

Experimental and Numerical Analysis of the Conceptual Next Generation Ecology Tire (First Report)

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ABSTRACT

With the rapidly increasing awareness on environmental issues, a competition of eco-friendly car development among vehicle manufacturers has become so intense. In fact, decent numbers of modern production vehicles which equipped with low fuel consumption means in various ways have been around in the world today. Since each vehicle manufacturer proposes brand-new vehicle systems one after another, vehicle types become significantly diversified and each one shows different characteristics indeed. On the other hand, these changes in requirements over vehicle performance bring corresponding changes in the development of tires suitable for a variety of the latest eco-vehicles.

Recent tire requirements can be basically represented by compatibility between low Rolling Resistance (RR) and other performance while pursuit of RR reduction results in poor force and moment characteristics in general. Therefore, in order for realizing a substantially eco-friendly tire which simultaneously offers appreciable drivability along with decent performance in necessity, investigations of a next generation tire concept in terms of a tire dimension beyond common knowledge has been done.

In this study, a size effect in terms of Rolling Resistance Coefficient (RRC), Cornering Power (CP), Stiffness, and Weight has been investigated through numerical simulations from tire deformation mechanism points of view [1][2][5], experimental analysis with actual tires as a verification by indoor measurements [8][9][10], and vehicle tests at proving ground [12][13]. Through the series of research activities, one of the directions of next generation tire sizes is proposed and the future work of this concept is discussed as well.

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INTRODUCTION

Among all the components mounted on a ground vehicle, the tires are the only parts which contact to the ground and generate the vehicle motion through forces and moments induced by tire-road interaction aside from aerodynamic and gravitational forces. Therefore, understanding of the tire characteristics is the essential but also crucial issue of the vehicle dynamics study.

During early 1900's until late 1960's, the pneumatic tires are dominated by the bias type which is currently utilized in particular means such as a small part of truck tires, tires for construction machinery, etc. Afterwards, the radial tire, which has been reached the modern belted radial construction equipped with two steel layers being currently considered as a de facto standard of the passenger car tires (see Figure 1), came on the market in 1968. While a tire construction has kept on improving, the progresses of rubber materials have shown enormous advancements not only on a top tread but for every single tire component as rubber filler. Above all,

tires are highly composite material on the basis of rubber materials along with reinforcements such as steel, textile, and others. Indeed the combination of these rubber and reinforcements make up the characteristics of tire features.



Figure 1. Modern belted radial construction

As a tire manufacturer, the three major requirements such as "environment", "resources" and "safety" are considered to be crucial factors towards the future. In order to adopt a range

of waste reduction initiatives as part of a wider effort to limit its ecological footprint, Bridgestone works on the development of new technologies considering 3R (Reduce, Reuse, Recycle) on tires. As an example of actual application, the retread technology in the field of Truck, Bus, and Aircraft tires plays an important role in “Reuse” category. The retread technology makes used tires available as retreads. In addition, this technology not only offers less energy and resources in the manufacturing phase, but also represents a more efficient use of materials and results in fewer tires for recycling or disposal.

“Recycle” in terms of materials is of great importance for a sustainable society. As a state-of-the-art technology, Bridgestone has developed a non-pneumatic (i.e., airless) concept tire that could prove to be a viable and more environmentally-friendly alternative to conventional tires in the future (see Figure 2). It is to help contribute to a more sustainable society, with particular emphasis on three areas - ecological conservation, resource conservation and reduction of carbon emissions.

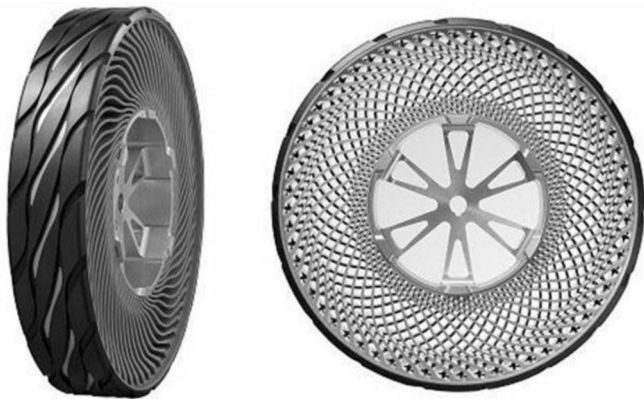


Figure 2. Non-pneumatic tire: Airless tire made from entirely recyclable material

“Reduce” is basically aiming at resource conservation through a development of long life tire, light weight tire, and so on. At this point, sidewall-reinforcement Run-Flat Tire can be contributing to the reduction of waste tires by making vehicles free from temporary tires (see Figure 3).



