Analytical and experimental comparison of basalt and carbon fiber composites overwrapping of highly pressurized steel cylinders

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Analytical and experimental comparison of basalt and carbon fiber composites overwrapping of highly pressurized steel cylinders

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ABSTRACT: This paper provides theoretical background, results of laboratory measurements and AE tests for the mechanical behavior of the composite reinforced metal cylinder subjected to pressure load of 200 MPa. Two types of composite fibers were compared, carbon and basalt fibers. At high loads, the composite reinforcement is found to effectively support the metal tube when the steel material approaches plastic yielding. This phenomenon has been clearly visualized by AE signals, appearing in the frequency range between 280kHz and 450kHz. It was concluded, that cheaper basalt roving can be safely used in the analyzed application.

1 INTRODUCTION

The hollow cylinders subjected to the mechanical loading are common structural elements being used in various industries. For centuries, steel tubes have played a major role in a wide range of applications including pressure or vacuum chambers, piping systems, hydraulic actuators, etc. They are designed to work with nominal pressures, however sporadic overloads must be also safely withstood. For this reason, steel cylinders are over-dimensioned, which leads to the undesired increase of their weights. In the present approach, steel tubes of nominal dimensions are overwrapped by a composite reinforcement, which allows to increase the stiffness of such hybrid structures, and also to reduce the total weight of the construction. It was generally found that, at high loads, the composite reinforcement provides a strong support for the metal tube when the steel material approaches yielding. In case of plastic flow within the steel, the bigger percentage of the external load is safely transferred to the composite fibers having much higher elastic limit, which prevents deformations of the metal tube from being too large.

2 ANALITYCAL ANALYSIS

The fundamental theoretical background for analysis of the anisotropic bodies was provided by Lakhnitskii [1], and his work has been referenced later in a large number of textbooks dealing with composites [2-4]. The application of the orthotropic material model into cylindrical thin- and thick-walled structures was also studied analytically and experimentally by Nowak and Schmidt [5-6], who explained the mechanism of the internal load distribution between the composite reinforcement and the steel liner, working in its elastic-plastic regime. They analysed the hybrid structures, as shown in Figure 1, where the steel tube is marked by index “1”, and the composite reinforcement by index “2”.

To determine the stress and strain fields in both the steel frame and the composite shell, one can apply equilibrium and constitutive equations:

$$\begin{Bmatrix} \sigma_{1X} \\ \sigma_{1Y} \\ \tau_{1XY} \\ \sigma_{2X} \\ \sigma_{2Y} \\ \tau_{2XY} \end{Bmatrix} = \begin{bmatrix} e_1 & 0 & 0 & e_2 & 0 & 0 \\ 0 & e_1 & 0 & 0 & e_2 & 0 \\ 0 & 0 & e_1 & 0 & 0 & e_2 \\ \frac{1}{E'} & -\frac{\nu'}{E'} & 0 & -\frac{1}{\bar{E}_X} & \frac{\bar{\nu}_{YX}}{\bar{E}_Y} & -\frac{\bar{\eta}_{XY}}{\bar{G}} \\ -\frac{\nu'}{E'} & \frac{1}{E'} & 0 & \frac{\bar{\nu}_{XY}}{\bar{E}_X} & -\frac{1}{\bar{E}_Y} & -\frac{\bar{\mu}_{XY}}{\bar{G}} \\ 0 & 0 & \frac{1}{G'} & -\frac{\bar{\eta}_X}{\bar{E}_X} & -\frac{\bar{\mu}_X}{\bar{E}_Y} & -\frac{1}{\bar{G}} \end{bmatrix}^{-1} \begin{Bmatrix} f_X = p_0 r \\ f_Y = c p_0 r \\ f_{XY} = 0 \\ 0 \\ 0 \\ 0 \end{Bmatrix} \qquad (1)$$

where σ_{ij}: stresses in respective directions, e_1: the wall thickness of steel tube, e_2: the thickness of composite jacket, p_0: is the internal pressure, and factor c equals to 1/2 in case of close-end cylinder, and zero for open-end cylinder. E, G, ν, η: are material properties. The ‘bar’ and ‘prime’ signs specify their relations with composite or steel material, respectively.

Unsurprisingly, first three rows in (1) refer to the equilibrium relations, and following three to constitutive equations. The equivalent material properties of composite layer may be derived using rules proposed by the Classical Lamination Theory.

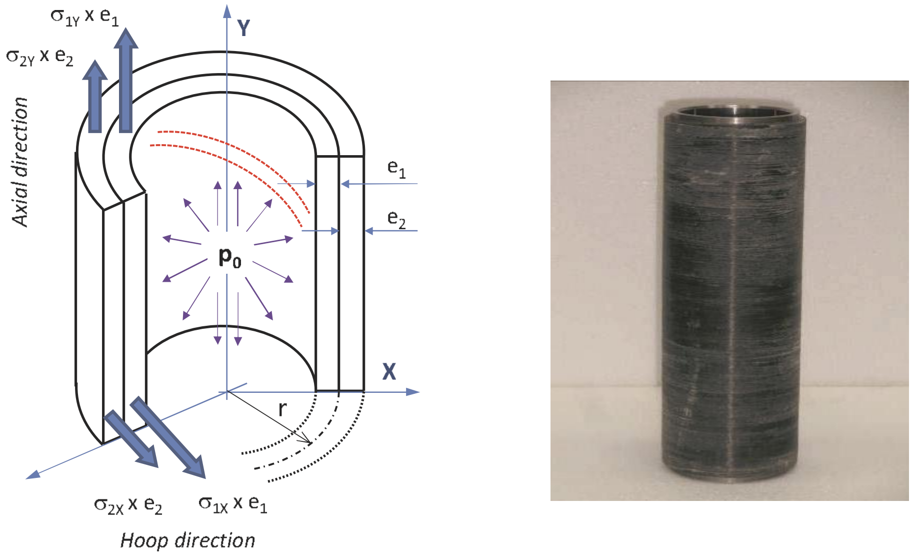

Figure 1: Geometrical model and equilibrium relations for the cylinder under study (left), and the test member.

A different approach is needed to develop steel properties in its plastic state. In order to solve eq. (1) in the elastic-plastic regime of steel behaviour, one may use the equivalent Young modulus (formally its secant value) E', and the respective Poisson ratio ν'. These equivalent quasi-elastic material properties may be calculated as given by eq. (2):

$$E' = \frac{\sigma_{Mises}}{\varepsilon_{EL} + \varepsilon_{PL}} = \frac{E\sigma_{Mises}}{\sigma_{Mises} + E\varepsilon_{PL}}$$
$$\upsilon' = \frac{1}{2}\left[1 - \frac{E'}{E}(1 - 2\upsilon)\right] \qquad (2)$$

where E and ν: the steel properties within the elastic range (E=205 GPa, ν=0.3), σ_{Mises} and ε_{PL}: the actual values of von Mises stress and effective plastic strain, respectively. Calculated equivalent Young modulus E', and the respective Poisson ratio ν' must be consistent with strain-stress curve, as measured during tensile test.

In this paper we compare two types of composite reinforcement – one is based on Texbas basalt fibers, while the other uses Tenax carbon fibers, as listed in Table 1. While the carbon fibers offer superior mechanical performance, the basalt is up to 10 times cheaper. For both composites, the EPOLAN resin with high thermo-mechanical properties was used as a matrix.

Table 1: Material properties of tested fibers.

	Texbas RB 1200TEX	Tenax HTS 12K800TEX
Thickness	0,013 mm	0,007 mm
Tensile strength	3000 MPa	4620 MPa
Modulus of elasticity	94 GPa	237 GPa
Elongation	3,3 %	1,8 %
Density	2,65 g/cm3	1,76 g/cm3
Operating temperatures	-260 do +700 oC	-240 do +750 oC
Price of 1200 TEX roving	6 EU/kg	40-60 EU/kg

Using the material properties, as presented in Table 1, the mechanical analysis was first managed using analytical approach, Figure 2. All the calculations and tests were made on the cylinders overwrapped with fibers in crossing arrangement (+/-10°) referred to the circumferential direction of the cylinder.

