Design of Composite Structures Using Advanced Numerical Tools

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The main topic of the presented paper is review of the mostly used tools in designing of composite structures. Consequently, practical demonstration of their using has been done on an example of a bending test of the wound, thin-walled composite rod. Further methods of definitions individual layers and the associated interface properties using the cohesive elements, based on that it is possible to detect arising delamination. Unlike conventional approaches, there is not possible to define a definite strength limit or nonlinear plasticity. For this purpose, the so-called failure criteria exist for the composite materials. In this way, it is possible to describe the real stress/ strain situation for the composite parts. Composite materials, due to their anisotropy, offer by suitable layer composition the possibility of significantly improving the efficiency of material utilization. Just in such cases, some advanced numerical tools like e.g. DOE, response surface and genetic algorithms could be used. Based on the above described methods, the experimental results of the carried three point flexure test have been numerically verified and the properties of the tested rod optimized.

Keywords: Composite Materials, Carbon Fibers, Bending Test, Design of Experiments, Failure Criteria

1 Introduction

The most effective replacement of conventional materials by composites is possible only with the appropriate combination of manufacturing technologies, stack up of individual layers and optimal ratio between the dispersion and matrix. For this reason is using of modern CAD technologies the key points in the future of designing composite parts as mentioned [1]. The undisputed benefits of using long fibres composites whose properties could be targeted for a particular application, consist mainly in the most efficient utilization of material. This approach is important because the saving of energy by weight reduction of final products has important role through almost all manufacturing sectors. Compared to metallic materials, composite laminates offer also some unique engineering properties while presenting interesting and challenging problems for analysts and designers [2,3]. This is mainly represented by the variability of the engineering constants in the 3 base directions. Whereas conventional materials show one failure mode i.e. cracking, composites can exhibit one or often more combination of failure modes, including fiber rupture, matrix cracking, delamination, interface debonding and void growth as described [4,5]. Among the basic and most widely used tools belong composite pre-post processors in Ansys (Ansys Inc.) and Abaqus (Dassault systemes). There are also the professional tools ANSA & μETA [8], and the open source platform, part of CAE Linux, Salome (GUI) and Code-aster (Solver), which are currently reaching dominant position among not only the open source solid modelers.

As the main part of the presented work, for practical demonstrations of the use of the mentioned tools and some further introduced method have been done on an example of a bending test of the wound, thin-walled composite rod. The four plies rod was created by the method of the pre impregnated fibers winding. The used material was the epoxy UD carbon prepreg with thickness 0.2 mm, the plies layout was 55/-55/55/-55, length 340 mm and weight 158 g. The tube was at first experimentally tested and then numerical model in ACP Ansys has been carried out. When composing a similar model we could meet the first question, assessment of two basic approaches, namely the modeling of the layered composite as solid or shell elements. Using of the solid one have advantages e.g. in modeling mutual plies delaminations and the seccond shell offers faster solution with usually better convergency.

When comparing the experimental and numerical results, in a well-constructed model, we could obtain very accurate results but only in the initial time steps, usually before the real deformation and rupture arise. Unlike conventional approaches, there is not possible to define a definite strength limit or nonlinear plasticity, thus just the right moment in which the behavior of components changes distinctly. That is why in the composite designing exist methods based on so called failure criteria. It is the analytically based approach to real stresses distribution in individual material elements that describe the probability of arising failure. The modes of failure in a bending with large deflection and destruction of the samples described [4]. In his work is possible to find description how in fiber composite begins damage at micro-scale with matrix cracking, fibre matrix debonding and fibre failure. This is followed by meso-scale damage such as intra-yarn cracking and inter-ply delamination. By comparison of strength properties of by particles, short and long fibres reinforced materials dealt [6]. Composite materials (usually composed of several orthotropic layers), due to their anisotropy, by suitable layer composition offer the possibility of significantly improving the efficiency of material utilization as mentioned e.g. [7]. Just in such cases, some advanced numerical tools like e.g. DOE (Design of experiment) and theories based on multimodal searching (e.g. genetic algorithms) could be used. The principle is that with using a suitable algorithm we are able to find the optimal results (ideal plies layout) with respect to the real loads and boundary conditions.