Figure 3. Sidewall-reinforcement Run-Flat Tire

Run-Flat Tire is one of the evolutionary figures of passenger car tires on the basis of a radial construction and the latest generation Run-Flat Technology, which considerably suppress heat generations, has made it possible to achieve almost the same riding comfort as conventional tires while keeping its superior function of running a certain distance after the complete loss of inflation pressure [7].

These latest technologies mentioned above possess particular meanings and motivations on 3R respectively to introduce in modern society where vehicles are in daily necessities. On the other hand, while these tires are mainly taking resource conservations into account, reduction of RRC can be considered as the most effective way for the reduction of CO₂ emission from a tire's life cycle assessment point of view. Therefore, in this time of a paradigm shift towards a new car-life due to the changes of ideal figures considering environmental situations, realization of overwhelming LRR tire without compromising other performance such as drivability is crucial as a tire manufacturer. For this purpose, as one of the directions of next generation tires, a new trend of conceptual tire size is proposed in this paper as a choice of the possible fuel economy improvement mean for next generation eco-vehicles suitable for the eco-friendly future to come.

PNEUMATIC TIRE

Historically, pneumatic tires have been extended their sizes towards wider and larger directions for enhancing tire's capability as modern vehicles get more powerful and heavier. A general tendency of the conventional common use tires can be seen in Figure 4.

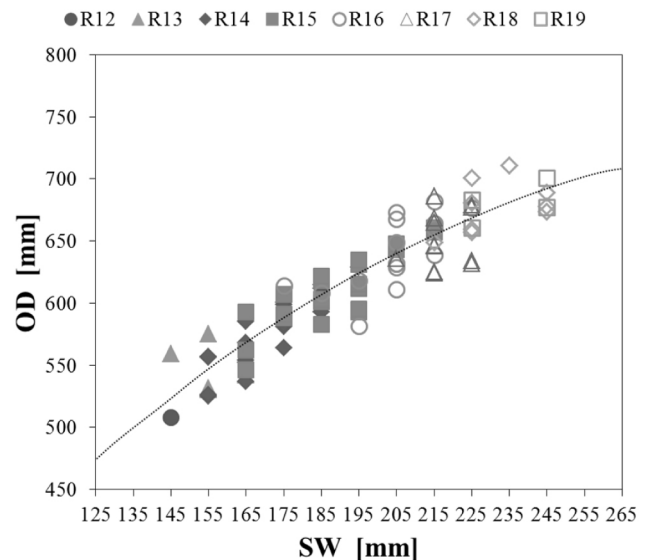


Figure 4. Conventional tire size trend

Over the past decade, considerable progress has been made in vehicle dynamics and stability control. However, since development of an eco-friendly technology has become one of the top priorities for the most of vehicle

manufacturers, Electric Vehicle (EV), Plug-in Hybrid Vehicle (PHV), and a vehicle equipped with other types of low fuel economy means have taken attention away from the customers. In this way, aside from the choice of a power train system, consideration of weight reduction and running resistances represented by rolling and aerodynamic resistances has become of great importance. Obviously, tires must take responsibilities on the rolling resistance part. In addition, recent research into a wind tunnel test suggests that a wheel and tire rotating effect cannot be negligible for the reduction of air drag [11]. An assembly tire & wheel weight effect should be taken into account as well.

Generally, the wider a tire section width is, the larger a tire overall diameter is as described in a tendency of conventional tire sizes shown in Figure 4; therefore, neither a combination of wide width and small diameter nor that of narrow width and large diameter was existed for the use of common vehicles except temporary and special utility tires. At this point, since about 50% of strain energy loss is induced by a tread deformation, its suppression has a strong impact over the reduction of RRC. One of the ways to reduce the total amount of tread deformation would be an encouragement of an eccentric ring deformation (see Figure 5).

