Semi Cylindrical Fluid Filled Hyperelastic Finger Model for Soft Contact

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Abstract – **In this paper a semi cylindrical fluid filled hyperelastic finger model for soft contact has been developed from the basic principles of mechanics. The deformation parameters namely contact width and radial deflection were calculated for different applied forces. To validate this analytical model, compression tests were conducted on silicone rubber finger specimens . Contact width and radial deflection were also calculated using Mooney-Rivlin, Ogden and Neo Hookean theories and compared with the analytical results. It has been found that , the analytical model deformation results are more agreeable with the experimental finger results.**

Keyword-Anthropomorphic, Soft Manipulation, Finger Model, Semi Contact Width, Young's Modulus, Deformable Body

I. INTRODUCTION

Robotics is the science of designing and building robots suitable for real-life applications. It is the latest and fast developing technology in automated manufacturing and other non-manufacturing environments. In automated industry robots are meant for performing multiple activities to assist man in a planned manner. An industrial robot is a general purpose programmable machine possessing certain anthropomorphic characteristics. The most typical anthropomorphic characteristics are found in the robot arm. The arm makes the robot ideally suitable to do a variety of production works like material handling, machine loading, spot welding, spray painting and assembly. The end of arm or end effectors is the bridge between the robot and the environment. The end effector action will vary according to the task. The most important task is to grasp and hold objects, which are to be transported from one point to another. The end-effectors of a robot is designed to have several fingers, joints and degrees of freedom. Combinations of these factors give different grasping phenamena like human finger grasping [1]. Two or three finger gripper is most popular. Soft contact interaction is important in robot object gripping. For that the robot fingertips are basically made to imitate the structure of human finger, which consists of soft epidermis and a cutis layer. The design of gripper and gripping force calculation is an important task in end-effector design. To achieve human like grasping, still more work is to be done in robot soft finger area.

II. DEVELOPMENTS IN ROBOT FINGER WORK

Robot grasping work was started by Reuleaux in 1875. Asada and Hanafussa [2], [3] proposed first elastic fingered robot hand. Salisbury [4] attempted to develop a three fingered robotic hand. Since then, many developments have been achieved in robot hand design from simple devices to very sophisticated multi-fingered hand such as the Utah-MIT hand [5]. Object gripping-force analysing methods use different contact models [6]. H. Hertz developed the first contact theory [7] for linear elastic models with small deformation. It was the well known contact model and has been used to predict the elasticity and pressure distribution at the contact patch. Pawluk and Hore [8] proposed a modification to this model to find indentation displacement from its force displacement curve. Then,Sinha and Abel [9] proposed an elastic contact model for finger-object contacts in multi-finger grasping with a variational approach. Wang, Kumar and Abel [10] proposed a similar approach for dynamic analysis. A simplification for this model was proposed by Winkler [11]. Selina, Mote and Rompel [12] modeled a liquid filled membrane model for the fingertip bulb based on the theory of elastic membrane. This model is useful for the representation of large strain deformations. Berselli and Vassura [13] modeled fluid filled hyper-elastic models of outer continuous skin layer and an internal layer having communicating voids, which are sealed and filled with a viscous fluid. Xydas and Koa [14] developed a contact model and studied soft fingertip contact mechanics using FEM and validated the results by experiments.

An analytical model for force distribution has been developed by Mirza, Hanes and Orin [15]. A method for calculation of additional grasping force required for stable power grasping of objects is developed by Ismail and Ellis [16]. Toro Omata[17] attempted to determine the static indeterminancy of the grasp force, which is a fundamental problem in power grasping, if static friction is considered in the contact points.

III. FINGER MODEL

Deriving an appropriate model and identification of suitable soft material for robotic finger to make a substitute for human finger is still an unfinished job. As an attempt to make more realistic model of humanoid finger, a semi-cylindrical shaped soft finger has been attempted here. The force-deformation relationship has been formulated from the basic principles of mechanics. To simulate the structure of the human finger, the configuration of the finger model is made as a thin skin like hyper elastic outer layer filled with an incompressible fluid, which uniformly distributes the applied force to the outer layer.

