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BEHAVIOR OF WELDED STRAWS IN VACUUM

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Поведение сварных строу в вакууме

Рассмотрена возможность работы сварных строу-трубок в условиях вакуума. Поведение строу в вакууме рассматривается в рамках теории цилиндрических оболочек. Приведено решение уравнения равновесного состояния строу, описывающее ее поведение при действии предварительного натяжения и перепада давления. Решение показывает, что вращение самоподдерживающихся строу происходит за счет момента, действующего на незакрепленные концы. Сделана оценка деформации преднатянутой строу под действием давления. Ее натяжение уменьшается пропорционально перепаду давления и коэффициенту Пуассона. Рассмотрено влияние температуры и скорости деформации на механические свойства строу. Указан оптимальный температурный режим для долговременной работы строу в эксперименте.

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Volkov A. D. E13-2016-73
Behavior of Welded Straws in Vacuum

The possibility of working welded straw tubes in vacuum is considered. The behavior of straw in a vacuum is considered in the framework of the cylindrical shells theory. A solution to the equilibrium state equation for a straw tube describing its behavior under the effect of pre-tensioning and internal pressure is provided. The analysis of the solution shows that the rotation of self-supporting straws is due to the moment acting on the unfixed ends. The estimation of strain caused by the overpressure is made. An original technique of measurement of straw Poisson's ratio is presented and its dependence on tension is investigated. The effect of the temperature and the deformation rate on the mechanical properties of straw is considered with polybutylene terephthalate as an example. The optimum temperature range for the long-term straw operation in the experiment is specified.

The investigation has been performed at the Dzhelepov Laboratory of Nuclear Problems and the Veksler and Baldin Laboratory of High Energy Physics, JINR.

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INTRODUCTION

Many experiments aimed at studying physical processes need track detectors with a lot of event detection channels, capable of operating in vacuum. The detectors are required to have a high coordinate resolution, small amount of material on the way of the beam, and low cost. In view of these requirements, drift detectors based on thin-walled tubes, straws, have found wide use as track detectors. A straw is a gas-filled drift detector made from plastic film. The inner side of the film is carbon coated or metalized. This layer simultaneously serves as a cathode and a screen, which decreases the effect of the fired straws on each other. The ends of the tubes are closed with plugs, to which the signal wire is attached and through the holes in which a working gas mixture is supplied. Characteristics and operation principles of the straws made by wrapping the film round a rod and gluing the wrapped layers are presented in [1]. While operating, the straw must maintain its cylindrical shape. Otherwise, inhomogeneous distribution of the electric field in angle φ occurs inside the tube, which leads to loss of accuracy in determination of the charge particle coordinate. In modern experiments straw detectors have to operate in a vacuum of $\sim 10^{-6}$ mbar, and the straw tubes therefore need to be pre-tensioned for reducing the effect produced on their shape by the pressure difference, gravity, and temporary creep of their material. A new straw production technology using ultrasonic welding has been developed at JINR [2], which allows producing straw tubes featuring high strength, high coordinate resolution, and ability to operate in vacuum for a long time. Straw tubes of this type find wide use [3–5]. Deformation of straws under the effect of forces is considered within the theory of shells [6–9], which was used in the study of a behavior of the straws. The experience of employing straws in vacuum reveals unsolved problems related to the optimum tension, internal pressure effect, and allowance for straw material creep. The authors of [10] were faced with such a phenomenon as rotation of the straw under the effect of the internal pressure and failed to find out its cause. The goal of this work was to investigate deformation of a pre-tensioned straw under the effect of the internal pressure and estimate the effect of temperature on mechanical properties of a straw.

MATHEMATIC MODEL OF THE STRAW EQUILIBRIUM STATE

Figure 1 shows the system of coordinates for an element of a cylindrical shell and the forces and moments acting on it. The figure and the equation are borrowed from [11].

