Comparison of experimental flexural test with FE analysis for specimen with different size and shape of internal structure created by 3D printing's

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Abstract. The aim of the paper was to compare experimentally measured values and bending test simulations. Specimens was created by 3D printing. Material for specimens is composite Onyx. The samples were different in the internal structure. The inner structure has a different shape and size. Flexural test measured stress from the force required to bend a beam under three points loading conditions. Aim this paper was to find out the data, which will used to select choice size and shape of the inner structure dimensions for parts that will loads with flexing. By optimizing the size and shape of the inner structure to ensure the choice of the right structure for a given issue with regard to material consumption. The samples are sized according to ISO 178. The test was carried out according to ASTM D790 and next ISO 178. Test measured the force required to bend the specimen he test is stopped when the specimen reaches 5 % deflection or the specimen breaks before 5 %. If the sample can withstand the desired deflection, the test will continue by norm ISO 178 and the test is stopped when the specimen breaks. The same was simulated in Ansys workbench using the FEM calculation method. These data processed in tables and graphs and mutually compared with boundary values. The lower limit or value will be a hollow sample. The upper limit was a solid sample where the highest stiffness is expected.

1. Introduction
Simulation of the flexural test measures the force required to bend a beam under three point loading conditions. Data are compared between practical flexural test and simulation from this test. The data is often used to select materials for parts that will support loads without flexing. Flexural modulus is used as an indication of a material’s stiffness when flexed. The sample lies on a support span and the load is applied to the center by the loading nose producing three point bending at a specified rate. The parameters for this test are the support span, the speed of the loading, and the maximum deflection for the test. By optimizing the size and shape of the inner structure, it is possible to ensure the choice of the right structure for a given issue with regard to material consumption. The specimens are sized according to ISO 178. The test is carried out according to ASTM D790 and next ISO 178. Test will measure the force required to bend the sample and test is stopped when the specimen reaches 5 % deflection or the specimen breaks before 5 %. If the sample can withstand the desired deflection, the test will continue by norm ISO 178 and the test is stopped when the specimen breaks. For the Specimen shape will used size from norm ISO 178. It is 10 mm × 4 mm × 80 mm [1–4].
2. Material and method of printing

Onyx is a composite filament for Mark Two Enterprise 3D printers. A composite material is a material made from two or more constituent materials with significantly different physical or chemical properties that, when combined, produce a material with characteristics different from the individual components. Onyx is not just only plastic material, it’s actually a fusion of engineering nylon and chopped carbon fiber. This chopped carbon fiber filament adds stiffness to 3D printed parts, not only providing micro-carbon reinforcement to keep parts true to their dimensions, but also giving parts a smooth, matte black finish. Onyx have properties, where are valued in 3D printing: hardness, nice surface finish, and good adhesion so parts don’t split along layer seams. Onyx is about 3.5 times stiffer than standard nylon because of the micro-carbon reinforcement. Because it also contains nylon, the engineering toughness and wear resistance is comparable as well, and the material has a heat deflection temperature of 145 °C. Onyx is can use it with high-strength fibers – carbon fiber, Kevlar, fiberglass, or HSHT fiberglass, to even further strengthen parts. In table 1 it possible showed material properties [1, 2, 5].

| Materials | Flexural strength (MPa) | Flexural modulus (GPa) | Heat deflection temperature (°C) | Specific weight (g cm\(^{-3}\)) |
|-----------|------------------------|------------------------|----------------------------------|---------------------------------|
| Onyx      | 81                     | 3.6                    | 145                              | 1.2                             |
| Nylon     | 52                     | 1.4                    | 41                               | 1.1                             |

Fused filament fabrication is a 3D printing process that uses a continuous filament of a thermoplastic material. Filament is fed from a large coil through a moving, heated printer extruder head, and is deposited on the growing work. The print head is moved under computer control to define the printed shape. Usually the head moves in two dimensions to deposit one horizontal plane, or layer, at a time. Print head is then moved vertically by a small amount to begin a new layer. The speed of the extruder head may also be controlled to stop and start deposition and form an interrupted plane without stringing or dribbling between sections. On figure 1 it possible showed Fused Filament Fabrication [2, 6–8].
3. Specimens
Specimens are created from material Onyx with additive technology Fused Filament fabrication. Specimens have 80 mm × 10 mm × 4 mm dimensions. Their differences are in shape of inner structure and dimensions of shape.

First group represent shape hexagonal (H), second group is square (S) and third group is triangles (T). Specimens are showed on figures 2, 3 and 4. This shapes have others sizes with parameter "l". Final number of types of the specimen is 9. Three different shapes (H, S, T) multiplied by 3 others sizes (2, 4, 6). Thickness fringes and wall between shapes is 0.8 mm. Settings by 3D printing are 2 layers by 0.4 mm and 4 roof and floor layers [3, 9, 10].

**Figure 2.** Specimen with hexagonal shape and 4 mm dimension of inner structure.

**Figure 3.** Specimen with square shape and 2 mm dimension of inner structure.

**Figure 4.** Specimen with triangle shape and 6 mm dimension of inner structure.
4. Results
The experimental flexural results obtained from three point bending tests are analyzed. The main objective is to compare the results for different shapes and sizes. The numerical results are in the table and plotted in figure 5.

