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Tire Design Methodology Based on Safety Factor to Satisfy Tire Life (Simulation Approach to Truck and Bus Tire Design)[3]

ABSTRACT: A tire is not only simply made of rubber, but also twisted cord, which we can call FRR (Fiber Reinforced Rubber). The rubber in FRR is made of many materials, including rubber compound, carbon black, silica, and other materials. FRR is a double composite material, which means a particle reinforced material in a microscopic view and also a fiber reinforced one in a macroscopic view. Therefore, it is very difficult to apply fracture mechanics to the evaluation of tire durability on a practical tire design level.

  This paper gives a proposal for a new design methodology considering the actual tire condition which gives tire profile growth and rubber aging due to heat build-up under operation. These two issues are especially important for truck and bus tire design. Tire profile growth is a very important one because the change of tire profile induces different strains in the rubber at the same location in the tire during its life. We apply the FEM (Finite Element Modeling) based Double Inflation Pressure (DIP) method to simulate the experimental fact of the change of tire profile. In order to use the relationship between the change of the tire profile and change of rubber properties, like breaking strain in the tire as service time passes, the concept of safety factor is introduced. The low modulus rubber parts in the tire dominate the strain field and allow the large deformations of the tire. Safety factors derived from the strain field are called "Margin of Safety." On the other hand, the durability of FRR, like the belt layer and carcass layer with the cord part, is evaluated by stress because the FRR part reacts to the stress of the internal pressure and load of the tire. But, the Margin of Safety of the rubber part is more important because the cord part has enough safety factor in comparison with the rubber part. Tire life is predicted with the Margin of Safety described above.

KEY WORDS: safety factor, margin of safety, tire growth, strain at break, double inflation pressure method, finite element modeling

Introduction

  There are many rubber products in the world, such as tires, conveyor belts,

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rubber fenders, rubber bearings, and rubber isolators. Usually, many rubber products are not only made simply of rubber, but also cord, which we can call FRR (Fiber Reinforced Rubber). Among these rubber products, a tire, which is shown in Figure 1, has the most complex construction. It is made of both rubber components, such as cap tread and sidewall, and cord reinforced rubber components such as belt layer and carcass layer. In the case of FRR, each cord of the belt layer and carcass layer has a twisted cord construction, which cannot be observed in the other composites, such as FRP (Fiber Reinforced Plastics or Filament Reinforced Plastic).[1]
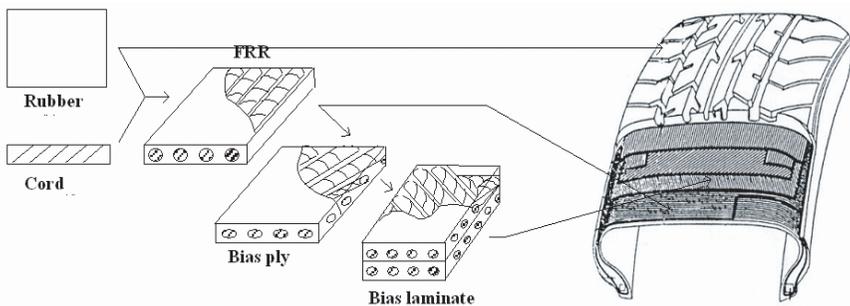

FIG. 1 - *Radial tire construction.*

These tire constructions are required to provide many functions including the following four basic ones: 1) Load - carrying capacity; 2) Transmission of driving and breaking torque; 3) Cushioning ability; 4) Road - holding ability; and many others to provide steering response, adequate mileage and dimensional stability, as well as to consume minimum power and to have minimum noise and vibration. In order to satisfy these essential functions, a tire forms a thin-walled composite toroidal shell with rubber and cord, which is both highly flexible and relatively inextensible so as to keep the characteristics of the tire shown in Figure 2.

