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Braid Angle and its Influence on the Hydraulic Hoses Behaviour Under Pressure Loading

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Abstract. This paper deals with the experimental analysis of the effect of the braid angle on the behaviour of a hydraulic hose under pressure loading. The main structural elements of the hose are a rubber tube and a steel braid or spiral. The material of the braid and the number of braids influence the magnitude of the pressure load on the hydraulic hose. The angle of the braid affects the deformation of the hydraulic hose when the inner wall is loaded with fluid pressure. For hydraulic hoses, it is a requirement to maintain a neutral braid angle during manufacture to ensure a balance between axial and circumferential stresses under pressure loading. An experimental device was set up to measure the hoses. This device can be used to measure the diameter of the outer braid, the length and the tensile force of the hose in the axial direction and, where appropriate, to evaluate the angle of the outer braid of the hose as a function of the fluid pressure loading on the inner wall of the hose. The object of the research is to determine the effect of the braid angle on the behaviour of the hydraulic hose under pressure loading. Based on the measurements, the dependencies of the tensile force, the braid angle and the change in length of hydraulic hoses on the internal pressure were determined. In order to compare the measurement results, hydraulic hoses with different inner diameters and different numbers of braids or spirals were selected.

Research background: Description of neutral braid angle, hydraulic hose geometry, tensile force of hose.

Purpose of the article: Influence of braid angle on the hydraulic hoses behaviour under pressure loading.
Methods: Experimental measurements.
Findings & Value added: Determining of the change of length dependencies on the pressure, determining of the tensile force dependencies on the pressure.

Keywords: *hydraulic hose, braid angle, tensile force, pressure loading*

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1 Introduction

Hydraulic hoses are an important part of hydraulic systems. Hydraulic hoses enable the connection of individual components when their relative positions are changed. This is due to the design of the hydraulic hoses. The construction of a high-pressure hydraulic hose consists of three parts, namely a rubber tube, a steel braid or spiral and a rubber sleeve. However, for special applications, there are other materials for the manufacture of hydraulic hoses, such as thermoplastic polymers [6]. The braid material and the number of braids affect the pressure load capacity of the hydraulic hose. In addition to the steel wire braid, there are hoses where the braid is made of aramid fibres [2]. Two types of high pressure hydraulic hoses can be distinguished according to the braiding method. In the first case, the steel wires are braided together to form a so-called hose braid. Both single-braid and double-braid variants are commonly available on the market [4]. The integration of two steel braids in the manufacture of a hydraulic hose increases its pressure load capacity. In this case, a thin intermediate layer of rubber is placed between the braids. In the case of the second variant, the hose manufacturing technology consists in winding the individual steel wires side by side along the helix. The individual spirals again have a thin layer of rubber between them. For high working pressures, a hydraulic hose variant with four layers of winding spirals is commonly available on the market. The robustness of this construction obviously increases the pressure load capacity of the hose, but at the same time reduces its flexibility in contrast to the steel braided construction.

The angle at which the braid is wound is also important for the design of the hydraulic hose. This angle has a significant effect on the change in geometric dimensions of the hose when the inner wall is loaded with fluid pressure [1, 9, 10]. The lifetime of the hose also depends on this angle [3]. Failure of a hydraulic hose can cause fatal problems, for example, in the braking system of automobiles [7]. Therefore, emphasis is placed on maintaining a neutral braiding angle during the actual production of hydraulic hoses, where the optimum longitudinal feed and braiding speed of the production machine must be maintained [5]. If the neutral angle is maintained, there is a balance between axial and circumferential stresses in the hydraulic hose [12]. The design of a hydraulic hose is very complex, for this reason, it is not easy to clearly determine the material properties of hoses, such as their modulus of elasticity [8]. Hydraulic hoses significantly affect the dynamic properties of hydraulic systems, mainly due to their capacitance or viscoelastic properties [13, 14].

2 Theoretical background

The working pressure of the hydraulic oil causes axial and circumferential stresses in the hydraulic hose, which stresses the hose in both directions. The design of the hydraulic hose is such that there is a balance between the applied stresses. The balance is ensured by the neutral braid angle of the hydraulic hose $\varphi_n = 54.7356°$. Failure to maintain the neutral braid angle during manufacturing results in a change in the geometry of the hydraulic hose under the influence of the working pressure. The hose is more stressed, which can lead to a shortened service life [1]. Table 1 summarizes the geometry change when the braid angle of the hydraulic hose is changed. If the braid angle is less than neutral, the length of the hydraulic hose is shortened. In this variant, a tensile force F_T is generated in the axial direction. This phenomenon is exploited in the case of pneumatic fluidic muscles [15]. The resulting tensile force F_T can put additional stress on the hydraulic hose ends and thus shorten the life of the hydraulic hose. On the other hand, if the braid angle is greater than neutral, the hose length is extended and a compressive force is generated [11].