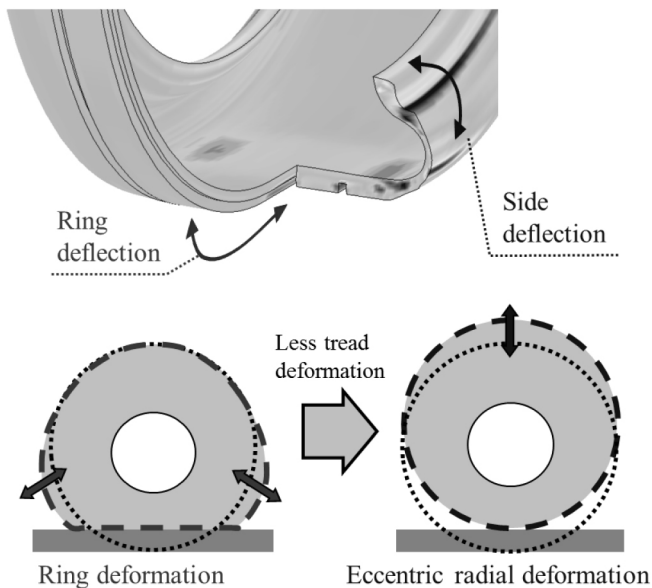


Figure 5. Tire deformation modes: ring deformation and eccentric radial deformation

The eccentric radial deformation can be effectively encouraged by stiffening ring stiffness or applying softer side construction; however, the former one would increase vertical stiffness while latter one would confront its limit rather shortly for durability reasons. These phenomena are closely related to tire size and shape effects indeed from a tire physics point of view. More precisely, tire stiffness can be controlled by arranging a distribution of tensions working on reinforcements such as belt plies by changing a cross section

shape, Section Width (SW), Overall Diameter (OD), and so on. Therefore, the basic idea of the conceptual tire size study comes from a control of the tire deformation by fully utilizing a tire size effect over a wide range of tire dimensions beyond common knowledge.

Size Effect

Larger tires possessing higher ring stiffness thanks to the large diameter have its advantages over suppression of tread deformation inversely proportional to a weight increase. In the case of the simplest structure, rubber balloon, a tension over the surface is evenly spread when it is blown up. On the other hand, tire's complex construction as a composite structure besides its cross section and size can characterize tire features. Especially a control of tension distributions working on reinforcements changes its deformations. By considering a geometric equilibrium under inflation pressure, the belt and side carcass tensions can be approximately expressed as:

$$T_b = 0.5 \times OD \times P \times (TW - 2r \sin \theta) \quad (1)$$

$$T_s = R_s \times P \quad (2)$$

where tire dimensions are described as shown in Figure 6.

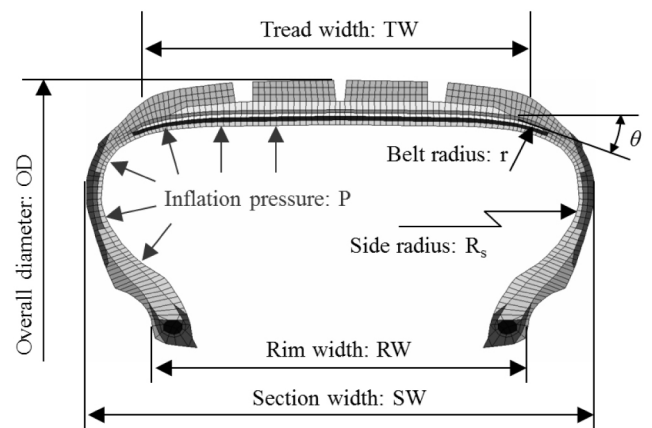


Figure 6. Dimensions of a tire's cross section

As it is mentioned above, encouragement of the eccentric radial deformation is one of the points of interest and a belt tension plays an important role. According to equation (1), the belt tension would increase proportional to inflation pressure, Tread Width (TW), and OD. Firstly, high inflation pressure has a strong advantage over the suppression of tread deformation in terms of tension increase. However, increase of the inflation pressure causes disadvantages such as shortened contact length and higher vertical stiffness resulting in harsh ride comfort and decrease of CP and Cornering Force (CF). Secondly, wider TW shows appreciable increase of total belt tension as a merit although wider tires tend to be bulky for wheelhouse to spare interior

space. Finally, larger OD gives appreciable increase of belt tension independent from a design of a cross section. At this point, while wider TW emphasize short contact length, larger OD could simply make circumferential belt tension representing ring stiffness higher. Therefore, the former one would not be suitable for high inflation pressure use due to an expansion of demerits. Nevertheless, it is definitely beneficial to combine each advantage for making full use of size and inflation pressure effects in order to realize an ultra-low RRC tire. Therefore, a suppression of the demerits described above is the point to be considered. In order to take the best possible performance to be obtained through a choice of the size and Inflation Pressure (IP) combination from a tire physics point of view, following "Narrow and Large Size Tire with High IP Concept" has been investigated:

- Large OD for low RRC, high CP/CF, and long Life
 - Merit: ring stiffness and tread volume
 - Demerit: weight and space
- High IP for ultra-low RRC and Load Capacity
 - Merit: ring stiffness and load carrying capacity
 - Demerit: vertical stiffness and contact length
- Narrow SW for long contact length, low weight, and assumed reduction of aerodynamic resistance
 - Merit: CP/CF, weight, space, and vertical stiffness
 - Demerit: load carrying capacity.

