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# Measurement of the mechanical properties of the skin using the suction test

## Comparison between three methods: geometric, Timoshenko and finite elements

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**Introduction:** The suction test is commonly used to study the mechanical properties of human skin *in vivo*. The unevenness of the stress fields complicates obtaining the intrinsic mechanical parameters of the skin *in vivo* because the values of the local stresses and deformations cannot be calculated directly from the displacements and forces applied by the test apparatus. In general, users only take into account the negative pressure applied and the elevation of the dome of skin drawn up in order to deduce the properties of the skin. This method has the major disadvantage of being dependent on the experimental conditions used: in particular, the size of the suction cup and the negative pressure applied. Here, we propose a full mechanical study of the test to provide rigorous results. We compare the frequently used geometric method (making the thin plate hypothesis), Timoshenko's method (which can take greater plate thicknesses into account) and finally various results obtained by the finite elements (FE) technique.

**Methods:** The suction test was modelled by FE with large displacements and large deformations both for orthotropic and isotropic plates. The results obtained in the elastic domain for various values of Young's modulus and of applied negative pressure were used as references and were compared with methods using analytical relationships.

**Results:** The geometric method generally used in the interpretation of suction tests gives results, which in certain configurations, are very different from those obtained by FE. The method of Timoshenko is suited to thick plates 'in contact' or embedded round the edge, the elevation of the dome and the tension and flexion stresss are analytically accessible through relationships involving four constants that are dependent on the limit conditions. Comparison with the FE results enabled the optimisation of the coefficients to adapt the relationships to the particular conditions of the suction trials.

**Conclusion:** We showed the limits of the geometrical method and proposed a solution, which while remaining simple to use, gives results that are closer to reality both for the calculation of the modulus and for the determination of the state of the stresses obtained.

**Key Words:** mechanical testing – suction – intrinsic mechanical properties


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The mechanical behaviour of skin *in vivo* is both viscoelastic (1, 2) and anisotropic (3–5). Currently, the suction test is the only real test that is in use in both research laboratories and dermatology departments. This is mainly because of the availability on the market of perfectly operational apparatuses such as the Dermaflex A (Cortex Technology, Hadsund, Denmark) (6) and in particular the Cutometre SEM575 (Courage Khazaka, Köln, Germany) (7). In general, the results analysed solely concern the amplitude of the maximum elevation of the dome of skin which is obtained as a result of the negative pressure applied i.e. suction. However, various types of load can be applied to give access to the elastic and viscoelastic parameters of the skin. The suction test is an adaptation of the plate inflation test long used in traditional mechanics to characterise thin sheet metal. Quite straightforward simplifying hypotheses allow the calculation of the stresses and the stresss at the centre of the bubble obtained as a function of the pressure exerted, the elevation of the dome in the centre and the dimensions of the specimen. Several authors (8, 9) have used this approach to calculate the mechanical characteristics of skin. Recently, a method has been proposed which allows the automatic calculation of the parameters of a four-parameter viscoelastic model (10). The various methods proposed are based on the hypothesis of a thin plate, i.e. the thickness must be small when compared with the planar dimensions. It follows that the state of stress can be considered constant through the thickness of the plate. But, in the case of the suction test, the thickness of the skin is roughly 1 mm for a probe diameter that is typically 6 mm but which can sometimes be 4 or even 2 mm. Making the hypothesis of the thin plate then no longer appears to be acceptable if the actual conditions of the test are to be represented correctly. We propose the use of a model developed by Timoshenko (11) for thick plates embedded in a support or resting against it. Comparison between these two methods is not experimentally possible with skin, and is also dubious using inert material, which only give an approximate representation of the behaviour of cutaneous tissue. We therefore propose to test the results by comparison with those obtained using a finite elements (FE) model – a technique that is widespread in mechanics and perfectly suited to dealing with structures that present complex heterogeneous stress patterns. It is particularly efficient in the elastic domain, which is our main focus here.

