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EXPERIMENTAL INVESTIGATIONS UPON FINITE LINE LENGTH CONTACTS BETWEEN NONLINEAR ELASTIC BODIES SUBJECTED TO LARGE DEFORMATIONS

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Abstract: This paper presents a series of experimental investigations conducted on finite line length contacts between nonlinear elastic bodies subjected to large deformations. The contacts were modeled using rubber rollers. The real contact area was determined at different load levels. The purpose of this study is to highlight the end effects due to finite length of bodies in contact. Experimental values measured for the contact area half-width were compared to the ones found theoretically by Diaconescu, in [1], for infinite length line contacts between nonlinear elastic bodies.

1. INTRODUCTION

Modern devices and technologies frequently employ guiding and transport systems supported or driven by rubber rollers. Several studies found in literature present rubber-like materials as showing nonlinear elastic behavior, [2],[7],[9]. Nonlinear elasticity of rubber has a significant influence on the shape and size of line contact elements.

The study of finite length line contacts is essential in order to optimize and increase durability of machine elements modeled by this type of contacts.

2. EXPERIMENTAL SET-UP AND METHODS

The experimental research presented in this paper is based on the investigation of imprints left by a rubber-like deformable punch pressed against a flat rigid surface. The contact was modeled using synthetic rubber rollers pressed on flat plates made of tool steel. The device illustrated schematically in figure 1, allows axial application and maintenance of a normal load to the deformable roller – rigid flat surface contact.

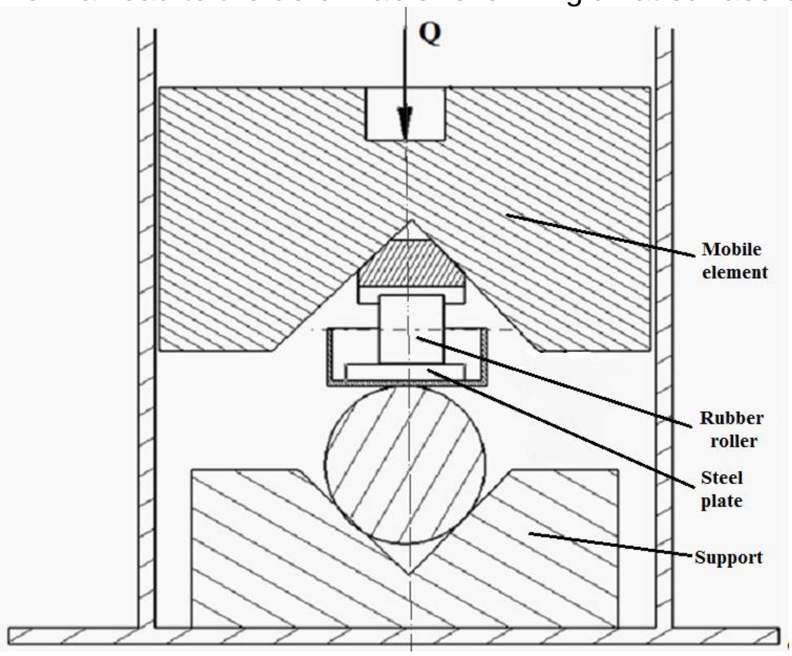


Figure 1. Schematic representation of the device used to investigate line contacts

In order to visualize the contact area shape and dimensions, the two bodies in contact (rubber roller and steel plate) are immersed in a vat filled with copper chloride water solution. Due to different electronegativity from that of iron, copper molecules bond with the free surface of the steel plate. Over the surface where the bodies come into contact the copper chloride water solution doesn't penetrate due to the roller's asperities, which are flattened, therefore leaving an area free of copper deposits. This way, after removing the load and opening the contact, an imprint remains on the flat steel surface, revealing the former contact area. The shape and size of this imprint are accurately measured using a laser profilometer.

3. EXPERIMENTAL RESULTS

The experimental investigations were conducted on a cylindrical rubber roller with $\Phi = 20mm,$ and $l = 11.4mm$, pressed against the flat surface of a rigid, steel plate. The contact was loaded at several normal levels of: 32N, 44N, 68N, 70N, 84N, 113N, 161N and 199N. A three-dimensional representation of the roller profile, as measured by aid of laser profilometry, is illustrated in Figure 2.