Concerning the concept described above, narrower SW shows suitable characteristics as a countermeasure to neutralize major disadvantages induced by high IP. Therefore, the basic idea of the conceptual tire size has been built up by taking narrow SW effects into account. In some aspects, conceptual size would be well fit for EV or PHV to locate batteries at lower part of a chassis as shown in [Figure 7](#) for lower Center of Gravity (CG) height and/or weight distribution control.

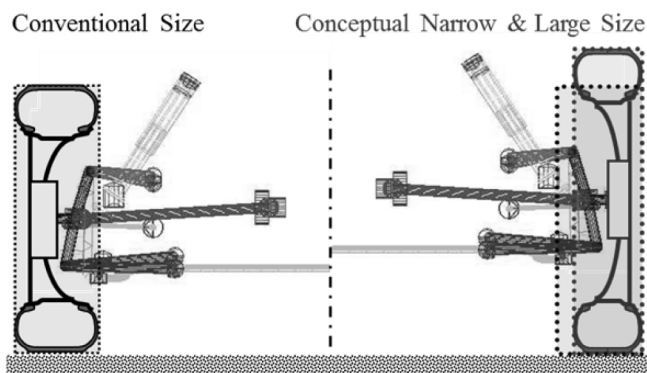


Figure 7. Imaginary drawing of the suspension layout change for the conceptual narrow & large size tire

In order to propose the next generation ecology tire with the new size concept towards vehicle manufacturers as a tire manufacturer, following intensive numerical simulation study and actual tire experimental analysis have been done.

NUMERICAL SIMULATION

In this paper, an internally developed nonlinear implicit static finite element analysis code for tires is utilized. As a reference tire, a fully validated conventional production eco-tire is prepared. In order to evaluate the size effect under fair conditions, tire models for the size effect evaluation presented in this paper are remodeled with respect to the validated eco-tire model. In addition, tire sizes to be compared are carefully chosen for clearly revealing the size effect. Not to mention that the material properties and tire construction of the different size tires are equivalent to the validated model. The tire sizes selected for size effect evaluation are listed in [Table 1](#).

Table 1. Tire sizes for verifying size effect

Tire size	LI	OD [mm]	Category
155/55R15	71	560	Narrow & Small
235/55R13	93	560	Wide & Small
155/55R20	77	685	Narrow & Large
235/55R18	100	685	Wide & Large

These sizes are located on the each corner of the conventional tire trend map as shown in [Figure 8](#).

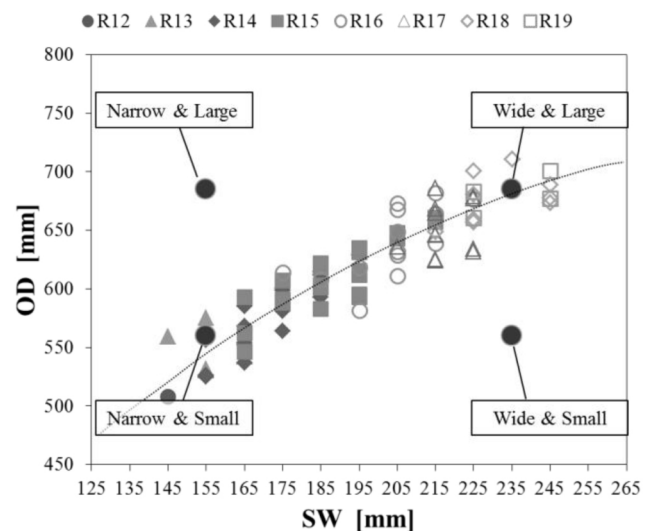


Figure 8. Position of the selected tire sizes on the conventional tire size trend map

Generally, tire performance should be examined with respect to their load index (LI) which defines load carrying capability as the most fundamental tire functionality. However, since tire performance with a vehicle is the point of discussion, a common size vehicle with an equal axial load is