## Methods

*Geometrical model*

We can refer to studies directly concerning inflation as a means of analysis, e.g. Siqueira (12) developed and studied a test machine and analysed the experimental conditions.

He demonstrated that when the radius of curvature was large with respect to the thickness, the influence of the stress normal to the surface $\sigma_{zz}$ can be ignored. In the central part of the plate the stress is uniform and biaxial, and the mechanical test is static i.e. knowing the limit conditions of force and displacement, it is possible to calculate the local stresses and strains. Making these hypotheses, the test will allow the determination of relatively simple mechanical characteristics.

From the various parameters of the test, we can write the relationships that give the stress and deformation at the centre of the dome:

- $a$: the radius of the probe;
- $e$: the thickness of the skin;
- $p$: the negative pressure applied;
- $R$: the radius of curvature of the dome obtained;
- $f$: the elevation of the dome;
- $E$: Young's modulus of the material;
- $\nu$: Poisson's coefficient

$$\varepsilon = \frac{\mathrm{Arc}\sin(a/R) - a/R}{a/R}, \quad \sigma = \frac{pR}{2e}, \quad \varepsilon = \frac{1-\nu}{E}\sigma$$

$$R = \frac{a^2+u^2}{2u} \text{ hence } \sigma = \frac{p(a^2+u^2)}{4eu} \tag{1}$$

When a test is carried out in fixed conditions, the parameters of the material can be calculated from the experimental results (13):

$$\frac{E}{1-\nu} = \frac{pa}{2e[\mathrm{Arc}\sin(2au/(a^2+u^2)) - 2au/(a^2+u^2)]} \tag{2}$$

This technique does not, however, allow separation of Young's modulus from Poisson's coefficient. Another experiment must therefore be designed to measure $\nu$ or approximations must be made. It is generally the latter solution which is chosen with a value of $\nu = 0.3$.

*Timoshenko's method*

The mechanics of continuous media allows more rigorous approaches to problems in which the geometry is relatively simple. When the deformations or displacements are large, the equations used to calculate variables such as dome elevation or the stress in a loaded plate are not linear and the only solution is often to give mathematical expressions that enable an approximate calculation of the variables. Although not perfect, this method does have the advantage of giving formulae that can be applied in most cases. Timoshenko (11), in a reference work gives the relationships that enable the straightforward calculation of the dome elevation, the stress in the middle plane and the flexion stresses for a thick circular plate that is uniformly loaded and for which the edge is either embedded or simply resting on a surface. These relationships introduce parameters that are calculated for a Poisson coefficient of 0.25 and which are dependent on the limit conditions.

The elevation of the dome $u_0$, the stress $\sigma_r^t$ in the median plane and the flexion strress $\sigma_r^f$ on the upper or lower edge at the centre of the plate are given by the following equations:

$$\frac{u_0}{e} + A\left(\frac{u_0}{e}\right)^3 = B\frac{p}{E}\left(\frac{a}{e}\right)^4 \tag{3}$$

$$\sigma_r^t = \alpha_r E \frac{u_0^2}{a^2} \tag{4}$$

$$\sigma_r^f = \beta_r E \frac{u_0 e}{a^2} \tag{5}$$

where $e$ is the thickness of the plate, $a$ its radius, $E$ Young's modulus, $p$ the pressure exerted, $A$, $B$, $\alpha_r$ and $\beta_r$ the parameters depending on the limit conditions as follows:

Comparing the two theories above reveals large differences, it is therefore necessary to find a way of determining which is the more accurate. As we are unable to compare experimental results, we used a FE model to assess the relative merits of the two approaches.