2 Materials and Methods

As has been already mentioned there are some leaders in the field of conventional simulation tools. Nowadays, probably the most widespread one is the composite module in Ansys. Beside the quite intuitive interface, there is very good default database of not only composite materials, but also some interphase properties and deformation criteria. This could help us correctly set our own models. Very important part is also possibility of mutual connection of individual modules with shared parameters. Another conventional tool is Abaqus, that solve the composite materials based on approach of the so-called continuum layered shell. Even if we missing some default material libraries and the creation of individual parts is more difficult, it is important to mention the very intuitive controls and settings of the plies, individual features and the possibility of displaying very well-arranged layout of the entire model. Unlike the other tools, the mesh is created after creation of the layers, which is quite unusual approach.

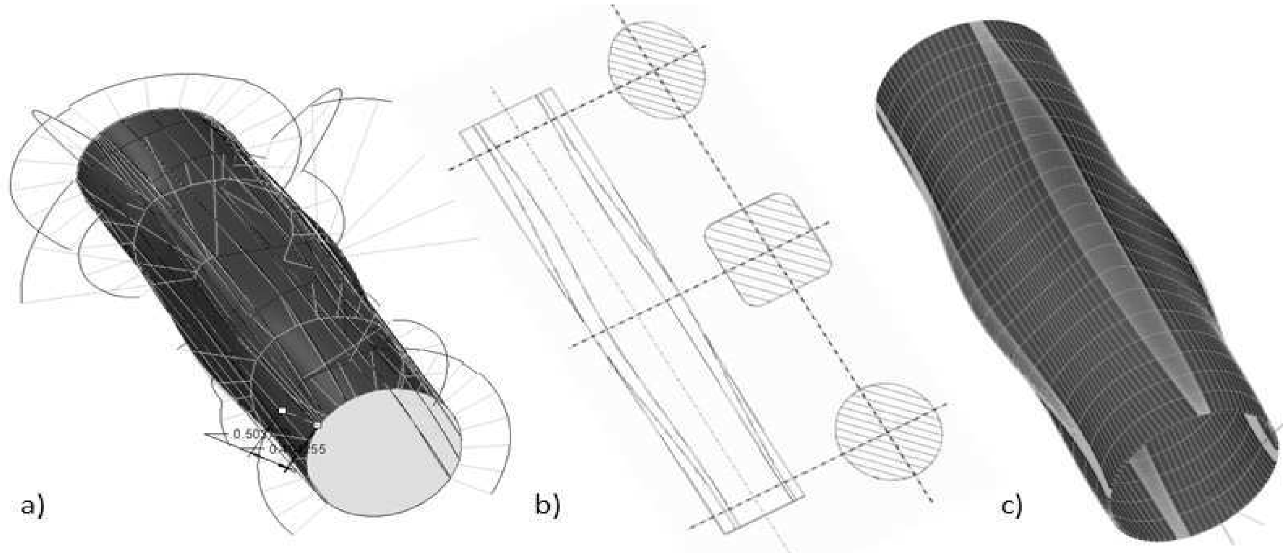

***Fig. 1** The example on a tested geometry: a) Curvature vectors of sample geometry in Creo b) Variable cross sections c) Mesh in Salome-Meca*

As a very promising tool especially because of the open source code is group of tools cooperated under Unix system (CAE Linux) in the area of mechanics of solid parts, namely Salome-Meca, ASTK, Eficas and as the solver Code_Aster. At the time of writing this work, the tools have been under significant development, combining language localizations from French to English and parallely coexist several versions, which caused often incompatibility of some commands, found scripts and plugins in the prepost-processors. Despite that at this time quite significant problems, author would like to mention this tools in faith in their very important future position that could be similar like e.g. Open Foam in the field of open source CFD. Practically this platform applied e.g. [9]. In the Fig. 1 we could see an example of very simply created mesh at a quite complicated various geometry of tube with various curvature and cross sections as a small demonstration how big potential this platform offers.

