THE EFFECT OF STEEL WIRE PRE-TENSION ON THE TENSILE PROPERTIES OF BEAD PLY IN RUBBER TIRES

A Kadhem¹, A Yasir², and M Enad ²
¹University of Kufa, Faculty of Engineering, Material Eng. Dep., Najaf, Iraq
²University of Kufa, Faculty of Engineering, Mechanical Eng. Dep., Najaf, Iraq
E-mail: pganimalganimy@gmail.com
alis.alathari@uokufa.edu.iq

Abstract. Continuous development in transportation sector makes the development of tires a necessity as manufacturers strive to meet increasingly high requirements. This work aims to study the effect of using a pre-tensioning technique to improve the tensile properties of bead ply in rubber tire to enhance performance and increase working life. Pre-tension levels ranging between 0 and 1,250 MPa were applied on single reinforcing wires at room temperature prior to the vulcanization process. The results show that the tensile strength and maximum tensile strain of bead specimens were increased by 86.66% and 14.7%, respectively, as the pre-tension level increased from 0 to 1,250 MPa. The stress strain curves for the specimens showed a large increase in strength with little increase in strain. The modulus of elasticity (Young's modulus) of bead specimens increased by 85.92% as the pre-tension level increased from 0 to 1,250 MPa.

1. Introduction
The bead ply is the internal part of the tire that borders the wheel rim and presses against the bead seat. This bead presses on the rim to transfer different forces such as steering, traction, acceleration, braking, and the directional forces of the wheel to other tire parts and the tread to move the vehicle using friction forces between the tread and the road, preventing air loss in tubeless tires. This location and function expose the tire bead to multiple forces and stresses, and thus the bead is frequently reinforced with high strength steel wires; the standard chemical composition of these is shown in table 1 [1,2].

| Elements | C | Mn | Si | S | P | (S+P) | Ni | Cr | Fe |
|----------|---|----|----|---|---|-------|----|----|----|
| wt%      | 0.72 | 0.6 | 0.57-0.66 | 0.2 | 0.05 | 0.05 | 0.08 | combined | 0.1 | 0.05 | bal. |

The bead can thus be classified as a composite material of rubber matrix and steel wire reinforcement, otherwise known as a Polymer Matrix Composite (PMC). These wires are also often coated with copper or bronze to maintain optimum adhesion to the bead rubber. Table 2 shows the general requirements of bead wires. The bead must also have very good mechanical properties and maintain these properties at service conditions that include high speeds and high temperatures. The bead ply is shown in figure 1 [4,5,6].
Table 2. General requirements of bead wires. [3]

| Wire         | Diameter | Breaking Force | Elongation at Break | Weight per unit length |
|--------------|----------|----------------|---------------------|------------------------|
| Units        | Mm       | N              | %                   | g/m                    |
| Mean         | 0.96     |                |                     | 5.7                    |
| Max.         | 0.98     |                |                     | 6                      |
| Min.         | 0.94     | 1220           | 5.0                 | 5.4                    |

| Plating (Copper) | Composition | Weight (plating/wire) | Thickness |
|------------------|-------------|-----------------------|-----------|
| Units            | Cu %        | g/kg                  | Micron    |
| Mean             | 100         | 0.82                  | 0.18      |
| Max.             | 100         | 1.18                  | 0.26      |
| Min.             | 100         | 0.45                  | 0.10      |

| Plating (Bronze) | Composition | Weight | Thickness |
|------------------|-------------|--------|-----------|
| Units            | Cu/Sn %     | g/kg   | Micron    |
| Mean             | 98/2        | 0.82   | 0.18      |
| Max.             | 99/1        | 1.18   | 0.26      |
| Min.             | 97/3        | 0.45   | 0.10      |

![Figure 1. Bead ply in radial and bias mounted tires. [7]](image)

Wire pre-tensioning can produce residual stresses in the composite structure when the tension applied on the fibres is removed. Such tension must thus be applied below the fibres' elastic limit (yield strength) so that the fibres can return to their initial state. Fibre pre-tension has a great influence in the creation of residual stresses, far greater than other causes, and the magnitudes of residual stress caused by fibre pre-tensioning are much greater. Several methods have been developed to apply pre-tension to the fibres in ways that make this operation more useful. The
influence and value of the residual stresses caused by fibre pre-tensioning depend on the magnitude of pre-tensioning placed on the fibres, the composite component properties, and the processing history of the composite. [8]

This work aims to study the effect of pre-stressing steel wires on the tensile properties of bead ply in rubber tire. The bead ply may be knocked crooked or deformed for many reasons. This bead deformation causes the tire to suffer internal pressure losses due to mismatches in the bead-rim contact area. Sometimes, a sudden internal pressure drop of this type may cause accidents, but usually the drop occurs slowly, which leads to the necessity to reinflate the tire periodically. To maintain good tensile properties and dimensional stability in this ply, the pre-tension method is thus used.

