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Design Elements of Steel Belted Radial Tires to Improve Belt Durability

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ABSTRACT
Since the invention of steel belted radial tires for automobiles, various technologies have been developed to improve tire safety. As demands for high speed rated tires grow, belt durability is becoming the governing safety aspect. That is, the tire's carcass life should exceed its tread life, ensuring that tires used until catastrophic breakdown will fail by blowout rather than by delamination. This paper is specifically focused on design elements of steel belted radial tires and how these elements affect belt durability. Finite element analysis on P-metric tires is used to assess various design factors affecting overall durability. For a variety of designs, interlaminar shear strain and strain energy densities at the belt edge regions are compared when the tire is inflated and loaded. It is shown that belt edge strip and nylon cap ply covering belt edge at the belt peripheries were the most effective elements improving belt durability. It is also shown the nylon full cover works better than an additional steel belt layer to reduce maximum interlaminar shear strain and strain energy density at belt edge.

INTRODUCTION
Tires are constructed with multiple layers of natural and synthetic rubber components and plies reinforced with non-rubber materials such as steel, rayon, nylon, or Kevlar^{TM}. During operation, interactions between plies result in interply stress and strain. To ensure tire safety, it is important to understand the interply stress/strain behavior of the tire structure. Figure 1 shows the components of a typical modern radial tire. Tire failures during service can mainly be classified into two major categories by failure location: tread and bead. In this paper, the authors focus on tread failure problems for P-metric tires that have 2-steel belts. Among tread failures, the belt-leaving-belt separation is a catastrophic failure. Due to the structural nature of modern steel belted radial tires, inter-laminar shear strains develop between the two steel belt layers that the belt wires of the each layer are laid in opposite directions.

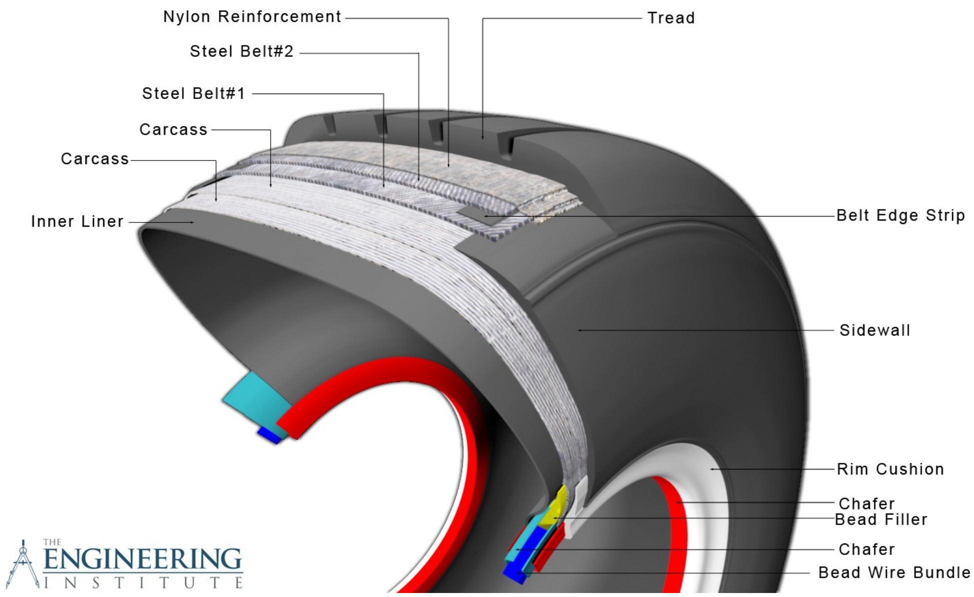

Fig.1: Cutaway view of a typical passenger radial tire.

Figure 2 shows a diagram of belt layers and shear strain under extension. A distribution of the shear strain between belt layers across the width of belts is shown in Figure 3. The maximum shear strain magnitudes are realized at the ends of the belt layer strips. At the center, the shear strain in the x-z direction becomes zero. This explains why cracks are typically initiated at the belt edges. Figure 4 shows an example of a belt edge initiated crack that has propagated. The maximum shear strain or strain energy density (SED) observed at the belt edges can mechanistically explain belt separations. As the tire rotates under loading, the belt layers are subject to cyclic loads; air pressure at non-contact positions and air pressure plus loads at contact positions. These cyclic strains generate interaction between components and degrade the belt edges. Thus, it is relevant to analyze the shear strain or strain energy density (SED) at the edges to determine tire durability.