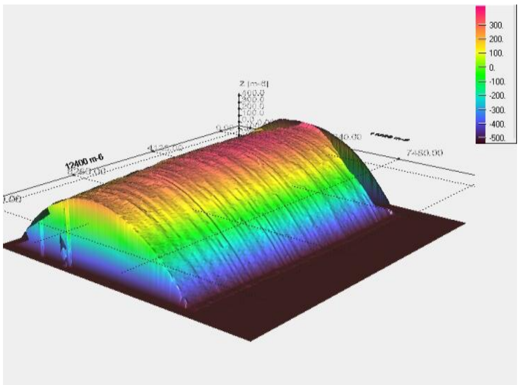
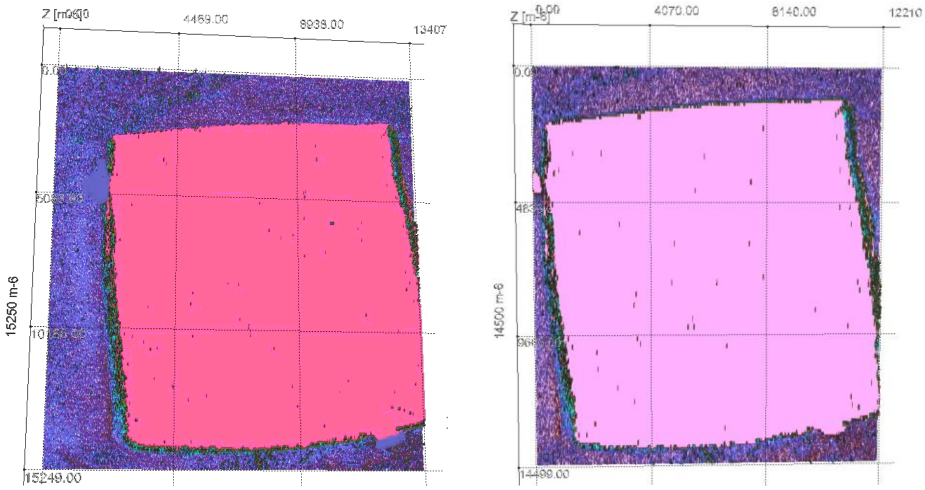


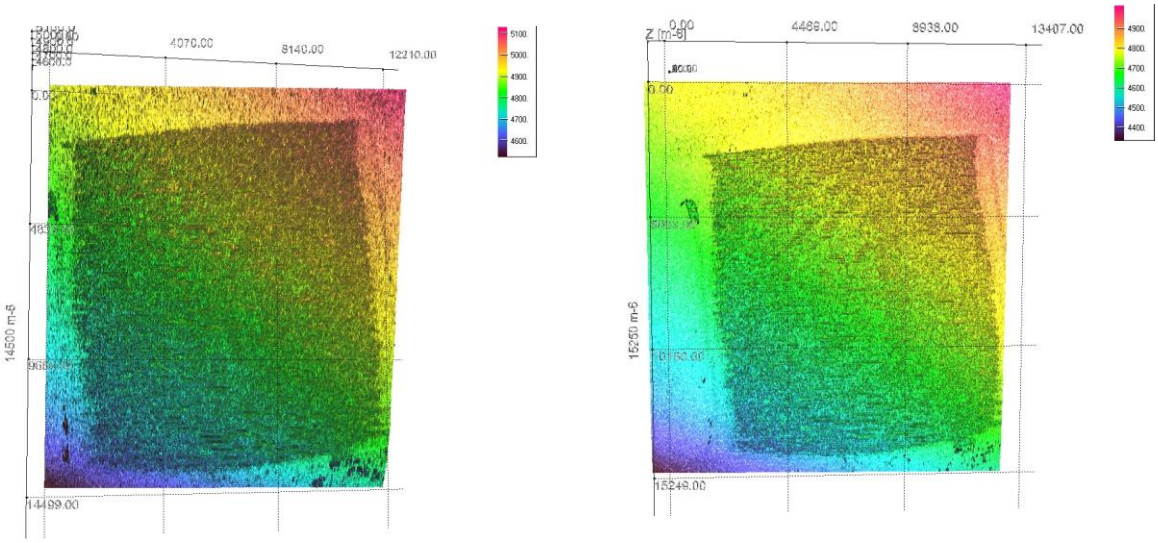
Figure 2. Three-dimensional profile of the roller

After removing loads and separating the two bodies in contact, the flat steel plate was placed on the x-y stage of a laser profilometer. The micro-topography of the area free of copper deposits is then mapped, thus accurately determining the former contact area.



a) 161N b) 199N

Figure 3. 3D representation of reflectivity variation for the contact area between cylindrical roller with $\Phi = 20mm, l = 11.4mm$ and a steel flat plate



a) 161N b) 199N

Figure 4. 3D representation of contact area microtopography for a rubber roller with $\Phi = 20mm, l = 11.4mm$, pressed against a flat steel plate