On the other hand, the matrix of rubber in FRR is made of many materials, including rubber compound, carbon black, and silica. Rubber itself is considered as a particle reinforced material as shown in Figure 3.[3] Therefore, we cannot apply fracture mechanics to the evaluation of tire durability, which is usually applicable to FRP made of plastics and fiber. This is because, when rubber is broken by a tear, the interface between the separations of rubber has a complex response. For example, rubber is simply broken in an area of rubber, or carbon black filler is broken. It is very difficult to detect how the break occurred. Therefore, it is very difficult to apply fracture mechanics to the evaluation of the tire durability on a practical tire design level.
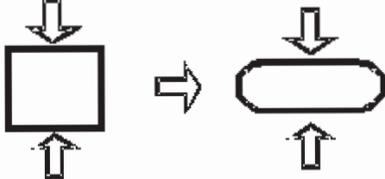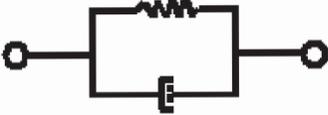
large deformation & large strain	
incompressibility	
material nonlinearity	
composite structure	
viscoelasitcity	
rolling contact	

FIG. 2 - *Characteristics of a tire.*

The authors would like to say that FRR is a double composite material from both the microscopic and macroscopic points of view, which means the particle reinforced material in the microscopic view and the fiber reinforced one in the macroscopic view.
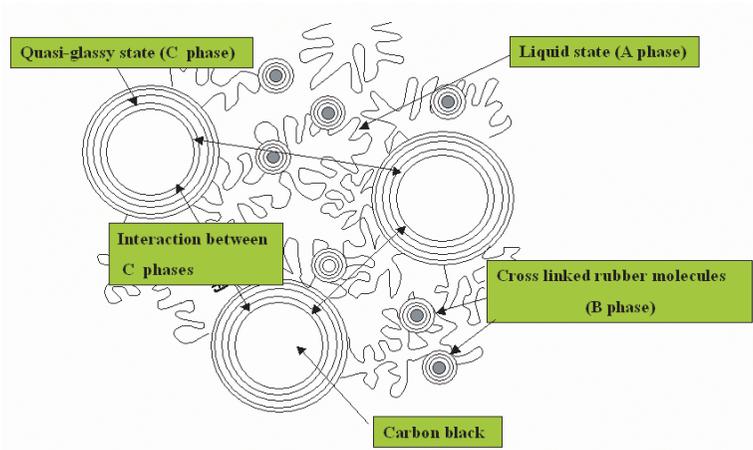
FIG. 3 – *Tire rubber model (heterogeneous structure model for carbon black filled rubber).*

This paper gives the proposal for a new design methodology considering the actual condition of a tire. A tire should provide many features and functions, such as being used in contact with a road, many different roads, and also giving driving, breaking and cornering force. Through repetition of these actions, the tire has tire profile growth and rubber aging due to heat build-up under operation. So, it is necessary to take tire profile growth and rubber aging into consideration while developing tires. These two issues are especially important for truck and bus tire design.
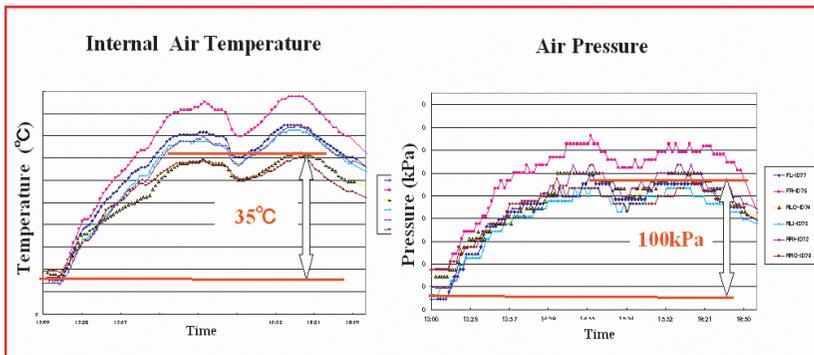
Tire Growth Under Operation

FIG. 4 - *Internal air temperature and air pressure change under operation.*

Figure 4 shows one example of internal air temperature and air pressure in

the case of a truck and bus tire. What kinds of phenomena occur in truck and bus tires under operation? By the vehicle running, heat is generated in a tire. This heat generation causes an increase of internal air temperature and air pressure, as shown in Figure 4, in which the air temperature increases by 35 degrees C and the air pressure increases by 100 kPa. These phenomena are especially important for the truck and bus tire design.