Used samples

As the default part for the application of the above mentioned tools and algorithms the winded carbon tube has been used. Winding is a manufacturing process of rotational wrapping of several filaments from coils with simultaneous movement of the mandrel in the axis direction (Fig. 2). That should keep fibers continuous and aligned throughout an entire part. As mentioned [10] this method offers a high degree of automation and relatively high processing speeds. The process is known for a long time. However, until recently this technology was concerned especially to field of textile engineering (braiding of ropes, fluid – air hoses) and parts usually from some atypical sectors. Nowadays, due to a big progress in using advanced composite materials instead of conventional, we could met the winded composite parts in many industries. In the Fig. 3 is possible to see layout of a model of the layered shell with shown fiber direction and real inner structure of the tested part.

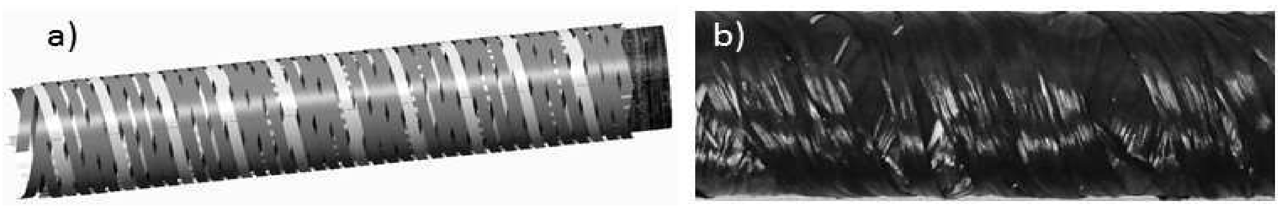

***Fig. 2** The winded tube a) CAD model b) Real part*

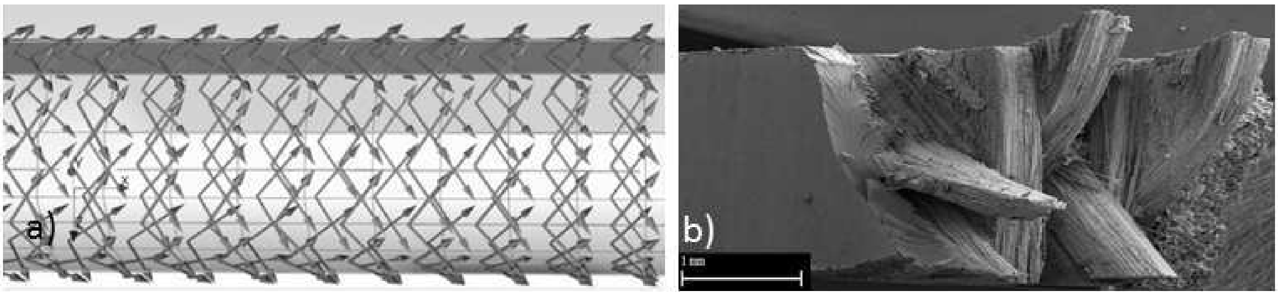

Fig. 3 *Multilayered winded shell from carbon prepreg a) Numerical model b) Real inner structure*

In the view of homogenization a transversally isotropic behavior is commonly assumed for the composite according to [12]. Consequently, the stiffness could be described by a set of five parameters: young-moduli ($E_{11}$and E_{22}), poisson's ratios (ν_{12} and ν_{23}) and a shear-modulus (G_{12}). With the help of homogenization techniques these five parameters describing the stiffness behavior of the composite can be derived.