It can be noticed from figures 3 and 4, that the contact area end regions have a different shape from the one determined theoretically in [3], [4], [5]. Longitudinally, the contact area presents an increase of the central region and then it narrows near the ends. This shape of contact area near end regions is due to stronger deformations occurring longitudinally than transversally. In the median region of the contact area, the strain state is bi-dimensional, the longitudinal deformations in this area being null. Due to rubber incompressibility, the roller's volume remains constant. As the median region predominantly deforms transversally, in order to maintain constant volume, transversal displacements will decrease near end regions, being mostly replaced by longitudinal ones. However at roller edges end effects appear, leading to a strain increase and a widening of contact area. At high load levels, end effects extend towards the central region. The combining of these effects lead to the curvilinear contour found along longitudinal direction of the contact area.

In order to accurately determine the contact area's dimensions along transversal and longitudinal directions, the reflectivity profile of the contact area was raised. The values for the contact dimensions were obtained from this profile, as illustrated in figure 5.

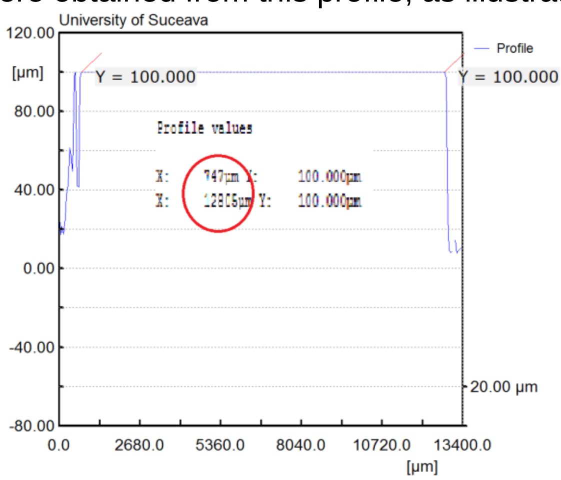


Figure 5 . Reflectivity profile of contact area along transversal direction, at a load of 161N

Using experimental measurements, a correlation between contact width in the median region and normal load was plotted, as shown in figure 6.

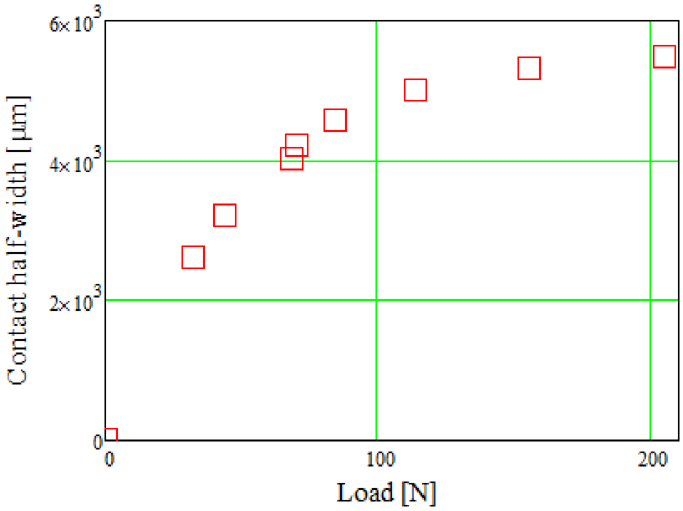


Figure 6. Contact half-width variation with normal load, for a cylindrical rubber roller with $\Phi = 20mm$, and $l = 11.4mm$, **pressed against a flat steel plate**

The contact area extension along longitudinal direction was also represented. The contact area longitudinal extension is defined as the difference between contact area central length, measured along longitudinal direction, and the initial length of the same roller region.