Table 1. Table of change in geometric properties of a hydraulic hose when the working pressure is applied to the inner wall [11].

Angle change	Hose geometry changes		
	Length	Diameter	Volume
Smaller than neutral	Decreases	Increases	Increases
Greater than neutral	Increases	Decreases	Increases

To determine the neutral angle of the braid, it is possible to consider the hydraulic hose as a cylinder closed at both ends with a radius r, and wall thickness s. Internal pressure in the hydraulic hose p generates axial stress σ_A (see Fig. 1) and circumferential stress σ_O (see Fig. 2) in the walls of the hydraulic hose [12].

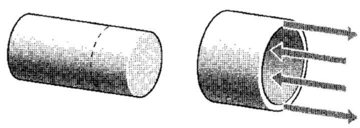

Fig. 1. Axial stress in a closed hydraulic hose [12].

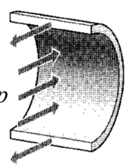

Fig. 2. Circumferential stress in a closed hydraulic hose [12].

The generated axial force F_A is the product of the internal pressure p and the internal area in the hydraulic hose [12]:

$$F_A = \pi \cdot r^2 \cdot p. \tag{1}$$

The axial stress in the wall of the hydraulic hose σ_A is equivalently given by the ratio of the axial force F_A and the area of the hydraulic hose in the cross section, assuming $r >> s$ [12]:

$$\sigma_A = \frac{F_A}{2 \cdot \pi \cdot r \cdot s}. \tag{2}$$

Expressing the axial force F_A from the equations (1) and (2) [12]:

$$F_A = \pi \cdot r^2 \cdot p = \sigma_A \cdot 2 \cdot \pi \cdot r \cdot s, \tag{3}$$

the axial stress in the hydraulic hose σ_A can be determined by the relation (4) [12]:

$$\sigma_A = \frac{p \cdot r}{2 \cdot s}. \tag{4}$$

The circumferential force F_O for a unit length of hydraulic hose can be expressed in the same way [12]:

$$F_O = 1 \cdot 2 \cdot r \cdot p. \tag{5}$$

The circumferential stress expressed for a unit length of hydraulic hose is given by equation (6) [12]:

$$\sigma_O = \frac{F_O}{1 \cdot s} \cdot \frac{1}{2}. \tag{6}$$

Expressing the circumferential force F_O from the equations (5) and (6) [12]:

$$F_O = 1 \cdot 2 \cdot r \cdot p = \sigma_O \cdot 2 \cdot 1 \cdot s, \tag{7}$$

the circumferential stress σ_O in the hydraulic hose can be determined according to the equation [12]:

$$\sigma_O = \frac{p \cdot r}{s}. \tag{8}$$

From equations (4) and (8), it can be seen that the circumferential stress σ_O is twice the axial stress σ_A. Fig. 3 shows a segment of the hydraulic hose and the forces acting on the braid wires. The braid wire makes a braid angle φ with the longitudinal axis of the hydraulic hose [12].

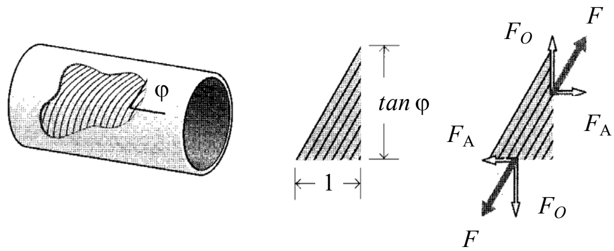

Fig. 3. Forces acting on the hydraulic hose braid [12].

After releasing an element of unit length, the height of the element equals *tan* φ. In order to maintain the equilibrium between circumferential and axial stresses when the internal pressure *p* is applied in the hydraulic hose, equation (9) for the circumferential load and equation (10) for the axial load must be valid [12]:

$$F_O = F \cdot \sin\varphi = \frac{p \cdot r}{s} \cdot 1 \cdot s, \tag{9}$$

$$F_A = F \cdot \cos\varphi = \frac{p \cdot r}{2 \cdot s} \tan\varphi \cdot s. \tag{10}$$

The braid angle φ can be expressed using the goniometric function [12]:

$$\tan\varphi = \frac{F_O}{F_A}, \tag{11}$$

where the axial force F_A and the circumferential force F_O can be divided into the product of the individual stresses and the surfaces on which they act [12]:

$$\tan\varphi = \frac{F_O}{F_A} = \frac{\sigma_O}{\sigma_A} \cdot \frac{1 \cdot s}{\tan\varphi \cdot s}. \tag{12}$$

After substituting equations (4) and (8) into relation (12) we get [12]:

$$\tan\varphi = \frac{2}{\tan\varphi}, \tag{13}$$

$$\tan\varphi = \sqrt{2} = 54.7356\ °. \tag{14}$$

The braid angles of the tested hydraulic hoses are determined in this work. In the case that the unloaded hose has a measured braid angle value less than the neutral angle φ_n, a tensile force F_T and a change in the geometry of the hydraulic hose is expected. For this reason, the effect of the braid angle on the build-up of the tensile force F_T as a function of the working pressure p applied to the inner wall of the hydraulic hose is investigated. The dependence of the hose geometry on the working pressure in the hydraulic hose is also investigated.

As already mentioned, the pressure load capacity is mainly influenced by the braid or spiral of the hydraulic hose. Fig. 4 shows commercially available braid variants. On the left is a close-up of a hydraulic hose with a single braid 1SN. The maximum working pressure of this hose is $p_{max} = 160$ bar. The middle photo shows a detail of a hydraulic hose with two braids 2SN, maximum working pressure $p_{max} = 275$ bar. The highest pressure $p_{max} = 420$ bar is achieved by the hydraulic hose with four spirals 4SP, which is shown on the right.

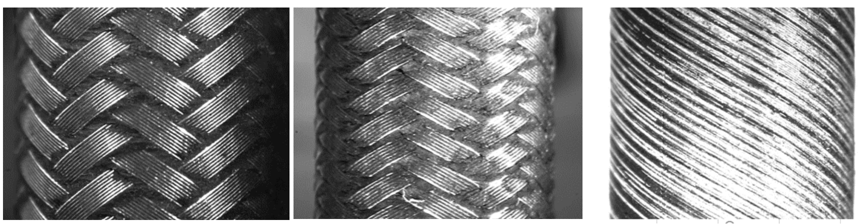

Fig. 4. Comparison of high pressure hydraulic hose braids with internal pressure $d_{in} = 12.5$ mm.

3 Experimental analysis

For the purpose of research in the field of hydraulic hoses, an experimental stand for measuring hydraulic hoses of different diameters was created (Fig. 5, Fig. 6). The support frame is made of modular aluminium profiles for easy modification. The tested hydraulic hose H is rigidly threaded to a plate which is fixed at the top of the support frame. The source of oil flow is the hydraulic power unit. The distribution of oil to the experimental stand is provided by a pressure line P and a return line T. The working pressure of oil p in the hydraulic hose is set to the required value by a proportional relief valve PRV. The working oil pressure p is measured by the pressure sensor PS. As the pressure p increases, the length Δl of the hydraulic hose H changes, which is measured by the laser distance sensor LS1. At the same time, the change in the diameter Δd of the hydraulic hose braid is measured by the optical micrometer LS2. In the case of the fixation of the hose H, as the working oil pressure p increases, the tensile force of the muscle F_T increases in its longitudinal axis, which is measured by the force sensor FS. The force sensor FS is located between the lower end of the hydraulic hose H and a plate which is rigidly connected to the frame of the structure. A CAM camera is used to take a picture of the hose H, on which the rubber cover has been removed and braid is visible. Images of the braid are taken over the full working pressure range of the hose or up to a pressure of $p = 200$ bar. The elements used are listed in Table 2.

Table 2. Table of elements used on the experimental device.

Symbol	Name	Type	Producer	Basic parameters
PRV	proportional relief valve	DBETBEX-1X	Rexroth	$p_{max} = 315$ bar
PS	pressure sensor	PR 400	Hydrotechnik	working range: (0 ÷ 250) bar
FS	force sensor	FO 200	Hydrotechnik	working range: (0 ÷ 20) kN

LS1	laser distance sensor	optoNCDT	Micro epsilon	working range: (0.5 ÷ 200) mm
LS2	optical micrometr	LS - 7070	Keyence	working range: (0.5 ÷ 65) mm
CAM	camera	FASTCAM MINI UX	Photron	frame rate: up to 2000 fps

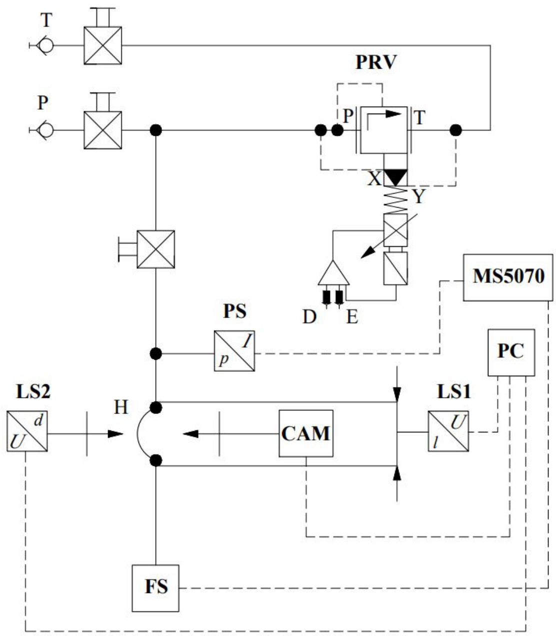

Fig. 5. Simplified scheme of experimental equipment for testing hydraulic hoses.

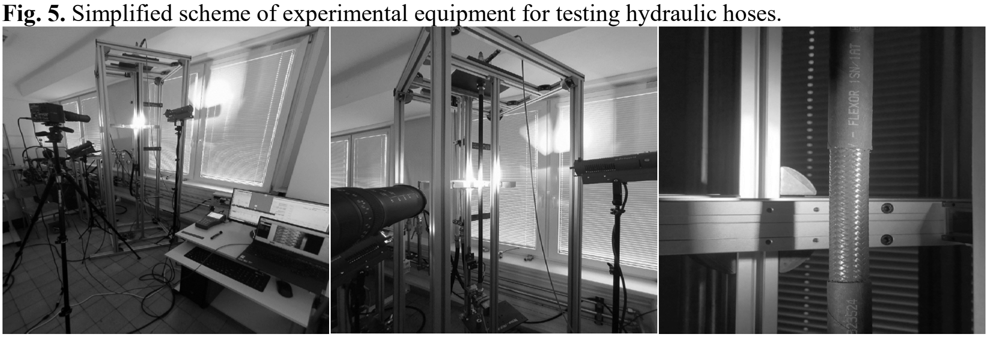

Fig. 6. Experimental equipment for testing hydraulic hoses.

Fig. 7 shows a detail photograph of the hydraulic hose braid angle φ. Using Photron FastCam Viewer software, the braid angles for the hydraulic hoses tested were evaluated over the entire working pressure range of the hose or up to a pressure of p = 200 bar. Furthermore, the measured data such as change in length Δl, braid diameter d, tensile force F_T over the entire working pressure range of the hose or up to pressure p = 200 bar were evaluated. Table 3 shows the list of hydraulic hoses tested.

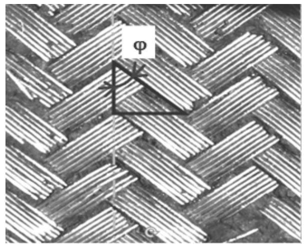

Fig. 7. Example of determining the braid angle of a hydraulic hose.

Table 3. Table of tested hydraulic hoses.

Hose	**Inner diameter d_{in}**	**Diameter of outer braid d**	**Length without fittings l**	**Number of braids/spirals**	**Maximal working pressure**	**Initial braid angle φ_0**
	[mm]	[mm]	[mm]	[-]	[bar]	[°]
DN12.5_1SN	12.5	17.8	1371	1 braid	160	54.73
DN12.5_2SN	12.5	18.8	1366	2 braids	275	52.74
DN12.5_4SP	12.5	20.5	1376	4 spirals	420	54.38
DN16_1SN	16	20.6	1350	1 braid	130	53.06
DN19_1SN	19	24.7	1345	1 braid	105	52.90

4 Results

Two variants of measurements were made. In the first case, the hose was fixed in the top plate and the lower end of the hose had one degree of freedom in the vertical direction. In this way, the change in braid angle φ and the change in hose length Δl were measured. In the second case, the hose was fixed in the top plate and the lower end was fixed into the force sensor. The tensile force F_T was measured in this way.

Fig. 8 shows the dependence of the braid angle φ on the working pressure p for hydraulic hoses with one braid and different inner diameters. The graph shows that for hose DN12.5_1SN the initial braid angle φ_0 was measured very close to the neutral braid angle φ_n. It can also be seen that for hose DN12.5_1SN the braid angle value does not change a lot with increasing working pressure p. This result confirms that at the value of the neutral braid angle, equilibrium between axial and circumferential stresses occurs and geometric changes do not occur. Hydraulic hose DN16_1SN has a braid angle value at atmospheric pressure $\varphi_0 = 53.06°$. The braid angle increases linearly with increasing pressure in the hydraulic hose. Hydraulic hose DN19_1SN has a braid angle value at atmospheric pressure $\varphi_0 = 52.90°$. Again, the braid angle increases with increasing working pressure p. The change in braid angle φ is accompanied by a change in geometry for these hoses.

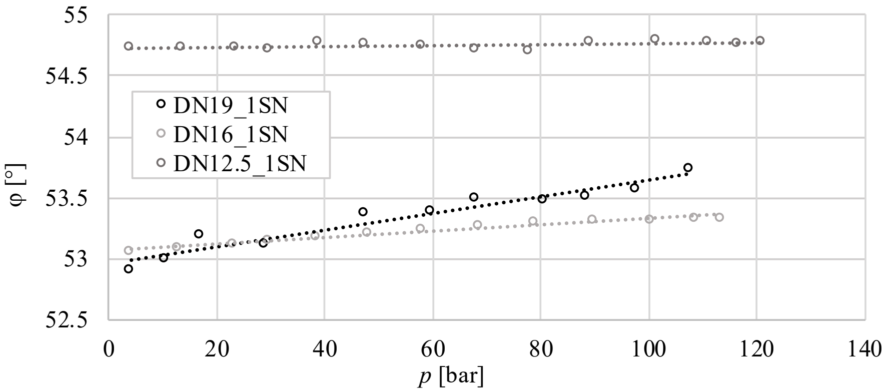

Fig. 8. Dependence of the braid angle φ on the working pressure *p* for one braid and different internal hose diameters.

Fig. 9 shows the dependence of the braid angle φ on the working pressure *p* for hoses of the same internal diameters d_{in} = 12.5 mm, but with different numbers of braids or spirals. For hose DN12.5_1SN, the values of working pressure *p* were not achieved as for the other hoses, due to the pressure load capacity of hose DN12.5_1SN. The graph shows that the hydraulic hose DN12.5_4SP has an outer spiral angle value at atmospheric pressure φ_0 = 54.38°. As the pressure in the hydraulic hose increases, the spiral angle increases linearly. It can be seen that the neutral angle value has been exceeded. According to the theory, the length *l* of the hydraulic hose should increase when the value of the neutral angle of the braid is exceeded. However, we must take into account that after removing the rubber cover we were only able to determine the spiral angle for the outer spiral. It was not possible to determine the angle for the inner spiral without destroying the hydraulic hose. The graph shows that the hydraulic hose DN12.5_2SN has a value of the angle of the outer braid at atmospheric pressure φ_0 = 52.74°. As the pressure in the hydraulic hose increases, the braid angle again increases linearly. For this hose, the braiding should result in the greatest reduction in the length *l* of the hydraulic hose and, in the case of fixing the hose, the greatest tensile force F_T. Again, it must be remembered that the braid angle has been determined for the outer braid only, which is visible after removal of the rubber cover.

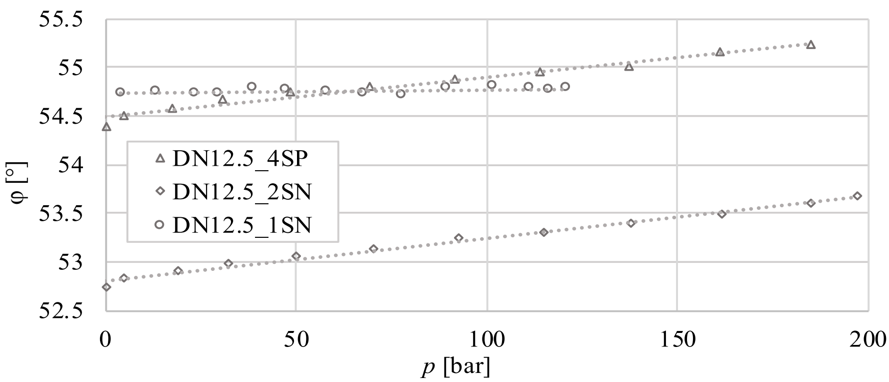

Fig. 9. Dependence of the braid angle φ on the working pressure *p* for the same hose inner diameter and different numbers of braids or spirals.

Fig. 10 shows the dependence of the hose length change Δl on the working pressure p for different hose inner diameters. The graph shows that the largest change in length Δl occurs for hose DN16_1SN (φ_0 = 53.06°). The smallest shortening occurs for hose DN12.5_1SN (φ_0 = 54.73°).

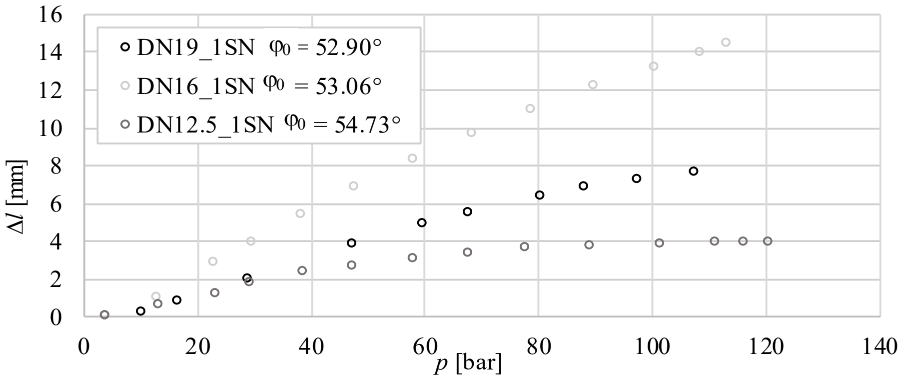

Fig. 10. Dependence of hose length change Δl on working pressure p for one braid and different hose inner diameters.

Fig. 11 shows the dependence of the hose length change Δl on the working pressure p for different numbers of hose braids or spirals. The graph shows that the greatest change in length Δl occurs for hose DN12.5_2SN (φ_0 = 52.74°). The least shortening occurs for hose DN12.5_4SP (φ_0 = 54.38°).

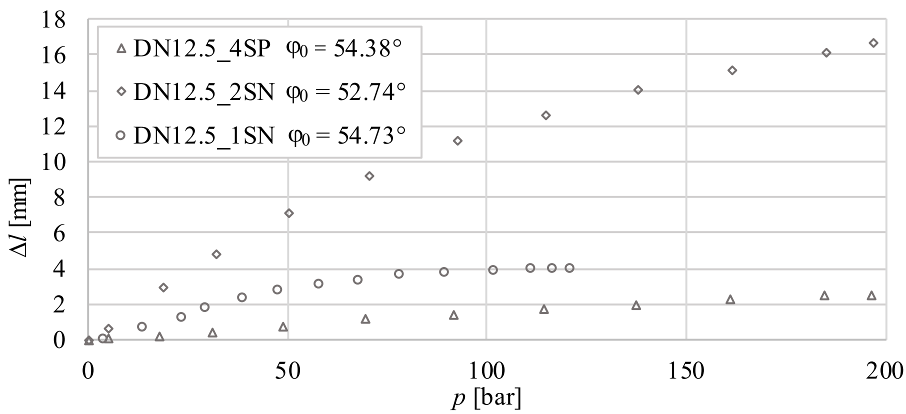

Fig. 11. Dependence of hose length change Δl on working pressure p for the same hose inner diameter and different numbers of braids or spirals.

Fig. 12 shows the dependence of the tensile force F_T on the working pressure p for different internal hose diameters. The graph shows that for hydraulic hose DN12.5_1SN (φ_0 = 54.73°) there is a very small increase in the tensile force F_T as a function of the pressure p. For hydraulic hose DN16_1SN (φ_0 = 53.06°) there is a significant increase in the tensile force F_T as a function of the pressure p, in contrast to hose DN12.5_1SN (φ_0 = 54.73°) where the increase in the tensile force F_T is negligible. The same trend of increase of the tensile force F_T as a function of pressure p applies to hose DN19_1SN (φ_0 = 52.90°). From the graph it can be determined that the initial braid angle φ_0 influences the dependence of the tensile force F_T on the working oil pressure p.