By the increase of internal air temperature and air pressure, the tire profile is transformed, as shown in Figure 5. This figure shows the transformation of a tire after 170 thousand km running on an indoor test under the following test conditions: tire size: 11R22.5 room temperature: 30 °C; road wheel diameter: 1.7 M; load: 21.4 kN; air pressure: 700 kPa; 100 km/h x 8 h + 60 km/h x 24 h; 1 set = 29,120 km x 6 set = 174,720 km. (The tires were run on a wear machine to remove 2 mm of tread depth after each set.)
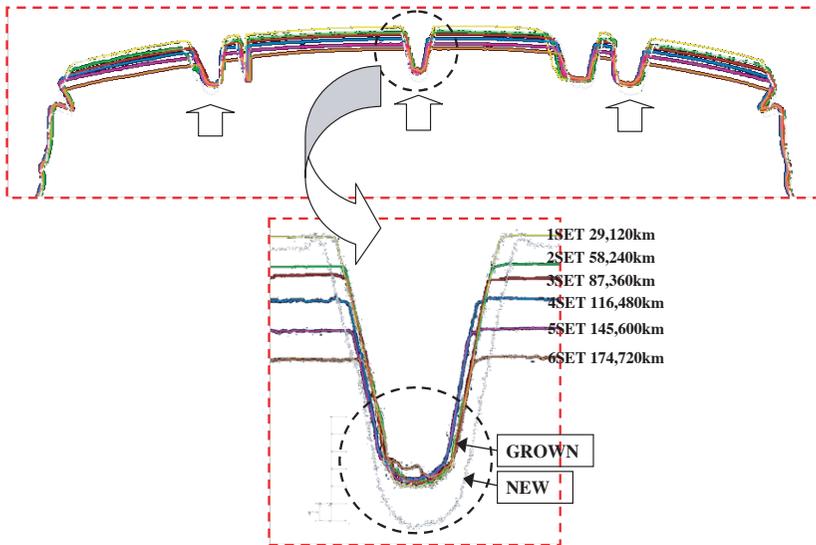

FIG. 5 - *Growth of overall diameter.*

This figure indicates that the change of tread profile is significant, but the change of tire width is small, as shown in Figure 8 and mentioned later.

Consequently, the first issue is tire profile growth, as shown in Figure 6, which shows the relationship between growth of OD (Overall Diameter) and mileage under rolling of a tire. The OD of the tire grows at the early stage of its life, but does not grow after the middle stage of its life.

Figure 7 shows the comparison of the overall diameters between a new tire and a grown tire. In this figure the horizontal axis is air pressure and the vertical axis is the tire's overall diameter. Marks (■) in this figure are the new tire, while

