to cyclic loadings on different geometries could be rapidly evaluated. So with this target in mind, five new different tread bars were designed in order to conduct strain energy analysis. These designs were modeled by altering the designs' tread bar pitch (labeled "P") and the "attack angle" (labeled "A"). Here is the list of the 5 new tread designs studied for this research: [P153_A12.5], [P123_A12.5], [P123_A30], [P153_A40] and [P149_A40]. The control or reference tread bar is labeled as [P153_A30].

The following image (Figure 4) shows the difference, albeit very little, between two new tread designs; the [P153_A30] and the [P153_A12P5].

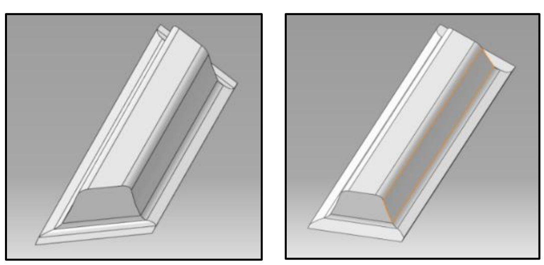

**Figure 4 – Control tread bar A30 (left) and modified A12P5 (right)**

Next, Figure 5 shows the FEA model of the rubber track with all the vital components needed for the simulation. In the left image one can see the bogie set up that would induce downward forces as well as the rolling of the roller sets. In the right image, the tread bars (using the control type P153_A30) attached to the track have been shown.

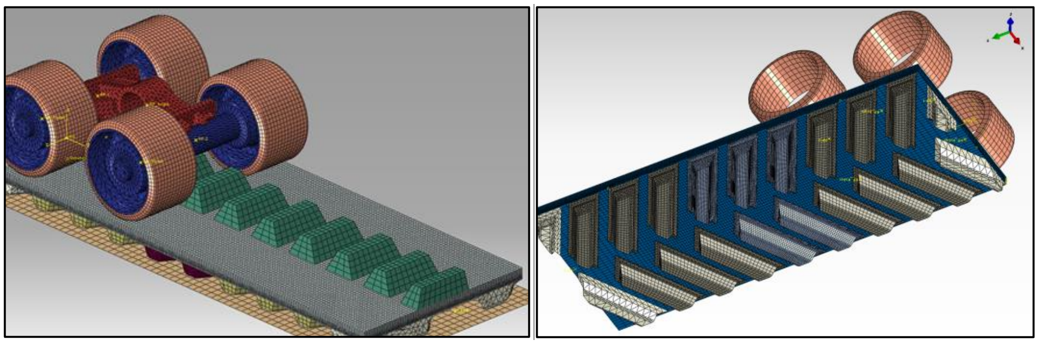

**Figure 5 – FEA model of the reduced track section**

What it cannot be seen in these images is all the reinforcement definition that was incorporated in the FEA model. This reinforcement definition, for disclosure reasons of proprietary information, will not be discussed here.

So, essentially, as it can be seen from the above images, the FEA model construction is a bit complex; composed of a large variety of element types, material models, constrains and contact definitions. The typical model would be composed of about 300,000 DOFs, which in accordance to today standards is not a large computational problem. For the analysis of these simulations, 15cores cluster computer (2.66 GHz processor CPUs) has been used. Our typical run time was between 6-8 hours.

## 3 Materials Characterization

There were a total of 4 different rubber compounds used for this research; comprising the compound for the lug, carcass, adhesion and of course the tread bar. AXEL Products provided us with all the data required for the calibration of constitutive material models. All compounds were tested for tension, planar and equibiaxial conditions.

All tests were conducted at a quasi-static strain rate of 1/sec and at a room temperature of 23°C. No viscoelastic characterization was needed due to the nature of our simulation procedure (steady-state), and that the FEA outputs were only required for one cycle.

