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SOME REMARKS ON THE PRINCIPLES OF SAINT-VENANT

The validity of the generalized Hooke's law is checked by the relations obtained from the solution of the boundary value problem of the equilibrium of the cylinder, the boundary conditions on the basis of which are simplified on the basis of the narrowed and general principles of Saint-Venant. However, these relations are not a generalized Hooke's law, but the kind in which these principles are invisibly present. With this in mind, they should be called Hooke–Saint-Venant relations. In this light, the deviation of experimental data from these relations should be discussed not as a deviation from the generalized Hooke's law, but from its simplified form by the principles of Saint-Venant. The ratios turned out to be inconsistent, the experimental points are not located in the way they envisage. This, it would seem, is the end of the question. But no, the load-strain diagram has gained independence. Based on the assumption, as shown in this paper, it began to be considered as an experimentally determined physical law.

The real deformation, as shown, cannot be explained at all by expressions (4), according to which the parts of the body do not interact with each other at all. But the acceptance of this assumption has become fixed – the tense state must necessarily be uniaxial.

Keywords: Saint-Venant principle, Hooke–Saint-Venant relation, Hooke's law, deformation, mechanics of deformable body.

Introduction

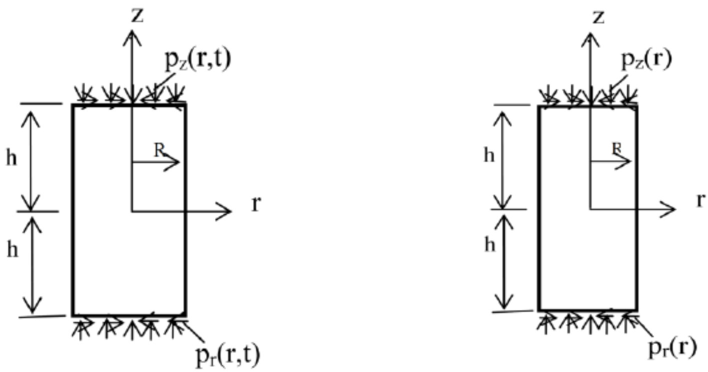
Let statically equivalent (having the same main vector and main moment) distributed loads act on a small part of the body surface. The Saint-Venant principle states that the deformations and stresses caused by these load distributions differ little at points sufficiently remote from the places of application of loads [1].

This is a general formulation of the general principle of Saint-Venant, which has no convincing proof. In this regard, V. Novatsky noted that «... the so-formulated Saint-Venant principle, also called the «principle of equivalent loads», is still insufficiently theoretically justified» [1]. This circumstance forced us to narrow down this principle.

Here is the formulation of the narrowed Saint-Venant principle made by A. Love [2]: «If the forces acting on a small part of the surface are equivalent to zero force and zero moment, then the stresses decrease with distance from the application sites and are negligible at distances significant compared to the linear size of the loaded part of the body.»

Materials and methods

Axial compression, stretching, undoubtedly represent a process with time-varying values of loads, stresses, deformations and displacements. Cut out a part of the sample in the form of a cylinder with a height of 2h and a radius of R.



a b

Figure 1 – Representations of boundary conditions on the bases of the cylinder, which correspond to reality (a) and the static boundary value problem (b)

In Figure 1 a, the external forces depend on time. This is something that is consistent with what is taking place in the trials. Axial stress distribution in the central cross section

$$\sigma_z(r,0,t) = \lambda(\frac{\partial u(r,0,t)}{\partial r} + \frac{u(r,0,t)}{r}) + (\lambda + 2\mu)\frac{\partial w(r,0,t)}{\partial z} \tag{1}$$

During loading , it undergoes changes depending on the boundary forces $p_r(r,t)$, $p_z(r,t)$. What is the nature of these changes?

First of all, we note that on the central cross-section with a very small error, the magnitude of the axial deformation can be assumed constant and equal to $\frac{\partial w(r,0,t)}{\partial z} = \varepsilon_z(R,0,t)$. Let's explain this.

Function $w(r,z,t)$ due to the symmetry of the loads at $z = 0$ does not depend on r , i.e $w(r,0,t) = 0$ (the central cross section remains flat). Here we can assume that with the values z , close to zero, the function $w(r,z,t)$ very little depends on r , which allows you to make the above representation. Thus, for the central cross-section, equation (1) has the form:

$$\sigma_z(r,0,t) = \lambda\left(\frac{\partial u(r,0,t)}{\partial r} + \frac{u(r,0,t)}{r}\right) + (\lambda + 2\mu)\varepsilon_z(R,0,t) \qquad (2)$$

Boundary condition on the lateral surface:

$$\sigma_r(R,0,t) = (\lambda + 2\mu)\,\varepsilon_r(R,0,t) + \lambda\,(\varepsilon_\varphi(R,0,t) + \varepsilon_z(R,0,t) = 0$$

we will write in the form:

$$\varepsilon_r(R,0,t) = -\frac{\lambda}{\lambda + 2\mu}(\varepsilon_\varphi(R,0,t) + \varepsilon_z(R,0,t) ,$$

and from it we calculate the values of the radial deformation. They turned out to be not equal to the values of the annular deformation (with the exception of one point of the diagram) [3–5].

Results and discussion

There is an inequality in the initial part of the diagram $\varepsilon_r(R,0,t) \succ \varepsilon_\varphi(R,0,t)$. The predominant development of radial deformations at this stage is what should happen. Deformation beyond the side face does not have such an obstacle as meets deformation in the annular direction.

Let's assume that this inequality persists at internal points, i.e. $\frac{\partial u(r,0,t)}{\partial r} \succ \frac{u(r,0,t)}{r}$

Multiplying both parts of this inequality by r and, differentiating by r, we come to inequality:

$$\frac{\partial^2 u(r,0,t)}{\partial r^2} \succ 0$$

This inequality suggests that at this stage of deformation, the function $u(r,0,t)$ the upward concave curve (Fig. 2 a). For such a curve, the sum in the parenthesis of the right side of equation (2) increases with increasing r, which leads to a decrease in the magnitude of the axial stress. At this stage, the distribution $\sigma_z(r,0,t)$ has the character indicated in Fig. 3 a.

Then comes the moment when $\varepsilon_r(R,0,t) = \varepsilon_\varphi(R,0,t)$. If the same equality exists at the inner points, then $\frac{\partial u(r,0,t)}{\partial r} = \frac{u(r,0,t)}{r}$.

This is the case if the function $u(r,0,t)$ it is straightforward (Fig. 2b). Here the sum in the parenthesis of the right side of equation (2) is constant, therefore, constant and $\sigma_z(r,0,t)$ (Fig. 3b).

Sharpening the uniformity of the stressed state $\varepsilon_r(R,0,t) \prec \varepsilon_\varphi(R,0,t)$

At this stage, the squeezing action of the internal parts of the body, which tend to satisfy their need for expansion, apparently increases. If such inequality also occurs at internal points, then $\frac{\partial u(r,0,t)}{\partial r} \prec \frac{u(r,0,t)}{r}$.

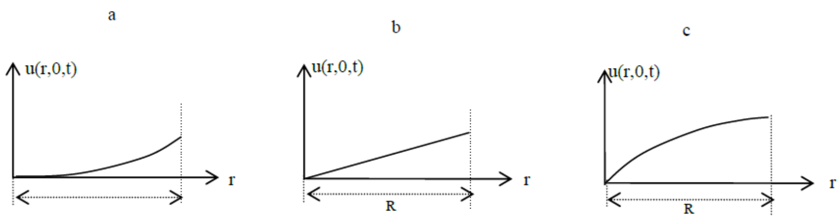


Figure 2 – Changes in the radial displacement function during loading

Multiplying both parts of this inequality by r and differentiating by r, we arrive at the inequality $\frac{\partial^2 u(r,0,t)}{\partial r^2} \prec 0$.

This inequality suggests that at this stage of deformation, the function $u(r,0,t)$ a downward concave curve (fig. 2 in). For such a curve, the sum in the parenthesis of the right side of equation (2) decreases with increasing r, which leads to an increase in the magnitude of the axial stress. At this stage, the distribution $\sigma_z(r,0,t)$ it has the character indicated in Fig. 3 c.

In the mechanics of a deformable body, the boundary conditions are represented in the form indicated in Fig. 1b, in which nothing depends on time.

However, the static boundary value problem is not solvable and with such simplification – efforts $p_r(r)$, $p_z(r)$ unknown. Based on the narrowed principle of

Saint-Venant, we assume $p_r(r)$=0. C this should be agreed, because this principle has a theoretical proof.

But what to do with the uncertainty of the function $p_z(r)$? Here the general principle of Saint-Venant comes to the rescue. According to him, the unknown $p_z(r)$ it can be replaced with any given distribution, as long as the equality is satisfied:

$$P = \int_0^R \int_0^{2\pi} p_z(r) r dr d\varphi, \tag{3}$$

where P – is the entire axial load.

There are an infinite number of such distributions (some of them are shown in Fig. 3).

The principle allows replacement even in the form of a single concentrated force equal to the entire axial force and applied in the center of the cylinder base (Fig. 3 g). For any specified and unspecified axial force distributions in Fig. 3, according to this principle, in the central part of the cylinder, there should be:

$$\sigma_r(r,z) = 0, \quad \sigma_{rz}(r,z) = 0, \quad \sigma_\varphi(r,z) = 0, \quad \sigma_z(r,z) = \frac{P}{\pi R^2}. \tag{4}$$

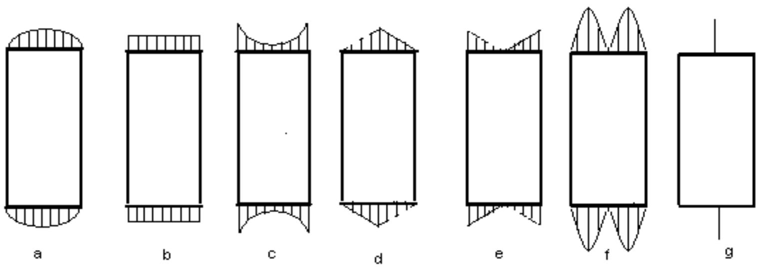


Figure 3 – Equivalent loads, any of which can be replaced by unknown distributions of external axial forces on the bases of the cylinder

The boundary value problem (equations of equilibrium, compatibility of deformations and boundary conditions) proves this assumption only for the distribution of external forces indicated in Fig. 3b:

$$p_r(r) = 0, \quad p_z(r) = \frac{p}{\pi R^2}.$$

For the other distributions indicated and not indicated in Fig. 2, assumption (4) is no longer a solution to the static boundary value problem and subject to the reservation h>>R. The possibility of accepting assumption (4) even with some approximations has not been proven.

Repeated attempts did not give the desired result.

However, by assumption (4) and the relations that follow from it:

$$\varepsilon_r(r,z) = -\frac{\nu}{E}\frac{P}{\pi R^2}, \quad \varepsilon_\varphi(r,z) = -\frac{\nu}{E}\frac{P}{\pi R^2}, \quad \varepsilon_z(r,z) = \frac{1}{E}\frac{P}{\pi R^2}. \qquad (5)$$

deformable solid mechanics is widely used. Usually, the generalized Hooke's law is identified by the relations (5). But this is not true. This law has the form:

$$\varepsilon_r(r,z,t) = \frac{1}{E}(\sigma_r - \nu(\sigma_\varphi + \sigma_z) \quad \varepsilon_\varphi(r,z,t) = \frac{1}{E}(\sigma_\phi - \nu(\sigma_z + \sigma_r) \quad \varepsilon_z(r,z,t) = \frac{1}{E}(\sigma_z - \nu(\sigma_r + \sigma_\varphi) \qquad (6)$$

It takes the form (5), if and only if we substitute assumption (4), which proceeds from the principles of Saint-Venant, into it. Because of this, representation (5) is more correct, in our opinion, to call the Hooke–Saint-Venant relations.

At the same time, the fact is forgotten that it is mechanically incorrect to study this process of deformation of bodies by a static boundary-value problem, and the general principle of Saint-Venant, due to its unprovenness, is still doubtful. Consequently, the relations (5) are also doubtful.

Assumption (4) is also incorrect. It contradicts what happens in the trials. Let's show this by the example of axial compression. Let the sample have sufficient length, which is stipulated when applying the Saint-Venant principle. Next, we will consider only the central part of the sample, where, according to this principle, there should be a uniaxial stress state:

$$\sigma_r(r,z) = 0, \quad \sigma_\varepsilon\ (r,z) = 0, \quad \sigma_\varphi(r,z) = 0, \quad \sigma_z(r,z) = \frac{P}{\pi R^2}$$

However, the stress state cannot be the same in this part of the sample.

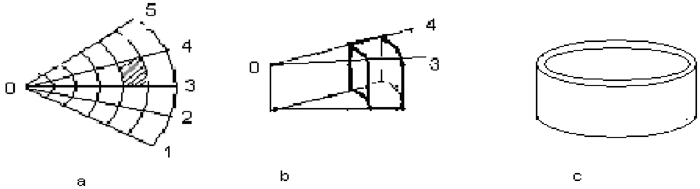


Figure 4 – Part of the cross section (a), volume element

(b) and thin-walled cylinder (c)

Figures 4 a and b show a part of the cross section and one of the cylindrical elements. According to assumption (4), this element does not experience any influence from the four such elements in contact with it. There is, as it were, emptiness behind its side faces. In this case, the center of mass of this element should not move in the radial direction, and the expansion should occur beyond all the side faces. But we know that the center of mass moves in a radial direction. The expansion is such that the element remains between the rays 0-3 and 0-4, and the radial side faces move only in the direction of increasing their radii, which can only take place if there is interaction with the surrounding elements. Thus, the voltage:

$$\sigma_r(r,z)\ \sigma_z\ (r,z)\ \sigma_\varphi(r,z)$$

Expressing this interaction cannot be equal to zero during the entire deformation time. Are their values small?

Let's cut out a hollow cylinder (Fig. 4c) with internal r and external r + dr radii. Radial stresses act on the inner and outer side surfaces $\sigma_r(r,z)$. hat should be the magnitudes of these stresses, so that under their action the radii increase even by some infinitesimal magnitudes. You can imagine their values by mentally pumping air or liquid into such a cylinder. These stresses, we agree, are not small at all. There are assumptions, as well as the development of this issue, but this is all a special case of a particular problem [6,7].

Thus, during the entire time of deformation, the stress state cannot be the same as it is indicated in assumption (4). According to it, the inner and outer side surfaces are free, there are no forces on them. The parts of the cylinder located inside and outside the hollow cylinder have no effect on its deformation.

Conclusions

The child of the general principle of Saint Venant (assumption (4)) turned the generalized Hooke's law (6) into one-dimensional relations (5), which "rewarded" it with almost zero consistency. From the point of view of relations (5), the body obeys the generalized Hooke's law if its experimental diagram is straight from beginning to end [8]. But the diagram is not like that. It is curved, has a rather complex outline. Consequently, this law, as it is commonly believed, is not valid. It is possible to partially apply it in the initial part of the diagram, if this part is straight or close to it. It should be noted here that the straightness of the initial part is a controversial position. The diagram here also has a curvature. As noted by academician Yu. N. Rabotnov [9], this can be detected already at small deformations the earlier the more perfect the measuring equipment. This led him to the conclusion that in the field of small deformations there is a systematic deviation from the law. Thus, there is little left of his solvency. This is the perception of the generalized Hooke's law, which is created by the usual criterion.

The generalized Hooke's law, as is known, is derived from modern ideas about the molecular structure of bodies [10] and has the form of equations (6). But, figuratively speaking, it was "forced" to deal only with uniaxial stress states (4), which it contains and looks like (5). And in this form, the generalized Hooke's law, taking the form (5) with the principles of Saint-Venant, «tries» to describe experimental measurements. And the real stress states are not uniaxial and the particles of the body still interact with each other.