marks (▲) are the grown tire. If we look at one diameter point, like at the tread-center of a tire, and compare OD between a new tire and a grown tire, it is clear that the diameter of the grown tire at low pressure is nearly the same diameter as the new tire when inflated to a high pressure. This phenomenon is called "amount of overall diameter growth".
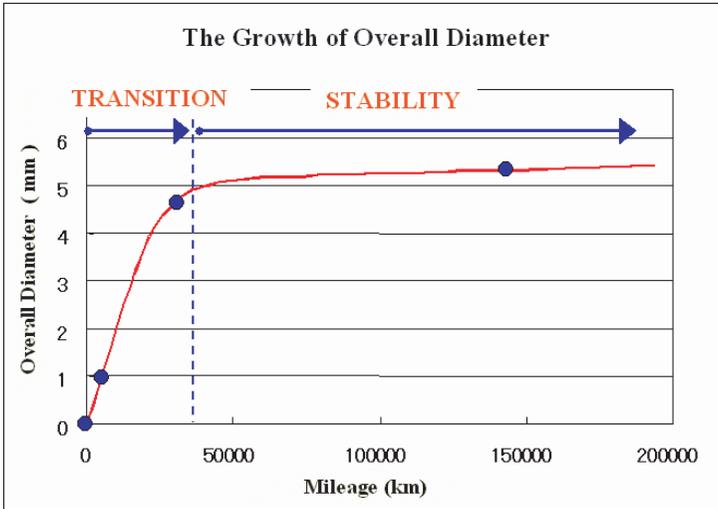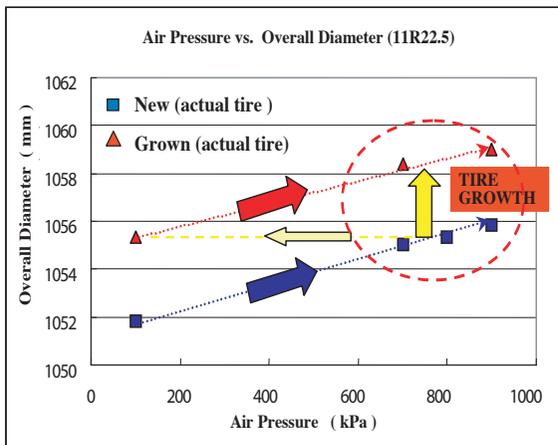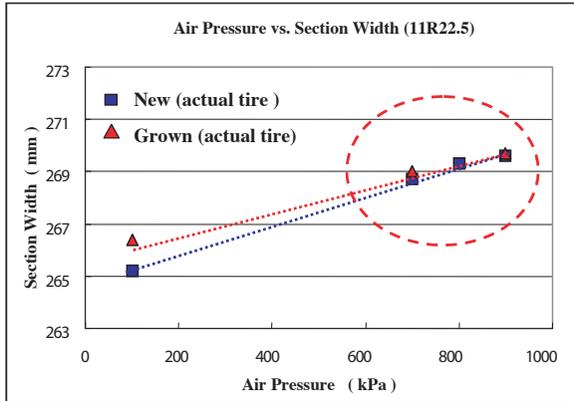

FIG. 6 - *The growth of the tire under operation.*

<The growth of tire under operation. >

Overall Diameter : Growth O.D. (low pressure) ≒ New tire O.D. (high pressure)

FIG. 7 - *The growth of the tire under operation (Air Pressure vs. Overall Diameter (11R22.5)).*

Figure 8 shows the comparison of tire section width between a new tire and a grown tire in the same manner as overall diameter in Figure 7. It is not clear if there are any significant changes in the tire section width between a new tire and a grown tire.

< The growth of tire under operation. >

Outside Diameter ：Growth O.D.(Low Pressure) ≒ New Tire O.D. (High Pressure)

Section Width ：Almost no-change

FIG. 8 - *The growth of tire under operation (Air Pressure vs. Section Width (11R22.5)).*

Double Inflation Pressure Method (DIP Method)

First of all, FEM is generally used for a new tire's profile prediction, as shown in Figure 9, in which a new tire model is prepared from the mold cavity profile. An inflated calculation is performed with air pressure, namely the general inflation analysis by FEM so far. But, this method is merely the analysis of the new tire condition only.

Figure 10 shows a new simulation method for grown tire prediction. This method is based on the tire characteristic that the grown tire's overall diameter under low pressure is nearly equal to the new tire's overall diameter under high pressure, as already shown in Figure 7. The result of first inflation analysis from the general analysis by FEM is re-modeled for a second analysis, and inflation is performed once again. As the inflation analysis is performed at least twice, this analysis procedure is called the Double Inflation Pressure Method.

Figure 11 shows a comparison between the predicted grown tire's profile and the actual grown tire's profile. In this figure, a solid line shows the actual grown tire's profile and a dotted line is the calculated grown tire's profile. As the

calculated profile corresponds to the actual tire profile in this figure, this method produces a useful simulation.
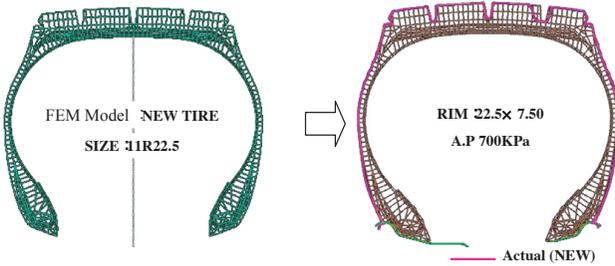
Procedure of NEW TIRE simulation

