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# Mathematical Approach for the Prediction of Compression Pressure

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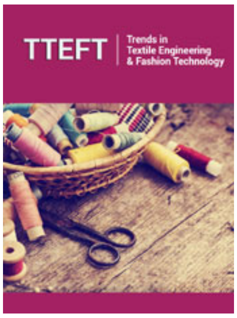


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## Introduction

Based on the theory of Laplace's Law that was developed to relate the wall tension and radius of cylinders (e.g. blood vessels) to the pressure difference due inflation and deflation of two halves of cylindrical vessels [1–3]. The equation can be expressed as

$$P=\frac{T}{R} \qquad (1)$$

Where; P denotes pressure (Pa), T is the tension in the cylinder wall (force per unit length; newton/meter) and R is the radius of the cylinder (m).

Leung WY et al. [4] designed a new model for compression pressure based on the Laplace's law. Objective of their research was to design pressure prediction model incorporating different factors as given below

$$p=\frac{2\pi E A_{\circ}\varepsilon}{133..2\ell_{\circ}(1+\varepsilon)C} \qquad (2)$$

Dubuis L et al. [5] studied patient specific FE model leg under elastic compression and design a model to evaluate compression pressure. They established a theoretical model that is given below

$$P=\frac{Stiff\,\varepsilon}{R} \qquad (3)$$

The main objective of current research includes modification of Laplace's law; development of mathematical model for prediction of compression pressure by incorporating some new parameters including true stress, true strain, true modulus, and deformed width etc.

## Experimental

### Materials

All of the socks samples were evaluated for their built-in physical and technical specifications as shown in Tables 1 & 2.

**Table 1:** Physical specifications of compression socks.

| Sr.# | Brand | Sample Code | Circumference at Ankle [cm] | Fiber Analysis [%] Polyurethane/ Polyamide | Category |
|---|---|---|---|---|---|
| 1 | Maxis | A1 | 19 | 30/70 | CCLI (2.40-2.80 kPa) |
| 2 | Aries | A2 | 18.6 | 31/69 | |
| 3 | Variteks | A3 | 14.4 | 28/72 | |
| 4 | Variteks | B1 | 15.6 | 33/67 | CCLII (3.06-4.27 kPa) |
| 5 | Variteks | B2 | 17.8 | 30/70 | |
| 6 | Variteks | B3 | 16.4 | 25/75 | |
| 7 | Sigvaris | C1 | 16.2 | 50/50 | CCLIII (4.53-6.13 kPa) |
| 8 | Sigvaris | C2 | 15.6 | 45/55 | |
| 9 | Maxis | C3 | 14.6 | 38/62 | |
| 10 | Variteks | C4 | 17.8 | 28/72 | |
| 11 | Aries | C5 | 15.6 | 40/60 | |
| 12 | Maxis | C6 | 14.6 | 32/68 | |
| 13 | Aries | C7 | 16.2 | 45/55 | |

*CCL= Compression class level

**Table 2:** Technical specifications of compression socks.

| Code | Thickness [mm] | Fabric GSM [g/m²] | Course Density [per cm] | Wales Density [per cm] | Stitch Density [Stitches/ cm²] | Main Yarn | Inlaid Yarn |
|---|---|---|---|---|---|---|---|
| | | | | | | Type | Type |
| A1 | 0.4 | 139.44 | 22.4 | 19.21 | 430.43 | MF* | DCV* |
| A2 | 0.46 | 134 | 24.6 | 16.2 | 398.52 | ACV* | DCV* |
| A3 | 0.54 | 149.28 | 18.2 | 20 | 360 | MF* | DCV* |
| B1 | 0.9 | 291.6 | 22 | 18 | 396 | ACV* | SCV* |
| B2 | 0.75 | 298 | 22.6 | 18.27 | 412.9 | MF+ACV* | DCV* |
| B3 | 0.64 | 306.08 | 23.2 | 22.06 | 511.792 | MF+ACV* | DCV* |
| C1 | 0.69 | 281.6 | 20.8 | 22.41 | 466.12 | MF+ACV* | SCV* |
| C2 | 0.68 | 265.2 | 21.8 | 20.34 | 443.41 | MF+ACV* | SCV* |
| C3 | 0.65 | 296 | 21 | 23.44 | 492.24 | MF+ACV* | DCV* |
| C4 | 0.86 | 360.56 | 19.2 | 19 | 364.8 | MF+ACV* | DCV* |
| C5 | 0.7 | 298.44 | 24 | 22 | 528 | MF+ACV* | DCV* |
| C6 | 0.87 | 312.8 | 16.8 | 24.48 | 411.26 | MF+ACV* | DCV* |
| C7 | 0.72 | 384.88 | 22.6 | 26 | 587.6 | MF+ACV* | DCV* |

*MF=Multi-filament yarn,*ACV=Air covered yarn,*SCV=Single covered yarn, *DCV= Double covered yarn.