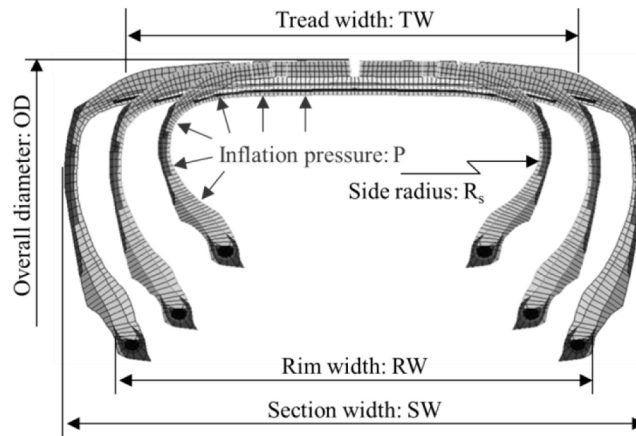


Figure 9. Cross sections of similarly enlarged tire models with an equivalent gauge distribution as a constraint: 55s tires with SW=155, 195, and 235

assumed for a loading condition in the numerical simulations (see Table 2).

Table 2. Assumed vehicle parameters

Gross weight	Weight distribution ratio	Wheel load
1.43 [t]	Front/Rear : 50/50	3.5 [kN]

In the numerical simulation study, size effect and inflation pressure dependency in terms of belt & carcass tension, strain energy loss representing rolling resistance, contact patch & CP for drivability, vertical stiffness for ride comfort have been examined. Regarding the tire models, by considering narrow and small size as a reference, wider TW tire models are similarly enlarged with gauge constraints around a periphery line. Larger OD sizes possess different wheel diameters and exactly the same cross section with respect to small sizes. Figure 9 shows similarly enlarged cross sections representing TW differences. OD differences are shown in Figure 10 as well.

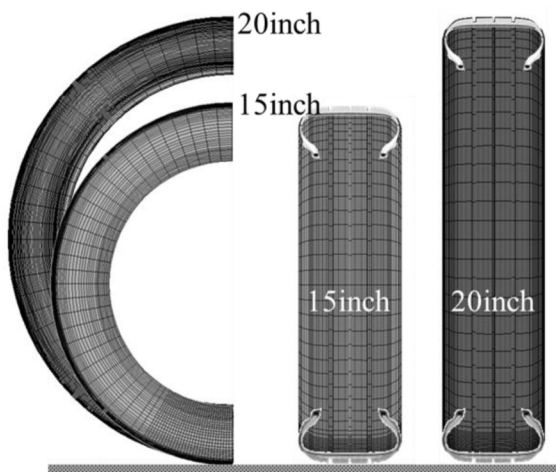


Figure 10. Front and side view of the tire models with an equivalent cross section and different wheel diameters

Belt & Carcass Tension

While equation (1) indicates total belt tension, actually the intensity of belt tension distributed along the belt line would increase proportional to OD and IP. On the other hand, TW has an impact over total belt tension as long as the stress placed upon a belt ply is expressed in a unit of stress. In order for making TW, OD, and IP dependencies on belt and carcass tension clear, characteristics of different size tires prepared (see Table 1) have been compared by Finite Element Analysis (FEA).

TW effect

Figure 11 shows belt and carcass tension distributions along an inner periphery line. As it is mentioned above, the intensity of belt stress is almost equal under same OD and IP conditions. In addition, belt stress is ten times higher than carcass stress due to the differences of curvature radii.

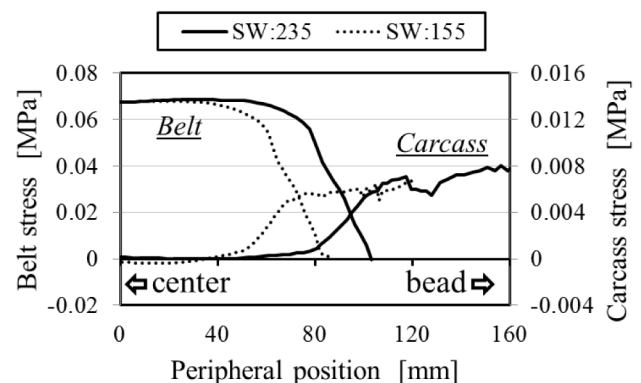


Figure 11. Comparison of belt and carcass tension between 235/55R18 and 155/55R20 at 220kPa

OD effect

Figure 12 clearly shows the increase of belt stress due to larger OD while carcass stress remains in a same level. About