NEW TIRE MODEL ⇨ INFLATED ⇨ LOADED ⇨ ANALYSIS

Inflated calculation ∶1 time

FIG. 9 - *Simulation of NEW TIRE by FEM.*
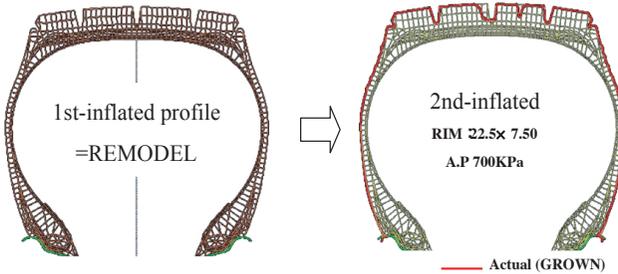
Procedure of GROWN TIRE simulation

NEW TIRE MODEL ⇨ INFLATED ⇨ INFLATED ⇨ LOADED ⇨ ANALYSIS

Inflated calculation & Inflated calculation (2 times)

Double Inflation Pressure Method

FIG. 10 - *Simulation of GROWN TIRE by FEM.*

Figure 12 shows overall diameter of the actual and calculated tire. The horizontal axis in this figure is air pressure and the vertical axis is overall diameter. The actual measurement and the calculation value are in very good agreement. So, this method is useful for practical tire design, too.

Figure 13 shows the actual procedures of the methodology of the simulation mentioned above. First of all, inflation and deflection analyses are performed on a new tire. Next, inflation and deflection analyses are performed again on the grown tire, where the result of the first inflation analysis is used as an initial
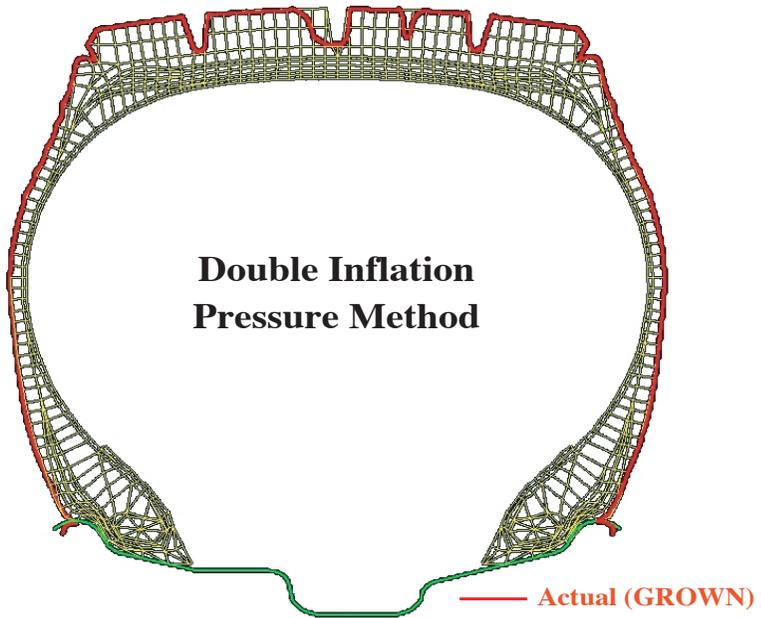
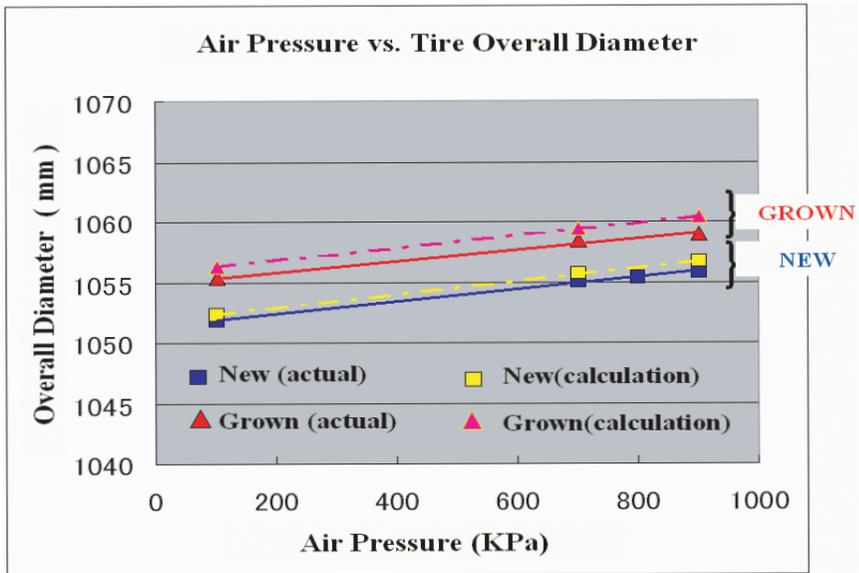FIG. 11 - *Calculated profile corresponds to actual profile.*

