The Effect of Inflation Pressure and Vehicle Loading on the Sidewall of a Radial Tire

An experimental investigation into the effect of inflation pressure, vehicle load and camber angle on the sidewall-surface strains in a radial tire is described. Photoelasticity and a specially designed strain-gaging technique are used

by C.L. Chow and C.W. Woo

ABSTRACT—The sidewall is one of the regions where service failures occur in a pneumatic tire. Knowledge of the stresses or strains developed in the sidewall under varying service conditions is required if such pneumatic-tire failures are to be avoided. This paper describes an experimental investigation into the effect of inflation pressure, vehicle load and camber angle on the sidewall-surface strains in a radial tire. Photoelastic coating and a specially designed strain-gaging technique were used.

For pure-inflation pressure, the magnitude of the measured shear strains in the sidewall is directly related to the inflation pressure. The maximum sidewall shear strains in pure inflation are located in the lower sidewall (18 mm from bead), irrespective of the magnitude of the inflation pressure. The meridional sidewall strain is predominant in the inflated but otherwise unloaded tire. The meridional strain is proportional to the square root of the inflation pressure. The maximum meridional strain is located in the mid-sidewall region.

For a constant vehicle loading, there is a transition inflation pressure below or above which the circumferential shoulder strain increases sharply. This observation highlights the importance of maintaining satisfactory inflation pressure in passenger-car tires as an under-inflated tire will induce severe strain development at the shoulder.

In addition to the vehicle load, the introduction of camber angle produces localized change in the meridional and circumferential strains within the contact zone. The increase of camber angle up to 10 deg causes continuous increase in the meridional strain in the lower sidewall but decrease in the upper sidewall. The mid-sidewall meridional strains remain practically unchanged. The circumferential strains along the load line are, in general, lower due to the increase in camber angle.

Introduction

A pneumatic tire is designed to satisfy a number of functional requirements, essential to the performance of a passenger car, which include load carrying, enveloping and vibration damping, transmission of driving and braking torque, development of traction for acceleration, deceleration and cornering, and provision of floatation and mobility. In addition, the tire must have performance characteristics such as road adhesion, ease of control, comfort, high-speed running, tread-pattern life, low rolling resistance or power loss, durability and safety. These functional and performance requirements cannot be adequately satisfied without a sufficient understanding and knowledge of the stress and strain developed within the entire tire structure under varying service conditions. It is obvious that, if excessive stresses and strains are allowed to develop, premature tire-design failure will occur in the tire structure.

The sidewall is one of the regions where service failures occur in a pneumatic tire. Dobie[1] reported that the location and percentage of hazard-damage failures in bias-ply passenger tires were tread region, 75 percent; sidewall region, 20 percent; and bead region, 5 percent. Since the introduction of the radial tire, belt-edge separation has also become one of the contributing sources of tire structural failures. The strains at the crown in the radial tire were reported by Janssen and Walter[2] to be approximately half those in the equivalent G-size bias tire under normal operating conditions. The maximum tensile and shearing strains in the mid-sidewall were found, on the other hand, to be greater in the radial tire than in the bias tire. In addition, the rolling resistance is known to be inversely proportional to the inflation pressure.[3] Future passenger-tire inflation pressures will be increased in order to reduce overall irreversible heat dissipation from the tire, so that the total vehicle thermal efficiency may be increased. The increase in inflation pressure will undoubtedly aggravate the strains already experienced by the radial-tire sidewall. This paper investigates the effect of inflation pressure, crown load and camber angle on the surface strain in the sidewall of a radial passenger-car tire.

Stress or strain distribution in the tire sidewall can be assessed by either analytical or experimental approaches. Unfortunately, the pneumatic tire today is probably the most notable example of a highly sophisticated engineering structure where viscoelastic, anisotropic and nonhomogenous properties render theoretical analysis extremely difficult. The bulk of the existing literature[4-10] dealing

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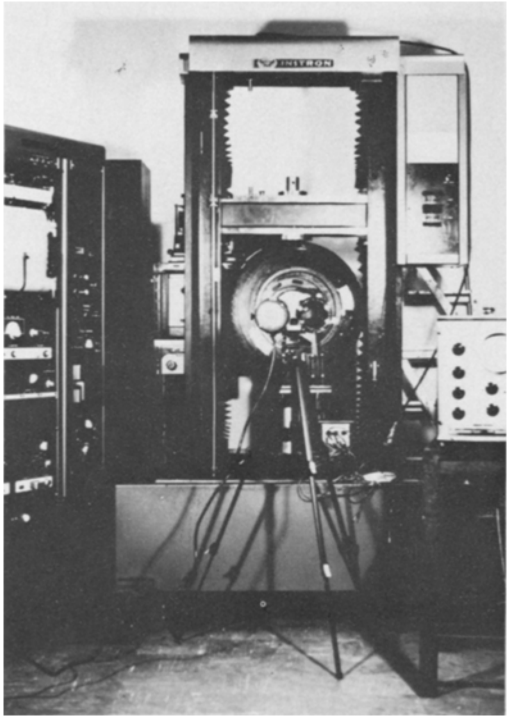

Fig. 1—Equipment used for photoelastic measurement

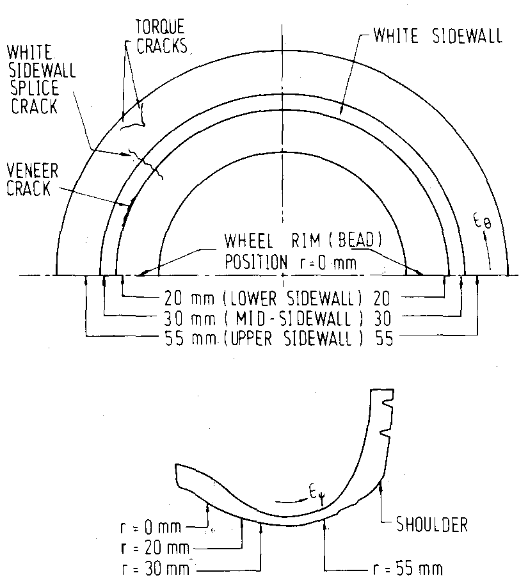

Fig. 2—Locations of strain measurement at r = 20, 30, 55 mm and shoulder

with tire stress analysis has been confined to purely idealized elastic treatments. This revelation is not surprising because of the mathematical complexity involved in modeling an inflated and loaded tire. The difficulty in mathematical modeling due to the geometrical and material nonlinearities created by large deformations is further aggravated by a lack of understanding of the cord–rubber composite. Attempts, however, have been made to theoretically deduce constitutive equations for a laminated plate based on the micromechanics of each ply.[11-16] The validity of the proposed equations for the tire application is not well established at the present time.

It is therefore logical to expect that the advanced level of improvement in the tire-design methodology has so far been brought about mainly by the application of experimental techniques.[17-23] The use of strain gages has been predominant in the past in the determination of strain distribution in the sidewall. Biderman[17] constructed a clip gage in which conventional electric-resistance strain gages are bonded to the upper and lower surfaces of a piece of channel-shape spring steel. Legs with pins extended from the backbone of the gage and small pieces of vulcanized rubber were pushed on these pins so that a definite spacing from the tire surface was achieved. This device had good temperature-compensation characteristics and because of the mechanical attenuation of the rubber deformation, it provided the strain measurements up to 20-30 percent or larger, depending on the length of the legs. The same device was successfully used by Pugin[18] to investigate the influence of crown angle on the sidewall deformation of bias tires rolling under load.

Biderman and Pugin[19] devised the rubber-wire gage (commonly known as Peekel gage) which consists of a small-diameter prestressed rubber thread with a coil of fine constantan wire wound on the thread. The coil had a small helical pitch. Compression or tension of the rubber thread was detected by an increase or decrease in the diameter of the thread producing a corresponding stress change in the wire.

The use of liquid-metal gages was first proposed by Hurry and Woolley[20] and later extended to measure strains in both bias and radial tires by Janssen and Walter.[2] The liquid-metal gage, which was fabricated with silicone-rubber strip filled with liquid mercury, was shown to be more versatile and adaptable for use with pneumatic tires than the previously developed transducers.

The strain gages mentioned above are known as point-measuring devices which require prior knowledge on the critical locations of the tire where the gages are to be bonded.

The object of this paper is threefold: first, to investigate the effect of inflation pressure, vehicle load and camber angle on the sidewall strains in a radial tire with photoelastic-coating technique; second, to provide a feasibility study on the application of a specially designed strain-gaging technique to the measurement of sidewall-surface strains; and third, to examine the strains developed in the lower, middle and upper sidewall regions where sidewall service failures are often observed.