*FE*

This technique is frequently used in the mechanics of continuous media as it enables the resolution of complex problems which do not have analytical solutions. It is very well suited to resolving problems of structures in which the heterogenous fields of stress and deformation. The difficulties involved in obtaining a correct result are essentially linked to the choices of the limit conditions and the mesh size. In the present case, for an isotropic material, the problem to be resolved presents is axisymetric. It therefore only calls for a two-dimensional study across a section perpendicular to the plane of the skin (Fig. 1), however, as our aim was also to resolve the problem for an anisotropic material, we carried out all the calculations in three dimensions. However, considering the symmetries involved, the study of only a quarter plate was sufficient. The strains and the displacements were quite large since the elevation of the dome was similar to the radius of the disc of skin tested. Calculations involving large displacements and large deformations were therefore used. This does not cause any particular difficulties but makes the calculations much longer and sometimes impossible.

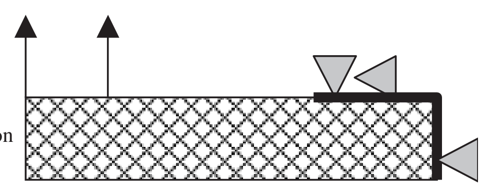


*Fig. 1. The various limit conditions imposed on finite elements calculations.*

The greatest difficulty to be overcome is therefore related to the choice of the limit conditions. The load is simple since it is a negative pressure on the upper part of the plate. For the conditions of movement at the edges, we tested several solutions considered to be representative of reality. Finally, we chose the solution described below under the name of ''suction'' which provides the best representation of the experimental conditions generated using equipment currently under development in our laboratory (Fig. 1).

The skin is prevented from moving by a circular groove (Fig. 2) which, once it is pumped out to a partial vacuum, draws up the skin and prevents the uppermost part from moving because of the high friction while the deeper layers of the skin are held in place by being blocked in the groove.

A FE model was generated for a plate of 1 mm of thickness composed of an isotropic material with a young's modulus of 0.8 MPa and a Poisson coefficient of 0.3. The depression applied at the surface was 0.03 MPa (or 300 mbars). The representation in Fig. 3 shows the shape of the displacements obtained for each case and the state of the stress in the direction Ox in the plane of the skin.

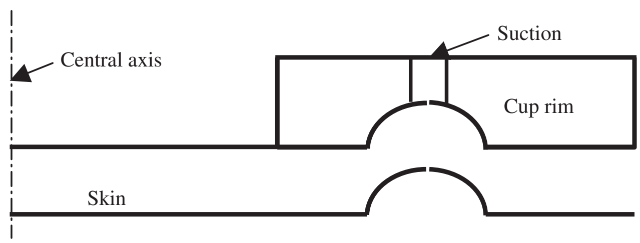


*Fig. 2. Schema of the system used to fix the rim of the suction cup.*

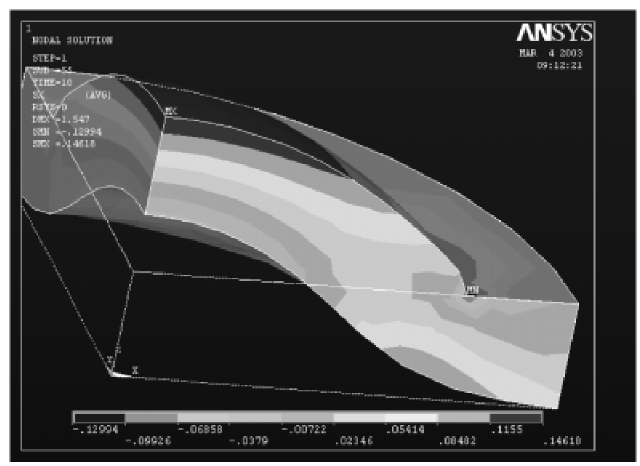


*Fig. 3. 'Suction' limit conditions – elevation = 1.05 mm. Distribution of stress $\sigma_x$ from −0.045 to +0.146 MPa on the central axis.*

The in-plane stress distribution clearly shows how there is superimposition of a constant tensile stress and a flexion stress. Maximum tensile stress on the upper part is between 0.145 and 0.150 MPa. The stress on the lower surface is slight compression: between $-0.03$ and $-0.08$ MPa.

