Virtual and real condition of composite material parts for special lightweight vehicle

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Abstract. The purpose of this contribution is comparison the results from FEM software analysis of construction profiles with real tests of concrete glass-carbon fiber components. We decided for experiments and simulations of carbon fiber tubes because our future project will be specially oriented for extremely terrain lightweight vehicle and there is a need of a light and safe frame with special chassis. The new vehicle project will be based on a modular universal design. Based on research in this area, we try to determine how we can trust the result of the virtual solution of parts of the composite structure. On the base of this outcomes we find out how to adjust the boundary conditions in phase of software computing to make relevant simulations, which can be even more precisely, effectively and true.

1. Introduction
The usage area of carbon composite materials is day by day wider and wider [1]. Problem with this kind of material is in their price and expensive cost of production. Cost of it going to be stable for few years. But sphere of research of carbon construction should become less expensive thanks to FEM analysis computer software [2]. It is also the aim of this study to learn how to adjust the boundary conditions and consider valuable of this virtual results. This can help in the phase of development and design to confirm required load conditions of final construction without physical model [4]. But for study purpose we needed to start with physical models and real load tests to compare real and virtual results of material conditions. In the end we will be able to design carbon car parts, which can stand the operating load based only on simulation results, without previous physical tests.

2. Methods
For intention of the study was used tensile test machine LabTest 5.20ST type: KAP-S. Device allows us to measure tensile test, but also bend test and wall collapse.

As mentioned before the material of tubes is carbon fiber roving. Carbon fiber roving is frequently supplied in the form of a continuous tow wound onto a reel. The tow is a bundle of thousands of continuous individual carbon filaments held together and protected by an organic coating. For study purposes were selected 3K carbon fiber, which is most common carbon fiber. It gives to the plate classic carbon fiber look. 3K is the workhorse of carbon fiber. It’s light, relatively stiff and easy to get and make. 3K got higher elongation before failure and ultimate strength than 6K, 9K or 12K. Because 3K is a smaller bundle of fibers, thinner fabric can be woven than with 12k, or thinner tubing can be filament wound, but if the fiber is the same grade, stiffness and strength are not affected by tow size. It is used in Aviation, industrial field, architecture, sporting, recreation goods.
First set of specimens are circular closed profile tubes. Internal diameter is 20 mm and length of tube is 240 mm. Wall is 0.8 mm thick and contain 4 layers of carbon fibers. It means that each layer measures 0.2 mm and was reeled in different angle direction. From bottom to top surface it’s 25°, 75°, 33° and 45° (Figure 1). Into the deep of 20 mm on both ends of tube was glued steel pin. Pin serves as grip to test machine.

Second set of test specimens are square profile tubes. Internal length of square edge is 40 mm and length of tube is 440 and 220 mm. Wall is 1 mm thick and contains 5 layers of carbon fibers. It means that each layer measures 0.2 mm and was reeled in different angle direction. From bottom to top surface it’s 25°, 75° 33°, 75° and 45° (Figure 2).

Difference between real and virtual results should cause layers. Tubes are made from carbon fiber roving on winding machine (Figure 3). There are areas of each one layer, where machine put the fiber more than once in same direction. So this crossings of fibers cause that real values were higher than virtual values in terms of deformation. In Ansys Workbench is possible to make only smooth layers, but allows us to see every layer separately if we want to see for example equivalent stress of each one layer.

3. Results

3.1. Tensile test of circular profile

Tensile test wasn’t measured till breakage of carbon material, because glue joint between tube and steel pin has smaller strength limit than carbon. Test lasted till moment of glue breakage. It’s obvious that carbon should resist even more tensile force, but laboratory equipment limited our possibilities, because we had to clamp steel pins to testing machine. So we are going to deal with phase from 0 N till 7730 N of load. Measured values at this range serves as comparison between virtual and real condition of carbon material. Curve of real values sign the real condition of load 10 Newton per second. Test lasted 388 seconds and reach 7730 Newton before breakage. The chart (Figure 4) shows linear curve of load in relation of tensile force and strain. Curve of simulation values is simulation of condition of Ansys analysis. For this purpose was modeled exact CAD model of test specimen. Boundary conditions entered for simulation was as similar as Ansys should offer. One steel pin was fixed in upper position and lower was loaded with tensile force. Table 1 shows the differences of calculation from real test status. Comparative values were chosen every 20 seconds. On the Figure 5 is shown course of deformation loaded with 7730 N of tensile force.
Table 1. Measured values during tensile test and simulated values.