## Methods

Measurement of compression pressure: Evaluation of compression pressure was done using MST MKIV (Salzmann) as shown in Figure 1.

## Derivation of Mathematical Model

### Theoretical background

Figure 1 is describing the mechanism of force of exertion from internal side of circular stretched cut strips per unit area of small arc length (dL= R.dθ) and reversal force of exertion assumed to be interface compression pressure (P). Due to static equilibrium condition

$$\sum \overline{F_y} = \vec{0}$$

Total sum of forces will become

$$\overline{2F} = \int_o^{\pi} \overline{P} w_f R d\theta$$

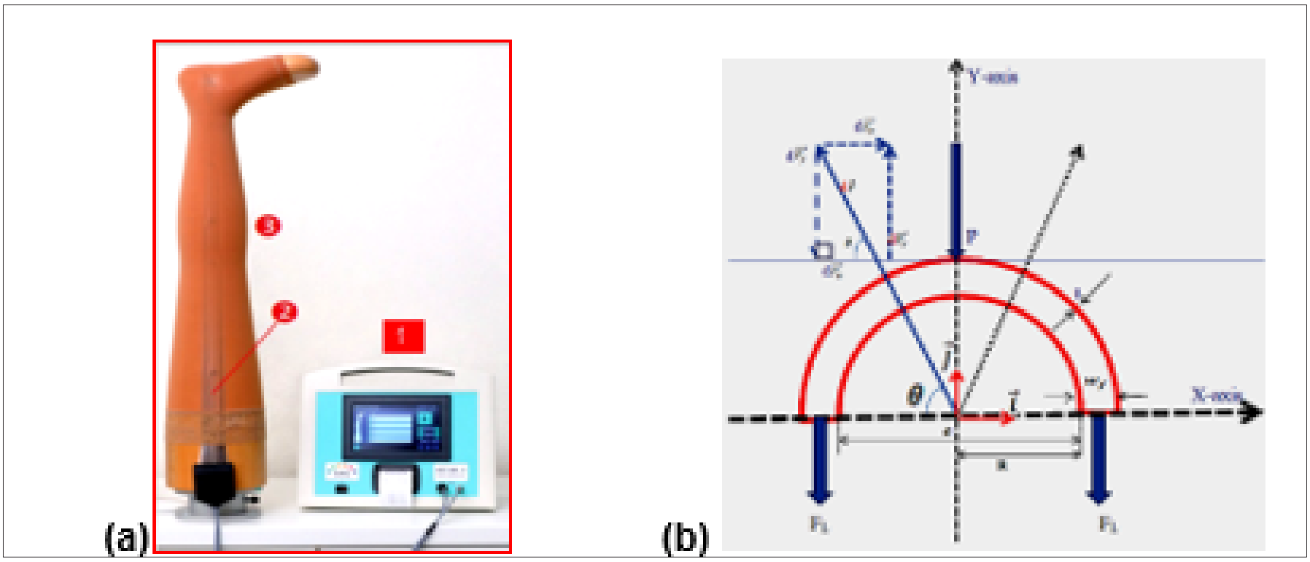


**Figure 1:** (a) MST Pressure measuring device (b) Mechanism of suppression of circular cut-strip due to wooden leg.

Where $\vec{P}$ can be replaced by P.sinθ so above equation will become

$$\overline{2F_L} = PRw_f \int_o^{\pi} \text{Sin}\ \theta\, d\theta = P.R.w_f \text{-}[\cos 180^O \text{-} \cos\text{-} 0^O]$$

$$F_L = PRw_f$$

Here $F_L$ is stretching force (circumferential force) of cut-strip around the leg, P is pressure [N/mm$^2$], R is radius of wooden leg, $w^f$= deformed width of socks strip around the leg [6].