The formulae presented below is used to calculate the effectiveness of individual internal adopted structures in terms of shape and size. In the first case, the stiffness effectivity $E_{\text{Stiffness}}$ is expressed by equation (1), and in the second case, the strength effectivity $E_{\text{Strength}}$ is expressed by equation (2). In both cases, efficiency is calculated as the ratio of force $F$ to volume $V$, as follows [3, 4, 10]:

$$E_{\text{Stiffness}} = \frac{F_{5\%}}{V}$$

(1)

$$E_{\text{Strength}} = \frac{F_{\text{Max}}}{V}$$

(2)

Table 2. Datasheet of Onyx from experimental flexural test by norm ASTM D790.

| Specimens | Force by 5% $F_{5\%}$ (N) | Maximal force $F_{\text{Max}}$ (N) | Volume $V$ (mm$^3$) | Stiffness effectivity Eq. (1) | Strength effectivity Eq. (2) |
|-----------|---------------------------|----------------------------------|---------------------|-----------------------------|-----------------------------|
| H2        | 10.87                     | 52.16                            | 2390                | 0.0045                      | 0.0218                      |
| H4        | 9.55                      | 48.61                            | 2075                | 0.0046                      | 0.0234                      |
| H6        | 8.76                      | 44.68                            | 1995                | 0.0043                      | 0.0224                      |
| S2        | 8.12                      | 43.22                            | 2393                | 0.0034                      | 0.0180                      |
| S4        | 7.72                      | 41.47                            | 2130                | 0.0036                      | 0.0195                      |
| S6        | 7.49                      | 39.70                            | 2077                | 0.0036                      | 0.0191                      |
| T2        | 8.91                      | 45.86                            | 2525                | 0.0035                      | 0.0181                      |
| T4        | 8.16                      | 42.51                            | 2270                | 0.0035                      | 0.0187                      |
| T6        | 7.69                      | 39.73                            | 2105                | 0.0036                      | 0.0189                      |

Figure 5. Setup for displacement measurement using digital image correlation [10].
Specimens was created like solid models. By simulation was used multilinear material model. Mesh was created with size 1 mm for element and method was used tetrahedron. In boundary condition was used force with magnitude 40N in vertical direction. Results have been registered in table 3.

### Table 3. Datasheet of Onyx from simulation of flexural test by norm ASTM D790.

| Specimens | Stress (MPa) | Directional deformation (mm) | Volume $V$ (mm$^3$) |
|-----------|--------------|------------------------------|---------------------|
| H2        | 29.99        | 9.49                         | 2390                |
| H4        | 34.19        | 9.94                         | 2075                |
| H6        | 38.47        | 10.47                        | 1995                |
| S2        | 30.61        | 9.49                         | 2393                |
| S4        | 33.74        | 9.77                         | 2130                |
| S6        | 37.98        | 9.90                         | 2077                |
| T2        | 32.15        | 9.47                         | 2525                |
| T4        | 32.24        | 9.90                         | 2270                |
| T6        | 35.27        | 9.93                         | 2105                |
| Full      | 26.91        | 8.43                         | 3200                |
| Empty     | 55.63        | 13.83                        | 1620                |

5. Conclusion

In plotted graphs, it is possible to see the differences between specimens. Generally, by observation of the results it is important notice that with increasing size structure volume the volume of material decrease. Naturally, the best inner structure have 2 mm of dimension ($l = 2$ mm), because this dimension have more volume of material than specimens which have bigger dimension of inner structure. By optimizing the shape and size of the internal structure, it is possible to save material. Therefore, it has been found that it is important to design and change the shape and size of the internal structure as needed for practical use.

Difference between results from experimental and simulation 3 point test bending are different. Best result from simulation had specimen with an internal structure of H2, where at a given magnitude of force $F = 40$ N the deformation results were almost identical.

As the size of the structure increased, the results differed substantially. There are more reasons for these differences. The main reason for this difference is the specified material model and the material properties. Ansys FEM software did not offer Onyx material and material values had to be entered manually. The entered values were obtained from experimental measurements. Experimental measurements revealed that the results for samples with the same structure were substantially different. It can be concluded that 3D printing technology fused filament fabrication in conjunction with onyx material does not guarantee constant strength properties. Subsequent averaging of these values and comparison with the simulation results resulted in differences.

6. References

[1] Markforget Material datasheet [online] Available: <https://static.markforged.com/markforged_composites_datasheet.pdf>

[2] 3D-PrintingTechnology [online] Available: http://3dprintingforbeginners.com/wp-content/uploads/2014/04/3D-PrintingTechnology

[3] Shimadzu Tensile test method for plastics: ASTM D638 [online] Available: <https://www.shimadzu.com/an/industry/petrochemicalchemical/n9j25k00000pyu05.html>

[4] Macko M, Flizikowski J, Szczepański Z, Tyszczuk K, Śmigielski G, Mroziński A, Czerniak J and Tomporowski A 2017 CAD/CAE applications in mill’s design and investigation Lecture Notes in Mechanical Engineering DOI: 10.1007/978-3-319-50938-9_35
[5] Kuric I 2011 New methods and trends in product development and planning Conference on Quality and Innovation in Engineering and Management 453–456

[6] Dodok T, Cuboňová N and Kuric I 2017 Workshop programming as a part of technological preparation of production Advanced in Science and Technology Research Journal 11 111–116

[7] Kuric I, Bulej V, Sága M et al. 2017 Development of simulation software for mobile robot path planning within multilayer map system based on metric and topological maps International Journal of Advanced Robotic Systems 11-12 1–14

[8] Sága M, Kopas P, Uhričik M 2012 Modeling and experimental analysis of the aluminium alloy fatigue damage in the case of bending - torsion loading Procedia Engineering 48 599–606

[9] Sapietová A, Sága M, Kuric I et al. 2018 Application of optimization algorithms for robot systems designing International Journal of Advanced Robotic Systems 1-2 1–15

[10] Domek G, Kołodziej A, Wilczyński M and Krawiec P 2017 The problem of cooperation of a flat belts with elements of mechatronic systems 55th International Scientific Conference on Experimental Stress Analysis 706–711

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