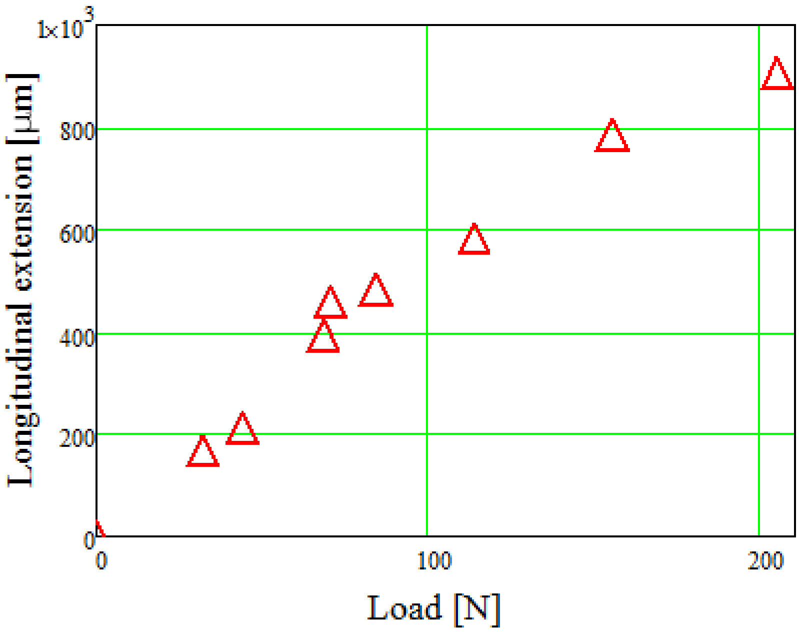


Figure 7. Correlation between contact area longitudinal extension and load for a cylindrical rubber roller with $\Phi = 20mm$, and $l = 11.4mm$, **pressed against a flat steel plate**

4. VALIDATION

Experimental measurements of contact area half-width in a median region determined for the contact of a cylindrical rubber roller and a flat steel plate were compared to theoretical results obtained for infinite length line contacts between nonlinear elastic bodies.

In order to model nonlinear elastic behavior, a secant Young's modulus, E_S, was defined as in [2] and [8]. This secant elasticity modulus is determined by the tangent of the angle created between a chord that links coordinate system origin to a point of interest on the stress-strain characteristic, and the abscissa, as illustrated in figure 8.

$$E_S(\varepsilon) = E_0 + E_1 \varepsilon^{m-1}. \tag{4.1}$$

where, E_0, E_1, m, are material constants, ε, strain, σ, stress.

Using the secant Young's modulus and Hertz's formulae for infinite length line contacts, Diaconescu, [1], inferred the following equation for nonlinear infinite length line contacts:

$$b^2 - b_H^2 + \frac{2^{2-m}}{\sqrt{\pi}} \frac{1}{(1-\nu^2)^{m-1}} \cdot \frac{b^{m+1}}{\rho^{m-1}} \frac{\Gamma\left(1+\frac{m}{2}\right)}{\Gamma\left(\frac{3}{2}+\frac{m}{2}\right)} \frac{E_1}{E_0} = 0. \tag{4.2}$$

where, b_H is the contact area half-width for linear elastic infinite length line contacts and Γ is Gamma function. By numerically solving equation (4.2), the contact half-width for nonlinear elastic infinite length line contacts can be determined. For comparison, experimental and theoretical values of contact area half-width were plotted on the same diagram, against applied load.

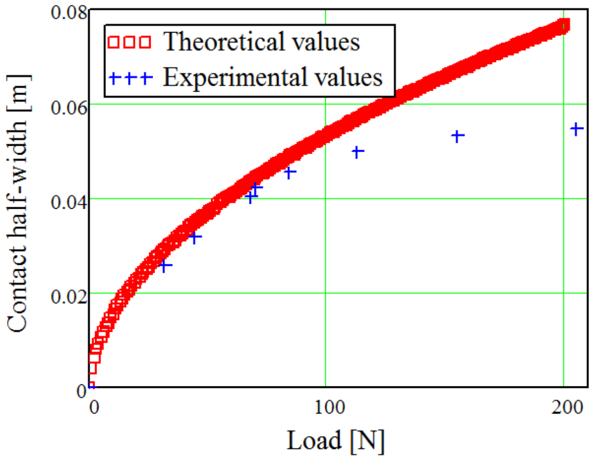


Figure 8. Comparison between theoretical results obtained by Diaconescu and experimental measurements of contact half-width in a median region of contact area

As illustrated in figure 8, up to approximately 100N, experimental and theoretical values of central contact area half-width are similar. At higher loads, when contact area width becomes comparable to roller length, the end effects become more obvious and extend towards the median region of the roller.

5. CONCLUSIONS

From the experimental research illustrated throughout this paper, several conclusions can be drawn, as follows:

- The shape of the contact area between a cylindrical roller and a flat plate is that of a stripe.
- At high loads, contact area has a different shape near the ends. The contact area widens along transversal direction and extends in a longitudinal direction. These shape modifications occur due to the end effects. The end effect is more pronounced when high loads and large deformations are involved.

- When the contact area width becomes close to roller length, the end effect extends towards the central region of the contact area.
- By comparing experimental results obtained for finite length line contacts with theoretical results obtained for infinite length line contacts between nonlinear elastic bodies, good agreement was found at low load levels.
- At high level loads, the roller is subjected to large strains and the end effects manifest up to central region of the contact area, determining higher difference between the experimental and numerical values.

6. ACKNOWLEDGEMENT

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