FIG. 12 - *Air Pressure vs. Overall Diameter.*

shape (remodel in Figure 13) of the grown tires. This inflation analysis on the grown tire is called the "DIP Method" (Double Inflation Pressure Method). Also,

each principal strain of belt edge parts is calculated by these analyses.

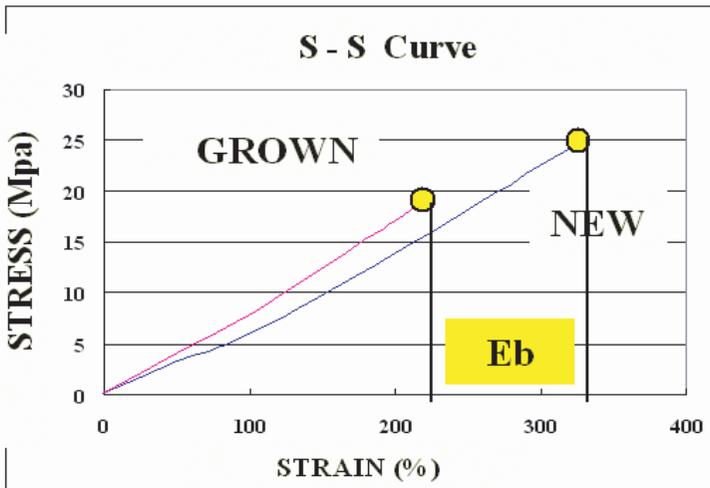FIG. 13 - *Double Inflation Pressure method by FEM.*

FIG. 14 - *Stress-strain curve of tire rubber.*

Safety-Factors Derived From Strain Field (Margin of Safety)

A second issue is rubber aging. This is shown in Figure 14, which illustrates the relationship between stress and strain of rubber. For example in Figure 14, at the belt edge part, Eb is the breaking strain of rubber, and "grown" means the tire with rubber aging after the middle stage of its tire life. This figure describes the relationship between the new and grown tires, where the grown one has generally less potential property than the new one. So, in order to use the relationship between the change of the tire profile and change of breaking strain, the safety factor concept is introduced to apply to the tire design as follows:

1. The first process (durability evaluation of a new tire). A simulation is conducted by the FEM with input data such as the tire profile and the rubber property of the new tire. After that, we introduce the safety-factors as follows:

$$\text{rubber part } S_R = \frac{\varepsilon_b}{\varepsilon_{max}} \begin{cases} \varepsilon_b ; \text{strain at break} \\ \varepsilon_{max} ; \text{maxium principal strain} \end{cases}$$

$$\text{cord part } S_F = \frac{\sigma_b}{\sigma_{max}} \begin{cases} \sigma_b ; \text{breaking stress of material} \\ \sigma_{max} ; \text{maxium principal stress } by \text{ FEM} \end{cases}$$

$$\text{(belt layer, carcass layer)}$$

Here, the durability of the rubber part is evaluated by the principal strain because it permits large deformation of the tire. On the other hand, the durability of FRR like belt layer and carcass layer with the cord part is evaluated by stress, because the FRR part has the stress of the internal pressure and load of the tire. But, the margin of safety in the rubber part is more important because the cord part has enough safety factor in comparison with the rubber part.

2. The second process (durability evaluation of the tire used at the early stages of its tire life). The change of tire profile observed in its service is simulated by the effect of the internal pressure on the calculation. Using material properties of a new tire, the same calculation as mentioned above is carried out. This calculation process is called the DIP method based on the experimental fact that the diameter of the grown tire while in service does not return to that of the new tire even if uninflated (Figure 4). After that, we introduced the estimation of the margin of safety in the same manner as the first process mentioned above.