*Comparison between the geometric and Timoshenko methods and the FE 'suction' method*

*Case of orthotropic materials*

The anisotropy of the skin varies with its location on the body. It is necessarily a complex phenomenon since it depends on the internal structure of the dermis and in particular on the orientation of the bundles of collagen or elastic fibres. The existence of these fibres suggests an analogy with composite materials reinforced with long fibres. Materials in which the anisotropy takes random directions lead to relationships in the mechanics of continuous materials, which are very complex and impossible to use in a straightforward way (14). Thin orthotropic materials have two planes of symmetry perpendicular to each other and to the plane of the membrane. This is the case of numerous composite materials. We will consider here that the skin has an anisotropy of this type, allowing us to use relatively simple mechanical calculations. FE calculations and analytical models must take this into account. To do so, we look for an equivalent modulus, which could provide a satisfactory representation of an anisotropic material during suction trials.

With an orthotropic material, the stress-deformation relationships can be noted as plane stresss in an anisotropy axis as a function of standard engineering constants ($E_1$ is the largest modulus, $E_2$ the modulus at right angles to it, $G_{12}$ the shear modulus and $\nu_{12}$ and $\nu_{21}$ the Poisson coefficients in the plane:

$$\begin{pmatrix} \sigma_1 \\ \sigma_2 \\ \sigma_6 \end{pmatrix} = \begin{bmatrix} Q_{11} & Q_{12} & 0 \\ Q_{12} & Q_{22} & 0 \\ 0 & 0 & Q_{66} \end{bmatrix} \begin{pmatrix} e_1 \\ e_2 \\ e_6 \end{pmatrix}$$

$$\begin{cases} Q_{11} = \dfrac{E_1}{1-\nu_{12}\nu_{21}} & Q_{12} = \dfrac{\nu_{12}E_2}{1-\nu_{12}\nu_{21}} = \dfrac{\nu_{21}E_1}{1-\nu_{12}\nu_{21}} \\ Q_{22} = \dfrac{E_2}{1-\nu_{12}\nu_{21}} & Q_{66} = G_{12} \end{cases} \tag{6}$$

when we perform a trial with a circular cup, the dome obtained is, of course, dependent on the elastic constants in all directions. The dome obtained is therefore dependent on the uniformised modulus of the composite material which can be calculated using the standard theory for composite materials (CLT) modelling the skin like a composite material of thickness $e$ composed of $n$ isotropic layers of thickness $dz = e/n$, the mechanical characteristics being those of skin in directions spread over $2\pi$ with a step of $\theta = 2\pi/n$.

After calculation and ignoring the second order terms, the formula of the equivalent modulus is obtained:

$$E = \tfrac{1}{8}(3Q_{11} + 3Q_{22} + 2(Q_{12} + 2Q_{66})) \tag{7}$$

In the case of composites with an organic matrix reinforced by fibres of random orientation (Mat), it is assumed that $Q_{12}+2Q_{66} = Q_{22}$ (15). This hypothesis, which is supported by experiment, enables the final formula to be made much simpler. We will accept this rule for the skin and will pursue with validation later. Assuming that $\nu_{12}\ \nu_{21}$ is much smaller than 1, equations (6) can be written $Q_{11} = E_1$ and $Q_{22} = E_2$, thus we obtain the relationship which gives an evaluation of the equivalent modulus of an orthotropic material under suction:

$$E = \tfrac{3}{8}E_1 + \tfrac{5}{8}E_2 \Rightarrow E = 0.375E_1 + 0.625E_2 \tag{8}$$

To check this proposition, we modelled different cases of orthotropy by FE. The results were combined with those obtained in isotropic conditions to refine the above relationship.

The models used the following conditions:

- Diameter of suction cup: 6 mm;
- Pressure applied: $-0.03$ Mpa;
- Poisson coefficient: 0.3;
- Shear modulus: 0.2 Mpa;
- Modulus $E_2 = E_3$.

For the above materials, we plotted (Fig. 4) the dome elevation obtained by geometric modelling, by FE for the isotropic materials (curve FE isotropic) and also by FE for an equivalent modulus calculated from formula (8) (curve FE mat). It can be noted that the geometric model is far from the results obtained by FE and the points obtained by FE are not exactly on the same master curve. We concluded that the hypotheses made to obtain formula (8) are not perfectly verified and so we sought to optimise the coefficients multiplying $E_1$ and $E_2$ so that the points representative of the isotropic and orthotropic materials are on the

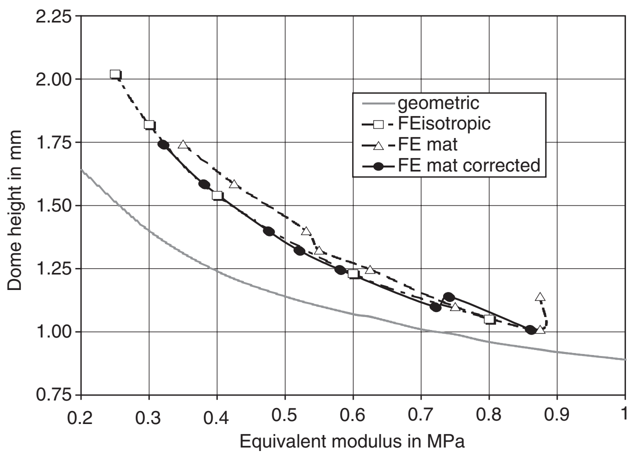


*Fig. 4. Comparison for the dome elevations obtained on orthotropic materials using different techniques.*

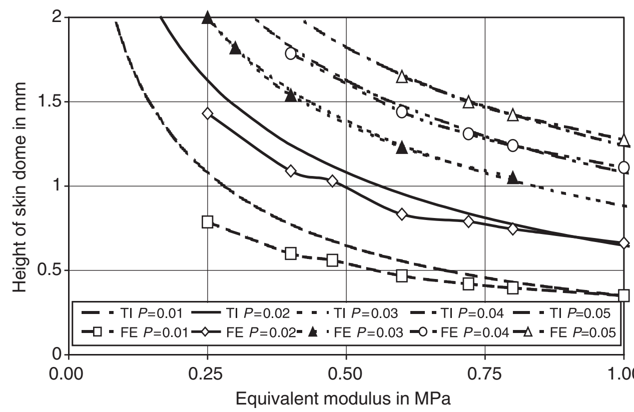


*Fig. 5. Comparison of the geometric method and finite elements.*

same curve. Following a few trials, we propose slightly different coefficients that appear to be satisfactory (curve FE mat corrected):

$$E_{\text{equi}} = 0.3E_1 + 0.7E_2 \qquad (9)$$

In summary, during a suction run on orthotropic skin, the elevation of the dome obtained corresponds to that which would be measured on isotropic skin with a modulus given by formula (9). In all cases, the result depends on a linear combination of the moduli in the main directions.

*Relationship between the elevation of the dome in the centre and the equivalent modulus*

*Comparison: FE and geometric*

To complete the above results, we used FE to model other load values: $-100$, $-200$, $-400$ and $-500$ mbar. The diameter of the suction cup remained 6 mm, the thickness of the skin 1 mm, the Poisson coefficient 0.3 and the shear modulus 0.2 MPa. The calculations carried out on orthotropic materials are taken into account by their equivalent modulus calculated using equation (9). The set of results obtained was compared with the values generated using the geometric method (Fig. 5). It is clearly seen that this method is insufficient for a correct representation of the suction test while the FE calculation of the equivalent modulus gives good results since, at all pressures, the points representative for isotropic and anisotropic materials are on the same master curves.