This is only the visible part of the iceberg. There is also a significant «underwater» part. If there were no relations (5), apparently, it would not be necessary to apply experimental data to the plane of load and axial deformation, i.e. to build a load-strain diagram. Such an application pursued, presumably, one single goal – to check the vitality of the ratios (5). The ratios turned out to be inconsistent, the experimental points are not located as they envisage. This, it would seem, is the end of the question. But no, the load-strain diagram has gained an independent life. Based on assumption (4), it began to be considered as an experimentally determined physical law.

The real deformation, as shown above, cannot be explained at all by expressions (4), according to which the parts of the body do not interact with each other at all. But the acceptance of this assumption has become fixed – the tense state must necessarily be uniaxial. However, the load-strain diagram, considered as a stress-strain diagram, could not be analytically described, although great mathematicians and mechanics struggled over it.

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СЕН-ВЕНАН ПРИНЦИПТЕРІ ТУРАЛЫ КЕЙБІР ЕСКЕРТУЛЕР

Гуктың жалпыланган заңының дұрыстыгы цилиндрдің тепе-теңдігі туралы шекаралық есепті шешуден алынган қатынастар бойынша тексеріледі, оның негізінде шекаралық шарттар тарылган және жалпы Сен-Венан принциптері негізінде жеңілдетіледі. Алайда, бұл қатынастар Гуктың жалпыланган заңы емес, оның осы принциптері көрінбейтін түрде болатын басқаша түрі. Осыны ескере отырып, оларды Гук–Сен-Венан қатынасы деп атаган жөн. Осы тұргыдан алганда, тәжірибелі деректердің осы қатынастардан ауытқуы Гуктың жалпыланган заңынан ауытқу ретінде емес, оның Сен-Венан принциптерімен жеңілдетілген түрінен талқылануы керек. Қатынастар бай емес болып шықты, тәжірибелік нүктелер олар қарастыргандай орналаспайды. Бұл мәселе таусылган сияқты. Бірақ жоқ, жүктеме-деформация диаграммасы дербестікке ие болды. Болжамга сүйене отырып, бұл жұмыста көрсетілгендей, ол тәжірибелі түрде анықталган физикалық заң ретінде қарастырыла бастады.

Көрсетілгендей, нақты деформацияны (4) өрнектермен түсіндіруге болмайды, оган сәйкес дене бөліктері бір-бірімен мүлдем әрекеттеспейді. Бірақ бұл болжамды қабылдау бекітілді-шиеленіскен күй міндетті түрде бір осьті болуы керек.

Кілтті сөздер: Сен-Венан принципі, Гук–Сен-Венан қатынасы, Гук заңы, деформация, деформацияланатын дене механикасы.

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НЕКОТОРЫЕ ЗАМЕЧАНИЯ О ПРИНЦИПАХ СЕН-ВЕНАНА

Состоятельность обобщенного закона Гука проверяется по соотношениям, полученным из решения краевой задачи о равновесии цилиндра, граничные условия на основаниях которого упрощены на основе суженного и общего принципов Сен-Венана. Однако, эти соотношения – не есть обобщенный закон Гука, а тот его вид, в котором незримо присутствуют эти принципы. Имея в виду это, их следует назвать соотношениями Гука–Сен-Венана. В этом свете, отклонение опытных данных от этих соотношений должно обсуждаться не как отклонение от обобщенного закона Гука, а от его упрощенного принципами Сен-Венана вида. Соотношения оказались не состоятельными, опытные точки располагаются не так, как того они предусматривают. На этом, казалось бы, вопрос исчерпан. Но нет, диаграмма нагрузка-деформация обрела самостоятельность. На основании предположения, как показано в данной работе, она стала рассматриваться как опытно определяемый физический закон.

Реальное деформирование, как показано, нисколько не может быть объяснено выражениями (4), по которому части тела вовсе не взаимодействуют друг с другом. Но принятие этого предположения закрепилось – напряженное состояние непременно должно быть одноосным.

Ключевые слова: Принцип Сен-Венана, соотношение Гука–Сен-Венана, закон Гука, деформация, механика деформируемого тела.

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