3. The third process (durability evaluation of the tire used until the middle stages of its life). In addition to the calculation of the second process

mentioned above, the change of the material property caused by high temperature and aging while in service is taken into account based on the experimental fact as shown in Figure 5. An FEM calculation is carried out with these input data and the tire profile in the same manner as the second process. This process is the method of predicting the condition of the tire used until the middle stages of tire life and thereafter. After that, we make the estimation of the margin of safety.

As mentioned above, the tire in its entirety is analyzed as an example of rubber products, and the idea of margin of safety is introduced with the change of rubber properties in the tire as service time passes, which is shown in Figure 13 as mentioned.

Numerical Example [4]

A numerical example of this calculation process is conducted on three models (A, B, C) of tire size (11R22.5), as shown in Figure 15, to predict the influence due to the difference of tire cavity profiles and body ply lines where the tire's construction and material data for these models are the same.
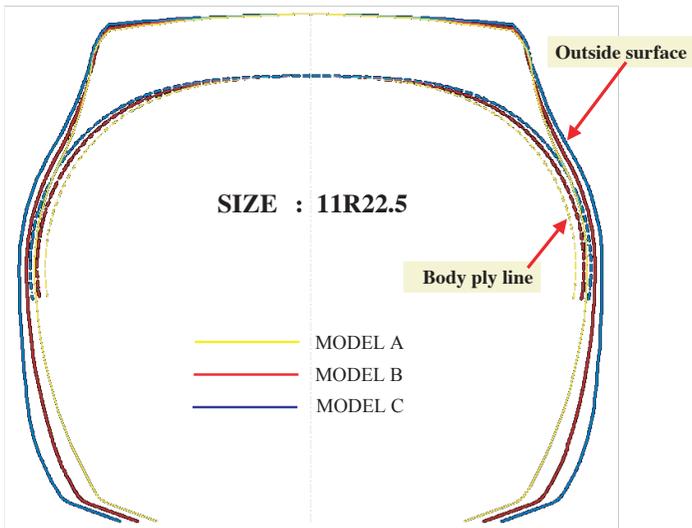

FIG. 15 - *Effect of tire profile on durability by FEM.*

Figure 16 shows one example of the calculation results, in which the principal strain in a belt edge part is shown. Also, this figure shows three conditions of the tire. The first condition is inflation pressure of 700 kPa. The second is 900

kPa, both on new tire. The third condition is 900 kPa on the grown tire all with a load of 3,000 kg. From this figure, principal strain goes up as inflation pressure increases, and goes up again with the grown tire. It is clear that the pressure dependence and tire growth can be evaluated by this DIP method.
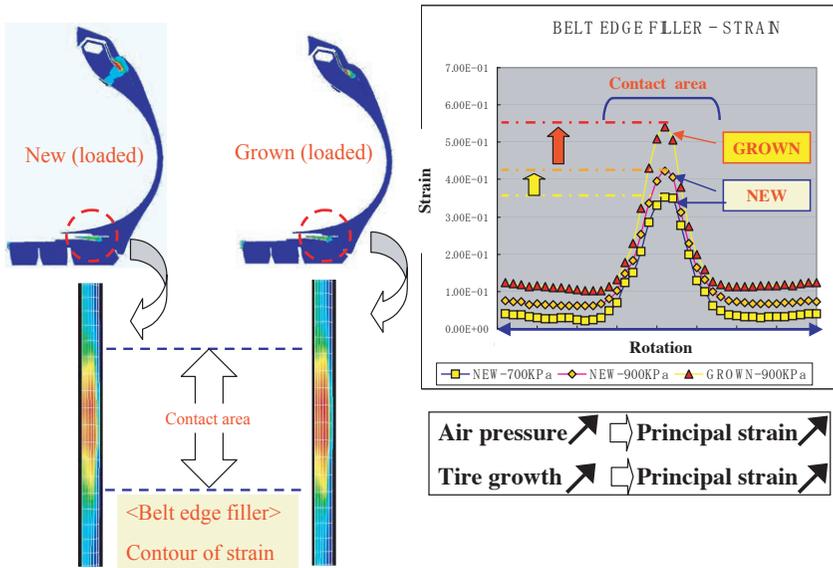