| No. | Tensile force [N] | Real deformation [mm] | Simulated deformation [mm] |
|-----|-------------------|-----------------------|----------------------------|
| 1   | 0                 | 0                     | 0                          |
| 2   | 427.68            | 0.25                  | 0.1044                     |
| 3   | 830.04            | 0.4                   | 0.20261                    |
| 4   | 1230.24           | 0.53                  | 0.30032                    |
| 5   | 1630.47           | 0.64                  | 0.39802                    |
| 6   | 2031.51           | 0.84                  | 0.49592                    |
| 7   | 2430.27           | 0.94                  | 0.59326                    |
| 8   | 2829.66           | 1.04                  | 0.69076                    |
| 9   | 3230.55           | 1.13                  | 0.78862                    |
| 10  | 3630.12           | 1.22                  | 0.88616                    |
| 11  | 4030.5            | 1.31                  | 0.9839                     |
| 12  | 4431.03           | 1.4                   | 1.0817                     |
| 13  | 4829.46           | 1.5                   | 1.1789                     |
| 14  | 5229.84           | 1.59                  | 1.2767                     |
| 15  | 5631.21           | 1.69                  | 1.3747                     |
| 16  | 6031.77           | 1.79                  | 1.4724                     |
| 17  | 6429.06           | 1.89                  | 1.5694                     |
| 18  | 6830.58           | 2.94                  | 1.6674                     |
| 19  | 7231.11           | 2.01                  | 1.7652                     |
| 20  | 7628.73           | 2.15                  | 1.8623                     |
| 21  | 7730              | 2.3                   | 1.934                      |

Figure 4. Chart of tensile test.

Interesting case is to see equivalent stress of each one layer individual. In the Table 2 are test specimens simulated with 7730 N tensile load. Top layer with angle 45° of fiber winding has maximum stress 78 MPa. Second lower layer of 33° angle stand the best in the layer test. Tensile load accumulated only 21.9 MPa. It means that this angle of winding is the best resist for tensile force. On the other hand worst for bending force as going to be described later. 75° angle shows the maximum stress of every layer and it is 199 MPa. Bottom layer of 25° angle indicates 53 MPa.
Figure 5. The course of deformation.

Table 2. Example of various stresses on each one layer.

| Layer      | Fiber Direction | Max Stress |
|------------|-----------------|------------|
| Layer 1    | 45°             | 78 MPa     |
| Layer 2    | 33°             | 21.9 MPa   |
| Layer 3    | 75°             | 199 MPa    |
| Layer 4    | 25°             | 53 MPa     |

3.2. Bend test of 40 mm square profile

Bend test was made on square profile tube of length 440 mm. Bend around 2 profiles in distance of 320 mm. Imprint was block with 20 mm edge length (Figure 6). Curve of real values signs the real measured values. The curve of virtual values are simulated values. As we can see they move off each other after 1000 N of bending load (Figure 7). At this time during test we heard first crack of material. So comparative values are only to this phase. Probably crashed the internal layer of 25° angle direction, because after simulation this one indicate the largest equivalent stress (Table 3). Next interesting thing is the finding that this profile has two layers of the same fiber angle direction and comparison during simulation is completely different. Behavior is of layer is almost the same, but stresses are different about 2000 MPa (Table 3). But this kind of angles of layer section caused more wall collapse than bend (Figure 8). Another interesting knowledge is that real test specimen after freeing of bend force entered into original shape (Figure 9). It means that carbon material has degree of memory effect. Broken layers are still broken but nearest area still hold the shape of profile (Figure 10).
Figure 6. Dimensions of bend test bench.

Figure 7. Chart of bend test.

Figure 8. Bend imprint.