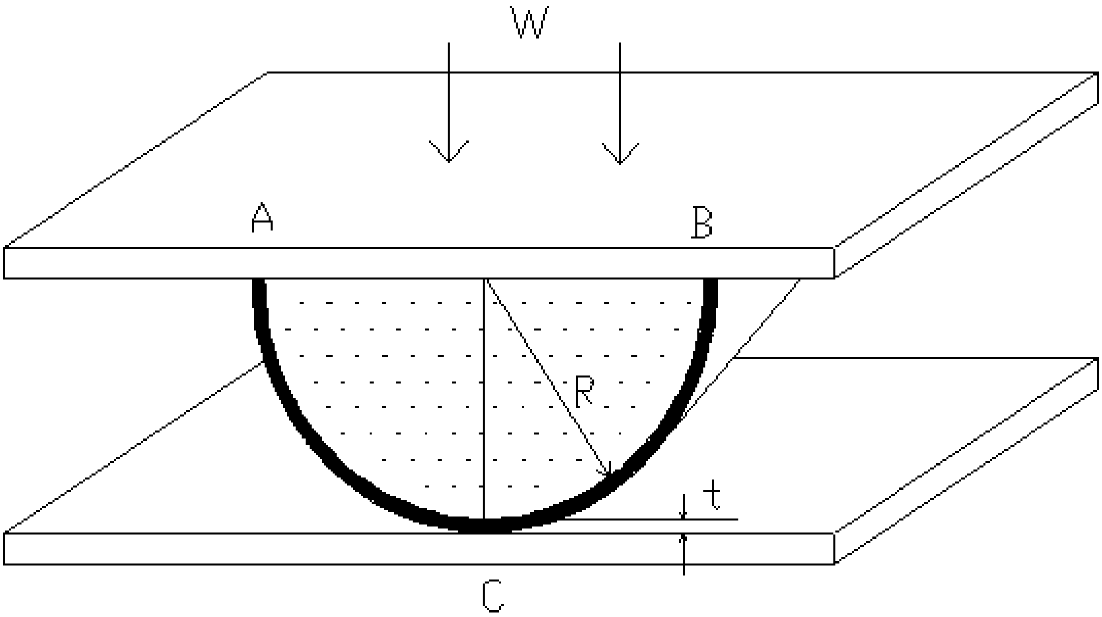

Fig. 1. Finger Model

Figure-1 shows the semi cylindrical finger model which has been modeled for the deformation analysis. The radius of the semi circular cross section is ‘R’ and the outer layer thickness is ‘t’. The length of the finger is taken as ‘L’. For simplicity of calculation it is considered as unity. The model is placed on a thick, flat plate against which it is to be compressed.

A Analytical Modeling

Refering to fig-2, when a load W/unit length of the finger is applied on the model, the fluid pressure increases and the model deforms until a force balance exists. The hyper elastic outer layer undergoes a radial deformation and an elastic linear expansion creating more space to accommodate the displaced volume of fluid due to radial compression. Since the fluid is incompressible the volume before and after deformation remains same. It is assumed that the friction at the contacting surface is negligible and hence not taken to in account for the deformation calculation.

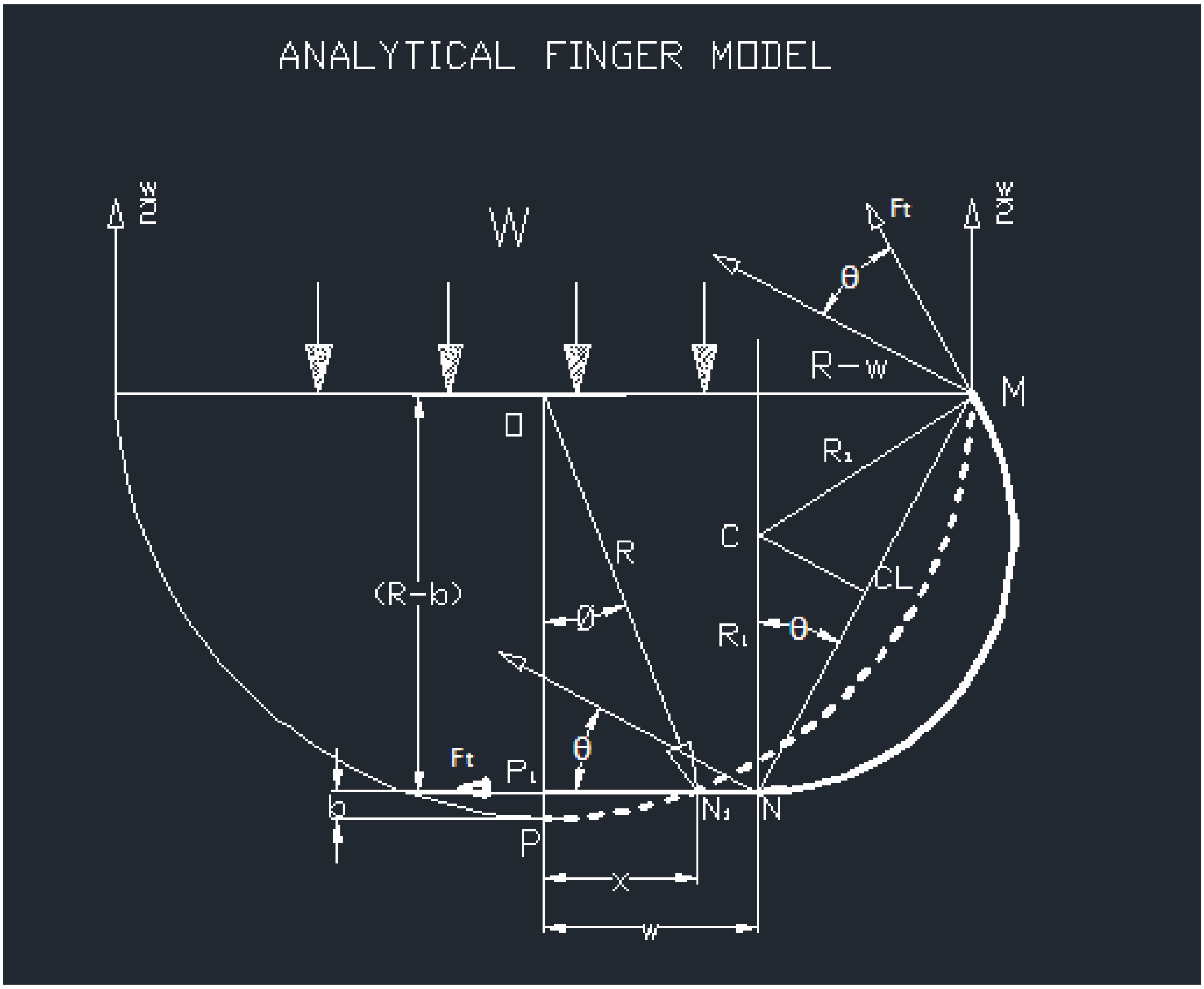

Fig. 2 . Deformation in Finger Model

In equilibrium condition, the total downward load 'W' is balanced by the Reaction forces $\frac{W}{2}$ at both ends. As the geometry is symmetrical about vertical axis, only one quarter is considered for analysis. Under equilibrium condition , let the contact width be 'w' and the radial deflection 'b'. The deformed free-body is tangential to the bottom plate at the contact point and is inclined to the top horizontal plate. The centre of curvature of the free body is now at point 'C', and the radius of curvature is 'R_1'. The thickness of the outer layer changes from 't' to 't_1'. If 'p_r' is the fluid pressure, thrust force acting on the free membrane will be equal to the pressure multiplied by the projected area. That is

$$F_N = p_r \times MN \times 1$$

At each end, the force acting will be $\frac{F_N}{2} = \frac{p_r \times MN \times 1}{2}$ in the direction normal to MN.

The component of this force along a line tangent to the free layer at the tip has to balance the force due to elongation of the outer layer .

Force due to elongation of the hyper elastic layer will be

$F_t = \frac{A \times E \times \Delta l}{l}$. Here 'A' is the area of cross section, 'E' the Young's modulus of the material, 'l' its length and 'Δl' its elongation.

$\frac{W}{2}$ and $F_t \cos(90 - 2\theta + (p_r \times w)$ will be equal under equlibrium condition. Here 'θ' is the angle between the direction of pressure force and outer skin tensile force .

For a particular value of 'b', the difference between $\frac{W}{2}$ and $F_t \cos(90 - 2\theta + (p_r \times w)$ is minimized to fourth digit through iteration using a computer program and the load carrying capacity $\frac{W}{2}$ at this condition is estimated. The procedure is repeated for different values of '*b*' and the value of load carrying capacity, contact width are estimated and recorded.

IV MATERIAL PROPERTY TEST

To achieve soft robot finger many materials are being tried [18]. Here Silicone rubber R401/50 is used as the finger material. The material property namely Young's modulus is derived from the uni-axial tensile test on sample specimens.

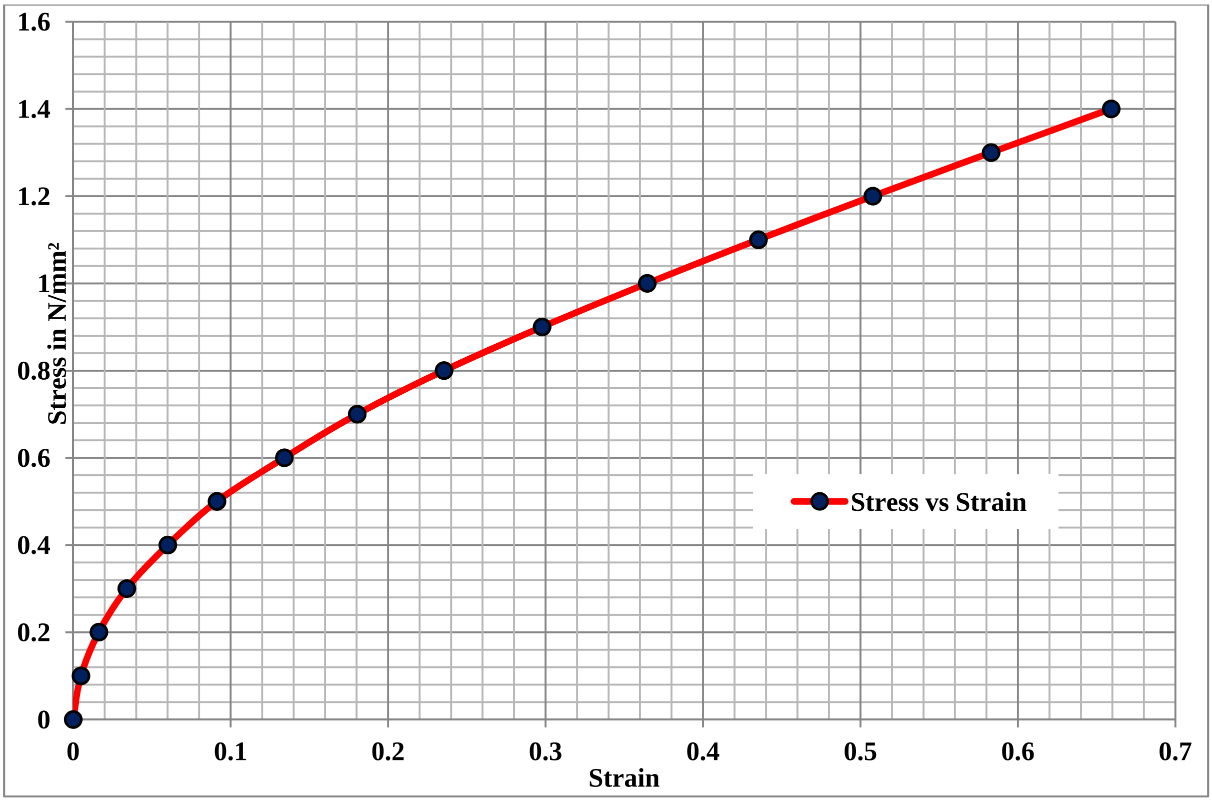

Fig. 3 . Stress vs Strain of Silicone Rubber

Standard size 'Dog Bone' specimens were used as per ASTM –D412/ ISO 37 standards. Fig-3 and 4 shows the Stress vs Strain and Young's modulus vs Stress curves of the silicone rubber. Since the Young's modulus for this hyper elastic material is found to be non-linear, the contact analysis was carried out using average value of 'E' and stress dependent value of 'E' (varying 'E' values).