Tab. 1 *Basic mechanical properties of the used material*

	E1 [MPa]	E2 [MPa]	ρ [g/cm^3]	μ [-]	Ductility [%]
Carbon	101 000	9 000	1.9	0.25	lim -> 0

Failure criteria

Because for composite materials with various layer compositions, angles etc. it is not easy just simply declare nonlinear behavior and maximal allowed stress, it is instead of that possible to use so called failure criteria. It is approach based on several theories that describe particular phenomenas and real stress arising inside the individual plies and their interphase. Generally we have to consider three (conventionally labeled I, II and III) basic failures modes (Fig. 4). With the basic types of failures dealt in his works e.g. [13] who among the other things mentioned that compared to metals, the characterization of fracture toughness of composite materials are still in the process of longtherm development. With deep study of the two basic Tsai-Wu and Puck criterium dealt [19] in his work and mentioned, that Tsai-Wu Failure Criterion is simple failure criterion which takes interaction of stresses in different directions into account by making use of strength tensors. It is considerably cheaper in computational effort compared to Puck criterion especially in 3D stress states. A drawback of this criterion based on von-Mises criterion is more suitable for ductile materials.

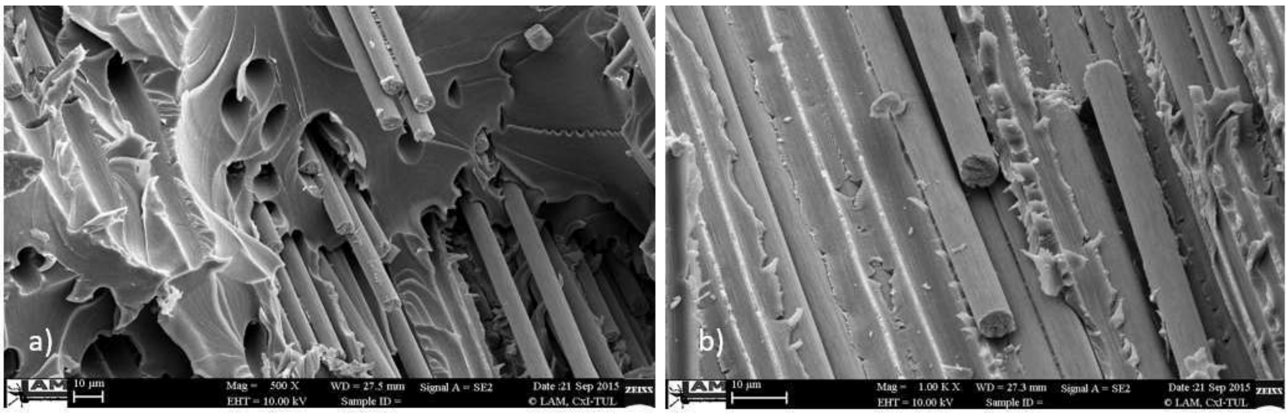

Fig. 4 *Typical problem in composite structures a) Extraction of fibers from the matrix b) Fiber rupture*

Optimization tools

Another, very powerful tools are algorithms based on another kind of mathematical and statistical approach. The aim of this work is by varying of some chosen parameters reach the required improvement of the target parameter. In our case it is with the combination of two, from totally four layers with the layout P1/P2/55/-55, find the best combination in order to improve the bending stiffness (presented by the force – parameter P3) of the tested rod. At first it is necessary to find the correlation between those parameters.

At first, it is necessary to define the possible values that the each point in the optimized generation of parameters Dp_{ij} could achieve (1). For the solved case - the winding angle in individual plies, could practically reach up 10 to 80 degrees. Also, because the accuracy of the manufacturing method is limited, the used number format was just integer, this step could make the numerical solution significantly faster. The fundamental function of the mathematical algorithm applied for generating the individual design points could be according to [14, 15] described as (2). Then it is necessary the newly created individuals compare with the previous members and to the next generation goes just the better of them.

$$Dpij = \{(type^j; Lo^j; Hi^j)\} \quad (1)$$
$$x_{ij} = Lo^j + rand(0,1)(Hi^j - Lo^j) \quad (2)$$

Where:

Type... mean the number character [real, integer, discrete set..],

Lo and Hi ... the lowest and highest possible value of the optimized parameter [-],

i … nr. of an actual generation [-],

j … nr. of the actual design point [-].

3 Model

The prediction of mechanical behavior is very complex problem, because the process induces fiber orientation, stacking sequence, interface of plies etc. According to [18] advanced methods could describe the entire damage process from its initiation to a complete failure of a composite structure. In our case the problem of numerical simulation of composite materials is an assumption of a homogeneous system with perfectly aligned fibers and their uniform distribution throughout the entire volume that in fact is for the winded composites not always true. Another question is, how accurate the simulation should be to be suitable [11]. It means how much really depend on the mesh relevance, chosen formulations, defined criteria etc., because we need to consider the fact that the initial error caused by the material model is for composite parts significantly bigger than for conventional materials. In our case, the model of shell composite plate and the tree solid tubes have been carried out in the ACP of Ansys. The model was solved as a fully contact task. For combination of solid and shell elements the pure penalty formulation with nodal-normal detection of integration points was used. The frictional support with asymmetric behavior has been set. In the Fig. 5 are the model layouts and first result of simulation before optimization.

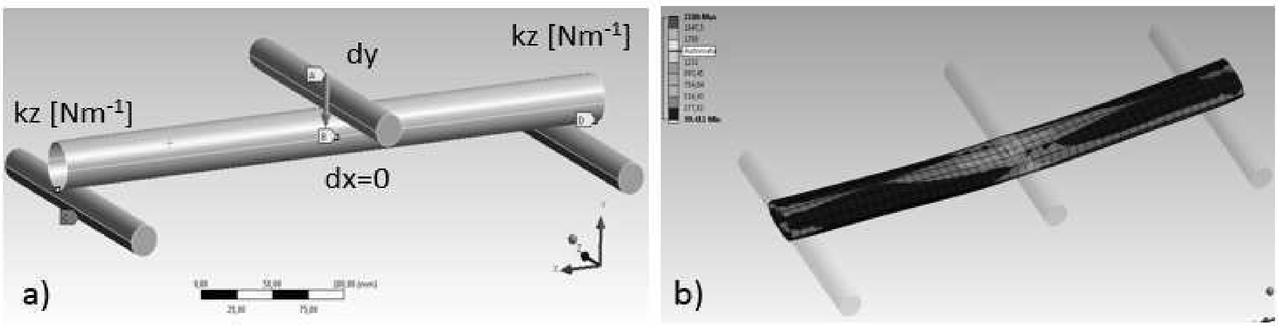

Fig. 5 *The carried model: a) Model scheme b) Resulting global stress*

Optimal layout

As had been mentioned in the chapter optimization, using the searching algorithms we would like to optimize the layout of winded tube to achieve the maximal possible bending stiffness. Generation of thousand design points was created in the used tool called Response surface [16]. The function value has been limited by the real manufacturing conditions it means the winding angle between 10-80°. In the Fig. 6a is possible to see the dependency of the two plies angle on to the maximal acting force in vertical direction. In Fig. 6b is the sensitivity of the targeted parameter on the two varied parameters. Even if the values logically should be equal, the two plies differ in the stacking nr. and also in the fact, that the used algorithm works only with a statistical sample of the entire population of possible combinations and the results offer generally just optimal not the best values.

In **Tab. 2** are the three founded candidates – design points with the best value of fitness function presented by the force value.