*Comparison: FE and Timoshenko*

Our aim here was to determine whether the Timoshenko method is able to generate results comparable with those calculated by FE, considered as the reference. The first calculation was carried out with coefficients $A = 0.471$ and $B = 0.171$ corresponding to an embedded plate with fixed edges. Quite a large discrepancy was found between the two solutions but we noted that modifying coefficients $A$ and $B$ led to considerable variations of the curves obtained. From a mechanical point of view, the anchoring of the skin under the walls of the suction device corresponds neither to a perfect fit into the grove, and hence perfect blockage, nor to a perfect simple contact. Indeed, although the top of the skin is correctly fixed to the suction cup, the lower part is in contact with the hypodermis and no mechanical link is really ensured. The upper part approaches perfect blockage whereas for the lower part, the situation is more like simple contact. Concerning the possibility of slipping, the same remarks can be made, the top of the skin, in contact with the cup presents a fixed edge while below, as sliding is possible between dermis and hypodermis, the situation is closer to that of a free edge. It is therefore only to be expected that none of the coefficients proposed by Timoshenko is perfectly representative of reality. We therefore looked for a pair of values, which give an optimal representation of the results obtained by FE. After having tested the values corresponding to a plate in contact with free edges, we tried different pairs of values ($A = 0.5/B = 0.55$, 0.7/0.55, 0.4/0.5, 0.3/0.55, 0.3/0.5) and finally selected the pair $A = 0.3$ and $B = 0.45$ which appeared to be the most suitable (Fig. 6). Concerning the ranges of depression values and equivalent moduli representative of actual conditions of use, equation (3) gives very representative results with the same coefficients A and B. There is a discrepancy for low negative

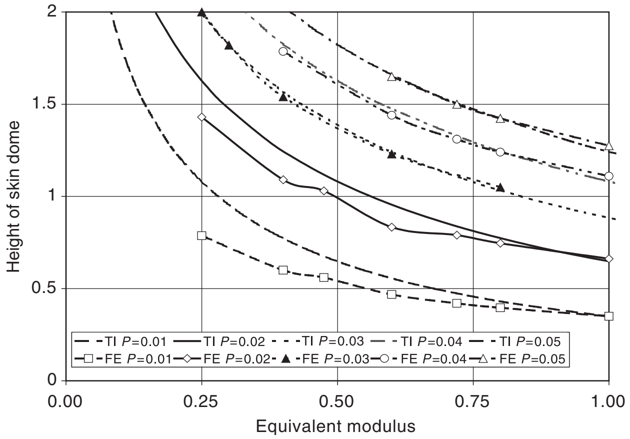


*Fig. 6. Comparison finite elements and Timoshenko $A = 0.3/B = 0.45$.*

*TABLE 1. Coefficients of Timoshenko's model in various conditions*

| Limit conditions | $A$ | $B$ | $\alpha_r$ | $\beta_r$ |
|---|---|---|---|---|
| *Embedded plate* | | | | |
| Fixed edge | 0.471 | 0.171 | 0.976 | 2.86 |
| Free edge | 0.146 | 0.171 | 0.500 | 2.86 |
| *Plate just resting on surface* | | | | |
| Fixed edge | 1.852 | 0.696 | 0.905 | 1.778 |
| Free edge | 0.262 | 0.696 | 0.295 | 1.778 |

*TABLE 2. Results obtained by FE for different types of materials*

| Modulus $E_1$ | Modulus $E_2$ | Elevation at centre in mm | Modulus Mat | Modulus Mat corrected |
|---|---|---|---|---|
| 0.8 | 0.8 | 1.05 | 0.8 | 0.8 |
| 0.6 | 0.6 | 1.23 | 0.6 | 0.6 |
| 0.4 | 0.4 | 1.54 | 0.4 | 0.4 |
| 0.3 | 0.3 | 1.82 | 0.3 | 0.3 |
| 0.25 | 0.25 | 2.02 | 0.25 | 0.25 |
| 1 | 0.8 | 1.01 | 0.875 | 0.86 |
| 1 | 0.6 | 1.10 | 0.75 | 0.72 |
| 1 | 0.4 | 1.25 | 0.625 | 0.58 |
| 1 | 0.25 | 1.40 | 0.531 | 0.475 |
| 0.8 | 0.4 | 1.323 | 0.550 | 0.52 |
| 0.8 | 0.2 | 1.586 | 0.425 | 0.38 |
| 0.6 | 0.2 | 1.74 | 0.350 | 0.32 |
| 2 | 0.2 | 1.14 | 0.875 | 0.74 |

pressures but it is much smaller than that found with the geometric method.