Additionally, a series of DMA tests have been conducted in order to obtain the parameters needed for the calculation of the hysteresis. These data would be used for later research in which we would obtain actual values on heat generation and steady-state build-up temperatures. However, as mentioned earlier, this was not part of the scope of this research and will not be shown in this paper.

Similarly, note that the material data presented in this paper will be shown with omitted information due to proprietary reasons.

### *3.1.* Experimental (stress-strain) Test Data

Following, it is the image of one of our compounds tested for 50% pre-strain condition. The material characterization was done at the strain conditions upon which we estimated they would be cycled. In Figure 6, the stress-strain behavior of a rubber material in tension, planar and compression loading is shown.

The next point to mention in this image is the lack of any permanent set and hysteresis or Mullins effects in our data.

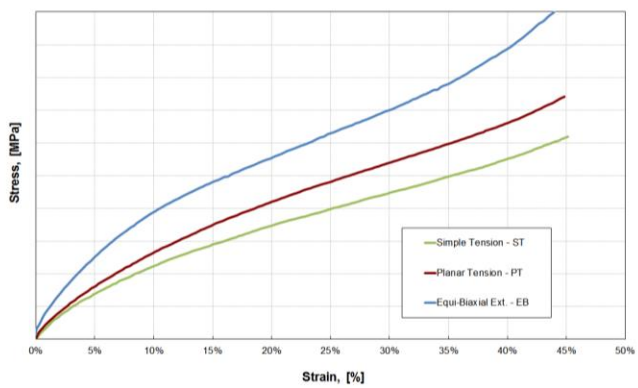


**Figure 6 – Stress-Strain curves for a 50%pre-strain test**

Similar test data were obtained for all the other compounds, at multiple pre-strain conditions to have a wide range of stress-strain characteristics. Next, these physical rubber responses were used in order to obtain the most appropriate mathematical model that best describes its behavior.

### *3.2.* Hyper-elastic model calibration

After obtaining all the experimental stress-strain data, the curve fitting processes can be done in order to calibrate the constitutive models in ABAQUS. As it is well-known, hyperelastic constitutive laws are used to model materials that respond elastically when loaded to very large strains. These laws are defined by equations that relate the free energy of the material to the deformation gradient (or the three invariants of the strain tensor). However, in practice these laws are specified by means of the strain energy density, to simplify the calculation. There are a large number of different constitutive laws in literature that one can find information for modeling hyper-elastic materials, however, these will not be discussed here.

For our research, the Odgen and Marlow models are mostly used for all five rubber compounds. Figure 7 shows a biaxial test curve fitting solution for one of our compounds. This process was done using the ABAQUS curve fitting tool.

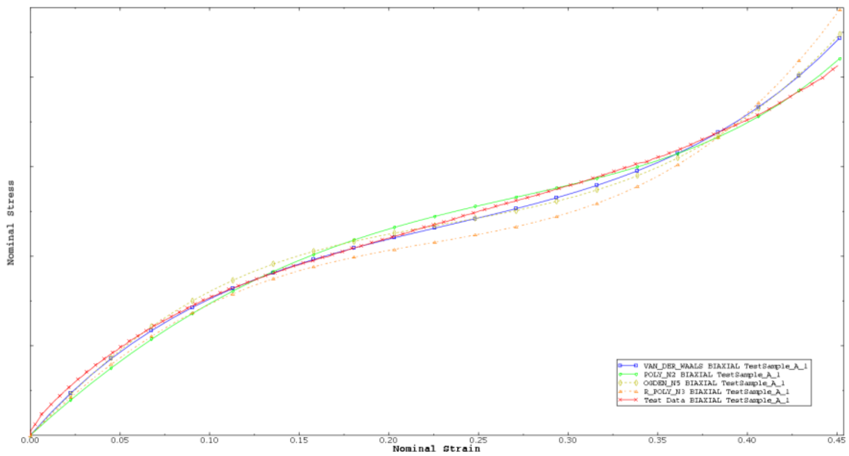


**Figure 7 – Curve fitting of rubber compound TestSample_A, with biaxial test data**

Note, that as part of the calibration process a good material model should be found that best defines the three modes of deformation, for a particular compound. From the image above, the best model that describes the behavior in biaxial is the $2^{nd}$ order Polynomial model. However, in tension or planar modes this model might not be the best fit. So, it is important to select a material model that provides a good fit for all the modes of deformation, and one that is stable at the strain values in which the simulations will be conducted.