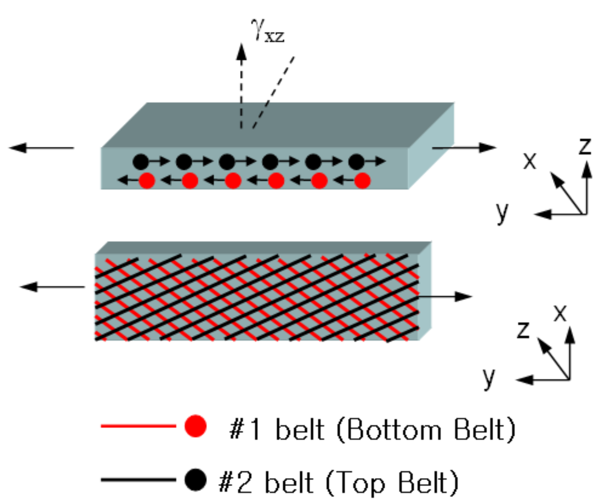

Fig.2: Belt layers and shear strain under extension.

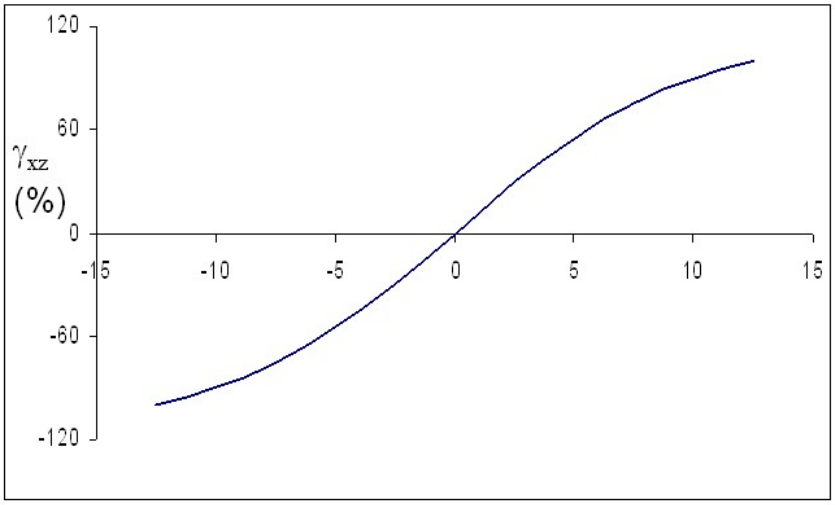

Fig.3: Interlaminar shear strain (xz) vs. position along belt width (when Ex=20%, belt angle=+/- 22 deg.)[2]

Fig.4: Small crack initiated from the belt edge between the two steel belt plies.

BELT-LEAVING-BELT TREAD SEPARATION

Belt-leaving-belt tread separations initiate at the edge of the belt package. [5] The maximum shear strain occurs at the belt edges and the total thickness of the belt edge area is the highest among tread region. For this reason, the area is relatively disadvantageous for heat diffusion. Once a small crack (or cracks) is initiated, it grows circumferentially and laterally along the belt edges. The areas of separation develop into crescent shaped patterns at various locations around shoulder of the tire. If they grow large enough, they can result in catastrophic tread detachment. Figure 5 shows multiple crescent shaped patterns and the characteristic separation pattern that has resulted in belt-leaving-belt tread separation.

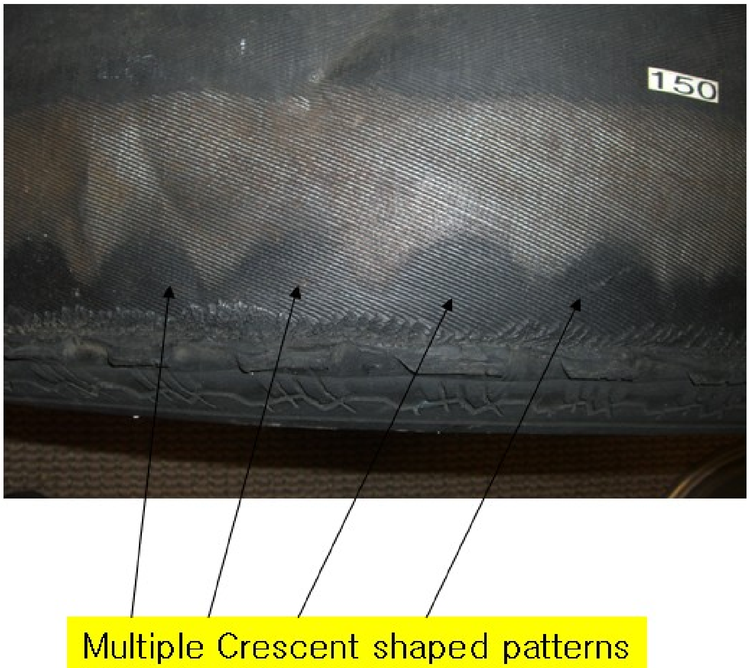

Fig.5: Crescent shaped patterns on a belt-leaving-belt tread separation incident.