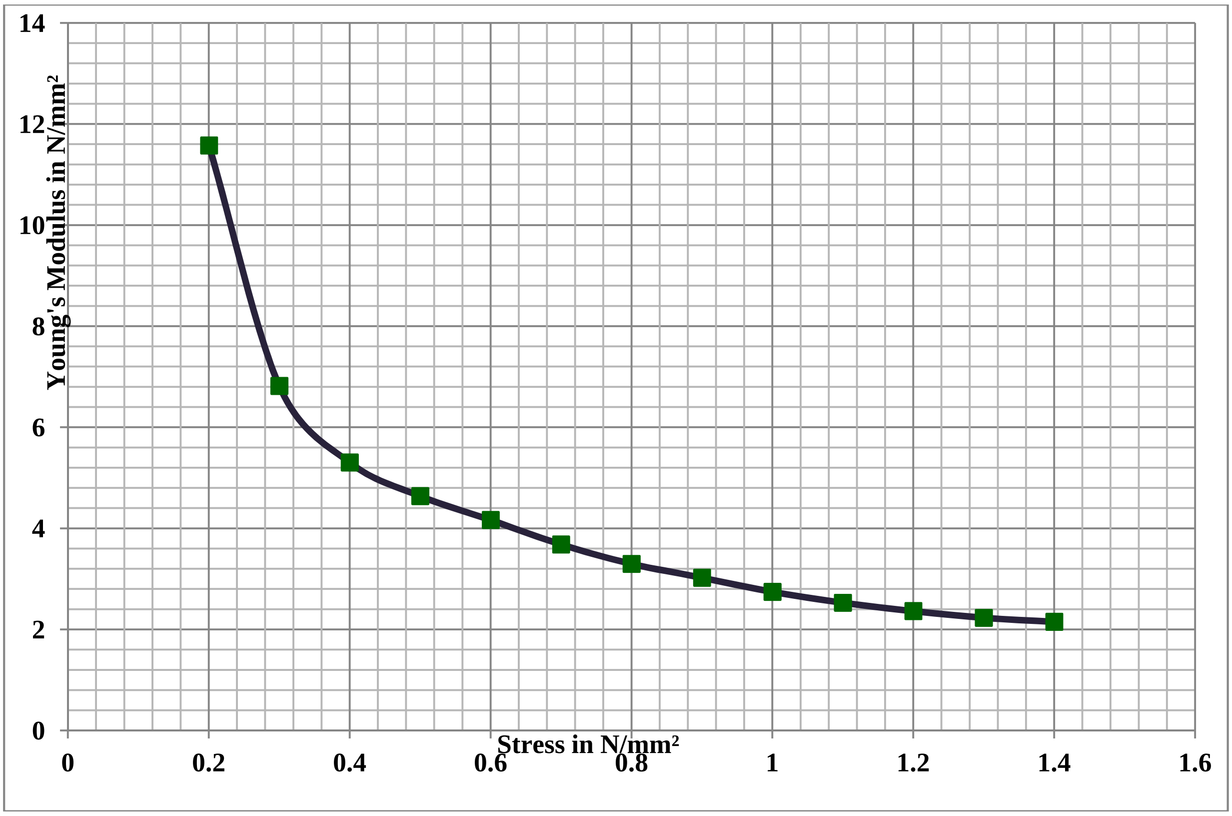

Fig. 4 . Young's Modulus vs Stress of Silicone Rubber

V. FINGER LOAD TEST

Silicone rubber fingers similar to the analytical model were manufactured by liquid injection molding as per ASTM D 695 standard. The mean radius of finger is 10 mm, thickness of outer layer 2mm and finger length 30 mm. The inner cavity is filled with SAE 30 oil, and the top opening is sealed by screwing a flat steel plate over it. The test is conducted in a compression testing machine, supplied by AVJ Engineering Industries, India. It has the maximum loading capacity of 25 KN, with a least count of 0.01N. The testing machine set-up is shown in Figure-5. Quality finger-print ink is applied over the finger surface. The finger specimen is placed between the movable and fixed steel platforms. A recording paper is placed between the finger surface and the top target platform . As the recording paper is very thin, the influence of its thickness is negligible. Initial contact between the specimen and top platform is determined, when force reading in load cell indicator shows as 0.01N. While loading, the finger is compressed against target surface, deforms and leaves a vivid print of its contact area over the recording paper . The contact width is measured by scanning the recorded image. The applied load is measured by Load-cell, which is mounted above the top platform and the unidirectional crush by a mechanical dial indicator fitted between the platforms. The accuracy of the dial indicator is ± 0.001mm.