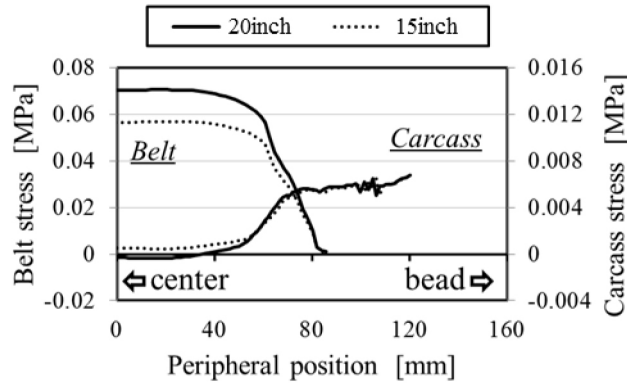


Figure 12. Comparison of belt and carcass tension between 155/55R20 and 155/55R15 at 220kPa

23% of the increase of belt stress intensity corresponds to that of OD, which shows good correlation with equation (1).

IP effect

While a modification of TW and/or OD for tension control requires a re-design of a whole tire, inflation pressure would easily and drastically change tire's characteristics without design changes. However, unfavorable counter effects such as higher vertical stiffness are there as well. Figure 13 shows about 45% of the drastic increase of the belt stress intensity, while increase of the carcass stress inducing harsh ride comfort can be seen at the same time.

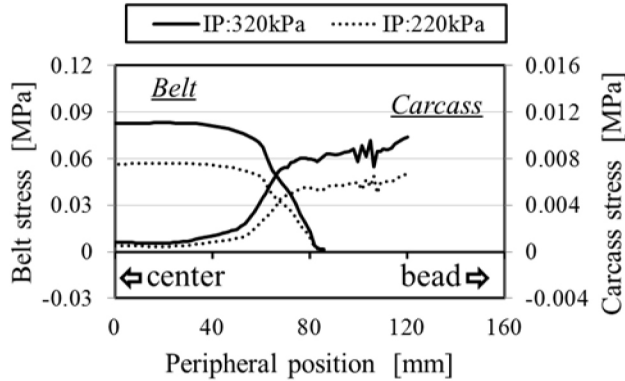


Figure 13. Comparison of belt and carcass tension of 155/55R15 at 220kPa and 320kPa

In summary, combination of OD and IP effects realizes over 80% of an increase of the belt stress intensity as a multiple effect with which a remarkable reduction of RRC can be expected.

Strain Energy Loss Analysis

Relationship between rubber material's strain energy loss and tire's rolling resistance [1], calculation methodology by means of FEA [2], and actual measurement methodology have been developed and widely accepted [3][4][5]. For a better understanding, basics of rubber material behavior are shown as follows [6]. In general, elastic materials can be

described by Hooke's law of linear elasticity where stress σ is proportional to strain ϵ . Hooke's law can be described as:

$$\sigma = E\epsilon. \quad (3)$$

where E represents Young's modulus. However, rubber materials exhibit viscoelasticity characteristics for which the relationship between stress and strain depends on time. In the case of viscoelastic material, when a sinusoidally varying stress is applied, strain appears also in a sinusoidal manner but must lag a stress by a phase angle δ as shown in Figure 14.

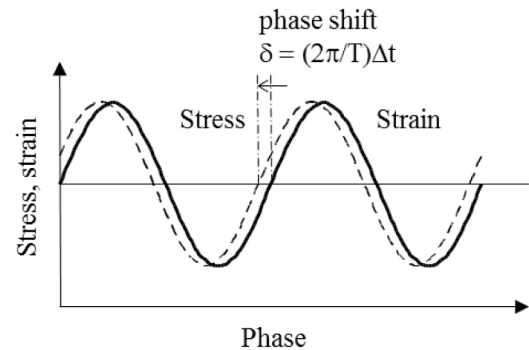


Figure 14. Stress and strain vs. phase behavior of a viscoelastic material

The stress and strain functions varying sinusoidally in time t can be expressed as:

$$\sigma_{(t)} = \sigma_0 \sin(2\pi f t), \quad (4)$$

$$\epsilon_{(t)} = \epsilon_0 \sin(2\pi f t - \delta), \quad (5)$$

where f represents frequency. Due to the presence of the phase lag δ between stress σ and strain ϵ , the dynamic stiffness such as storage modulus E' and loss modulus E'' shown in Figure 15 can be written as a complex number: