FEM ANALYSIS OF MULTILAYER PIPES DESIGNED FOR SUBSEA UMBILICALS

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Трубопроводи управління, що використовуються в морській промисловості, піддаються механічним і екологічним навантаженням під час їх монтажу та обслуговування. Для забезпечення задовільної надійності і терміну служби трубопроводів управління потрібне застосування нових матеріалів з поліпшеними характеристиками. Це збільшує витрати виробництва, і, тим не менш, не гарантує повного задоволення потреб у властивостях трубопроводу.

Трубопроводи управління які можуть бути зроблені як багатошарове поєднання окремих труб з різних матеріалів із заданими механічними властивостями, представляються вигідними з точки зору витрат на виробництво і якості всього трубопроводу. В роботі проведено аналіз методом FEM поведінки багатошарових труб під час різних навантажень і порівняння її з поведінкою суцільної труби. Застосовані типи завантажень були обрані відповідно до умов експлуатації трубопроводів, а також навантажень, які є загальними для механічних випробувань труб.

Іншим можливим способом виконання вимог до надійності і довговічності трубопроводів управління з відносно низькими витратами виробництва є застосування багатокутних труб. Було вивчено поведінку під навантаженням двох типів труб з некруглою формою поперечного перерізу: "гексагональна", яку рекомендовано використовувати для центральної зони, і "зіркоподібна", яку краще розміщувати у периферійній частині трубопроводів управління.

Ключові слова: *трубопровід управління, багатошарова труба, полігональна труба МСЕ моделювання.*

The umbilicals, used in the offshore industry, undergo many mechanical and environmental loads during their mounting and service. To secure the satisfying reliability and lifetime of the umbilical's pipelines the application of novel materials with advanced characteristics is required. This increases the production costs and nevertheless doesn't guarantee the full meeting of demands in properties of the pipeline.

Pipelines with tailored properties across the wall thickness, which can be produced as a multi-layered composition of separate pipes of different materials with adjusted mechanical properties in each layer, seems to be advantageous in the context of production costs and resulted quality of whole pipeline. A comparative FEM analysis has been performed, to analyze behavior of multi-layered pipe under different types of loading and compare it with behavior of solid pipe. Applied loading types were chosen in accordance with loads, which are common for exploitation conditions of umbilical pipelines, as well loads, which are common for mechanical testing of pipes.

Another possible way to fulfil requirements on reliability and durability of umbilical pipelines with relative low production costs is to apply polygonal pipes. Two main types of polygonal pipes have been studied: "hexagonal-" for inner part and "star-" shaped for outer part of umbilical pipeline.

Key words: *umbilical, multilayer pipe, simulation, mechanical testing.*

Introduction

Sea umbilicals play an important role in today's oil and gas offshore industry. They can be used to transmit control signals, power and fluid long distances from the platform to the remote operated vehicles (ROV) and other underwater equipment. Their advantage is that all communications are placed in a single compact shell and simultaneously play the role of the load carrier [1-3]. The main areas of umbilical development are increasing their strength and capacity as well as reduction of the specific weight and diameter without loss of performance. The first is achieved by increasing the pressure in the pipe that consequently increases its cross section and the wall thickness, and hence the specific weight. The second way involves the use of reinforcing fibers, which also escalate the specific gravity and dimensions of the pipeline. An alternative is to use the pipe elements for the transmission of fluids as a load carrier.

Structural analysis

An important factor is the resistance of pipes to a variety of loads during installation and operation [4]. The following aspects have to be considered during the umbilical`s pipe design and proper material grades selection [5]:

- Mechanical, fatigue and fractural properties;
- Internal fluid properties and service temperature;
- Resistance to corrosion;
- Environmental and loading conditions;
- Installation methods and procedure;
- Weight requirement;
- Weldability and connectivity.

During the design of umbilical`s cross-section the load commissioned by the pipeline and its components must be taken into account [2]. According to the ISO Standard [6] this loads can be divided into three following groups: functional, environmental and accidental.

In the most used combined electro-hydraulic offshore umbilicals the pipelines are located planetary over the cross-section. Centerline pipe is subjected to the operation of the following loads:

- Bending at a small degree, equal to the bending degree of the whole umbilical;
- Twisting;
- The internal pressure of the transported fluid;

- The external hydrostatic pressure of the water column;
- Longitudinal axial tension under the pipeline's weight;
- Reeling – unreeling.

Planetary disposed pipes undergo twisting [7], but have permanent bending load equal to the winding angle adding the angle of the pipeline reeling. The remaining loads are similar to them of centerline pipe. For the pipes undergoing the constant influence of several of these loads at the same time the requirements to mechanical properties are increased. This considers especially the true strength, flexibility, resistance to the alternating loads, endurance and the shape maintain ability. It is important that the material properties shouldn't be significantly degenerated under the influence of low temperatures.

Particular attention at the selection of the pipe material must be paid to its corrosion resistance [8], since usually the transporting fluid is chemically active substance (as well as consideration of pigging fluids). Additionally it may have a relatively high pressure and temperature to compensate the environmental cooling and to increase the pipeline productivity. All of these factors have a negative impact on the resistance of the pipe walls and in some cases may lead to a breakthrough that would result in equipment halt or damage and in environmental disaster. Another important quality is also a roughness of the pipe internal wall [9], significantly affecting its capacity, resistance to adhesion and pipe channel overgrowth.

The pipeline weight is also important, since it is a significant limitation due to the capacity of the installation vessels. Thus, to reduce the weight and increase pipeline strength the use of new materials or their combinations with advanced and unique properties is necessary [10].

The purpose of the structural analysis is determination of umbilical`s pipelines components that will be able to withstand the loads in all processes of manufacturing, shipping, extraction, repair, installation as well as in operation during the service period.

To predict the stability of umbilical`s pipeline construction in their design the numerical simulation, as well as the mechanical testing of the pipeline as a whole and its components are used (Fig. 1).

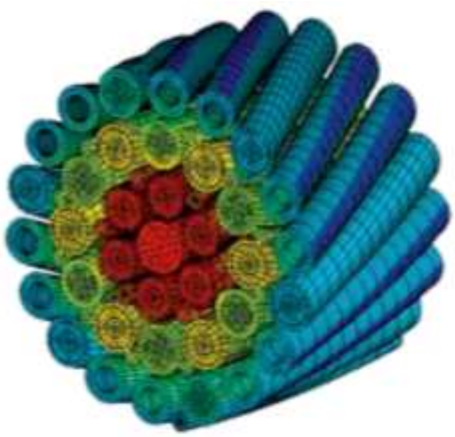


Fig. 1. Visualization Example of the umbilicals FEM analysis [11]

An extensive range of testing services providing to the umbilicals is described in [6] and [12].

The stainless steel remains one of the main materials used in the manufacture of umbilical pipeline. Its main advantage is the high durability, reliability, corrosion resistance, weldability, versatility in manufacture and operation. Other materials that are wide implemented for the production of pipes in the umbilical design are thermoplastic, Al - and Ti – based alloys.

As can be seen from the Fig. 2, one of the main disadvantages of steel pipes in comparison with plastic is their low or difficult predicted corrosion resistance. Thus, diagram in Fig. 2 shows that the number of accidents in pipelines due to their corrosion is on the first place. This chart does not specify the type of corrosion. But even stainless steel due to technology failures can be damaged by corrosion. For some austenitic steels typical is the development of intergranular corrosion at some distance from the weld. This is due to the formation of chromium carbides at a certain temperature, which are not only soluble in an aggressive environment, but also provoke electrochemical corrosion. Manufacturing or welding defects also provoke pitting corrosion. Some technologies of thin corrosion-resistant coatings on the inner surface of pipelines are known [13-15]. However such layer cannot be the tensile strength member of the pipe.

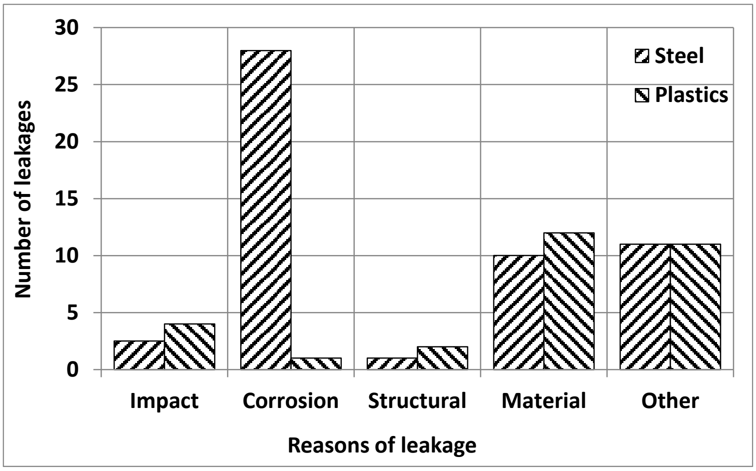


Fig. 2. Steel and plastic pipelines leakages statistics. (Based on [16] data)

For the production of high quality pipelines that meet the requirements of resistance to the above mentioned conditions ferrite-austenitic duplex and super duplex steel are applied.

Steel pipes are generally used for pipelines installation at the medium and large depths of 2-4 km.

The modern duplex stainless steels [17, 18] in comparison with austenitic, have a sufficiently high tensile strength allowing good fracture resistance. The value of elongation at fracture lies at the level of 15-25%. However, the ductility directly affects many pipeline features such as flexibility and resistance to the strain accumulation. Along with the relatively high production costs, relatively low ductility is the main disadvantage of these steels.

In the process of umbilical manufacturing and assembly the pipelines in it are subjected to several cycles of plastic strain associated mainly with reeling-unreeling, straightening and other intermediate operations. Accumulated plastic strain is defined as "the sum of plastic strain increments, irrespective of sign and direction" [19]. In the book of Y. Bai concluded, that accumulated plastic strain can occur in the steel tubes of an umbilical during fabrication and installation. The accumulated plastic strain needs to be maintained within certain limits to avoid unstable fracture or plastic collapse for a given tube material and weld procedure. Accumulated plastic strain is the general criteria used by umbilical suppliers to determine whether the amount of plastic loading on the steel tubes is acceptable. An allowable accumulated plastic strain level of 2% is recommended for umbilical design [2].

The way to avoid the undesirable accumulated plastic strain level and to improve the properties of the pipeline can be found in the replacement of monometallic pipes in umbilical hydraulic for multilayer multimaterial pipes.

Multilayer cold rolled seamless tubes with OD 16…76 mm, and with up to 12 layers with a thicknesses of 0.16…0.25 mm, made of corrosion-resistant steels are used for blocking fittings and flexible pipelines for aircraft, space and defense facilities [20]. Known technologies, based on cold pilger rolling [21-23] or sink drawing [24] provide the production of these tubes only in straight condition with length to 6…9 meter. Such pipes can consists of several (2...12) metallic seamless or longitudinal welded pipes, not bonded to each other (Fig. 3). The absence of strong bonding between the layers is the main feature of multilayer pipes. In this case the best ratio between the properties of the pipe and length of tubes is obtained with 2...4 layers with a thickness of each not exceeding 0.4 mm [20].

Fig. 3. Rings of multilayer stainless steel pipes with longitudinal cuts of the outer layers [20]

Multilayer pipes are favorably different from the solid ones with the possibility to use variable materials in each layer. Furthermore, such pipes have increased resistance to avalanche fracture.

The stress distribution in the multilayer tubes differs from that in solid ones even if they are made of the same material. This is due to the fact that the layers work independently and glide to each other. As a result the accumulated strain concentrates not throughout the thickness of the pipe wall, but in the each layer separately. The longitudinal stresses in the wall of the solid tube compensated with friction and slip of the layers. This increases the flexibility and durability of the pipeline. Also known, that resistance to bending without loss of carrying capacity and circular resistance of multilayered pipes is lower than in the solid ones [25]. This is due to the appearance of local stresses in thin layers at lack of their co-work (for example, low friction between the layers). Nevertheless, even for large-diameter welded pipelines the resistance of multilayer structure to limit bending is only 1.5…2 times lower than for solid pipes.

Thus, use of materials with different mechanical characteristics allow widely disclose the possibilities of umbilical design. So, for the most responsible core layer of the pipe the essential requirements are corrosion resistance, low roughness of the inner walls and high resistance to loss of load bearing capacity.

It is expedient to use a material with a high ductility in an inner layer. Such materials are capable to continuous forming under load without losing their integrity. This feature avoids abrupt and extended cracks in the pipelines and minimizes probability of fluid leakage. Significant changes in the wall thickness or shape of the pipe can be diagnosed even before the complete loss of its load-bearing capacity and crash. With this configuration, the main longitudinal load is distributed between the other layers of the pipe. As the material of the inner layer may be used stainless steel, aluminum alloys of 3XXX, 5XXX and 6XXX-series (EN AW) [26] as well as other corrosion-resistant materials.

The main requirements to the other pipe layers are low cost, low weight and high strength. Some steel grades have very high tensile strength in combination with very low corrosion resistance and cannot be operated in direct contact with chemically active fluids. For example boron steels have high strength properties. But their disadvantage is the low corrosion resistance, which in the case of application in the middle layers of the multilayer tube does not play such an important role. These steels have high strength properties in addition to another important advantage, which is low (≈300°C) tempering temperature. This allows the heat treatment of the finished multilayer pipes of different materials including non-ferrous metals, without loss of structural properties in the final production stage to eliminate the accumulated strain as well as residual stresses.

The outer layer of the tube can play the role of sheath, tensile member or isolation and could be made also from material, different to other layers.

Thus, by using different materials for the layers a structure could be developed, in which each of the layers will carry different loads and perform different functions. In the design of the pipeline is necessary to achieve the optimal balance of layers thicknesses and materials to meet all requirements for the pipeline with minimal weight and production costs. To predict the stability of a multilayer pipe to the different loads an application of mathematical modeling and mechanical testing is possible [27]. By optimal selection of materials and layer thicknesses a composite pipe having higher strength, ductility and flexibility characteristics, than solid pipe, can be designed. Moreover, its geometric dimensions, weight, capacity and production costs remain at the same level.

The purpose of the present work is investigation of substitution potential of solid pipes through the multilayered multimaterial pipes for the application in the offshore umbilicals.

Numerical simulation – analysis of multilayered pipes

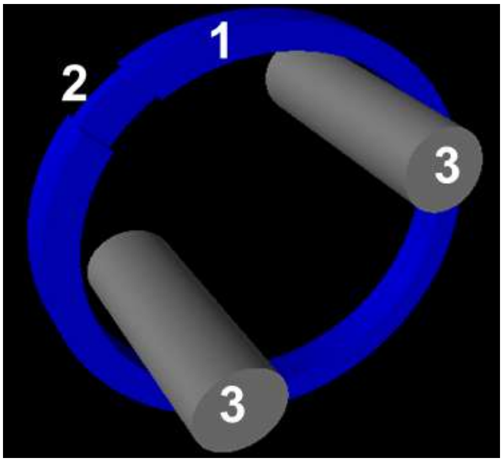
For the comparative analysis of the behavior of multilayer pipes under load and evaluation of their flexural strength the comparative FEM-simulation of the identical size pipe segments with the solid and layered wall were carried out. The material used in the both simulation specimens is Super-duplex steel 1.4410 [28, 29]. The properties of material used in simulation are given in the Table 1.

Table 1. Mechanical properties of materials used in FEM-simulation

Layer material	1.4410	22MnB5	EN AW-5056 O
Tensile strength, MPa	800	1400	290
Yield strength, MPa	550	1100	150
Elongation at fracture, %	25	7	35

To simulate the plastic flow of the metal the FE-software ANSYS Mechanical of ANSYS Inc. was used. As a reference sample a 1 inch diameter pipe with a wall thickness of 2 mm was taken. Tubes of similar size are widely used in the manufacture of umbilicals. For comparison the four-layer sample with the 0.8 mm thickness inner layer and 0.4 mm thickness outer layers was chosen. The 0.5 m length pipes segments with end holders were subjected to unidirectional bending at an angle up to 20 degrees.

Bending simulation allows estimating of the pipe ductility, but to assess its strength properties the numerical simulation of the tensile testing of ring pipes samples was applied. It is similar to the standard tensile test for pipes. The pipes samples of the same size with a solid as well as four-layer wall of steel 1.4410 were used in simulation. Simulation was performed using FE-software Forge 3D of Transvalor Company (License holder: Czestochowa University of Technology) [30, 31]. The ring pipe samples with the stress concentrators were expanded between the two rods. Method of this test described in [32]. Figure 4 shows the samples model in initial condition before the simulation.



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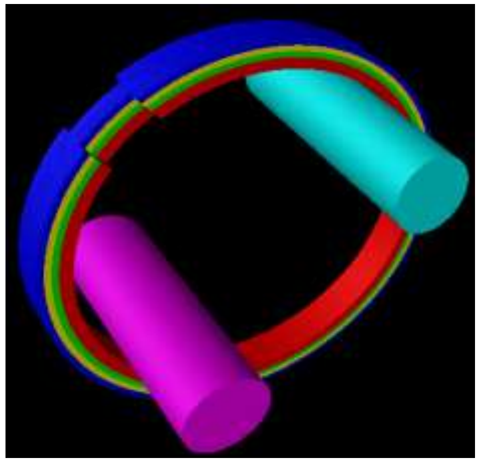

b

Fig. 4. Non-deformed model of the solid (a) and multilayer (b) samples: 1 – Ring pipe sample, 2 – Stress concentrator, 3 – Rods [30, 31]

For the analysis of the behavior of multilayer multimaterial and solid pipes under load a comparative FEM-simulation was carried out. The materials used in simulation had the following mechanical properties (see Table 1). The following material-layer configurations, analogous to the described above comparative simulation, were selected for FEM-analysis (see Table 2).

Table 2. Material and thickness of the layers, used in numerical model

	Thickness	Material
Solid pipe ID = 1 inch		
1 Layer	2 mm	1.4410 Super-duplex steel
Multilayer pipe ID = 1 inch		
1 Layer (inner)	0,8 mm	EN AW-5056 Aluminum alloy
2 Layer	0,4 mm	22MnB5 Boron steel
3 Layer	0,4 mm	22MnB5 Boron steel
4 Layer (outer)	0,4 mm	1.4410 Super-duplex steel

The first part of the simulation was directed to assessment of the multilayered pipe resistance to fracture under high internal pressure. Safe working pressures have traditionally been expressed as proportions of either the burst pressure or yield point of a tube. These proportions have varied over time as production methods have improved and steels have evolved. Different industries and pressure vessel codes have also adopted different standard practices. The most common ratio used over the past 50 years has been 4:1 burst pressure to the max. operating pressure. However, some codes are now reducing this factor to 3.5 or even 3. The problem with using this factor for modern austenitic stainless steels is that it does not permit the mechanical properties of such steels to be used to their maximum potential. There fore for such materials a factor of 1.5 or 1.6 x yield pressure has become customary.

To analyze the high pressure loads explicit dynamics module ANSYS Autodyne of ANSYS Inc. was used. The 5 mm width O-samples of multilayer and solid pipes with stress concentrators (see Fig. 5) were loaded with a constant internal pressure of 100 MPa until the complete pipeline destruction.

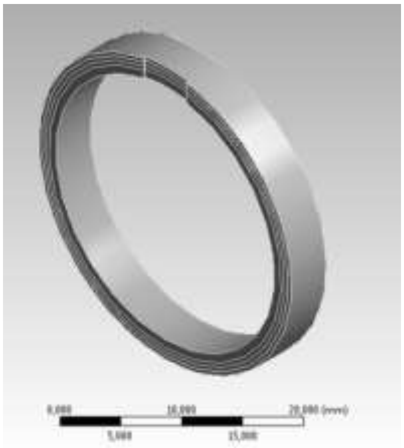

Fig. 5. Model of the multilayer pipe sample

During their operation the umbilical pipelines are loaded with tensile force equal to the wet weight of the whole umbilical length. To analyze the pipes resistance to the tensile load - one of the main loads in umbilical – the FEM-simulation using ANSYS Mechanical of ANSYS Inc. was carried out for 100mm length samples of solid and multilayer pipes by applying monotone increasing load up to 0.2 MN in 10 seconds. Fig. 6 and Fig. 7 show the geometrical model and the multilayer sample under load.

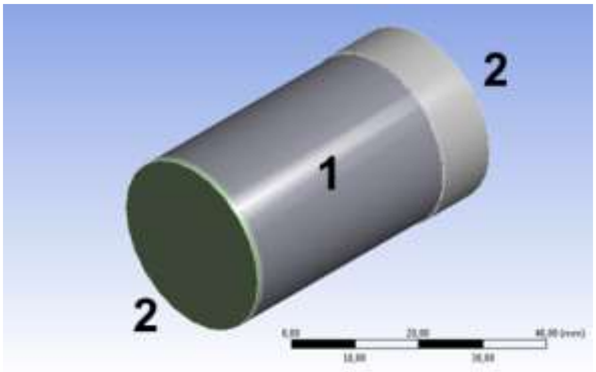

Fig. 6. The model used for tensile simulation: 1 – Pipe sample, 2 – End holders

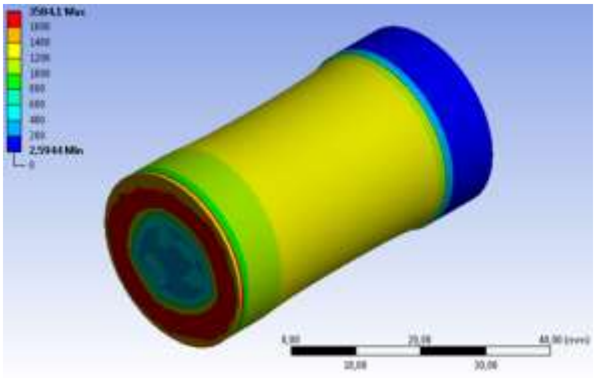

Fig. 7. Multilayer pipe sample under the tensile load

Results

As a bending simulation result, the von Mises stress distributions, shown in fig. 8 and 9, for the both solid and multilayered samples were obtained.

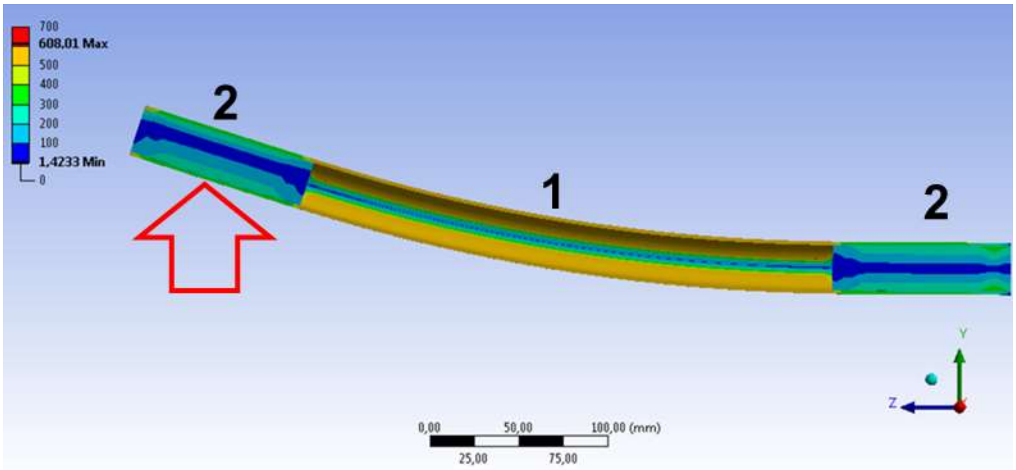

Fig. 8. Von Mises stress distribution in solid pipe sample at the one-directional bending: 1 – pipe sample, 2 – end holders

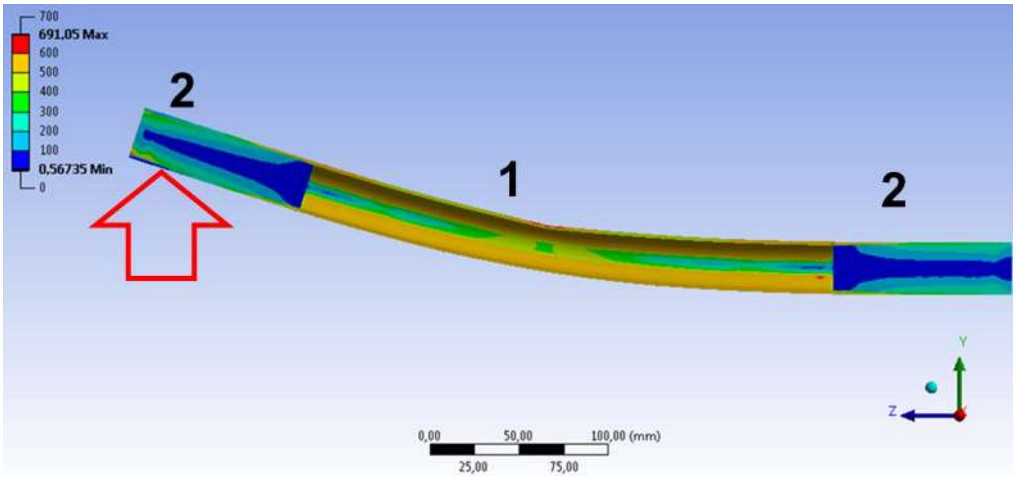

Fig. 9. Von Mises stress distribution in multilayer pipe sample at the one-directional bending: 1 – pipe sample, 2 – end holders

As can be seen, under the bending to the values near 20 degrees the break in the multilayer pipe unlike solid is formed. Moreover the stresses in the solid pipe are distributed more uniformly at the level around 600…610 MPa. However, the maximum stress occurring in the outer layers of the multilayer pipe lies at the level of 690-700 MPa and do not achieve the tensile strength of 800 MPa. In the inner layer due to slippage of layers the stresses are lower and do not reach even the yield strength (green area on Fig. 10), which provides long pipeline carrying capacity retention.

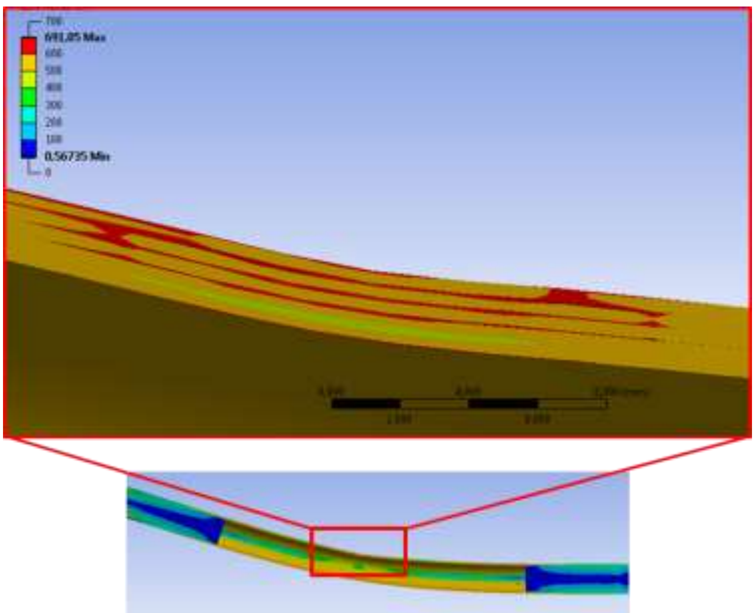

Fig. 10. Von Mises stress distribution in the layers of multilayer pipe sample near the break area

As the result of simulation of pipes sections fracture tests the distribution of stresses in the samples of solid and multilayered pipes was obtained. Fig. 11 shows the distribution of stresses in the samples at the fracture beginning point.

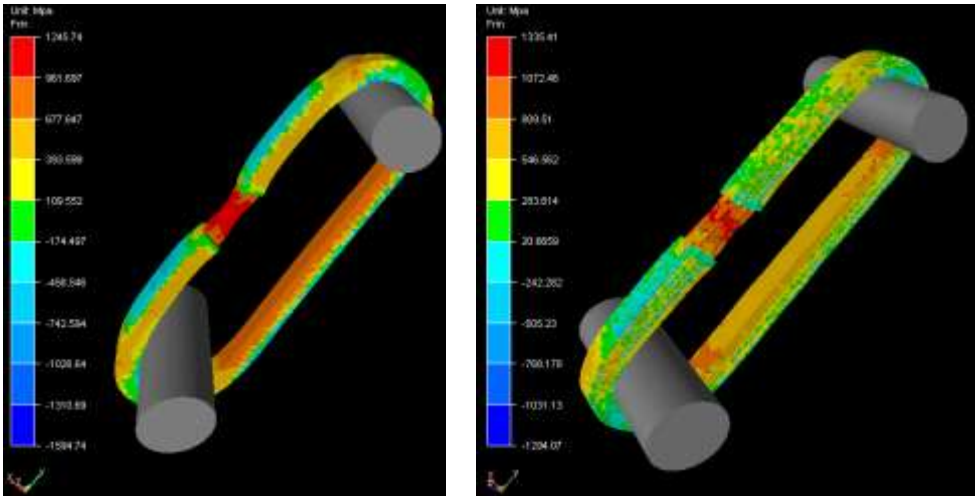

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Fig. 11. Stress distribution in the solid (a) and multilayer (b) samples at the crash beginning point [30, 31]

As can be seen, the stresses in the inner layers of the multilayer pipe are lower than in the outer layers, that provides favorable conditions for the maintaining of pipeline's bearing capacity under load.

Simulation also showed that the multilayer pipe sample has in average lower stress levels than the solid, until the destruction begins and withstands a little higher maximum effort to complete destruction.

The simulation highlighted:

- The first fracture of a multilayer sample occurs in the inner layer;
- In the used type of ring stretching before tension of the sample there is an area of pipe straightening in which a multilayer sample behaves more ductile than solid. This inhibits the strain accumulation inside the sample at the low flattening during production and operation of umbilical;
- Crash load in both samples lies at the same level;
- After the destruction of the inner layer (core pipe) the time gap before the destruction of the whole pipeline is larger than in the solid sample;
- This behavior at ring stretching tests suggests the feasibility of using materials with different plastic and strength properties for different layers of the pipeline.

The results of dynamic simulation of pipe loading with internal pressure are presented in the Fig. 12-14. Figure 12 shows the cross-sections of the pipe prior to destruction. As can be seen, the wall of the solid tube fully supports the load and the stress in it is maximum and approaching to the tensile strength. In the multilayer pipe the maximal stress is concentrated in the middle layers and is significantly lower in the inner layer, since it is more ductile.

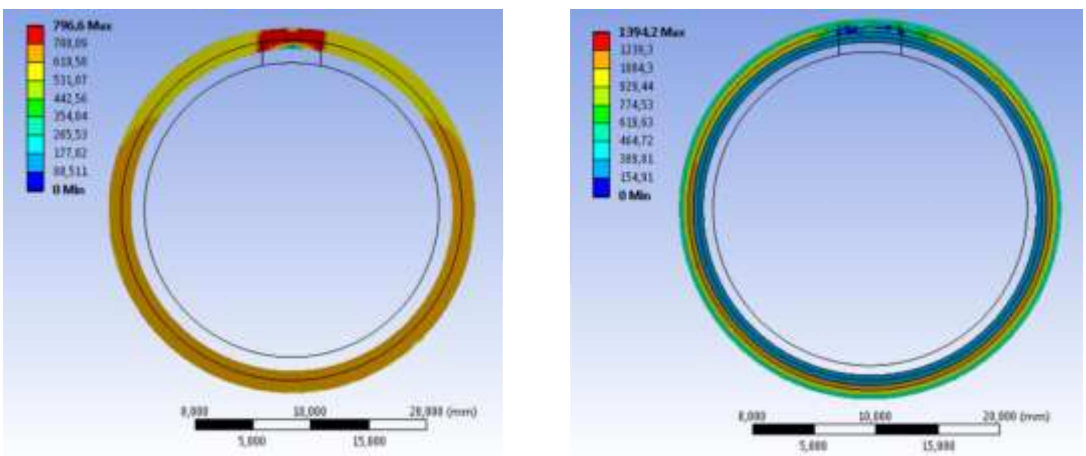

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Fig. 12. Stress distribution in the solid (a) and multilayer (b) samples prior to the crash

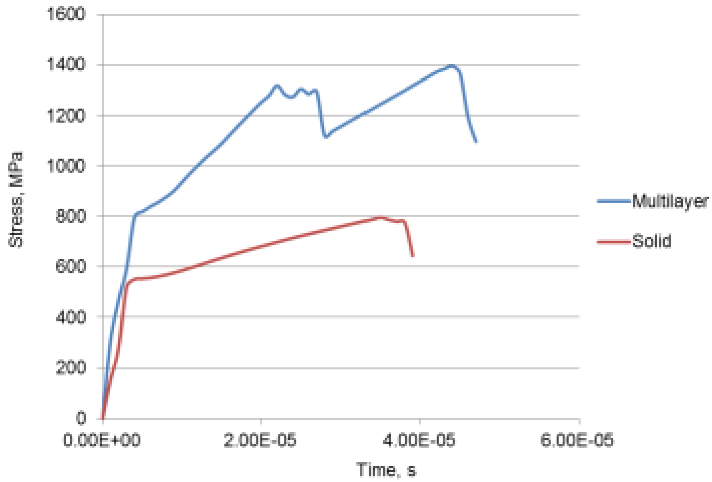

Fig. 13. Maximum stress in the samples over 100 MPa pressure load time

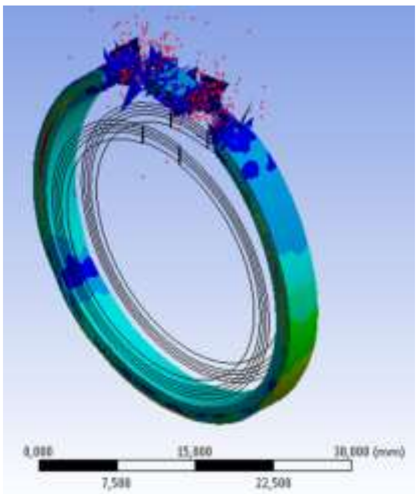

Fig. 14. Multilayer sample after the complete destruction at 5,5e-5 seconds

Obtained as a result of the simulation the dependences of maximum stress over the 100 MPa pressure load time are shown in Fig. 13. The stresses in the multilayer tube are much higher, but they are concentrated in the middle high-strength layers. That allows the multilayer tube to avoid destruction until about 5e-5 seconds (see Fig. 14). It is 25% longer than for the solid tube, in which destruction process starts around 4e-5 seconds. This means that a multilayer pipeline has a larger resistance to the internal pressure. Nevertheless, the inner layer will have a lower weight and a higher corrosion resistance than the solid pipe.

The last simulation series had to disclose the behavior of the pipe sections under a tensile load. Figure 15 shows stress distribution in solid and multilayer samples prior to the beginning of fracture. For the observation convenience the models were sliced. It is seen that the stress in the outer layers is much higher than in the interior ones. The inner layer does not loose continuity, which increases the reliability of the pipeline. As can be seen from the graph on Fig. 16, the destruction of a single-layer pipe comes about a load of 115 kN. The destruction of the multilayer structure starts about a load of 155 kN. Thus, the tensile resistance of the multilayer pipe is 35% times higher than of the solid one.

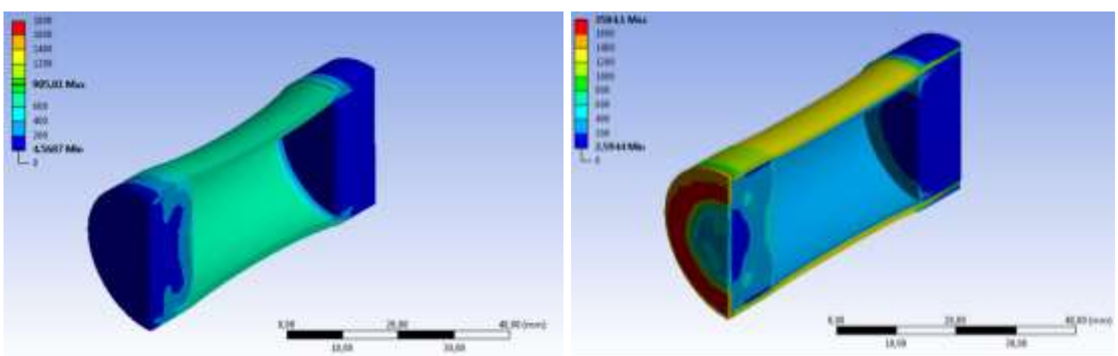

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Fig. 15. Stress distribution in the solid (a) and multilayer (b) samples prior to the fracture

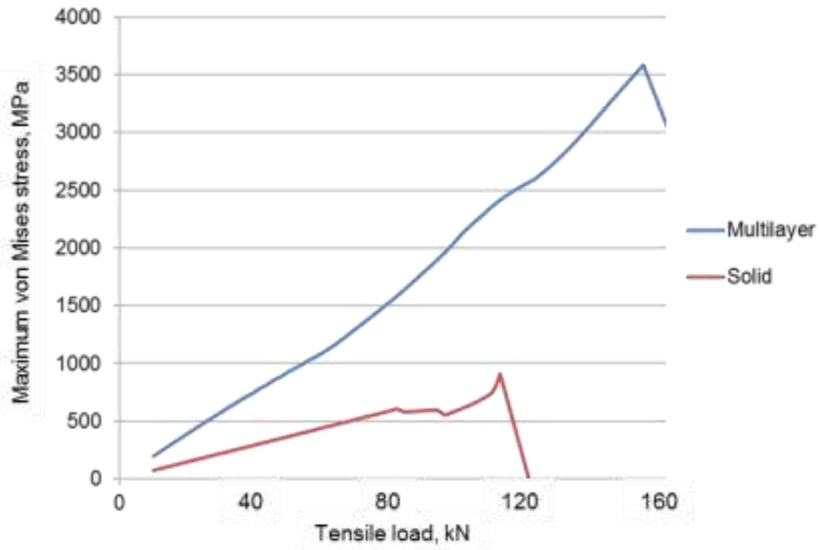

Fig. 16. Maximum stress in the samples over the tensile load

By applying of the tensile stress to a multilayer pipe, the more durable layers take on the basic load, allowing the plastic layers to deform without fracture, resulting in that the pipeline carrying ability is not deteriorated. In the case of application of the high-strength materials in the middle layers this characteristic is even increased.

At the twisting loading of the multilayer pipe the torque stresses arising therein also have lower values than the solid due to layer slippage relative to each other.

So the multilayer design of the pipelines can open the wide prospective for use of different materials with proper characteristics in every single layer of the pipe. A high resistance to stress of the multilayer pipeline can be reached by the optimum friction coefficient between its layers, allowing the layers to work together and at the same time provide them a small slip. This condition should be considered during the design of the production technology for such pipes. Several techniques of manufacturing multilayer pipes are known. In some of them used electric welding of pipe layers, the basis of other is cold pilger rolling and drawing of the package of nested seamless pipes.

Numerical simulation – analysis of multilayered pipes

Studied sections of pipes were: circle, hexagon, octahedron ("star type").

As base section a circle was used with outer diameter 29,4 mm. Wall thickness for all sections is 2 mm. Inner square for all types of sections is 506 mm^2. Cross section area for all sections was approximately 180 mm^2. Studied pipes length is 500 mm. Material: alloyed steel with ultimate tension stress of 723 MPa and yield stress of 620 MPa. The distance to the section for which results of all tests are given is 250 mm from the end of tube.

Research of strength characteristics of tube sections were carried out by simulation in a package SolidSimulation of the program SolidWorks 2012. Used loadings:

1) inner pressure;
2) external pressure;
3) bending;
4) torsion.

1. Inner pressure

For this test the pressure on an internal surface of tube of 30 MPa was applied. For section of circle, hexagon (side), octahedron (side) and octahedron (edge) the normal tension in direction X are presented (Fig. 17). For section a hexagon (edge) the normal tension in direction Y is presented.

2. External pressure

For this test the pressure on an external surface of tube of 30 MPa was applied.

For section of circle, hexagon (side), octahedron (side) and octahedron (edge) are presented the normal tension in direction X. For section a hexagon (edge) the normal tension in direction Y is presented.

3. Bending

At this bending test one end of the tube was rigidly fixed and on another force of 1000 N was applied. For all types of sections the normal tension in direction Z (along the tube) was applied. Bending was carried out in XZ plain.

4. Torsion

In a torsion test one end of a pipe was rigidly fixed and on another the torque 1000 N*m was set.

For all types of sections von Mises tension is presented.

Results of the four above mentioned tests are showed in Table 3.

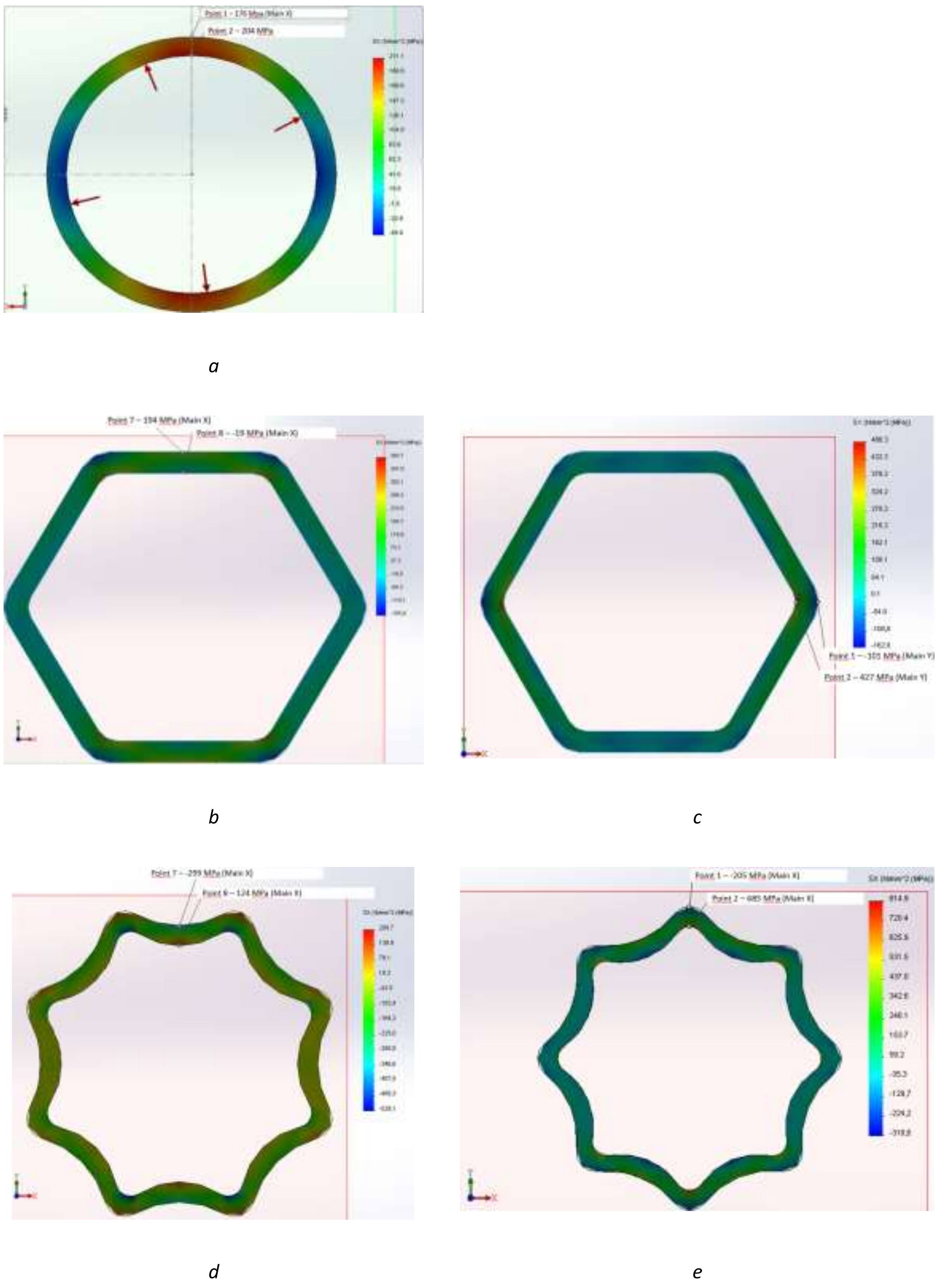

Fig. 17. Tension stresses in wall thickness due to inner pressure loading: a – round; b – hexagon, side; c – hexagon edge; d – "star", side; e – "star", edge

*Table 3. Stresses [MPa] under different loadings for considered sections**

		Round	Hexagon (stress in the side),	Hexagon (stress in the edge)	"Star" section
Inner pressure	Point 1	176		-101	-205
	Point 2	204		427	685
	Point 7		194		-299
	Point 8		-19		124
Outside pressure	Point 1	-206		-8	-3,8
	Point 2	-233		-103	-90
	Point 7		-25,3		-304
	Point 8		-33,7		124
Bending (Main on Z)	Point 1	222		223	226
	Point 2	193		196	204
	Point 3			172	178
	Point 4			150	150
	Point 5				163
	Point 6				140
	Point 7		201		192
	Point 8		174		163
	Point 9	191	194		211
	Point 10	166	167		183
	Point 11				136
	Point 12				114
Torque	Point 1	782			440
	Point 2	684			954
	Point 3				957
	Point 4				459
	Point 7		833		
	Point 8		622		
	Point 9		561		
	Point 10		820		

* Bending force 1 kN, inner pressure 30 MPa, outside pressure 30 MPa, torque 1000 H*m

The presented results show the following.

Hexagonal section works better (compare to other types) under external pressure.

Hexagon and octahedron sections at the bending test have similar results with the circle section. Besides it is fair as at force loading on a hexagon and octahedron side, and at loading on an edge.

Section like octahedron at the torsion test has the smallest tension stresses on external surface of the edge and on internal surface of the profile side.

CONCLUSIONS

It has been shown, that mechanical properties of multi-layered pipes with layers of the same material are similar to those of solid pipe. However, in case of layers of different materials higher strength and ductile properties of the whole composite pipe can be achieved. In addition, tangential stresses in multilayer pipe under twisting load have lower values than in solid pipe due to slippage of layers. Thus, multi-layered pipes exhibit higher corrosion resistance as well as reduced weight in comparison with solid pipe.

Another possible way to fulfil requirements on reliability and durability of umbilical pipelines with relative low production costs is to apply polygonal pipes. Two main types of polygonal pipes have been studied: "hexagonal-" for inner part and "star-" shaped for outer part of umbilical pipeline. These pipes have bigger moment of inertia and second moment of area in comparison with common round pipe. It has been shown, that usage of "hexagonal-" as well as "star-" shaped pipes instead of the round pipes allows to increase flexibility of umbilical in general. In addition, it prevents possible local plastic deformation of pipe‘s wall under payload.

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