Figure 9. Profile after test.

Figure 10. Inside tear of bottom layer.
3.3. Wall collapse of square profile

Wall collapse was tested on square profile the same size as profile on bend test, but length was 220 mm. During bend test we saw that bend load cause wall collapse so we considered to test as next single wall collapse. Imprint was circular cross section of 15 mm diameter and loaded test specimen in the middle of the profile.

From the chart (Figure 11) we see the biggest similarity between the simulation and real test values. Difference of values happened after 2547 Newton of load (Table 4). It is caused because of sharp edge of imprint body. At this case occur cutting of material, no in the whole profile, but only in one layer. We guess it was in the top first layer based on values from simulation (Table 5).

Table 4. Measured values during wall collapse test and simulated values.

| No. | Load force [N] | Real deformation [mm] | Virtual deformation [mm] |
|-----|----------------|-----------------------|--------------------------|
| 1   | 0              | 0                     | 0                        |
| 2   | 375.00         | 1.03                  | 0.89                      |
| 3   | 877.17         | 2.03                  | 2.08                      |
| 4   | 1515.48        | 3.02                  | 3.26                      |
| 5   | 1794.54        | 4.03                  | 3.60                      |
| 6   | 2267.46        | 5.03                  | 5.39                      |
| 7   | 2547.00        | 6.03                  | 6.05                      |
| 8   | 2639.70        | 7.02                  | 6.27                      |
| 9   | 2802.66        | 8.02                  | 6.66                      |
| 10  | 2888.70        | 9.03                  | 6.86                      |
| 11  | 3000.00        | 12.03                 | 7.13                      |
This case of test shows that usage of minimum count of boundary condition which are needed provide the best results. In the simulation was fixed only bottom wall of profile (Figure 12). Comparison between virtual (Figure 12) and real condition (Figure 13) during wall collapse seems to be very similar. However after freeing of force after bending test the specimen entered into original shape at this case of wall collapse test the test specimen didn’t return into previous shape. It is because the inner layer was totally broken in the imprint area (Figure 14).

![Figure 12. Simulation of total deformation at 2547 N load.](image1)

![Figure 13. Square profile during wall collapse test.](image2)

![Figure 14. Wall collapse of carbon construction from inside profile view.](image3)

### Table 5. Comparison of each one layer.

| Layers from top to bottom | Layer 1 - 45° angle direction | Layer 2 - 75° angle direction | Layer 3 - 33° angle direction | Layer 4 - 75° angle direction | Layer 5 - 25° angle direction |
|---------------------------|-------------------------------|-------------------------------|-------------------------------|-------------------------------|-------------------------------|
| Deformation area          | ![Image]                      | ![Image]                      | ![Image]                      | ![Image]                      | ![Image]                      |
| Equivalent stress [MPa]   | 4676                          | 1818                          | 2019                          | 1780                          | 4200                          |

3.4. Results of measurement transform to the purpose of the project study

The purpose of this study was to adjust the boundary condition of simulations to compare with the real tests and also learn how the carbon material behave in real tests against virtual simulations. We also learned how different angle fiber direction cause on final load of material. So we are more able to design car parts for our unconventional all-terrain vehicle. At this time we are designing the arm suspension. At figure 14 is only conceptual view of arm suspension, not the final result. Study continue with many simulations of the test for the best shape of arm and also the best fit of fiber angle
direction. For interest we publish preliminary results of loaded special arm suspension on figures 15 and 16, where wall thick is only 1 mm and angle direction from top to bottom are 45˚, 75˚, 33˚, 75˚ and 25˚. So it’s the same as in previous tests. On figure 15 is result of equivalent stress after 3000 N of load. It indicates maximum stress of 1369 MPa on the edge so the next steps leads to erase this unwanted stress. On the figure 16 is shown the same simulation, but result is total deformation of arm. On the bottom edge it signs the biggest deformation of 10 mm so this dedication leads us to find better set of fiber angle direction of each layer.

Figure 15. Conceptual view of the arm suspension.

Figure 16. Representation of equivalent stresses.

Figure 17. Representation of total deformation.

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