Experimental Techniques

Full-field photoelastic observations of the strain distribution can easily identify the critical strain locations and reveal the full effects of varying modes of loading, as well as the relative significance of individual loads and/or load directions in the tire-sidewall surface. Before the application of the photoelastic coating, the tire-sidewall surface was thoroughly cleaned. In order to match the

TABLE 1—TYPICAL MECHANICAL PROPERTIES OF TIRE MATERIALS

Material	Gauge Diameter, d, mm	Young's Modulus, E, GN/m²	Shear Modulus, G, MN/m²	Poisson's Ratio, ν
Rayon	0.737	4.88	4.83	0.7
Steel	0.686	84.12	32407	0.3
Rubber	—	0.0055	1.84	0.5

properties of the sidewall rubber and obtain the required sensitivity, PS-4B (Photolastic, Inc.) photoelastic-coating sheet of 2.18-mm thickness with an optical sensitivity of 0.009 was chosen. The photoelastic material has a maximum elastic modulus of about 6890 kPa and a maximum elongation capability of 150 percent. The strain measurement was recorded using 030-series photoelastic-reflection polariscope also manufactured by Photolastic, Inc.

The post-yield TML series "Y" strain gages manufactured by Tokyo Sokki Ken Kyujo Co. Ltd., Japan was chosen for strain-gage measurements. The gage utilizes a special-plastic carrier base capable of withstanding an elongation of 10-20 percent without creep or cracking. The TML series "Y" strain gage consists of two gages having gage length of 5 mm each and positioned perpendicular to one another.

The tire chosen for this investigation is a Michelin X155 SR12 ZX radial passenger car tire which is steel-belted with two-ply rayon carcass. Typical mechanical properties of rayon cord, steel-belt and rubber are described in Table 1.

The application of the vehicle load was achieved by mounting the tire axle on a supporting rig placed within an Instron Universal Testing Machine (see Fig. 1) which provides autographic recording of load and displacement from the tire contact surface. Camber-angle simulation was accomplished by inserting wedged slabs between the Instron compression platen and the tire footprint.

The curvature effect of the reflective coating on fringe measurement was for the first instance investigated. This also served as a check on the calibration of strain-fringe value of the PS-4B photoelastic-coating material under simple tension. A PVC pipe of 100-mm internal diameter and 7 mm thick was internally pressurized. The fringe development on the externally coated surface was measured and found to be in excellent agreement with the tensile data.

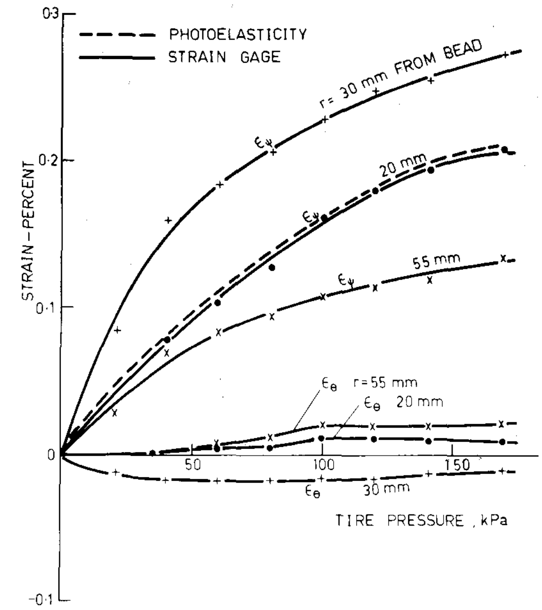

Fig. 3—Meridional and circumferential-strain variation of tire-sidewall surface due to inflation pressure

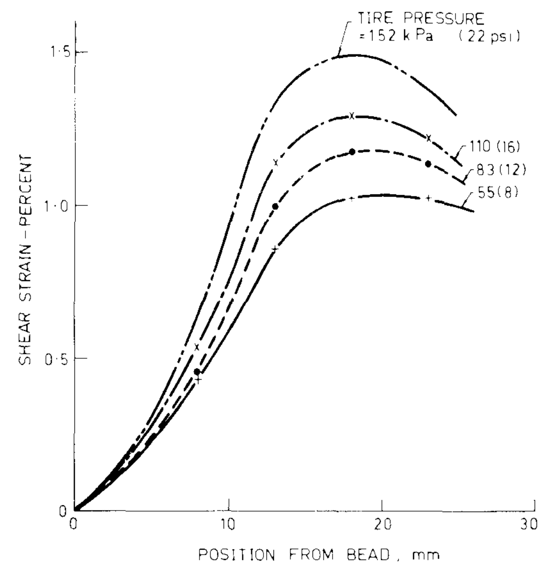

Fig. 4—Shear strain on radial sidewall surface due to inflation pressure

Experimental Results and Discussions

Sidewall Strains Due to Inflation Pressure

The meridional (ϵ_ψ) and the circumferential (ϵ_θ) strains on the sidewall surface shown in Fig. 2 due to tire-inflation pressure were measured with the photoelastic-coating technique and the strain-gage method. Particular emphasis on the strain measurement in the sidewall locations at r = 20, 30 and 55 mm illustrated in Fig. 2 is made throughout this paper. This is because tire-sidewall failures such as veneer cracks, white-sidewall splice cracks and torque cracks (see Fig. 2) are often initiated at these locations in the sidewall surface. For the sake of illustration, the sidewall locations at r = 20, 30 and 55 mm are designated in this paper as lower, middle and upper sidewall regions, respectively. The strain variations at these locations are plotted as shown in Fig. 3 for various inflation pressures. The nonlinear effect of the pressure loading is clearly evident and the straining is predominantly in the meridional direction, an observation also reported in a previous investigation.[2]

The strain due to inflation appears to be directly proportional to the square root of the inflation pressure. The maximum meridional strain occurs in the mid-sidewall region and is of the order of 0.3-percent strain at an inflation pressure of 165 kPa (24 psi). A comparison of the results measured using the photoelastic coating and the strain-gaging method is also shown in Fig. 3 and the agreement is satisfactory.

From the photoelastic-coating measurement, the maximum shear strains on the sidewall can be located. The results were plotted as shown in Fig. 4 for various tire-inflation pressures. Increase in the inflation pressure was seen to be accompanied by the overall increase of the shear-strain profile. The shear strain increases rapidly from the bead position towards the lower sidewall and then decreases towards the shoulder position. It is of interest to note that the maximum shear strain occurred in the lower sidewall about 18 mm from the bead irrespective of the pressure loading. The reinforcements at the bead and tread regions confined the shearing effect in the lower sidewall region.

Sidewall Strains Due to Inflation Pressure and Vehicle Load

The strain distributions on the sidewall due to the combined loading effect of inflation pressure and vehicle load were measured. The meridional and the circumferential-strain components due to an inflation pressure of 165 kPa (24 psi) and a vehicle load of 1500 N (~330 lb) were plotted as shown in Fig. 5. The presence of the vehicle load caused changes, as expected, in the strain distributions in the neighborhood of the contact area, up to about 90 deg from the center of tire contact. Though the change in strain in the mid-sidewall was relatively moderate, the meridional strains in the lower and the upper sidewall regions were significantly altered. The meridional strains in the upper sidewall were increased while those in the lower sidewall were reduced. Such an effect was thought to be attributed to the increased bulging of the sidewall profile as a result of the vehicle-load application.

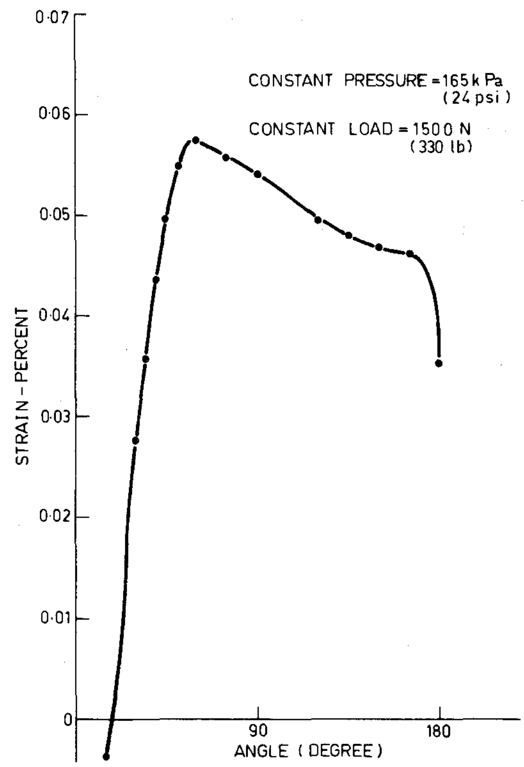

Fig. 6—Variation of circumferential shoulder strain with angle of rotation at constant pressure and vehicle load

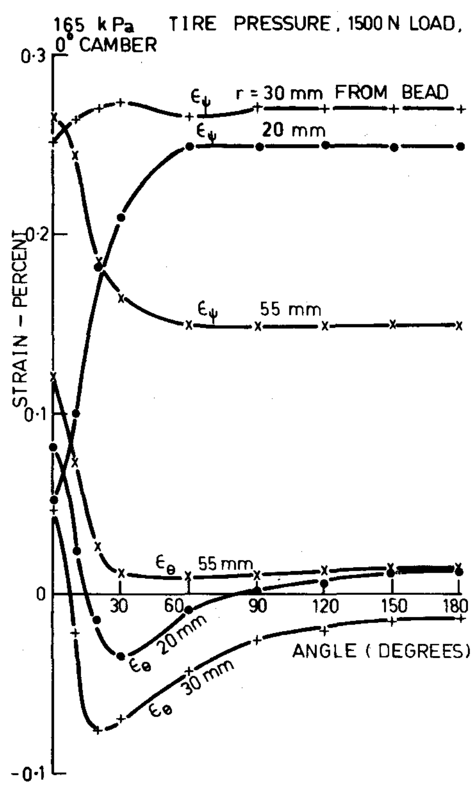

Fig. 5—Tire-sidewall strain at 0-deg camber angle

Although the effect of the vehicle load on the circumferential-strain distributions was less significant, there was however a considerable bending effect introduced in the lower and mid-sidewall regions near the center of tire-contact zone. All the sidewall circumferential strains along the center of tire contact were in tension but the lower and mid-sidewall strains changed rapidly to compression at about 10 deg from the center of tire contact. The compressive circumferential strain in the mid-sidewall was shown to be higher than that due to inflation pressure alone.

The combined effect of the vehicle load and inflation pressure on the strain distribution in the tire shoulder is shown in Fig. 6. The circumferential shoulder strains being compressive near the center of tire contact rapidly changed to tension at about 15 deg and the maximum tensile strains occurred at 55 deg from the center of tire contact.

The position at which the maximum circumferential strain occurs is expected to vary with the tire-inflation pressure and the magnitude of the vehicle load. This was demonstrated by performing a test for which the tire was subjected to a constant load of 1500 N and various inflation pressures from 55 to 150 kPa. The position at

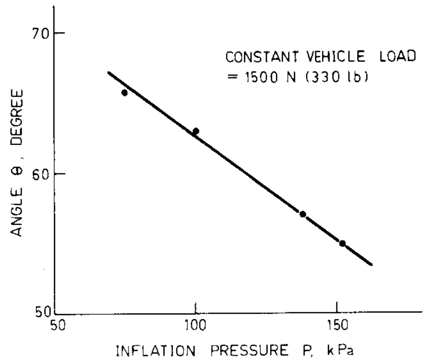

Fig. 7—Variation of angle of maximum shoulder strain due to inflation pressures and constant vehicle load

which the maximum circumferential strain occurs was measured and is illustrated in Fig. 7. It can be observed from the figure that the maximum shoulder strain occurred at an angular position between 55 to 65 deg from the center of tire contact. As increase in the inflation pressure causes corresponding increase in the overall tire stiffness, the maximum tread strains moved closer to the center of tire contact.

In order to examine the straining effect in the shoulder region more closely, measurements were made at 25 deg from the center of tire contact under different loading conditions. At the constant inflation pressure of 165 kPa (24 psi), the circumferential shoulder strain increased parabolically with the increase of vehicle load as shown in Fig. 8(a). This nonlinear effect was also observed for the loading condition under which the vehicle load was kept constant, but the inflation pressure varied as shown in Fig. 8(b). The effect of the under-inflated tire is clearly illustrated here: as the inflation pressure is reduced the shoulder strain increases noticeably. This observation highlights the importance of maintaining adequate inflation pressure in a passenger car tire in order to avoid the development of high shoulder strains.

Sidewall Strains Due to Inflation Pressure, Vehicle Load and Camber Angle

The strain distributions due to the combination of inflation pressure and vehicle load at the camber angles ranging from 2 to 8 deg were examined. The strains measured on the surface of sidewall where the cambering effect is simulated are shown in Figs. 9(a) to 9(d). Although the strain profiles for the various camber angles follow closely with the one at zero camber angle as described in Fig. 2, there are definite effects on the sidewall-strain distribution close to the center of tire contact.

Figures 10(a) and 10(b) show the variation of the meridional strains at different locations in the sidewall for various camber angles. An increase in the camber angle was accompanied by a corresponding increase in strain in the lower sidewall but decrease in the upper sidewall. The mid-sidewall meridional strain remained practically unchanged. The circumferential strains along center of tire contact were generally lower due to the increase in camber angle. It is of interest to note that the bending effect was removed at the camber angle of 8 deg.

Conclusions

An experimental investigation into the effect of inflation pressure, vehicle load and camber angle on the sidewall of a radial passenger-car tire was performed. This was achieved with both the photoelastic-coating method and specially designed strain-gaging technique. The measurements taken from both methods were found to be in satisfactory agreement.

Particular emphasis on the strain measurement in the sidewall locations at r = 20, 30 and 55 mm was made throughout this paper. This is because tire-sidewall failures are often initiated at those locations in the sidewall surface.

For pure-inflation pressure, the magnitude of the measured shear strains in the sidewall is directly related to the inflation pressure. The maximum sidewall shear strains in pure inflation are located in the lower sidewall (18 mm from bead), irrespective of the magnitude of the inflation pressure. The meridional sidewall strain is predominant in the inflated but otherwise unloaded tire. The meridional strain is proportional to the square root of the inflation pressure. The maximum meridional strain is located in the mid-sidewall region.

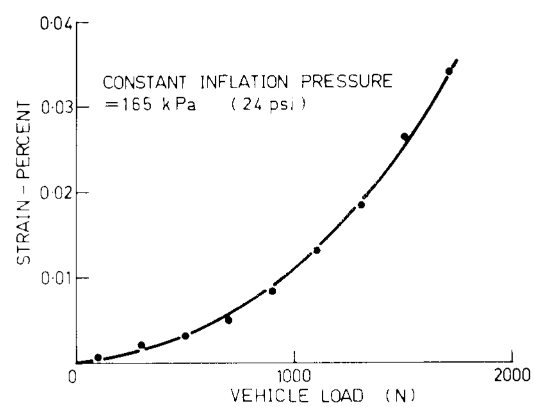

Fig. 8(a)—Variation of circumferential shoulder strain with vehicle load at constant pressure at 25 deg from load application

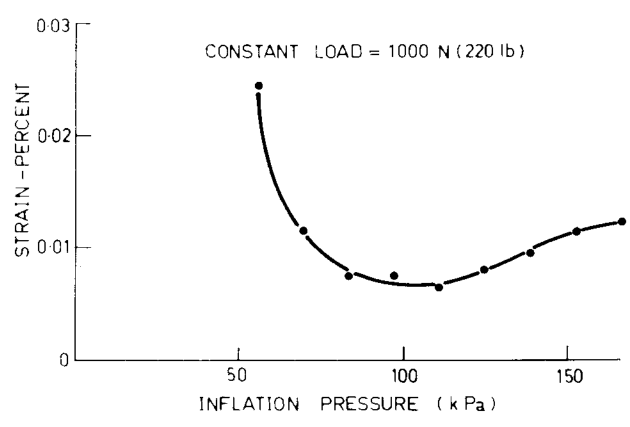

Fig. 8(b)—Variation of circumferential shoulder strain with inflation pressure at constant load at 25 deg from load application

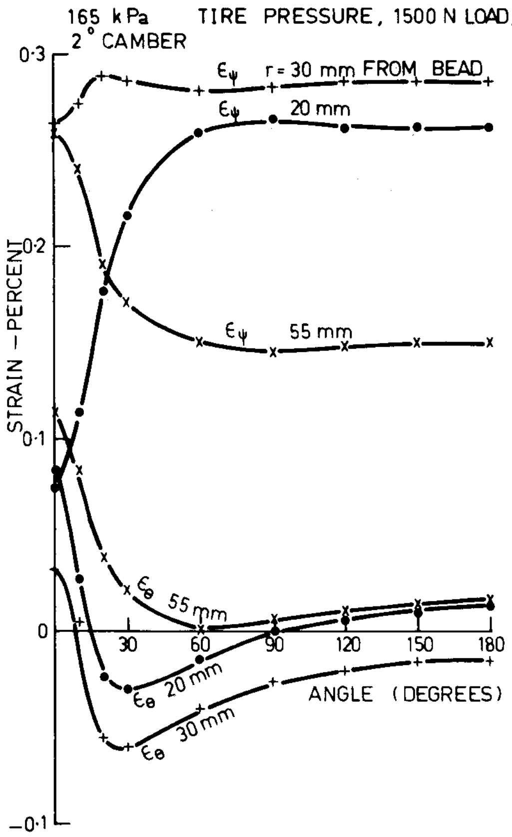

Fig. 9(a)—Tire-sidewall strain at 2-deg camber angle

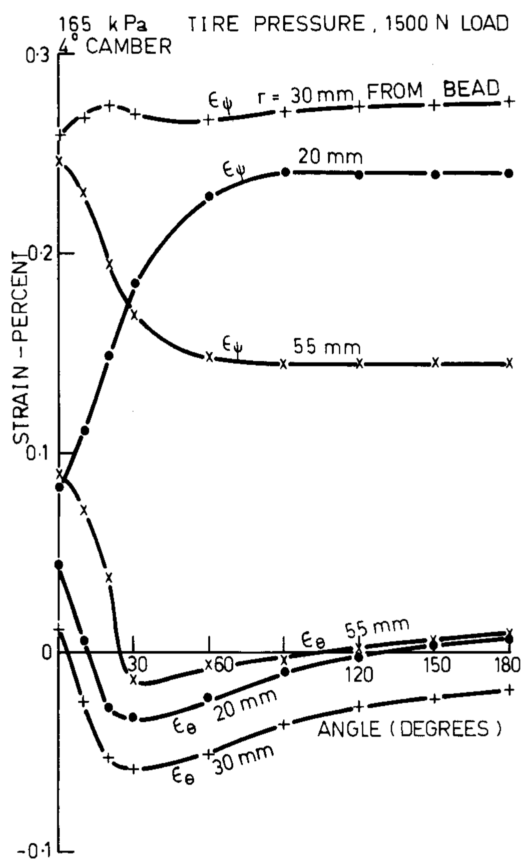

Fig. 9(b)—Tire-sidewall strain at 4-deg camber angle

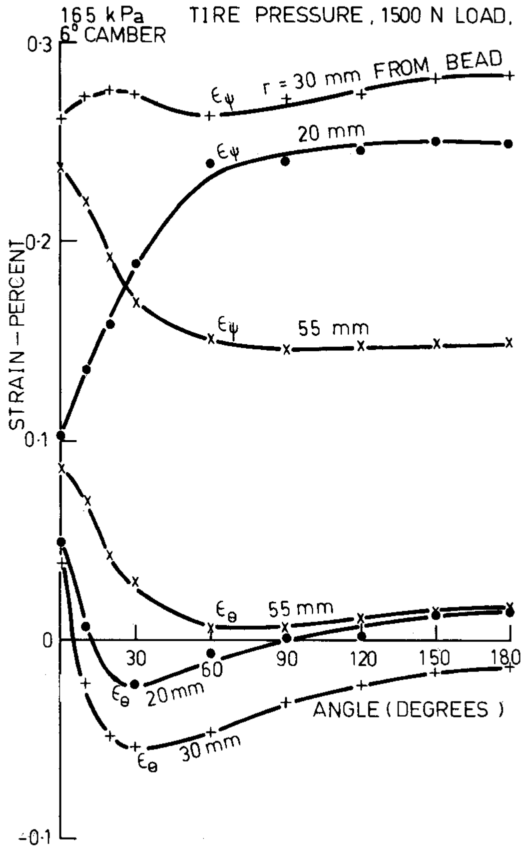

Fig. 9(c)—Tire-sidewall strain at 6-deg camber angle

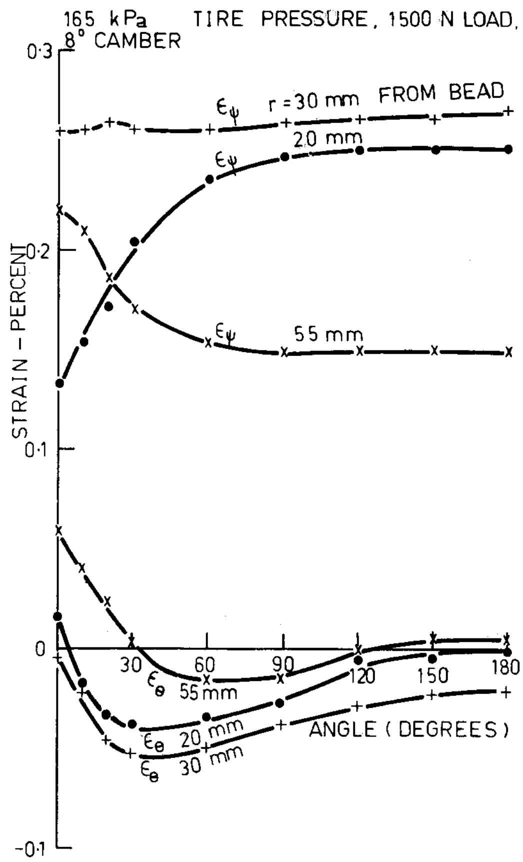

Fig. 9(d)—Tire-sidewall strain at 8-deg camber, angle

Under combined inflation pressure and vehicle loading, the maximum circumferential shoulder strains are located between 55 and 65 deg from the center of tire contact. Since the vehicle load superimposes a compressive effect on the tensile strain due to inflation, compressive circumferential shoulder strains are developed up to about 15 deg from the center of tire contact.

The circumferential shoulder strain appears to increase parabolically with increased load. This nonlinear behavior, contrary to the linear one reported in the literature, was also observed for the tire under a constant vehicle load but with varying pressure.

For a constant vehicle loading, there is a transition-inflation pressure below or above which the circumferential shoulder strain increases sharply. This observation highlights the importance of maintaining satisfactory inflation pressure in passenger-car tires as an under-inflated tire will induce severe strain development at the shoulder.