Fig. 5 . Robot-finger Compression Testing Machine set-up

The test is repeated three times for each of the specimen and the average values noted. The tests are conducted up to 70 % strain of the material with a compression rate of 6.0 mm / minute to meet the quasi static condition and to reduce hystresis effects. The results are tabulated. Finite element deformation analysis is carried out on the designed analytical model using ANSYS ™ software. Mooney-Rivlin, Ogden and Neo-hookean methods are used to simulate and estimate the deformation parameters of the finger model. For the applied normal load, the semi contact width and vertical deflection are taken-out from the FEA analysis.

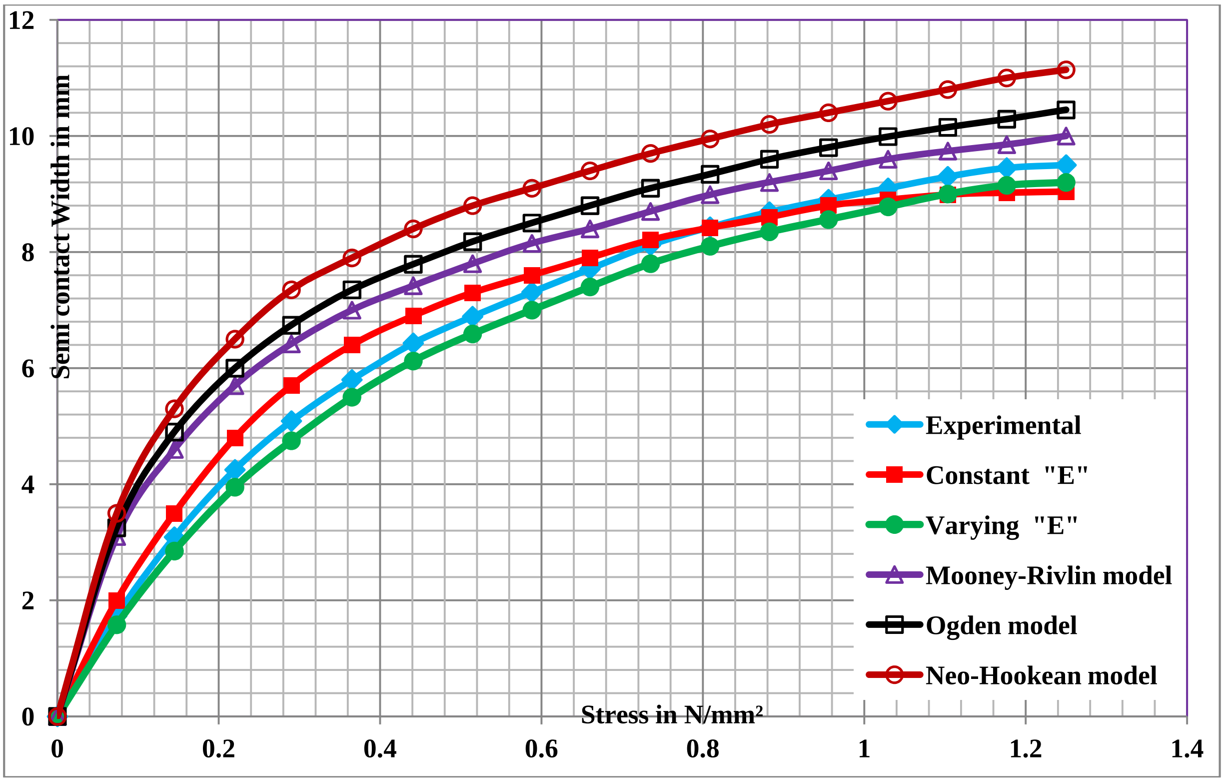

Fig. 6 . Semi-contact width vs Stress of Finger

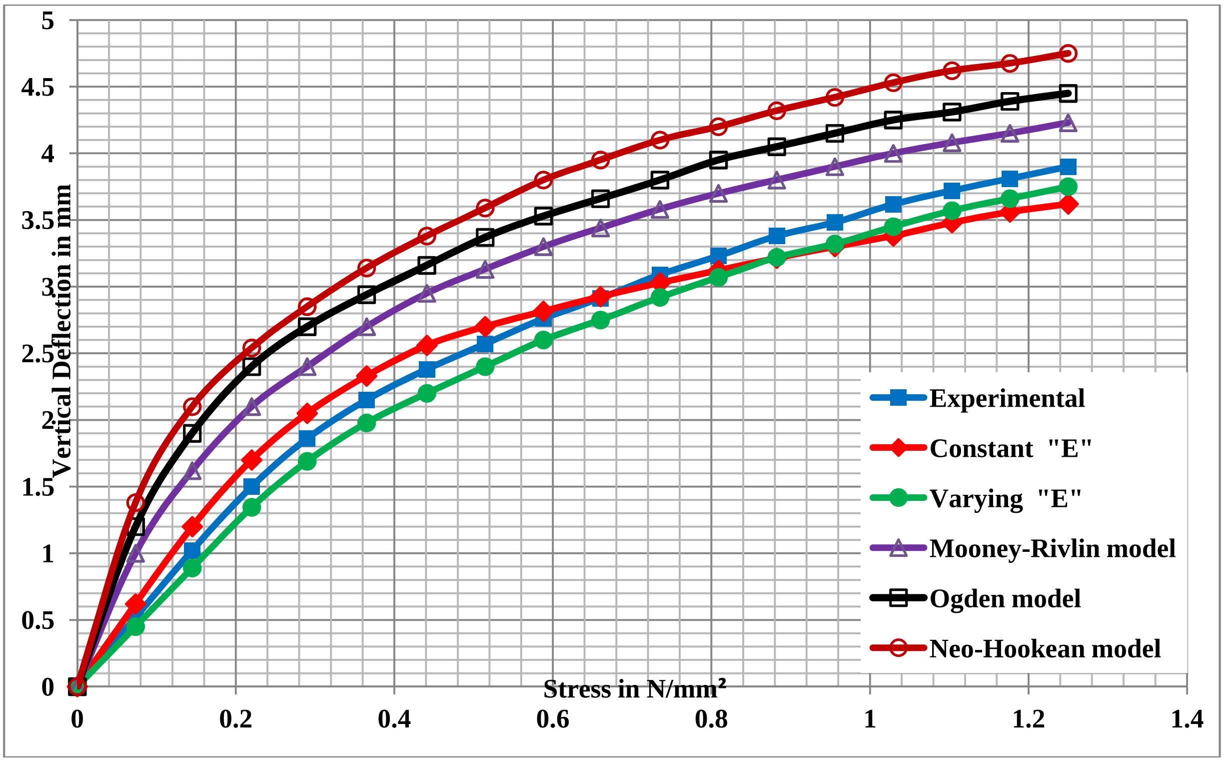

Fig. 7 . Vertical Deflection vs Stress of Finger

VI ANALYSIS AND DISCUSSION

The results of analytical, experimental and finite element analysis are plotted in Fig 6 and 7, and the results are discussed below:

A. Contact width and Normal force

Refering to Fig 6, it is found that the analytically calculated semi-contact width is slightly higher than the experimental results initially, but it reduces at higher loads. This is because the Young's Modulus value used in the calculation is the average of the values over the range. When the Young's Modulus value is taken corresponding to the stress level under consideration, the curve is close to the experimental one. Maximum deviation is 8.67 % and is found to exists at a stress level of 0.0735 N/mm^2. Semi-contact width predicted using FEM analysis by Mooney-Rivlin, Ogden and Neo-Hookean theories fall on the higher side with more deviation from experimental results.

B. Vertical deflection and Normal force

Fig 7 shows the Vertical Deflection vs Normal Stress curves for different methods. Similar to the above results, the vertical deflection verses normal stress curve considering varying Young's Modulus shows good agreement with the experimental curve. The analytical results based on average young's modulus value also shows close agreement with the experimental results but having fluctuational deviations on both side of the experimental values. The Mooney-Rivlin, Ogden and Neo-hookean method results shows less agreement with the experimental results.

VII CONCLUDING REMARKS

A new contact model has been developed considering basic principles of mechanics.

- The deflection parameters such as semicontact width and vertical deflection were calculated for various applied normal forces.
- Selecting Silicone rubber as the finger material, tensile tests were conducted on the sample specimens as per the standards to determine its material property (Young's modulus) .
- Finger compression tests were conducted to find-out contact width and the vertical deflection against the target surface.
- A comparison between the experimental, analytical and finite element deformation results were done and it was found that the analytically predicted results are closer to the experimental values.

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