The action of the forces, tension, and pressure difference is symmetric about the central axis, which allows an analytical solution to be obtained for the equilibrium state equation. The equilibrium equation for a cylindrical shell describes its radius variation under the effect of the applied forces. With gravity ignored, the equation for a shell with constant thickness and homogeneous properties has the form

$$\frac{d^4 w}{d^4 x} + 4\beta^4 w = \frac{1}{D}\left(q_z - \frac{\mu}{r} N_x\right), \tag{1}$$

where w is the cylinder radius variation, β is the parameter depending on the properties of the material of the cylinder and on its size, D is the rigidity of the cylinder, μ is Poisson's ratio for the material of the tube, q_z is the density of the radial force, N_x is the force per unit length of the tube perimeter acting along the X axis, r is the inner radius of the cylinder, E is the elastic modulus of the tube material, and h is the tube wall thickness. The cylindrical rigidity D and

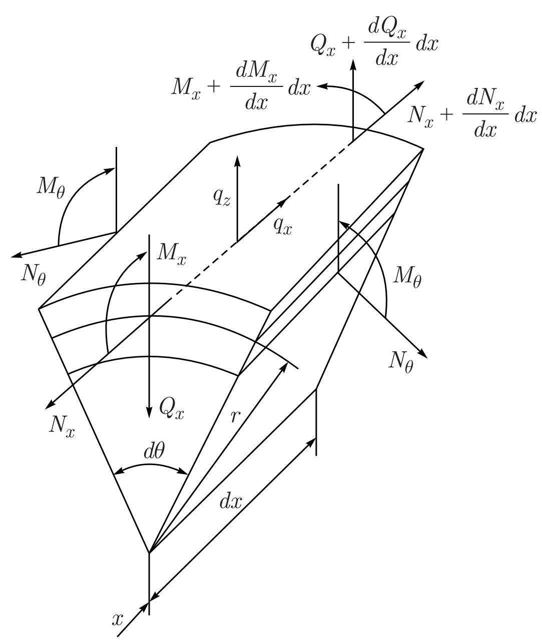

Fig. 1. Cylindrical shell

the parameter β are defined by the expressions

$$D = Eh^3/12(1-\mu^2), \tag{2}$$

$$\beta^4 = 3(1-\mu^2)/r^2h^2. \tag{3}$$

To describe the equilibrium of the straw, Eq. (1) will involve the force q_z, which is equal to the action of the internal and external pressure difference, and the tension force N_x. When the straw operates in vacuum, the stress caused by the pressure difference P will be equal to $q_z = P$, which amounts to about one atmosphere (1 kg/cm^2). In the theory of shells, forces are expressed per unit length or unit area of the corresponding cross section [11], and the longitudinal force N_x in Eq. (1) will therefore be $N_x = T_0/2\pi r$. With the values of the acting forces substituted into it, the equilibrium equation takes the form

$$\frac{d^4w}{d^4x} + 4\beta^4 w = \frac{1}{D}\left(P - \frac{\mu}{2\pi r^2}T_0\right). \tag{4}$$

THE SOLUTION TO HOMOGENEOUS EQUILIBRIUM EQUATION

The solution to (4) includes the solution to the homogeneous equation $w_1(x)$ and the particular solution to the equation $w_2(x)$, which show the amount of change in the straw radius along the X axis. The solution to the homogeneous equation is given in [12]:

$$\frac{d^4w}{d^4x} + 4\beta^4 w = 0, \tag{5}$$

$$w_1(x) = \frac{\mathrm{e}^{-\beta x}[\beta M_x(\sin\beta x - \cos\beta x) - Q_0\cos\beta x]}{2\beta^3 D}. \tag{6}$$

The bending moment M_x and the transverse force Q_0 at the ends of the straw tube are defined by the relations

$$M_x = -D\left(\frac{d^2w}{dx^2}\right)_{x=0,L} = M_0 = P/2\beta^2,$$

$$Q_0 = -D\left(\frac{d^3w}{dx^3}\right)_{x=0,\,L} = -P/\beta.$$

According to the moment theory of shells, the action of forces on the shell gives rise to not only the moment M_x but also the moment $M_\theta = \mu M_x$ [6, 8]. The action of the moment M_θ on the straw with unfixed ends causes its rotation. This effect will manifest itself in detectors based on self-supporting straw tubes [13]. The moments M_x and M_θ and the transverse force Q are shown in Fig. 1. It follows from (6) that the maximum change in the radius is at the straw attachment points $x = 0$ and $x = L$,

$$(w_1)_{x=0,L} = -\frac{1}{2\beta^3 D}(\beta M_0 + Q_0) = 28.7\ \mu\text{m}. \tag{7}$$

The solution to the homogeneous equation involves a factor $\mathrm{e}^{-\beta x}$, and its amplitude therefore quickly decays along the X axis. When $\beta x > 3$, its contribution is ignored. The condition $\beta x > 3$ is fulfilled for them at the straw length $x > 2$ mm. Thus, the edge effect is observed at the attachment points. Below the straws under consideration were made of polyethylene terephthalate and measured $r = 4.95$ mm, $h = 36$ μm and $L = 2$ m. Their mechanical properties were characterized by Poisson's ratio $\mu = 0.31$ and the elastic modulus $E = 3 \cdot 10^9$ N/m^2. According to (3), $\beta = 3.04 \cdot 10^3\ \text{m}^{-1}$. The moments M_0, M_θ like the transverse force act only at the ends of the straw.