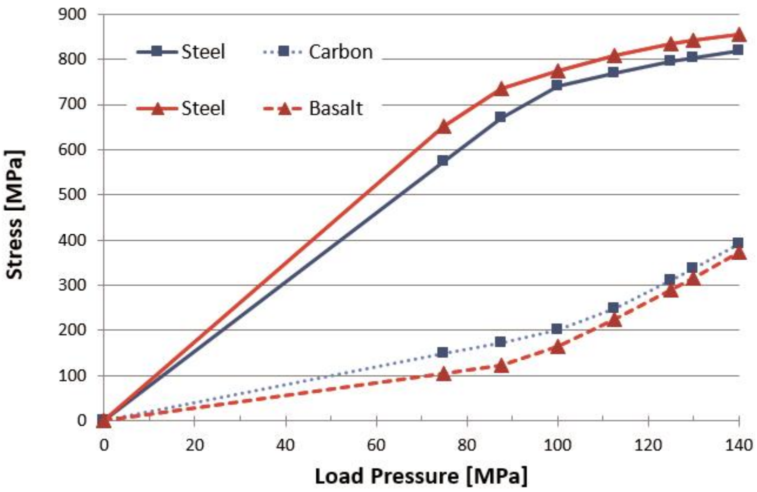

Figure 2: Effective stresses in steel tube and stresses along fibers within composite vs. load pressure (curve with triangles represents structure with basalt composite, curve with squares depicts structure with carbon fibers).

As shown in Figure 2, the structure reinforced with basalt composite reaches its elastic limit at the pressure level of about 75 MPa. The use of carbon fibers allows to shift this limit to the threshold of about 100 MPa. However, in both cases composite jackets exhibit evident reinforcing effects. At higher pressures, composite shells take bigger percentage of the load, and the steel tube can safely work above its elastic limit. Very similar results were achieved by Finite Element Method.

3 EXPERIMENTAL TESTS AND ANALYSIS

The usefulness of basalt fibers was checked experimentally for heavily-loaded hybrid cylinders and compared to reference carbon fibers offering high mechanical properties. Tests were carried out on cylinders of hybrid construction made as 60/66 mm diameter metal components with composite fiber winding of 66/75 mm diameter overwrapping the outer diameter of the cylinder. The cylinders were loaded with internal pressure using a specially designed system based on Zwick Z100 control. The mode of loading, adopted in the experimental trials, involved a gradual increase in pressure with holding at each step. Tests continued until the composite winding showed complete loss of its loading capacity. The AE signals generated in the material were recorded by SE25-P (Score Dunegan) resonance sensors with Vallen AMSY 6 system.

The test results were plotted in the diagrams as a relationship between the selected parameters of acoustic emission signals and the operating load. Plotted relationships included the results of loading the cylinders with basalt fiber reinforcement and with carbon fiber reinforcement (Figures 3 and 4). Useful for the evaluation of the damage process were selected changes in the amplitude and in the frequency spectrum of AE signals under the conditions of gradual increase in cylinder loading.

The highest values of the amplitude of the generated signals corresponding to the local fracture of the composite reinforced with basalt fibers were reached by single signals and the values ranged from 91dB to 97dB. In the cylinders with carbon fibers reinforced composites, these values were 70dB to 77dB. The differences in the amplitude observed throughout the entire process of loading were driven by differences in the energy of deformation and cracking characteristics of each type and diameter of the fiber. The apparent high AE activity in the first stage of loading was the result of the alignment of local deformation of the composite structure caused by its manufacturing process.

The observed relationships have indicated the occurrence of three active frequency ranges. Signals from the range of 300kHz to 450kHz corresponded to the major mechanisms of damage suffered by components of the composite structure with either of the two applied types of the reinforcing fibers. They also indicated the occurrence under the conditions of load increase of the same damage mechanism operating in each composite irrespective of the type of the reinforcing fibers. Different AE activities quantitatively determined in materials of both cylinders during load increase were an indirect consequence of significant differences in the deformability of each fiber type used.