**Relationship between engineering Young's modulus E.Y.M) and compression pressure (Ps) Engineering modulus**

Take an ideally elastic material satisfying Hooke's law and let $\sigma_E$ be the engineering stress and $\varepsilon_E$ be an engineering strain Then, Young's modulus E is defined as the ratio of stress to strain so we can write.

$$E_E = \frac{Engineering\ Stress}{Engineering\ Strain} = \frac{\sigma_E}{\varepsilon_E} = \frac{F_L}{A_0 \varepsilon_E} \quad \text{-------------- (5)}$$

Here $\sigma_l$ is engineering stress; $\varepsilon_l$ is engineering strain while $E_l$ is modulus of elasticity [7]. Comparing equation (4) and equation (5), we can get

$$F_L = F_L$$
$$P_E = \frac{2\pi E_E A_0\ \varepsilon_E}{C\ w_f} \quad \text{-------- (6)}$$

**Relationship between true Young's modulus of elasticity (T.Y.M) and compression pressure (Ps) True elastic modulus/ Young's logarithm modulus**

$$E_T = \frac{True\ Stress}{True\ Strain} = \frac{\sigma_T}{\varepsilon_T} = \frac{\sigma_E(1+\varepsilon_E)}{In(1+\varepsilon_E)} \quad \text{-------------- (7)}$$

Equation (4) and (7) can be modified to

$$F_L = \frac{E_T A_0\ In(1+\varepsilon_E)}{(1+\varepsilon_E)} \quad \text{----------- (8)}$$

Equating equation (1) and equation (8), relation will become

$$F_L = F_L$$
$$P_T = \frac{2\pi E_T A_0\ In(1+\varepsilon_E)}{(1+\varepsilon_E) C\ w_f} \quad \text{------------ (9)}$$

Equation (9) can be named as Model 1 with respect to true Young's modulus (T.Y.M)

**Calculation of pressure measurement , experimental measurement of compression**

In order to measure compression pressure we put on the socks samples on wooden leg keeping the MST Salzmann sensors sleeve between wooden leg and sock samples are given in Table 3. Force *Vs* practical extension results were measured using Testometric tensile tester for calculation of stress and strain values.

**Table 3:** Measurement of engineering stress, strain, modulus and theoretical compression (PE).

| Sample Code | Longitudinal/ Circumferential/ Engineering Strain | Deformed Width on leg | Engineering Stress | Engineering Modulus | Model 2 (E.Y.M) | Experimental Pressure | True stress [machine] | True strain | True Modulus | Model 1 (T.Y.M) |
|---|---|---|---|---|---|---|---|---|---|---|
| | No unit | [mm] | [N/m²] | [N/m²] | [kPa] | [kPa] | [N/mm²] | | [N/mm²] | [kPa] |
| | $\varepsilon_E$ | $W_f$ | $\sigma_e$ | $E_E$ | $P_E$ | $P_S$ | $\sigma_t$ | $\varepsilon_t$ | $E_T$ | $P_T$ |
| A1 | 0.263 | 44.3 | 0.198 | 0.753 | 2.34 | 2.24 | 0.25 | 0.234 | 1.071 | 2.34 |
| A2 | 0.29 | 43 | 0.221 | 0.76 | 2.87 | 2.4 | 0.285 | 0.255 | 1.117 | 2.872 |
| A3 | 0.667 | 36 | 0.182 | 0.273 | 2.83 | 3.07 | 0.303 | 0.511 | 0.593 | 2.832 |
| B1 | 0.538 | 48 | 0.151 | 0.28 | 4 | 3.65 | 0.232 | 0.431 | 0.538 | 3.999 |
| B2 | 0.348 | 44 | 0.167 | 0.48 | 3.73 | 3.75 | 0.225 | 0.299 | 0.754 | 3.726 |
| B3 | 0.463 | 48 | 0.228 | 0.492 | 4.29 | 4.34 | 0.334 | 0.381 | 0.876 | 4.294 |
| C1 | 0.481 | 49 | 0.225 | 0.467 | 4.47 | 4.71 | 0.333 | 0.393 | 0.847 | 4.472 |
| C2 | 0.538 | 42 | 0.255 | 0.474 | 5.19 | 4.83 | 0.393 | 0.431 | 0.912 | 5.193 |
| C3 | 0.644 | 46.5 | 0.279 | 0.434 | 5.39 | 5.46 | 0.459 | 0.497 | 0.924 | 5.395 |
| C4 | 0.348 | 45 | 0.207 | 0.594 | 5.18 | 5.33 | 0.279 | 0.299 | 0.934 | 5.178 |
| C5 | 0.538 | 47.8 | 0.277 | 0.515 | 5.29 | 5.29 | 0.427 | 0.431 | 0.99 | 5.295 |
| C6 | 0.644 | 45 | 0.258 | 0.4 | 6.52 | 6.26 | 0.424 | 0.497 | 0.852 | 6.518 |
| C7 | 0.481 | 51.5 | 0.317 | 0.659 | 6.39 | 6.46 | 0.47 | 0.393 | 1.197 | 6.388 |