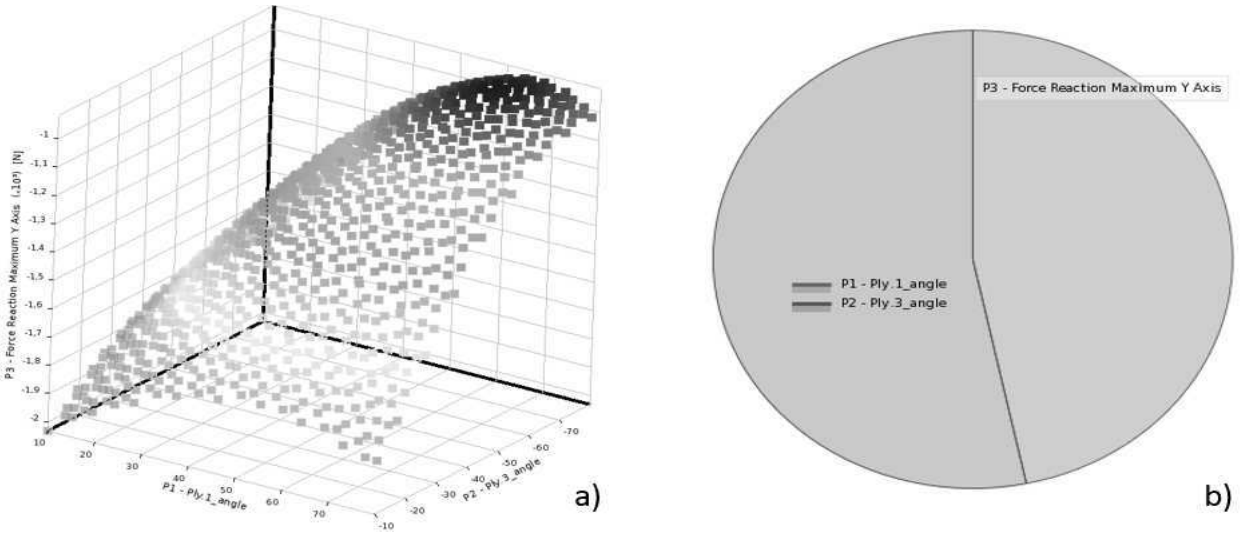

Fig. 6 *The bending force and angle of two plies a) Mutual dependency b) Sensitivity of force on the parameters*

Tab. 2 *The founded best candidates from the created generation of thousand design points*

	Candidate Point 1	Candidate Point 1 (verified)	Candidate Point 2	Candidate Point 3
P1 - Ply.1_angle	10		21,165	79,405
P2 - Ply.3_angle	-10		-11,879	-11,127
P3 - Force Reaction Maximum Y Axis (N)	-2031,5	-2031,5	-1889	-1851,7

Post processing

Apart from the significant anisotropy differ the simulations of composites and conventional materials in one other important thing. It is, that there is usually not possible to just simply declare value like strength limit. This is mainly caused by the fact, that value of stress does not consider the actual stress / strain relation inside the material, between the individual layers. It means, even if the angle layout should be optimal, the stacking could cause big stress concentrations in the interlaminar boundaries. An example of the forces distribution through the shell in the point in the middle of tested tube could be seen in Fig. 7.

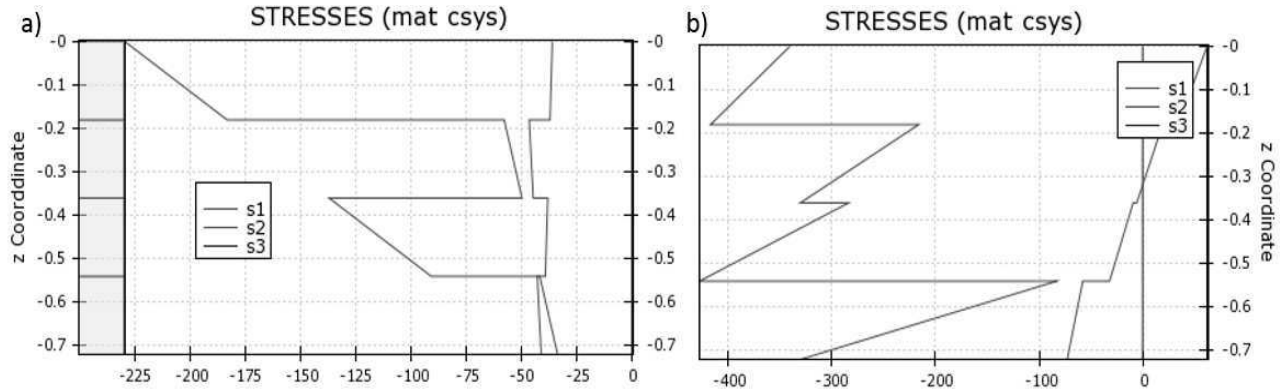

Fig. 7 *The sampling point: Inner forces in the plies and their interfaces: a) Original b) Optimized*

Failure criteria

The main principle in composite material designing is to use the material as effectively as possible. In this point of view, we computed the failure criteria with the original and with the optimized tube. In the Fig. 8, we could see that in the first case, there was a lot of material that was not fully exploited (the green areas without stresses and big loading concentration in the middle part). At the second case, is possible to recognize, that after transformation of the two plies angle, the stress distribution in the part is significantly better. It means that for our case of bending is the material utilized more effectively.