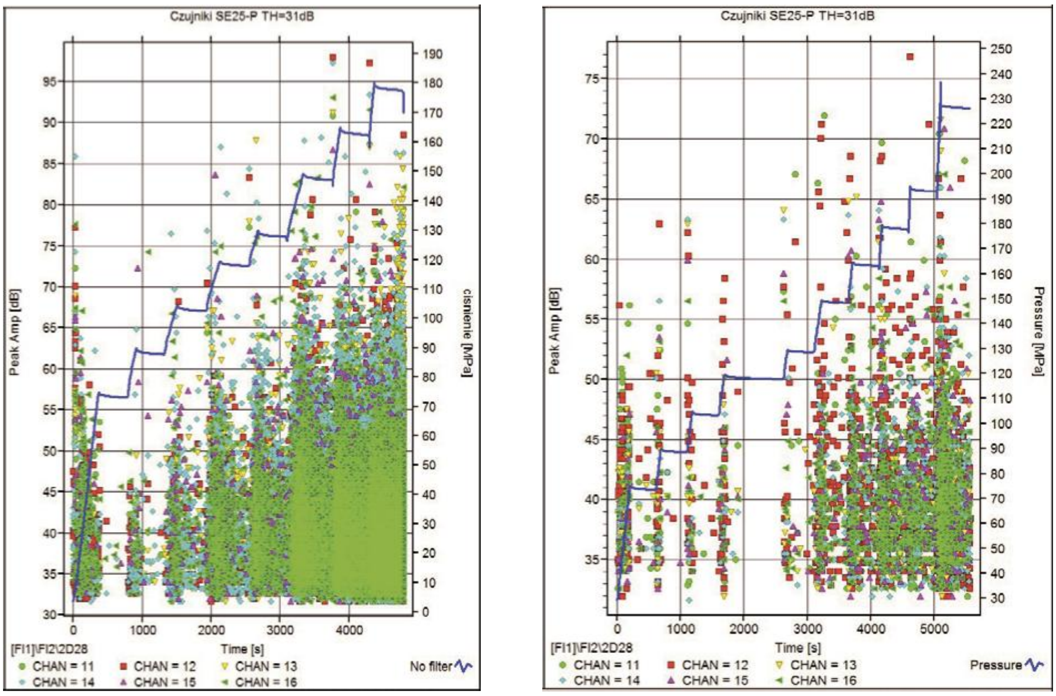

Figure 3: Amplitude of AE signals during gradual load application and holding: cylinder with basalt fibers (left), and carbon fibers (right).

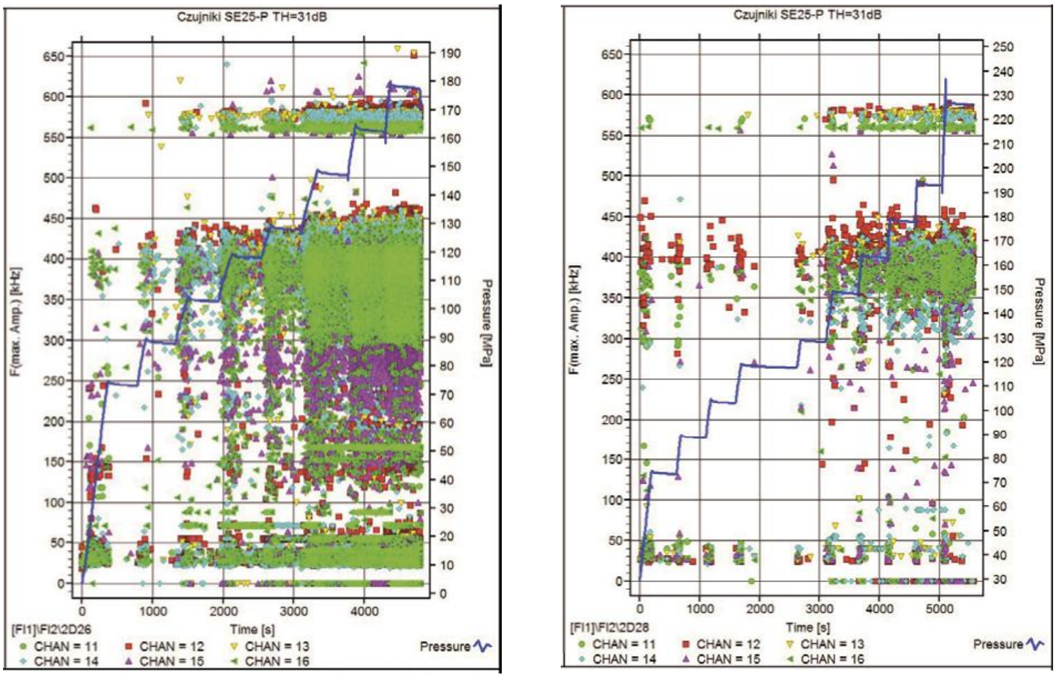

Figure 4: Frequency of wave signals during gradual load application and holding: cylinder with basalt fibers (left), and carbon fibers (right).

To obtain correct correlation between parameters of the recorded AE signals and composite damage process, loading was also applied to metal cylinders without the overwrapping fibers. Studies showed the amplitude of AE signals to be up to 50dB and the occurrence of frequency ranges from 25kHz to 100kHz. Evaluation of the AE activity in the performed experiments has pointed out to the type and range of parameters associated with the deformation process of the composite structure. The relations between deformation processes within composites and their AE signals were recently reviewed by Ono [7].

For direct assessment of the structural applicability of the composites reinforced with basalt fibers and with carbon fibers, a classification system was developed for groups of the AE signals with characteristics reflecting the phenomena occurring under the loading conditions. To identify separate signal groups, the measurement data were subjected to an analysis using Vallen Visual Class application.

As most important for the groups of signals identified by the classifier were considered parameters such as the frequency distribution, the number of events, the assigned duration of signals and their amplitude. To assign the active physical phenomena to the individual developed classes of signals, it was necessary to know the state of damage of the composite structure due to deformation. The condition of the composite structure elements was examined on a cylinder cross-section before and after the impact of selected load levels qualified by stress calculated for the steel cylinder.

Structure examinations were made by optical microscopy and scanning electron microscopy. For the purpose of AE analysis, additional basic characteristics of the AE activity of deformation were set for the composite materials with basalt fibers and with carbon fibers. Flat composite samples were made by the same technology which was used for the fabrication of cylinder windings. Tests were carried out under the conditions of quasi-static unidirectional tension. For the composite with basalt fibers, the state of fracture of the fibers was characterized by the amplitude level of 90dB, while for the composite with carbon fibers this was at 65dB. Both composites under the conditions of the increasing stress were characterized by the same frequency band activities. Basalt fiber-reinforced composite showed a significantly higher AE activity expressed in the count in dominant frequencies band.

As a result of the Visual Class analysis, six classes were distinguished and considered sufficient for a comprehensive description of phenomena occurring during the cylinder loading. Based on the results of the analysis, a straight relationship was derived and complex processes associated with the damage of composite fiber and matrix were ascribed to the activities in class 1 and class 2. These classes are defined by the activity of responsible AE parameters, as further confirmed by the lack of their development in the loaded metal cylinder without a composite winding. Class 6 is associated with the phenomena of the deformation of steel cylinder and its interaction with the composite fiber. Other classes are associated with various phenomena resulting from the operation of the loading system.

In assessment of the failure mode of composite, interaction of structural components resulting from the concurrent deformation running in both radial and circumferential directions should be taken into account. This condition is due to the strain being transmitted from the steel sleeve to the composite structure. The consequence is intensive process of friction co-acting with the fiber and matrix damage mechanisms. Physically, this results in the occurrence for each class of the composite damage of interoperable mechanisms acting in the background of the leading and dominant mechanism.

Respective drawings show the AE activity of classes during loading of cylinders with basalt fiber (Figure 5) and with carbon fiber (Figure 6). The development of activity in individual classes confirms the same damage mechanism operating in each cylinder. The beginning of the steady growth in class 2 is the symptom of the load effect being actively taken over by the composite winding.

4. CONCLUSIONS

The applicability of composite fibers as a reinforcement of steel cylinders has been experimentally documented. This solution shows high mechanical usefulness, equally well acceptable with either of the two fiber types used. The results of the analysis indicate that the same physical phenomena are responsible for damage occurring to both composites and are described by similar AE characteristics. Studies based on the AE clearly point out the existence of similar destruction mechanisms and criteria, both of which should be considered at an early stage of the structure design.

The carefully examined developments in the classes of AE signals applied to the heavily loaded cylinders enabled the detection of a critical level of loading to be about 15%. This is the lower limit applying to the basalt fiber reinforcement and upper limit to the carbon fiber reinforcement. In experiments, the circumferential deformation of basalt fiber-reinforced cylinder was 1.3 times higher in the linear range and 2.0 times higher in the elastic-plastic range than those of the cylinder reinforced with carbon fibers. This difference is mostly accounted for by the modulus of elasticity of these fibers.

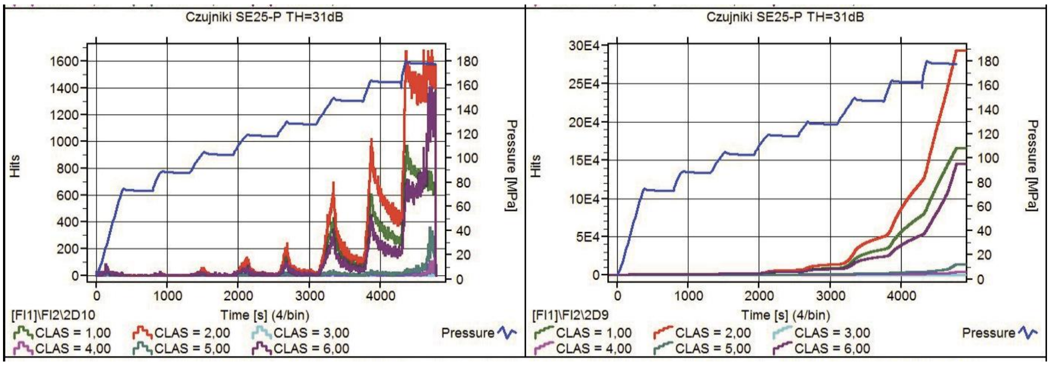

Figure 5: Activity of signal classes during gradual load application and holding: cylinder with basalt fibers

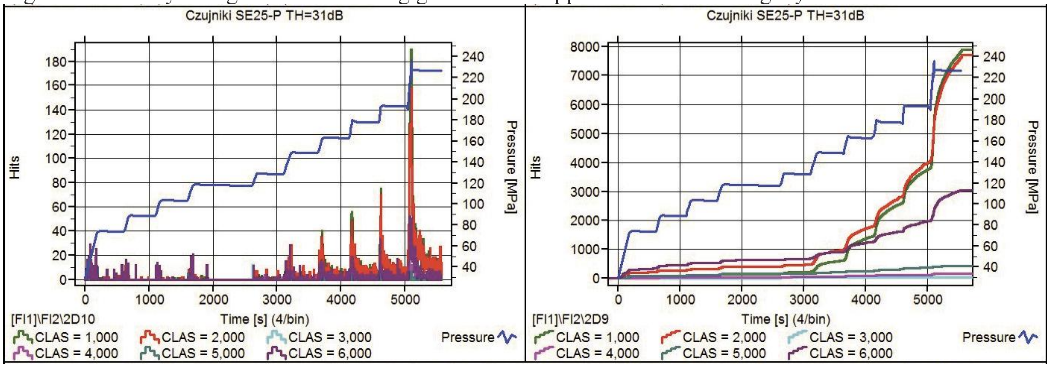

Figure 6: Activity of signal classes during gradual load application and holding: cylinder with carbon fibers

The method for cylinder reinforcement, analytically examined in this study and experimentally tested in practice, is characterized by high mechanical applicability in the design of hybrid cylinders. The present analysis gives the designer the opportunity to choose the fiber winding most economically viable and well-adjusted to the geometry of the structure. It also indicates full applicability of basalt fibers as a reinforcement material for heavy duty structures. At the same time, the results document high usefulness of the advanced methods of acoustic emission in experimental evaluation of the effort of hybrid materials and in the determination of safe working stress.

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REFERENCES

[1] Lekhnitskii, S.G., (1981) Theory of Elasticity of an Anisotropic Body (English translation). Moscow: Mir Publishers, 1981.
[2] Herakovitch, C., (1998) Mechanics of Fibrous Composites. New York: John Wiley & Sons.
[3] Jones, R., (1998) Mechanics of Composite Materials 2nd ed. New York: CRC Press.
[4] Gay. D., Hoa, S.V., Tsai, S.W., (2002) Composite Materials: Design and Applications. New York: CRC Press.
[5] Nowak, T., Schmidt, J., (2014) "Prediction of Elasto-Plastic behavior of Pressurized Composite Reinforced Metal Tube by means of Acoustic Emission Measurements and Theoretical Investigation", *Composite Structures,* 118: pp.49-56.
[6] Nowak, T., Schmidt, J., (2015), "Theoretical, numerical and experimental analysis of thick walled fiber metal laminate tube under axisymmetric loads", *Composites Structures,* 131: pp.637-644.
[7] Ono, K., Gallego, A., (2012) "Research and applications of AE on advanced composites", *Proceedings of the 30th European conference on acoustic emission testing*. EWGAE Granada, Spain.