DESIGN PARAMETERS

In this paper, the following design parameters for belt durability are considered. Figure 6 illustrate components of a P-metric tire.

1. **Nylon Overlay (aka Nylon Cap Ply):** Since the late 1960s, nylon overlays have been applied to steel belted radial tires to increase belt durability. They not only reduce the stress/strain level at the belt edges, but also retard crack propagation once a crack has initiated. They also restrict expansion of belt layers due to centrifugal acceleration during operation. Nylon overlays in steel belted radial tires function as restraints, similar to seat belts in motor vehicles. Today, most tire manufacturers apply the cap ply by spiral wrapping a narrow rubber coated nylon strip around the steel belts circumferentially. Two types of nylon overlays are dominant in modern radial tires: nylon edge cover and nylon full cover. Nylon edge covers overlay the edge of the belts with minimum width of covering belt end steps, while nylon full cover covers the entire belt width and is more effective in retarding crack propagation in the belt width direction.
2. **Belt Edge Strip (aka Belt Wedge):** Belt wedges are strips of rubber located between the two belts near both sides of the belt edges. They are known as a critical design feature used by tire manufacturers to suppress the initiation and growth of belt edge cracks. [5] It is very important for steel belted radial tires to have sufficient thickness and adequate rubber compound of the belt wedge since they are inserted at the location where the maximum stress/strain around belt edge are realized. A belt wedge that is designed with sufficient thickness and proper materials will efficiently reduce stress/strain concentration on belt edges.
3. **3-Belt Construction:** Typical P-metric steel belted radial tires are constructed with 2 steel belt layers. There are, however, 3-belt layered P-metric tires that are commercially

available that emphasize specific performance such as off road use. The 3rd belt layer is mainly for protecting stone punctures. Most 3-belt tires do not have nylon reinforcement. In this study a 3-belted tire's shear strain and strain energy density at the belt edges is compared with those of a 2-belted tire with nylon reinforcement to predict belt separation resistance.

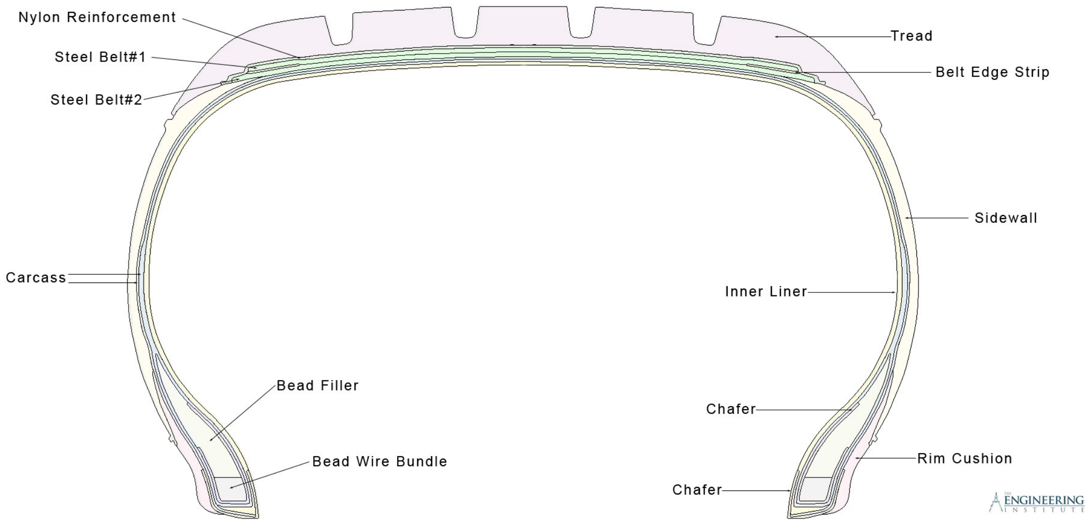

Fig.6 2-D Section View of a P-metric Tire

FINITE ELEMENT MODELS

The finite element method has been widely used to calculate stress/strain levels of tires on various design contributions. This enables tire designers to calculate inter-laminar shear strain and strain energy density to assess tires' belt separation resistance. In this study a p-metric radial tire having a typical architecture illustrated in Figure 1 is selected and modeled. For FE analysis, ABAQUS 6.10-1 is used with a hyper-elasticity material consideration of rubber part. Figure 7 shows 3-D FE tire model used in this study. Each component construction is represented by different color from section view. A displacement control is utilized to apply loads.