THE PARTICULAR SOLUTION TO EQUILIBRIUM EQUATION

For the equilibrium state of the straw, the particular solution $w_1(x)$ is of interest. It should be borne in mind that the straw radius variation along the X coordinate is a smooth, slowly varying function of small amplitude. Therefore, the term d^4w/d^4x can be ignored in the search for the particular solution. In this case, the particular solution will have the form

$$w_2(x) = \frac{1}{4\beta^4 D}\left(P - \frac{\mu}{2\pi r^2}T_0\right). \tag{8}$$

It follows from (8) that the radius variation is constant over the straw length and depends on the properties of the material of the straw, its size, tension T_0, and pressure difference P. Pressure causes an increase in the straw diameter, while tension leads to a decrease in the diameter. When there is no tension ($T_0 = 0$), the increase in the radius $w_2(x)$ of the straw with the above parameters under the effect of the 1-atm pressure difference will be

$$w_2(x) = 0.2252 \cdot 10^{-9} \cdot 9.81 \cdot 10^4 \cong 22.1\ \mu\text{m}.$$

Experimental tests under these conditions revealed a change of 25 μm in the radius. The change in the radius can also be estimated from the radial stress σ_r defined by the relation [11]

$$\sigma_r = Pr/h.$$

Strain ε in the elastic region will be $\varepsilon = \sigma_r/E$. Considering the above relations, the increase in the radius will be

$$w_2(x) = \varepsilon r = Pr^2/hE = 22.26\ \mu\text{m}.$$

An insignificant difference in the estimates of the transverse deformation $w_1(x)$ arises from solving Eq. (4) while ignoring the term d^4w/d^4x, whose contribution is less than 1%.

According to (8), the straw tension of 2 kg under the atmospheric pressure (pressure difference $P = 0$) decreases the straw diameter by 8.9 μm. When the straw operates in vacuum, the tension will partially compensate for the pressure effect. The tension $T_0 = 2\pi r^2 P/\mu = 5$ kg fully compensates for the change in the straw diameter under the effect of 1-atm pressure difference because, according to (8), $w_2(x) = 0$. In this case, the straw diameter will be equal to that under no exposure to external forces, but the straw suffers stretching while being tensioned and then under the effect of the pressure, which results in that it becomes thinner.

EFFECT OF PRESSURE IN THE LONGITUDINAL DIRECTION

Let us consider the effect of the internal pressure on the tension of a straw with rigidly fixed ends. According to the theory of shells, the uniaxial tension σ_x directed, for example, along the X axis causes the orthogonally directed stress $\sigma_y = \mu\sigma_x$, where μ is Poisson's ratio. The longitudinal stress caused by the straw tension is $\sigma_{T_0} = T_0/2\pi rh$. Under the effect of pressure P the stress will decrease down to

$$\sigma_m = \sigma_{T_0} - \mu P, \tag{9}$$

where σ_m is the resultant stress over the cross section. Relation (9) is valid at the constant thickness of the homogeneous straw material. Note that under these conditions the stress along the X axis remains constant at each point of the cross section. The pressure inside the straw is also constant. Therefore, relation (9) can be expressed in terms of the measured forces

$$T_m = T_0 - \mu F_P. \tag{10}$$

Here $F_P = 1$ kg/atm is the force of the atmospheric pressure per cm^2 over the straw tube perimeter at a pressure of 1 atm, and T_m is the resultant tension of the straw simultaneously affected by tension and pressure difference. It follows from (10) that at the pressure $F_P = T_0/\mu$ the straw tension will be zero. Poisson's ratio for a straw of polyethylene terephthalate is $\mu \approx 0.31$, and at the tension $T_0 = 2$ kg the internal pressure $P = 6.45$ atm will lead to complete loss of tension. In vacuum the internal pressure of 1 atm will cause a decrease in the tension of welded straws by $\mu F_P \cong 310$ g/atm. Measuring the straw tension before and after supplying a known pressure into it, we can obtain Poisson's ratio of the straw material with a good accuracy. The effect of the pressure was experimentally tested. The straw was pre-tensioned with a force $T_0 = 1560$ g, then pressure was supplied into it at a step of 0.5 atm, and its tension was measured