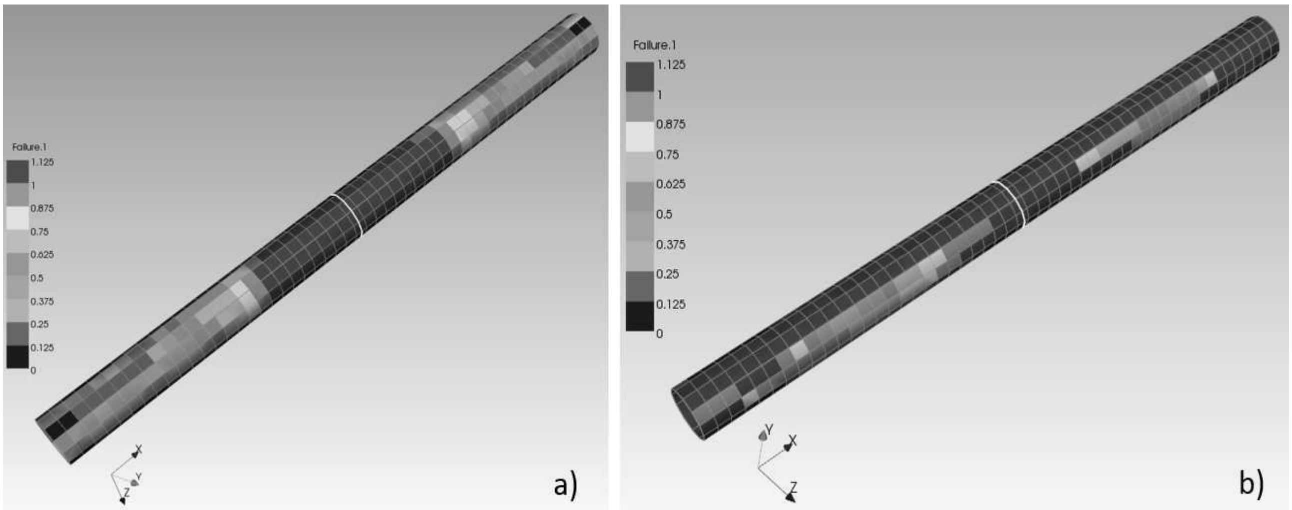

Fig. 8 *Puck failure criterium for the: a) Original 55/-55/55/-55/ (b) Optimized tube 10/-10/55/-55/*

4 Experiment

The flexural strength of a material is the maximum stress that material subjected to bending load could resist before failure. A classical three point bending test [3, 17] (Fig. 9) was used to demonstrate the founded properties of composite tube and comparison the results with carried model. The experiment was carried with the velocity of 0,5 mm/s up to the total destruction of the object.