## Results and Discussion

Measuring results of engineering stress($\sigma_E$) true stress($\sigma_t$), circumferential strain ($\varepsilon_E$), engineering modulus ($E_E$) true modulus ($E_t$) along with theoretical engineering pressure ($P_E$), experimental pressure (PS) results are given in Table 3. While deformed width ($W_f$) was measured results by donning the sliced cut strip in Table 3.

Figure 2 portray that the coefficent of determination value (R-square values) of Model 2 (E.Y.M) explaining 97.02% of experimental results. Figure 2 portray that the coefficent of determination value (R-square values) of Model 1 (T.Y.M) explaining 97.02% of experimental results.

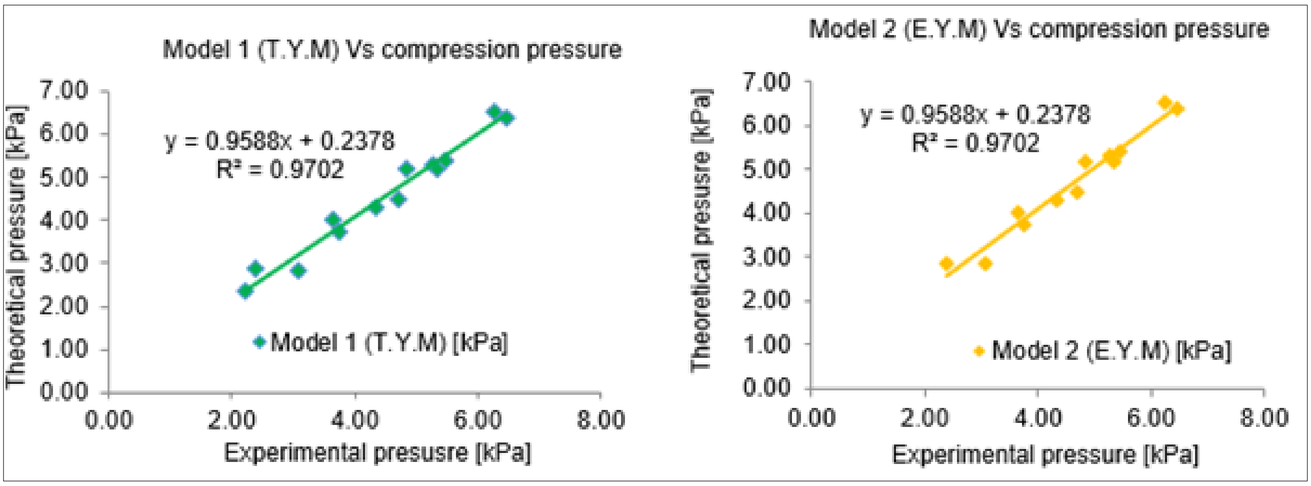


**Figure 2:** Linear regression analysis of Model 1(T.Y.M) and Model 2 (E.Y.M) pressure.

## Conclusion

In this research we have : Modified the Laplace law by incorporating the new term of deformed width ($W_f$). We developed the two new models; Model 1 (T.Y.M) as well as model 2 (E.Y.M) by incorporating some new parameters including true stress ($\sigma_t$), true/logarithm strain ($\varepsilon_t$), true modulus of elasticity ($E_t$), deformed width ($W_f$) along with measurement of engineering stress ($\sigma_E$), engineering strain ($\varepsilon_E$) and engineering modulus of elasticity ($E_E$) at b position (ankel, minimum girth area) expressions into Hook's Law and modified equation of Laplace's law. Statistical validation of newly developed models using linear analysis technique comparison to experimentally measured compression pressure results.

## Acknowledgement

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