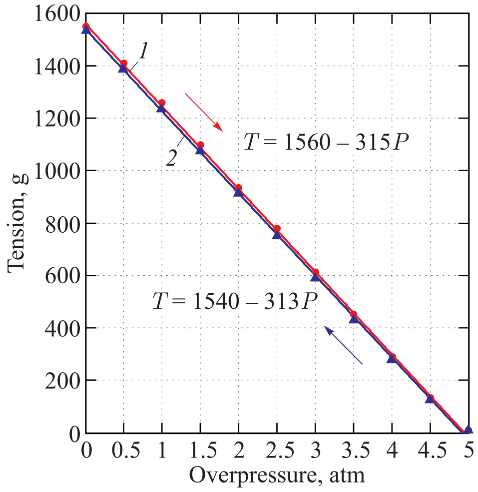

Fig. 2. Straw tension variation under the effect of the internal pressure

at each new pressure value. To eliminate the pressure valve play, measurements were performed as the pressure was successively increased to 5 atm and then decreased at the given step. The test results are shown in Fig. 2.

The experimental data are well described by the linear dependence. The straight line *1* presents the data obtained at successively increasing pressure, and line *2* shows the data obtained at decreasing pressure. The change in pressure direction is shown by arrows. The slope of the dependences corresponds to Poisson's ratio, which was $\mu = 0.315$ at increasing pressure and $\mu = 0.313$ at decreasing pressure. The average of Poisson's ratio found in this way is 0.314. The error in the determination of Poisson's ratio is $\pm 0.32\%$. This value of μ falls within the acceptable range $0.2 \leqslant \mu < 0.5$ [14] and agrees with the tabulated value measured by other methods. At the internal pressure of 4.95 and 4.92 atm the measurements show nonzero straw tension. In both cases the measured tension was 10 g. The deviation of the data from the linear dependence might be caused by the instrumental error and the nonlinear deformation in the region of zero tension.

The zero straw tension means that the straw tube elongation due to the internal pressure is equal to its pre-elongation under tensioning. Further increase in pressure leads to the elongation of the straw that causes its sagging in a horizontal arrangement or bending in a vertical arrangement. Note that for a 2-m-long straw tube a change in its length L by 10 μm at the zero tension leads to its center sagging H by 4.5 mm:

$$H = \sqrt{(L/2 + \Delta L)^2 - (L/2)^2} \cong 4.5 \text{ mm}.$$

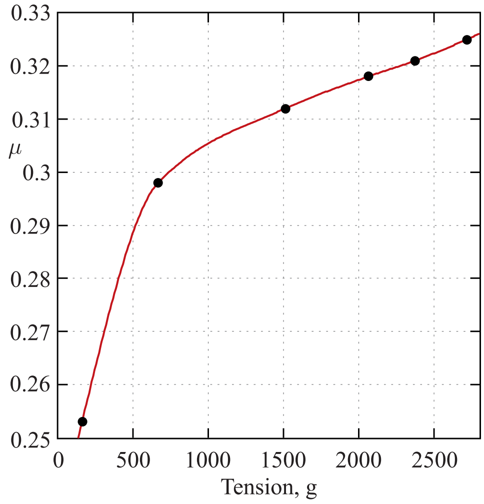

Fig. 3. Dependence of Poisson's ratio on the straw tube tension

The estimation is based on the linear dependence of the sagging over the tube length. It shows that even a small change in the straw length leads to its considerable sagging, which can be avoided by tensioning.

Measurement of Poisson's ratio requires pre-tensioning the tube. Tension affects molecular bonds in the plastic material and ultimately Poisson's ratio. This effect was studied. The results of measuring Poisson's ratio at different tension are shown in Fig. 3.