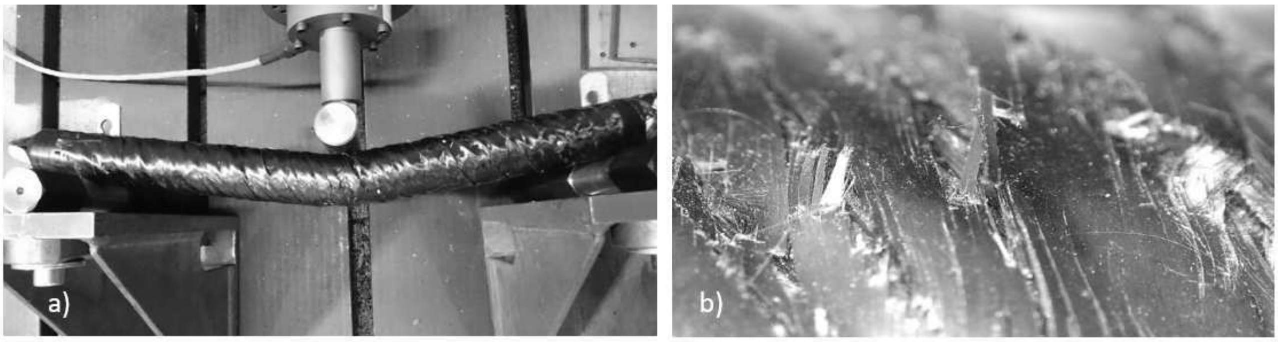

Fig. 9 *The bending test a) Tube loading b) Material fracture and delamination*

5 Results and discussion

The carried model (Fig. 10a) was in a good agreement for approx. first 10 mm. Then, in the real case start the force decreasing because of arising nonlinear deformations, delamination, ruptures etc. That is the time, when we need to take into account the failure stats. In the Fig. 10b there is a numerical comparison of the individual optimized parts. There are the original one 55/-55/55/-55, the found optimized to maximal strength 10/-10/55/-55 and also the weaker one 70/-70/55/-55.

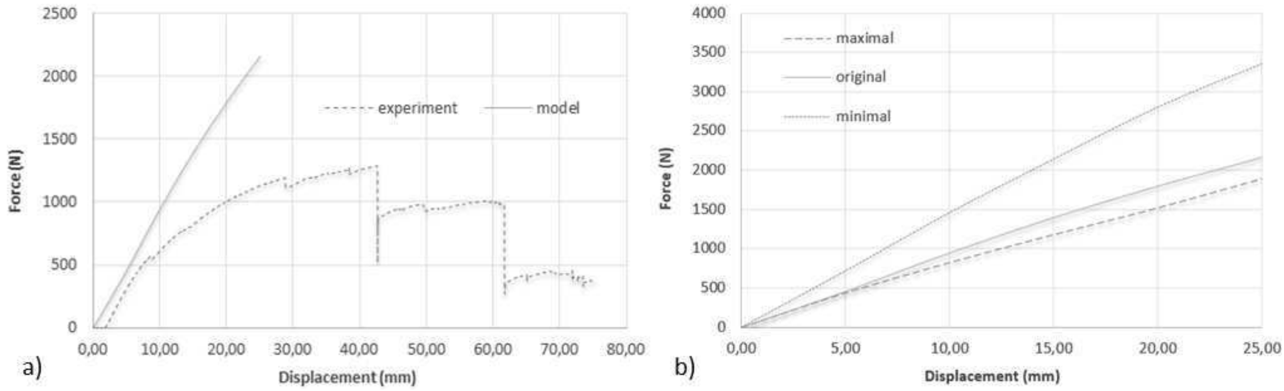

Fig. 10 *The found results of the bending test: a) Experimental and numerical b) Numerical comparison*

6 Conclusion

In the individual chapters of this work are basic introduction and demonstration of methods used in designing long fibre composite parts. This article should not have solve any specific task, but on the example of three point bending test demonstrate the actually most important tools in Computer Aided Engineering. For the study the winded tube from carbon prepreg with default layout 55/-55/55/-55 has been used. This method is suitable not only for straight shapes but with appropriate settings of the winding angle also for curved or closed shapes.

The experimental results were evaluated by numerical model, carried in advanced composite preprocessor of Ansys. Up to the moment of the first deformations, were results of the model and experiment in a good agreement. Unlike conventional materials for the composites it is not possible just specify the critical point or arising rupture, but we could statistically describe the probability, that the failure will happen using failure criteria and interlaminar delamination.

In the last part of the article, by parameterization of the two angles P1/P2/55/-55 and using the advanced numerical optimization methods, we tried to improve properties of tested tube for the case of bending. Several possible combinations of angles that could increase the stiffness have been found. Another advantage of using optimization algorithms is, that the founded results – like in our case the optimal layout of the rod for three point bending, are universal and valid also for different material combinations. The aim of our future work will be concentrated on study using the presented tools for curved and closed shapes, where the winding angles, especially in the elbows, are not constant and also the acting forces and moments will be more complex.

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