2. Experimental work

2.1. Rig for applying pre-tension loading on bead wires

The rig consisted of a steel frame of 80 x 80 x 120 cm, with moulds made of low carbon steel, and a water container, as shown in figure 2. This water container was used to provide the required weight when filled with a specified amount of water. There were two parallel beams at the top of the frame; the distance between these beams was controlled by sliding them horizontally in order to suit all moulds. Each mould had a pair of hooks, and the mould was perpendicularly fixed by these hooks between the beams. The pre-tensioning load was then applied to the bead wires in three steps:

1-All wires were fixed by their one ends to one of the mould sides, then the mould was set between the beams of the frame;
2-The other end of the first wire was connected to the water container after the container had been filled with the required amount of water;
3-The first wire was fixed to the other side of the mould, and the load was removed. The latter two steps were repeated for all other wires.

Eight values of load, all below yield strength, were applied on the wires as shown in table 3.
Table 3. Wires pre-stresses and equivalent loads

| No. | Wire Pre-Stress (MPa) | Load on individual wire (N) |
|-----|-----------------------|-----------------------------|
| 1   | 0                     | 0                           |
| 2   | 178                   | 129                         |
| 3   | 357                   | 258                         |
| 4   | 535                   | 387                         |
| 5   | 714                   | 516                         |
| 6   | 892                   | 645                         |
| 7   | 1071                  | 775                         |
| 8   | 1250                  | 904                         |

Yield strength = 1,325 MPa Wire diameter = 0.96 mm
Yield force = 958.505 N Wire cross-section area = 0.7234 mm²

2.2. Rubber compound preparation

The rubber compound was prepared in four stages at the labs of the State Company of Rubber Industries. It consisted of thirteen (13) different materials, which were mixed together in specified amounts by Parts Per Hundred Rubber (PPHR), as shown in table 4. The mixing and homogenization processes for the first three stages are explained in table 5, while the fourth stage is explained in table 6 [9].

Table 4. Raw materials of rubber compound IK 4110. [9]

| Compound                 | Amount  |
|--------------------------|---------|
| SMR 9720                 | 72.00 PPHR |
| SBR 1502                 | 28.00 PPHR |
| Whole Tyre Reclaim       | 70.00 PPHR |
| PCTP-50                  | 0.15 PPHR |
| Zinc Oxide               | 5.00 PPHR |
| Stearic Acid             | 4.00 PPHR |
| Process Oil              | 12.00 PPHR |
| Phenolic Tack Resin      | 6.00 PPHR |
| N660 Black               | 140.00 PPHR |
| 6PPD                     | 0.70 PPHR |
| TMQ                      | 0.60 PPHR |
| Insol Sul:Oil (80:20)    | 0.10 PPHR |
| MBS                      | 6.27 PPHR |
| CPT-100                  | 1.00 PPHR |
| Total                    | 345.82 PPHR |
Table 5. Preparation stages of IK 4110 rubber compound (1st, 2nd, and 3rd stages). [9]

| Material              | PPHR | Percentage (%) | Time (min.) |
|-----------------------|------|----------------|-------------|
| **First stage**       |      |                |             |
| SMR 9720              | 0.624| 26.327         |             |
| SBR 1502              | 0.242| 10.241         |             |
| Whole Tire Reclaim    | 0.607| 25.602         |             |
| PCTP-50               | 0.001| 0.054          |             |
| Zinc Oxide            | 0.043| 1.830          |             |
| Stearic Acid          | 0.034| 1.463          |             |
| Process Oil           | 0.104| 4.395          |             |
| Phenolic Tack Resin   | 0.052| 2.193          |             |
| N660 Black            | 0.650| 27.415         |             |
| 6PPD                  | 0.006| 0.258          |             |
| TMQ                   | 0.005| 0.217          |             |
| **Average**           | 2.372| 100            | 3.5         |
| **Second stage**      |      |                |             |
| 4107 Stock            | 2.372| 87.240         |             |
| N660 Black            | 0.346| 12.759         |             |
| **Average**           | 2.719| 100            | 3           |
| **Third stage**       |      |                |             |
| 4108 Stock            | 2.719| 92.609         |             |
| N660 Black            | 0.216| 7.390          |             |
| **Average**           | 2.935| 100            | 2.5         |

Table 6. Preparation stages of IK 4110 rubber compound (4th stage). [9]

| Material                  | PPHR | Percentage (%) | Time (min.) |
|---------------------------|------|----------------|-------------|
| Fourth stage              |      |                |             |
| 4109 Stock                | 2.935| 97.866         |             |
| Insol Sul:Oil (80:20)     | 0.054| 1.815          |             |
| MBS                       | 0.008| 0.289          |             |
| CPT-100                   | 0.0008| 0.028         |             |
| **Average**               | 3.00     | 100            | 2           |

2.3. Preparation of test specimens
This testing consists of two parts. The first part dealt with specimen preparation, with materials produced as vulcanized sheets. The second part dealt with cutting the specimens to their final
shape and testing them in the tensile test machine. The two parts were done according to ASTM standards D 3182-89 and D 412-98, respectively.

For the first part, the mould was pre-heated after applying pre-tension on the wires and before inserting the rubber into the temperature required for vulcanization (145 °C). After that, 70 g of rubber compound IK4110 was inserted into the mould cavity and the vulcanization process was initiated.

For the second part the completely vulcanized rubber sheets were cut into their final specimen shape (Dumbbell specimens). The sheets were cut using a manual punch with a steel cutter with sharp edges at the end, as shown in figure 3.

There are many types of cutters that meet ASTM standards D 412-98, as shown in figure 4; cutter type C was used in this part of the work, as shown in table 7. The final specimen shape is shown in figure 5 [10,11].

![Image 1](image1.png)

**Figure 3.** The manual punch and its cutter.

![Image 2](image2.png)

**Figure 4.** General shape and dimensions of rubber sheet cutters [11]
2.4. Specimen testing

The specimens were tested according to ASTM standards D412-98 at strain rate of 10 mm/min. Three specimens were tested for each pre-stress level in a universal test machine type ED-UTM, made in Korea.

By moving the lower grip at a speed of 10 mm/min, the correct tensile load was applied to each specimen while the upper grip remained stationary. When the load was fully applied to the sample, the computer plotted load-displacement and stress-strain factors on the screen and on continuous form paper using a printer connected to the computer. The applied load was held on the specimen until failure occurred [11].
2.5. Calculations

From the relationship curves of load and displacement for the tensile specimens and the specimen dimensions, the following values can be calculated:

2.5.1. Tensile strength

The tensile strength can be calculated from the following relationships [11]:

\[
\sigma_b = \frac{F_{\text{max}}}{A_b} \quad (1)
\]

\[
A_b = w_b \times t_b \quad (2)
\]

\(\sigma_b\) ---- bead specimen ultimate tensile strength (MPa).

\(F_{\text{max}}\) ---- maximum load on sample (N).

\(A_b\) ---- bead specimen cross sectional area (mm²).

\(w_b\) ---- bead specimen width (mm).

\(t_b\) ---- bead specimen thickness (mm).

and the relationship between the pre-stress levels and maximum normal stress for the specimens thus emerges.

2.5.2. The strain

The strain can be calculated from the following relationship [1]:

\[
\varepsilon_b = \frac{\Delta L_b}{L_{o_b}} \quad (3)
\]

where:

\(\varepsilon_b\) ---- bead specimen strain

\(\Delta L_b\) ---- bead specimen elongation (mm).

\(L_{o_b}\) ---- bead specimen original length (mm).

and the relationship between the maximum strain and pre-stress levels for each sample can thus be calculated.

2.5.3. Modulus of elasticity

The following equation is used to find the modulus of elasticity of bead specimens [12]:

\[
E = \frac{S \times L_b}{A_b} \quad (4)
\]

\[
S = \frac{F_{\text{max}}}{\delta} \quad (5)
\]

\(E\) ---- bead specimens modulus of elasticity (MPa).

\(L_b\) ---- bead specimen length (mm).

\(S\) ---- bead specimen stiffness (N/m).

\(F_{\text{max}}\) ---- maximum force (N).

\(\delta\) ---- maximum displacement (m).
3. Results and discussion

3.1. Stress-strain curves:
Figure 6 shows the experimental stress-strain relationships for bead specimens. For the pre-stressed composite plate, it can be noted that there is an increase in stability under stress and little increase in strain with increases in the pre-stress value; this indicates improvement in composite material properties under increasing pre-stress levels, probably due to the increase in plate stiffness with increasing pre-stress, which gives the composite the ability to deform in small amounts at high tensile stresses.

![Figure 6. The stress-strain curves of bead specimens.](image)

3.2. Maximum tensile stress (tensile strength) and strain
Figure 7 shows the relationship between the pre-stress levels and the maximum tensile stress for the experimental results. This figure shows that the tensile strength of the specimens began at 30 MPa at a zero pre-stress level, reaching 56 MPa at a 1,250 MPa pre-stress level. This means that the strength is increased by 86%. This increase in strength takes place due to the pre-stressing placing specimens under compression, which makes the composites able to withstand higher external applied loads to failure. It also occurs because the pre-stressing increases the adhesion of the wire to the rubber matrix, which increases the efficiency of the wire as a reinforcement agent and increases the share of the load carried by the wire, which is the stronger phase, by allowing more load transfer from the matrix to the wire.

Figure 8 shows the relationship between the pre-stress level and the maximum tensile strain. It can be seen that increasing the pre-stress level leads to increases in the tensile strain, with a maximum percentage increase of 14.7%. The increase in the maximum tensile strength occurs due to the increase in the stiffness of the composite plate subjected to pre-stress for the wire. This pre-stress places the composite under compression. If this composite is subjected to the tensile stress, the total stress will then be the algebraic summation of the stresses, and the tensile stress needed to fracture the composite plate will be increased as the pre-stress levels increase. An increase in the maximum tensile strain will also occur due to the increase
in pre-stress stiffness of the composite plate; thus, failure will not occur for a composite plate with low strain but only with high strain levels as a result of increasing the composite plate stiffness.

![Graph showing the relationship between pre-stress level and tensile strength for bead specimens.]

**Figure 7.** Relationship between the pre-stress level and maximum tensile strength for bead specimens.

![Graph showing the relationship between pre-stress level and tensile strain for bead specimens.]

**Figure 8.** Relationship between the pre-stress level and maximum tensile strain for bead specimens.

3.3 Specimen modulus of elasticity

Figure 9 shows the relationship between the pre-stress level and the modulus of elasticity (Young’s modulus). This figure shows that the Young modulus was increased from 648.4395 MPa for zero pre-stress to 1205.579 MPa for 1,250 MPa pre-stress, a percentage of increase of 85%. This increase in elastic
modulus means the specimen require extra stress to deform and that the strain is decreased at constant stress. The increase in elastic modulus is due to compression stress in specimens created by wire pre-tensioning, as well as by the residual stress at the interface created by this pre-tensioning.

Figure 9. The relationship between pre-stress level and Young’s modulus of specimens.

4. Conclusions
- The maximum pre-stressing value of 1,250 MPa on steel wires increased the tensile strength and tensile strain of the bead specimens by 86% and 14.7%, respectively.
- The maximum pre-stressing value of 1,250 MPa on steel wires increased the modulus of elasticity for bead specimens by 85%.

References
[1] Doradla, A K 2005 Failure Mode of the Weftless Bead and Evaluation of Improved Continuous Single Wire Based Bead MSc. Thesis (University of Kentucky)
[2] Burton W E 1954 The story of tire beads and tires McGraw-Hill
[3] Mohamed J 2000 Alternative Method for the Production of Wire Reinforcement in Babylon Tire MSc. Thesis (Babylon University)
[4] Gent A N and Walter J D 2006 Pneumatic tire Mechanical Engineering Faculty Research 854
[5] Kersker T M, Kovac F J and Dague M F 1969 The tire composite Fibre Science and Technology 2(1) 41-57
[6] Frank F and W Hofferberth 1967 Mechanics of the pneumatic tire Rubber Chemistry and Technology 40 271-322
[7] WTC 2017 What You Need to Know About Mounting Radial Tires on Classic Vehicle Rims https://www.sema.org/files/attachments/WTC-2011-05-Bias-vs-Radial-Tire-Wheel-Fitment.pdf
[8] Motahhari S 1998 Fibre Prestressed Composites PhD. Thesis (Queen’s University Kingston)
[9] Dunlop Company 1989 *Compound Specification and Mixing Cycles* Dunlop Manual No.2 section 2.2
[10] Standard A. S. T. M. 2004 Standard Practice for Rubber—Materials, Equipment, and Procedures for Mixing Standard Compounds and Preparing Standard Vulcanized Sheets D 3182-89
[11] Standard A. S. T. M. 2004 Standard Test Methods for Vulcanized Rubber and Thermoplastic Elastomers—Tension D 412-98
[12] Ashby M F 2005 *Materials selection in mechanical design* MRS Bull 30(12) 995