# 4 Results

In this section the results of simulations performed on different designs are presented. There were basically three main steps in the simulations. During the first step, a tension load is applied on the track. The second step, the full load per axle of the undercarriage (data obtained from our field tests) was applied and this was carried on by loading down the bogie. Then, the final step was the rolling simulation. This is done at a slow speed, quasi-statically. The reason for this is to avoid any artificial kinetic effects that can be added to the system when accelerating the rollers from zero velocity.

The following image, Figure 8, is a section cut of the track for the P153_A30 model, which shows what is happening at the center of the tread bar. It can be noticed on the left image that the $LE_{min}$, or minimum principal strain, happens to be at the center (excluding edge effects) of the tread bar.

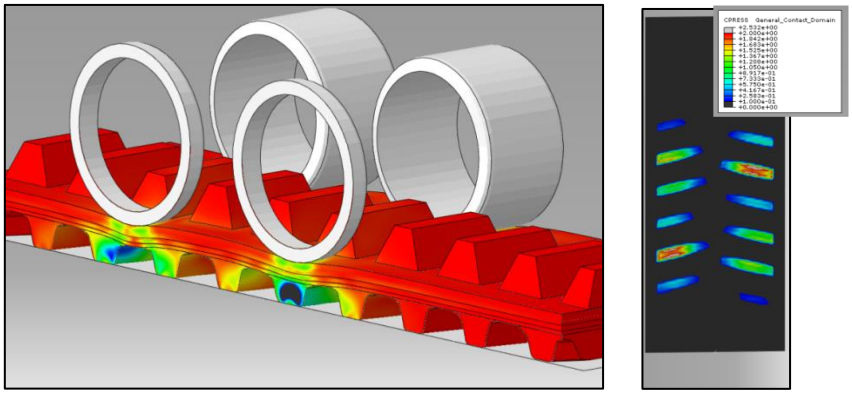

**Figure 8 – Left, section cut of Minimum Principal Strain field. Right, CPRESS or contact pressure distribution (model P153_A30)**

Additionally, the contact pressure footprint of the tread bars as the rollers move across the ground can be obtained, as shown on the right picture above. This indicates how the stresses are distributed throughout the contact patch, and consequently the impact of our tread bar design in terms of pitch and attacking angles can be investigated.

Since the goal was to study the strain energies generated on each of our tread bar, it is focused on the strain energy acquired for a tread bar located somewhere in the center of the track, during this simulated one cycle event. The following image shows what happens inside the tread bar in terms of the strain energy density function, which is the element contour plot of the strain energy per unit volume. Figure 9 shows on the left the ESEDEN contour plot for the P153_A30, and on the right the ALLSE or strain energy history for the same tread bar.

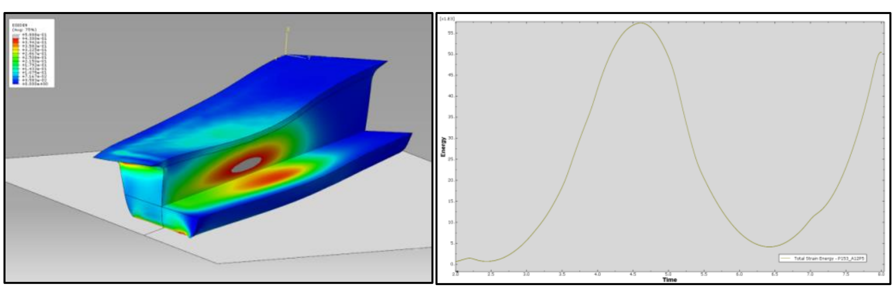

**Figure 9 – Left, section cut of P153_A30 showing strain energy density function ESEDEN. Right, strain energy history**

The region with high strain energy happens to be at the center of the tread bar. Subsequently, the strain energy history of the entire tread bar (which is a volume summation of all the strain energy functions of the tread bar) can be plotted, and characteristic plot describing the rise and fall of its strain energy during the one cycle event can be obtained.

Note, the image on Figure 9 shows two rises corresponding to the two roller set, as the bogie passes along the length of the track. The simulation was stopped before the second roller completed passing the tread bar. This was done to save computational time. In preceding simulations we found that there was very little difference between the two roller passes. So with this in mind, all our six tread bar designs were analyzed against the strain energy and results for comparison were plotted. The following figure, Figure 10, shows the difference in strain energy between the designs.

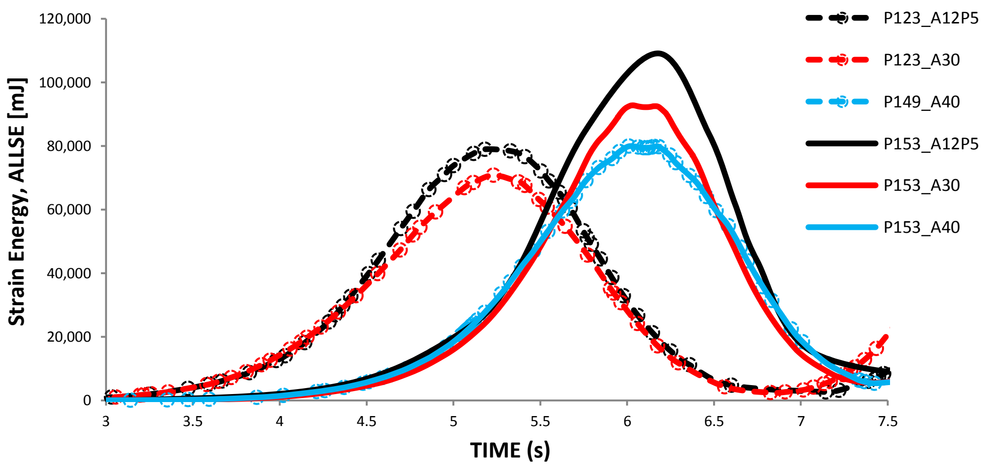


**Figure 10 – Strain energy comparison between all six tread bar designs**

According to this plot, by modifying just the pitch and the angle of tread geometry, the generated strain energy can be changed. The solid red line corresponds to the control or reference tread bar model P153_A30. By reducing (solid black line) or increasing (solid blue line) the angle of attack this strain energy can be changed, and thus affecting how much heat would be dissipated. Similarly, an effect on the varying the pitch can be noticed as well.

To validate our finding and determine if indeed design changes in tread bar geometry are influencing the strain energy, it is decided to re-design a new tread bar which is considerably different in size and shape from our control P153_A30 model. This new prototype tread bar, which is called PRTYP, was built and tested. The following image, Figure 11, shows the comparison in terms of strain energy of this prototype tread bar with our reference model, using our loading cyclic conditions. This analysis was also conducted at different loading scenarios.

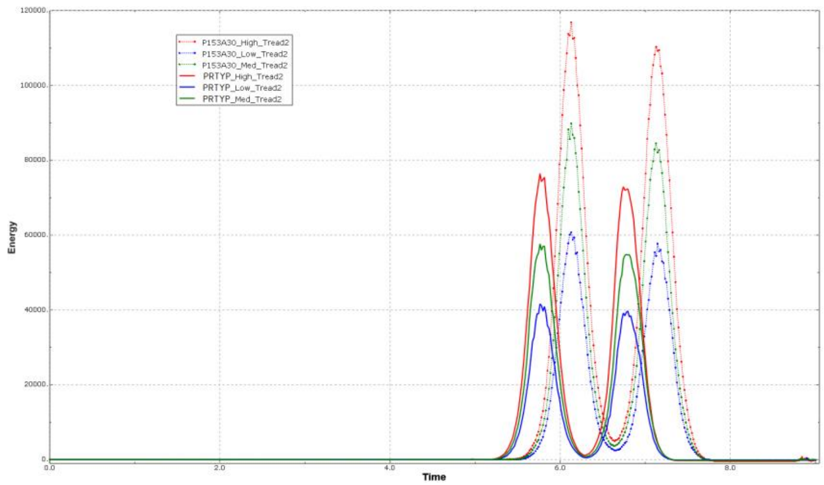


**Figure 11– Strain energy comparison between reference tread bar P153_A30 with a new prototype tread bar**

According to the image above, the tread bar performance, in terms of strain energy, can be drastically improved by varying some geometric parameters such as those done on the PRTYP. It can be deduced, similarly, that the change in heat build-up at each tread bar is proportional to the strain energy variation.

Both tread bars including the new prototype tread bar and the reference tread bar were tested using a simple cyclic compression test, and found that indeed the new prototype bar produced less heat for the same loading conditions.

## 5 Conclusion

From this limited and initial investigation of the world of self-heat generation of rubber, it can be concluded that indeed our claim of using strain energy for designing tread bars against heat build-up is, at least, a quick and reliable method to measure qualitatively heat build-up. It is observed that slight changes in the tread bar geometry would have an impact in our total strain energy output. By accepting that most of the energy dissipation is due to the characteristics of the rubber (i.e. hysteresis ratio), and this is a constant in our analysis, a proportional measurement of the heat generation properties of our tread design bars can be obtained.

Note, for proprietary and confidential reasons no information regarding the calculation of the Heat Generation Rate and temperature research is disclosed in this paper. Further research into the area of heat generation will be to make use of other commercial software packages such as *FE-Safe/Rubber* that would facilitate all the calculation of the heat build-up characteristics of compounds and designs.

## 6 References


1. A. N. Gent, M. Hindi. “Heat Build-up and Blow-out of Rubber Blocks”, *Institute of Polymer of Science*, Akron, Ohio. 1988
2. A. N. Gent, J. D. Walter. “The Pneumatic Tire”, *National Highway Traffic Safety Administration*, Akron, Ohio. 2005
3. A. I. Medalia. “Heat Generation in Elastomer Compouds: Causes and Effects”, *Rubber Chem. Tech*, pp481-492. 1991
4. K. K. Kar, A. K. Bhowmick. “ High-Strain Hysteresis of Rubber Vulcanizates Over a Range of Compositions, Rates, and Temperatures”, *Journal Applied Polymer Science,* pp1429-1439. 1997
5. L. Pesek et al. “FEM Modeling of Thermo-Mechanical Interaction in Pre-Pressed Rubber Block”, *Engineering Mechanics*, pp3-11. 2007
6. R. K. Luo et al. “A Method to Predict the Heat Generation in a Rubber Spring Used in the Railway Industry”, *Journal of Rail and Rapid Transit*, pp.239-244. 2005
7. Y-J. Lin, S-J. Hwang. “Temperature Prediction of Rolling Tires by Computer Simulation”, *Mathematics and Computers in Simulation*, Vol. 67, pp. 235-249. 2004
8. L. C. Yohan et al. “Cyclic Approximation of the Heat Equation in Finite Strains for the Heat Build-Up Problem of Rubber”, *Journal of Mechanics of Materials and Structures*, Vol. 4, N-2. 2009
9. M. S. Banic et al. “Prediction of Heat Generation in Rubber or Rubber-Metal Springs”, *Thermal Science*, Vol. 16, pp.S527-S539. 2012