At low tensions $T_0 < 500$ g, the ratio is seen to increase rapidly with increasing tension, mainly due to the orientation of the transverse fibers in the plastic. The rate of Poisson's ratio change relative to the magnitude of tension is $\mu_T \approx 0.1$ kg^{-1}. At tensions of 0.5 to 1 kg the rate of μ increase slows down to $\mu_T \approx 0.03$ kg^{-1}. At tensions of 1 to 2.7 kg the behavior of μ can be described as $\mu_{\Delta T} = 0.305 + 0.012 \cdot \Delta T$, where $\Delta T = (T - 1)$ is the excess of the tension over the value $T = 1$ kg. At these tensions the transverse deformation of the fibers decreases, and the dependence on tension becomes linear. Poisson's ratio is determined using the atmospheric pressure force per cm^2. This value is not constant in time and depends on the location. Therefore, the value F_P should be corrected for barometer readings to obtain the real value of μ. Measurement of μ at elevated pressure using the constant $F_P = 1$ kg/atm will yield an overestimated value for Poisson's ratio.

In [15] the authors report the results of investigating the temperature and deformation rate effect on Poisson's ratio for a polybutylene terephthalate film (Fig. 4) and the temperature effect on its elastic properties (Young's modulus)

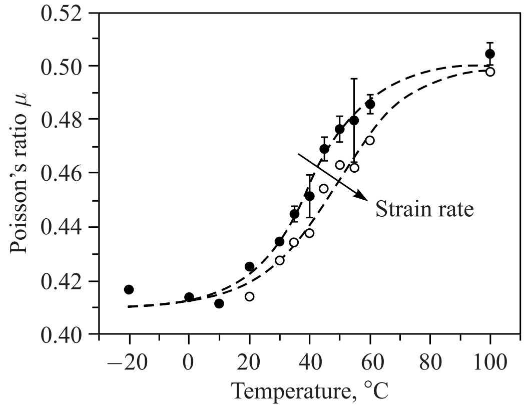

Fig. 4. Dependence of Poisson's ratio on the temperature and deformation rate: • — deformation rate 0.003 s^{-1}, ∘ — deformation rate 0.05 s^{-1}

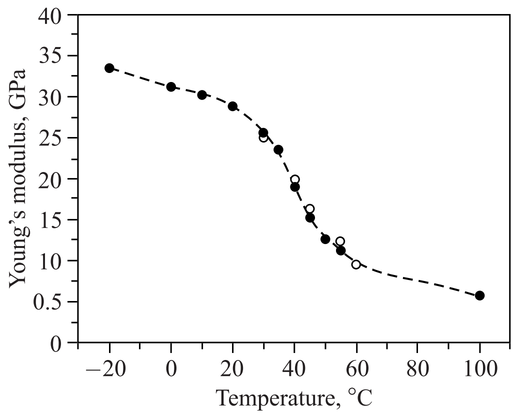

Fig. 5. Dependence of Young's modulus on temperature

(Fig. 5). The dependences obtained in that work also apply to the behavior of a polyethylene terephthalate straw. The difference in properties between these materials is higher strength of polyethylene terephthalate. As a consequence, it has higher Young's modulus and lower Poisson's ratio, which is shown in Figs. 3 and 4. The temperature dependence of the deformation for various materials is also considered in [9]. High-rate deformation of a material leads to its strengthening [16] manifested in decreasing Poisson's ratio.

The increase in temperature causes softening of the material, which increases its plasticity, and an increase in μ. The most stable behavior of Poisson's ratio is observed in the temperature range of -10 to $+10$°C, where it is almost constant.

Young's modulus is an important characteristic of mechanical properties of a material. In the elastic region it governs the amount of strain ε in a body affected by stress, $\varepsilon = \sigma/E$. In the range of temperatures from -20 to $+20$°C Young's modulus changes by less than 10%. The next is the interval of 20 to 60°C, in which elasticity decreases several times. For operating of straw detectors in experiment it is possible to recommend the temperature operating mode $+18 \pm 3$°C, where mechanical properties of tubes are stable.

CONCLUSIONS

Deformation of a straw tube affected by tension and internal pressure has been analyzed. It is revealed why self-supporting straws rotate. Rotation of a straw will lead to its shape deformation causing accuracy loss in the detection of the charged particle coordinate and shortening its service life in the experiment. It is shown that the straw tension depends on the pressure difference. This allows highly accurate determination of Poisson's ratio for thin-walled cylindrical shells. The effect of the straw tension on the determination of Poisson's ratio is investigated. The influence of temperature is considered, and the range is determined in which the mechanical properties of the straw (Young's modulus and Poisson's ratio) are optimal for its operation in the experiment. The results of the investigations are illustrated by experimental dependences, which can be helpful for development of straw detectors.

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