FIG. 16 - *Principal strain of belt edge by FEM.*

Figure 17 shows the results of the numerical example. This figure shows peak value and amplitude of the principal strain on the belt edge part for both the new tire and grown tire of the three models with different cavity profiles. If we compare the results numerically of peak value and amplitude for both the new tire and grown tire, Model B shows the lowest value of peak and amplitude of principal strain of all three models. So, from the viewpoint of durability around the belt area, Model B is the best profile of the three models.
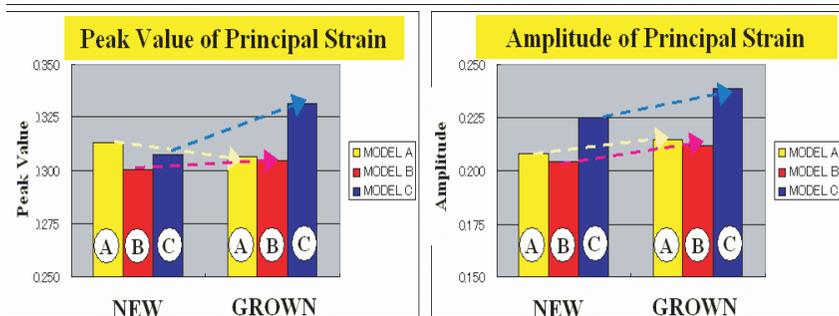

FIG. 17 - *Effect of tire profile on durability by FEM (Peak Value and Amplitude of Principal Strain).*

Through the calculation process, the margin of safety at each stage is determined for each model, as shown in Figure 18. In this figure, each margin of safety at time zero (new tire) is almost the same, but that becomes different at the middle stage of tire life and thereafter. In other words, Model B has higher margin of safety than the other models at all stages, particularly at middle stage of its tire life and thereafter. So, Model B gives higher durability than the other models. Here, the tire life is predicted by the margin of safety versus time or mileage.
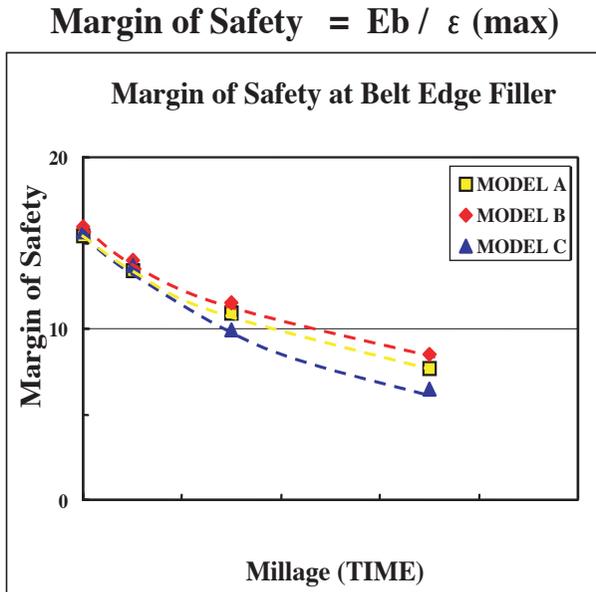
$$\text{Margin of Safety} \ = \ Eb \ / \ \varepsilon \ (max)$$

FIG. 18 - *Effect of tire profile on durability by FEM (Margin of Safety = Eb / ε(max)).*

Tires were constructed using the different mold profiles of Models A, B and C. The tires used the same construction and rubber components. They were tested on a drum machine under test conditions that included a lateral force. The results relative to belt edge separation were as follows: Tire A: 2-6 mm; Tire B: 2-4 mm; Tire C: 4-8 mm. These results confirm that tires designed by this methodology have better durability than conventionally designed tires.

Conclusion

This paper gives a proposal for a new design methodology considering the actual condition of a tire, in which the conclusions are as follows:

1. The Double Inflation Pressure Method was developed as a prediction of tire profile change under operation.
2. Margin of Safety was introduced, which means not only judging durability by the principal strain amount itself, but also applying the aged material property of the tire.
3. A new tire design methodology was developed applying the above concept through the whole life of the tire.

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