*Modelling the stress state*

*Comparison: geometric method and FE*

The geometric method allows the calculation of the stresses in the plate subjected to a suction test. Biaxial stress uniform in the depth of the plate was found; its value is given by formulae (1).

*TABLE 3. Comparison between the results obtained by the Timoshenko and the geometric methods*

| Dome elevation | $E$ Tim | $E$ Geo | $\Delta\ E_T/E_G$ | $\sigma$ Tim | $\sigma$ Tim $F$ | $\sigma$ Geo |
|---|---|---|---|---|---|---|
| 0.25 | 4.29 | 41.1 | 0.1 | 0.013 | 0.167 | 0.27 |
| 0.5 | 2.03 | 5.25 | 0.38 | 0.025 | 0.158 | 0.13 |
| 0.75 | 1.25 | 1.6 | 0.78 | 0.035 | 0.146 | 0.09 |
| 1 | 0.84 | 0.72 | 1.16 | 0.042 | 0.131 | 0.075 |

$$\sigma = \frac{pR}{2e} = \frac{p(a^2 + u^2)}{4eu}$$

from a FE point of view, each model calculates the stress at each node of the vertical passing through the centre of the plate. It is therefore easy to compare the results obtained by the two methods. We saw, in Fig. 3, that the stress was not constant through the thickness of the plate; it is the sum of a tensile stress and a flexion stress, which is not compatible with the results of the geometric method and therefore not representative of reality.

*Comparison: Timoshenko method and FE*

We saw that the Timoshenko model enabled the calculation of a tensile stress that is constant through the thickness of the specimen (equation (4)) and a flexion stress changing in the bulk of the specimen with a negative maximum at the top becoming positive at the lower surface (5). The values of coefficients $\alpha$ and $\beta$ involved in the formulae depend on the limit conditions (Table 1). As already done for coefficients $A$ and $B$, we sought to optimise these coefficients to bring the Timoshenko model closer to the FE calculations with limit conditions of the 'suction' type. Timoshenko's stress is then given by equation (10) which, for a position in the thickness $Z$ varying from 0 (lower surface) to 1 (upper surface) is:

$$\sigma_x^z = \alpha E \frac{u_0^2}{a^2} + \beta E \frac{u_0 e}{a^2}(-1 + 2z) \qquad (10)$$

following a few trails, we can propose the values $\alpha = 0.45$ and $\beta = 1.4$ which enable the relationships given by Timoshenko to give a good representation of the results obtained by FE (Fig. 7).

## Conclusions

From the calculations carried out using FE for large displacements and large deformations, we propose to use Timoshenko's method for analys-