When load is applied, the meridional strain in the upper sidewall increases but the meridional strain in the lower sidewall decreases for the area within a few degrees of the contact patch. Both the meridional and circumferential strains are affected by the vehicle load but the effect on the meridional strain is more pronounced.

In addition to the vehicle load, the introduction of camber angle produces localized change in the meridional and circumferential strains within the contact zone. The increase of camber angles up to 10 deg causes continuous increase in the meridional strain in the lower sidewall but decrease in the upper sidewall. The mid-sidewall meridional strains remain practically unchanged. The circumferential strains along the load line are in general lower due to the increase in camber angle.

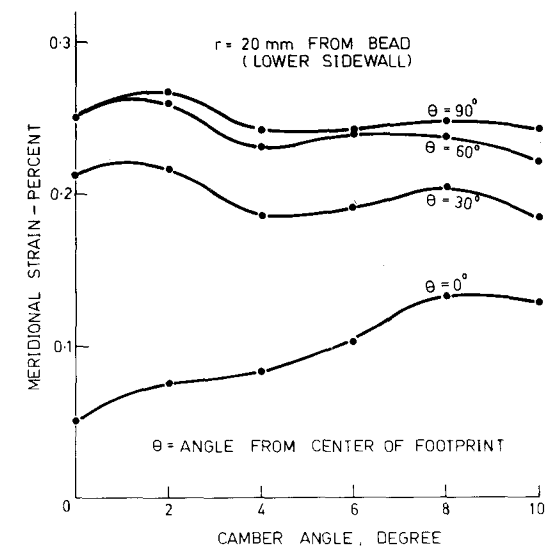

Fig. 10(a)—Effect of camber angle on meridional sidewall strain at r = 20 mm

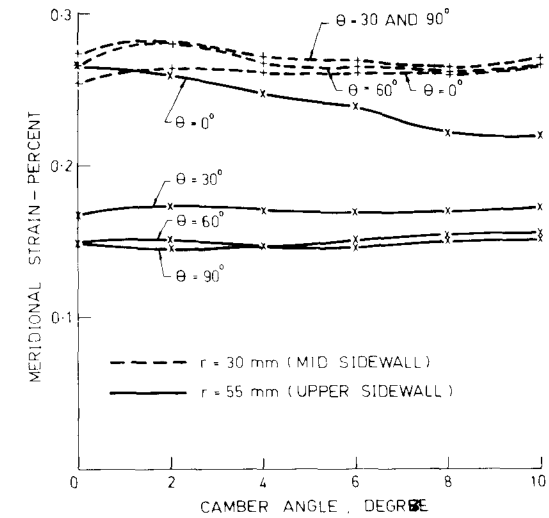

Fig. 10(b)—Effect of camber angle on meridional sidewall strain at r = 30 mm and r = 55 mm

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