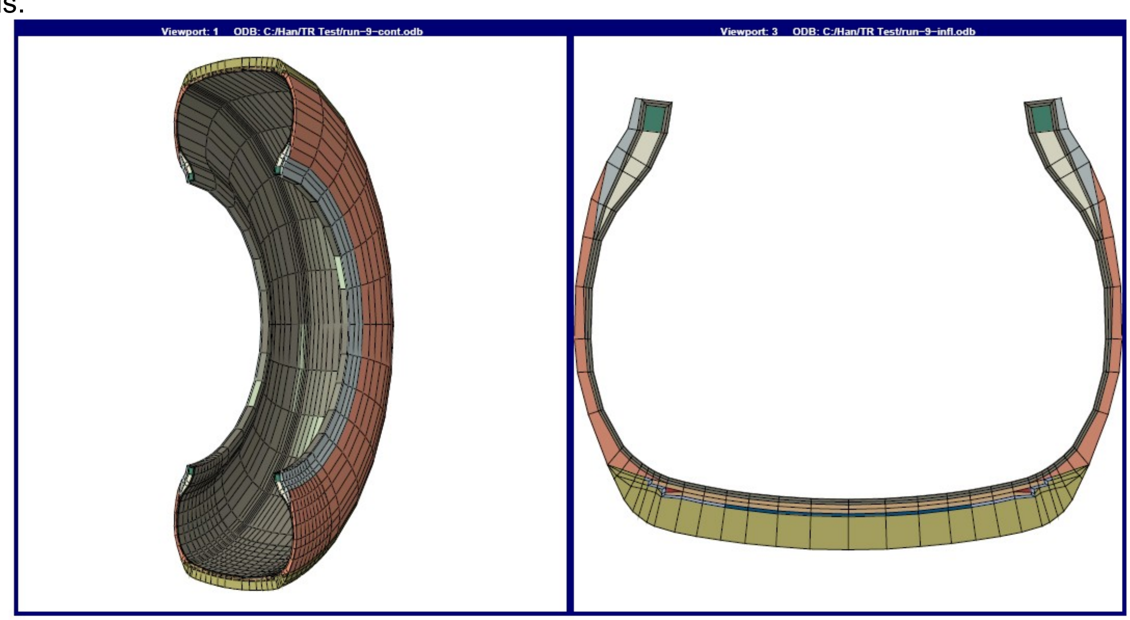

Fig.7 Three dimensional FE model

Figure 8 shows a result of interlaminar shear strain analysis of a three dimensional finite element model. The shear strain concentration is observed on belt edge.

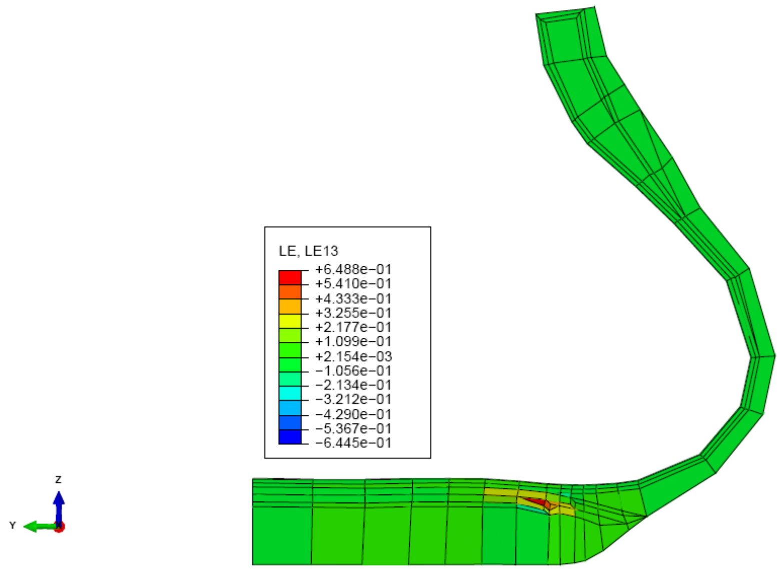

Fig.8: Shear strain concentrated on belt edge from 3-D FE simulation

FE ANALYSIS & DRUM TEST RESULTS

The interlaminar shear strain, shear strain amplitude, strain energy density and strain energy density amplitude at the belt edge are calculated when the tire models are subject to inflation pressures and the vertical loads. The Tire and Rim Association (TRA) year book is referenced for inflation pressure and loads. The amplitudes are the difference between maximum and minimum values of shear strain and strain energy density of an element at the belt edges when the tire is inflated and loaded. The analyses are pursued on various models in accordance with design variable change.

1) **Nylon Overlay (aka Nylon Cap Ply):** The FE models without nylon cap plies and with nylon cap ply are compared. From Figures 9 and 10, it is shown that the maximum shear strain, strain energy density and their amplitudes of the nylon edge cover model and the full cover model are reduced compare to the model without a nylon cap ply. The amplitudes of shear strain of nylon edge cover and nylon full cover reduced by 7% and 14% respectively. The drum test data in Figure 11 shows that the tire reinforced by a nylon edge covered tires achieved higher belt durability index than regular tires by 25% while the tires reinforced by a nylon full cover showed 30% higher index. The durability indices are calculated from the actual drum tests pursued until failure. The tests consist of step speed test and step load test and P-metric tires are used. The drum test achieved greater nylon cap ply effect than the FE analysis results. This is due to the dynamic effect of the nylon cap ply that it restrains expansion of the belt package during highway speed operation. Thus it is shown that the use of nylon cap ply can reduce maximum shear strain and strain energy density and will improve belt durability.

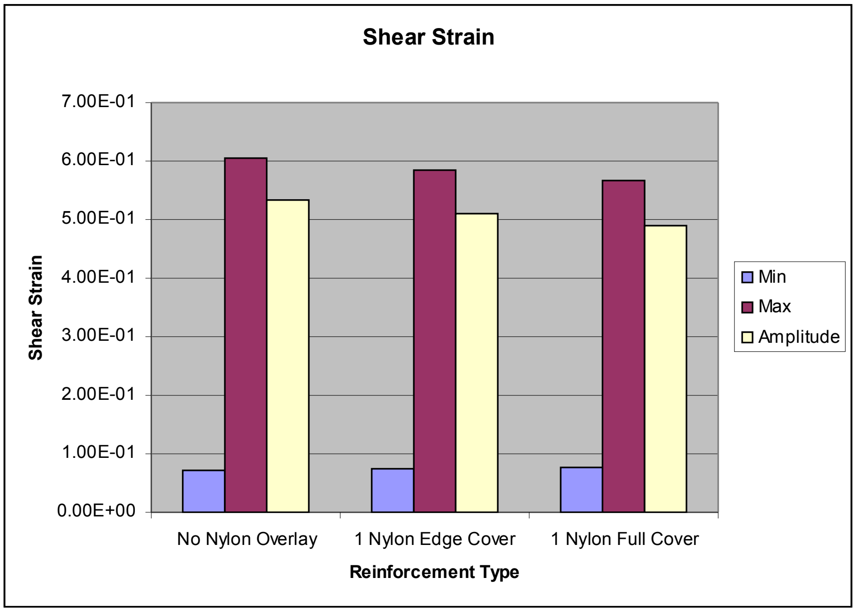

Fig.9: Shear strain and shear strain amplitude by reinforcement type.

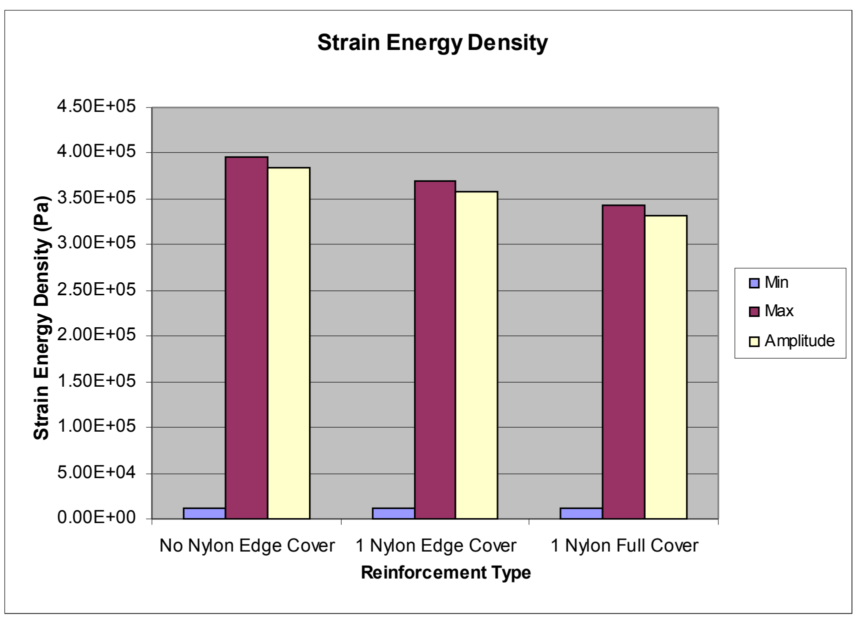

Fig.10: Strain energy density (SED) and SED amplitude by reinforcement type.

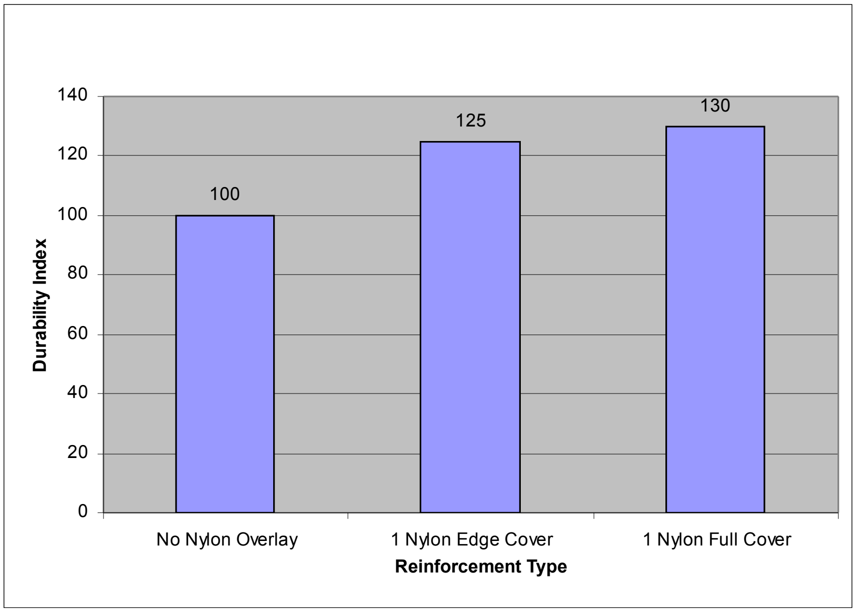

Fig.11: Drum test data showing nylon overlay reinforcement effect
(Data courtesy of Q Tires Inc. Greenville, SC)

2) Belt Edge Strip (aka Belt Wedge): 2 levels of belt wedge thicknesses are modeled; 0.5mm & 1.5mm. From the results, the tire with a 1.5mm belt wedge showed significant reductions in its shear strain, strain energy density and their amplitudes, see Figures 12 and 13. The amplitude of maximum shear strain of 1.5mm model is reduced by 25% as compared to 0.5mm model. The maximum strain energy density and the amplitude of strain energy density of the 1.5mm model are significantly reduced.

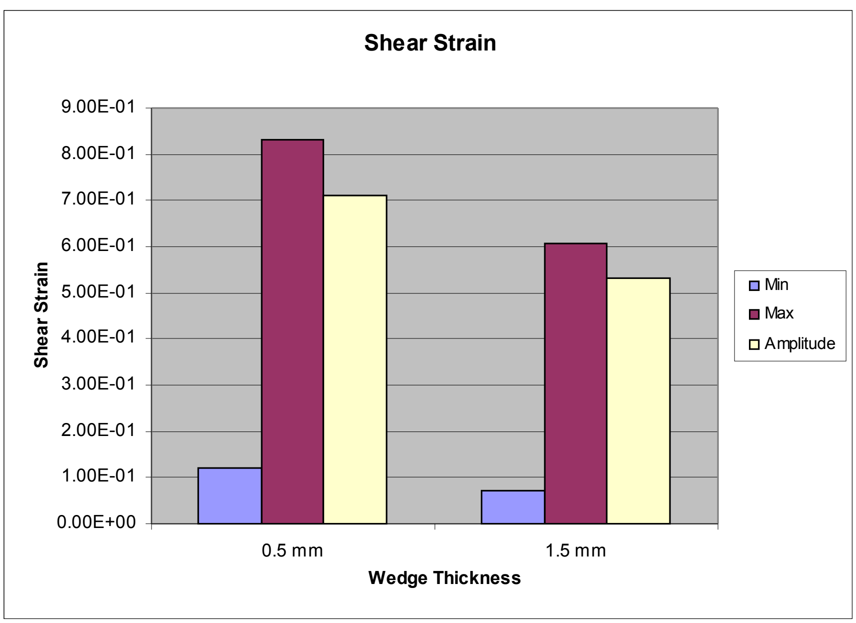

Fig.12: Shear strain and shear strain amplitude by belt edge strip thickness.

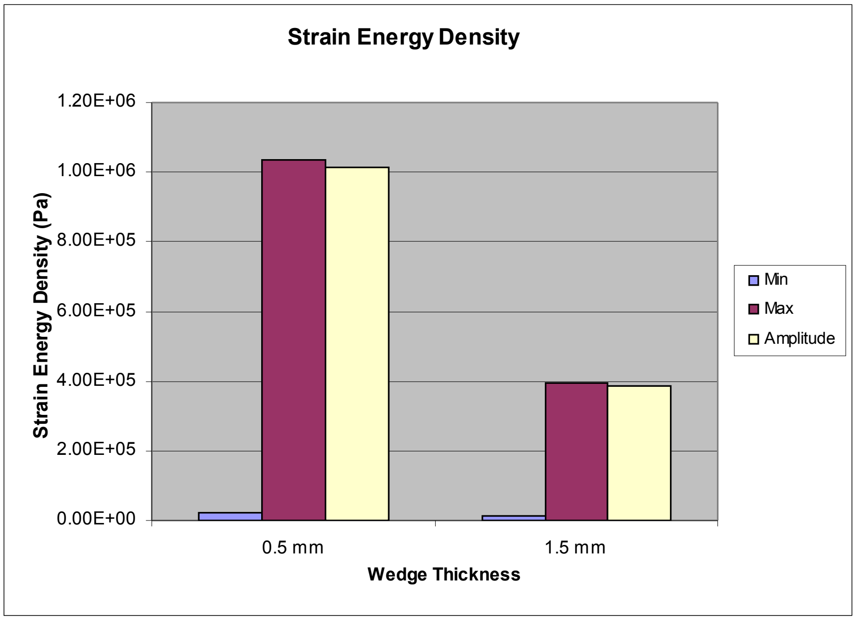

Fig.13: Strain energy density (SED) and SED amplitude by belt edge strip thickness.

The results indicate that the thicker belt wedge can reduce maximum shear strains when inflated and loaded. Reference drum test data by changing belt wedge thickness are available in Figure 14. The data are average of step speed tests and step load tests on multiple sizes of P-metric tires. From the results the thicker belt wedge group showed better durability. The trend of the drum test results agrees well with the analytic results.

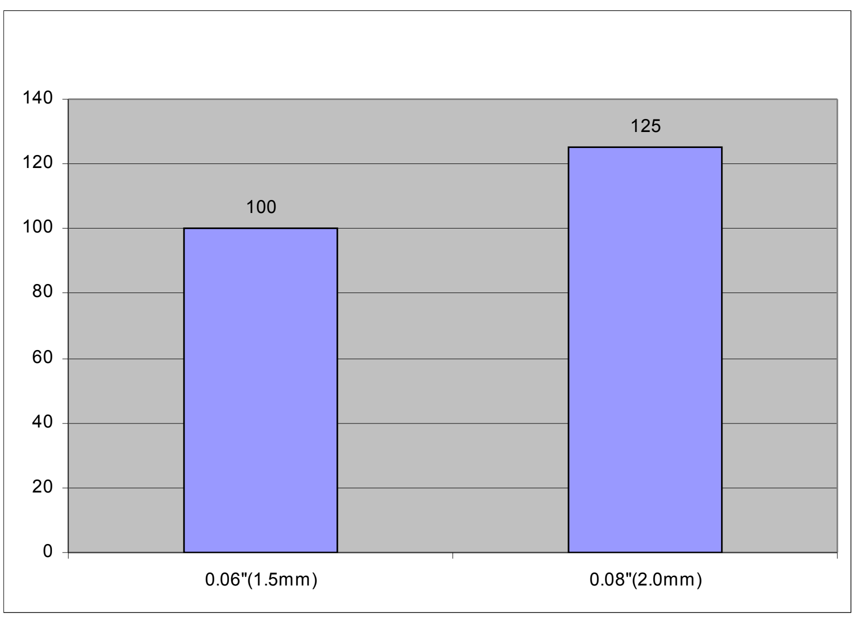

Fig.14: Drum test data showing belt edge strip gauge effect
(Data courtesy of Q Tires Inc. Greenville, SC)

3) 3-belt layered belt package: An additional steel belt layer on top of the conventional 2-ply belt package is known as a protection layer. The orientation of the 3rd belt is same as the 2nd belt and in general the width of the 3rd belt is narrower than the other 2-belt layers. Therefore the 3rd steel belt does not cover the belt edge step as nylon overlay does. In this study, 3-belt layered model is compared with 2-belt layers plus 1-nylon full cover model. The results showed that the shear strain and strain energy density (SED) of the 3-belt layered model at the belt edge when inflated are lower than those of 2-belt layers plus 1-nylon full cover by 35% and 45% respectively. This means that the 3rd steel belt layer can restrain the growth of the tire more than the nylon overlay when inflated. However when loaded, the shear strain and SED of 3-belted model were higher than those of the nylon full cover model by 11% and 27% respectively. This resulted in the amplitudes of shear strain and SED increased by 18% and 29% respectively. This result shows that adding a steel belt layer cannot reduce maximum shear strain and strain energy density at belt edges. Figures 15 and 16 show minimum, maximum and amplitude of the shear strain and strain energy density by belt package construction.

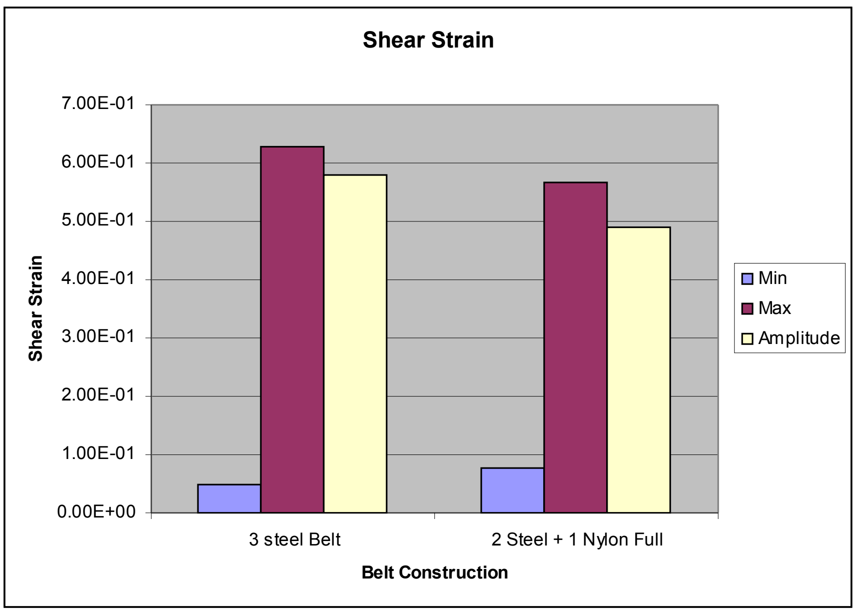

Fig.15: Shear strain and shear strain amplitude by belt package.

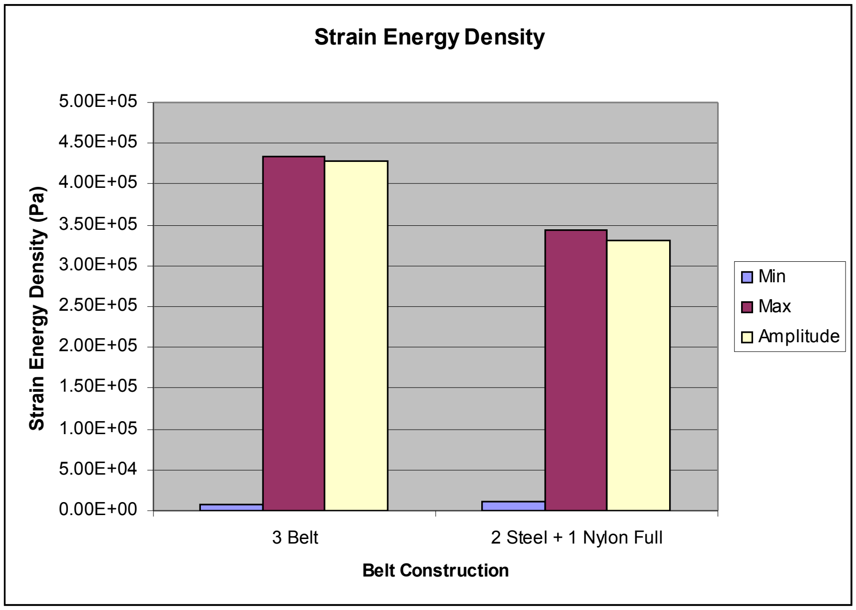

Fig.16: Strain energy density (SED) and SED amplitude by belt package.

CONCLUSIONS

3-dimensional FE analyses on P-metric tires have been pursued and the shear strains and the strain energy densities have been calculated by changing various design parameters. The following conclusions are evident:

1. The shear strain amplitude and the strain energy density can be used to predict belt durability of steel belted radial tires.
2. The use of nylon cap plies including the nylon edge cover and the nylon full cover can reduce belt edge shear strain and shear strain amplitude and it can improve belt durability. The FE results agreed with the drum test results.
3. The thickness of belt edge strip (belt wedge) affects the shear strain and strain energy density at belt edge. Keeping sufficient thickness of the belt wedge is critical to belt durability.
4. Adding a steel belt layer (protection belt) cannot reduce maximum shear strain at belt edge. The use of nylon cap ply is more efficient way to improve belt durability

Further study will be followed to assess other design parameters affecting to belt durability of steel belted radial tires. The design factors may include tire in-mold contour feature, rubber compound and material properties.

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