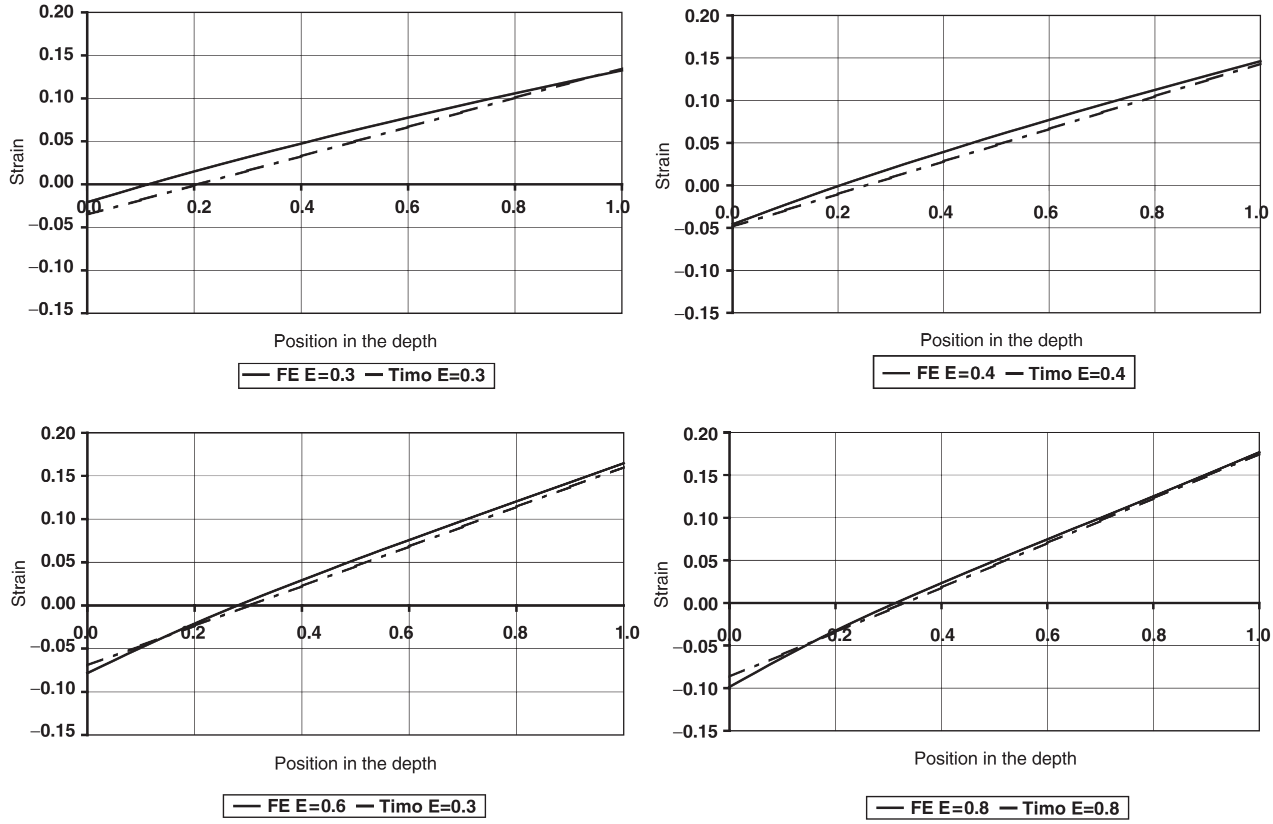


*Fig. 7. Comparison of the optimised finite elements and Timoshenko stresss (MPa). α = 0.45 β = 1.4 for different values of the modulus.*

ing the results of suction tests. The coefficients of the relationships giving the modulus and the stress have been optimised and lead to the following equations:

$$E = \frac{0.45pa^4}{e^4\left(\dfrac{u_0}{e} + 0.3\left(\dfrac{u_0}{e}\right)^3\right)},$$
$$\sigma^t = 0.45E\frac{u_0^2}{a^2}, \qquad (11)$$
$$\sigma^f_{\max} = 1.4E\frac{u_0 e}{a^2}$$

where $E$ is Young's modulus of an isotropic material or the equivalent modulus (0.3 $E_1$+0.7 $E_2$) for an orthotropic material, $p$ the applied negative pressure, $a$ the radius of the cup, $e$ the thickness of the skin and $u_0$ the elevation at the centre of the dome.

It can be recalled that the geometric method gave the following values:

$$E = \frac{pa(1-\nu)}{2e[Arc\sin(2au_0/(a^2+u_0^2)) - 2au_0/(a^2+u_0^2)]},$$
$$\sigma = \frac{p(a^2+u_0^2)}{4eu_0}$$

The differences between the two methods can be illustrated by a few examples. For $p = -0.03$ MPa, $a = 3$ mm, $\nu = 0.3$ and $e = 1$ mm, we can compare the values obtained for the modulus and for the stress.

The differences in the values obtained by the two methods are sometimes very large but in some configurations, the geometric method can give values that are quite acceptable. This probably explains why it still has so much success for the interpretation of suction test results.

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