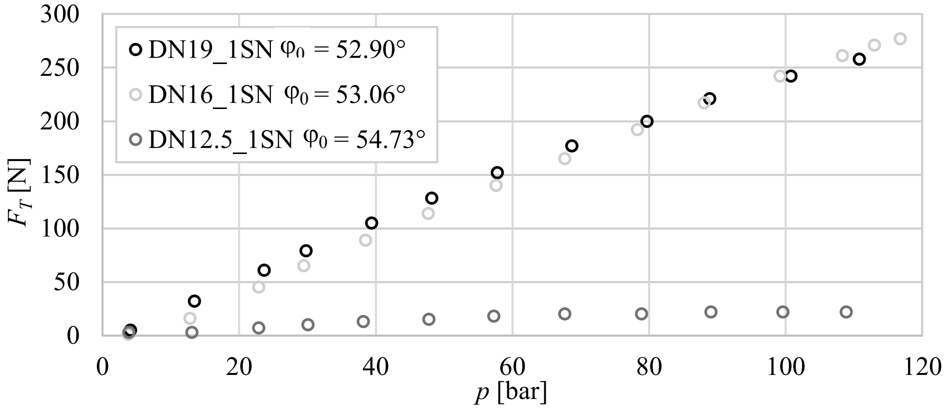

Fig. 12. Dependence of the tensile force F_T on the working pressure p for one braid and different internal hose diameters.

Fig. 13 shows the dependence of the tensile force F_T on the working pressure p for different numbers of hose braids or spirals. The graph shows that for hydraulic hose DN12.5_4SP ($\varphi_0 = 54.38°$) there is a very small increase in the tensile force F_T. The trend of the increase of the tensile force F_T as a function of the working pressure p is similar to that of the hydraulic hose DN12.5_1SN ($\varphi_0 = 54.73°$). For hydraulic hose DN12.5_2SN ($\varphi_0 = 52.74°$) there is a significant increase in the tensile force F_T. This graph again confirms the influence of the initial braid angle j$_0$ on the tensile force F_T as the working pressure p changes.

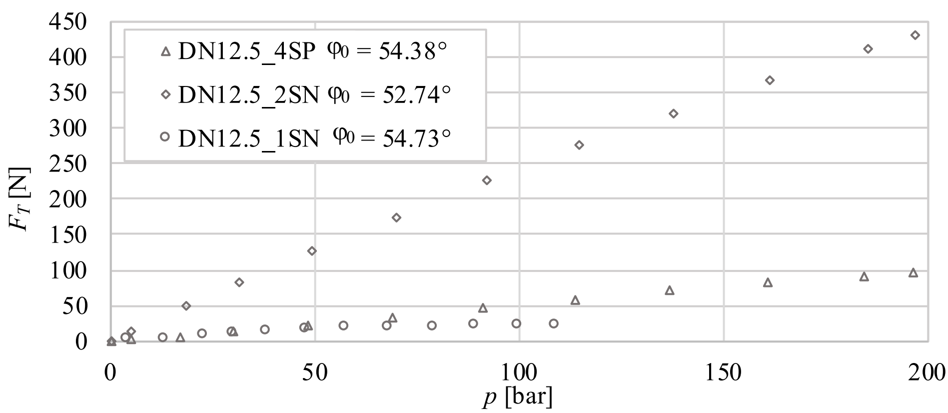

Fig. 13. Dependence of the tensile force F_T on the working pressure p for the same hose diameter and different numbers of braids or spirals.

5 Conclusions

This paper deals with the experimental analysis of the effect of the braid angle on the behaviour of hydraulic hoses under pressure loading. The dependencies of the braid angle, the change in hose length and the hose tensile force on the working oil pressure were successively measured and evaluated. Within the results, the data for the tested hydraulic hoses are compared. The result shows that the braid angle has a significant effect on the behaviour of the hydraulic hose under pressure load. The smaller the initial braid angle is compared to the neutral braid angle, the greater the change in hose length with oil working pressure and the greater the tensile force is induced. It is also observed that the characteristics determined are independent of the inner diameter or number of braids or spirals of the measured hoses.

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