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Experimental Measurement and Testing of 3D Printed Parts in Terms of the Material Used

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As part of the practical component of the research, the author focuses on optimizing 3D printing parameters for components of a robotic kit. This involves selecting a suitable 3D printer, designing a set of experimental measurements, and conducting tests to gather essential data. The objective is to identify an appropriate filament material and determine optimal printing parameters that ensure the desired mechanical properties of the parts while maintaining cost-effectiveness in the 3D printing process."

Keywords: Kit, Robotics, 3D printing, VEX, VEX IQ, Education, Destructive testing, Tensile loading, Deflection

1 Selection and modification of parts for 3D printing

By comparing the two kits, when the VEX GO kit has 275 parts and the VEX IQ kit has 1000 parts, 2 parts were selected, while the tracked part of both robotic kits had to meet the following conditions:

- Found in both types of kit, both VEX GO and IQ,
- Has suitable dimensions for attachment to machines and fixtures for experimental measurements and testing.

The parts selected were 2x8 Smooth Panel (228-2500-524) and 2x12 Beam (228-2500-026). This was followed by preparation for attachment to the machine and to the device for experimental measurement and testing. The 2x8 Smooth Panel part (228-2500-524) proved completely unsuitable for this type of experimental measurement and testing. The 2x12 Beam part (228-2500-026), on the other hand, was completely satisfactory both in terms of dimensions and in terms of attachment. It is for this reason that the 2x12 Beam part (228-2500-026) was chosen as the final part for the intended project.

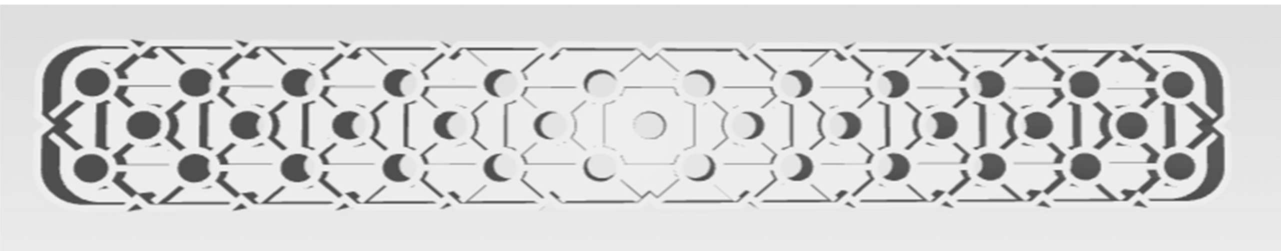

Fig. 1 *Original item 2x12 Beam (228-2500-026) VEX*

After a test print of the 2x12 Beam part (228-2500-026), it was found that the given model is unnecessarily complicated for subsequent post-processing, or during slicing, an extensive system of supports was created, which represented, first of all, an "unnecessary" consumption of material due to the fact of printing the part for the needs of destructive experimental measurement and testing, and also a significant time burden when removing these supports from the printed part. For this reason, it was necessary to adjust the model of the part so that the printing was as fast and simple as possible, and the subsequent post-processing after printing was minimal, or no. In the original model, the underside was aligned and the pin holes were blocked. From the point of view of testing, this fact does not have a fundamental effect on the result, as the dimensions and shape of exactly the same parts printed from different filaments are compared [1, 2].

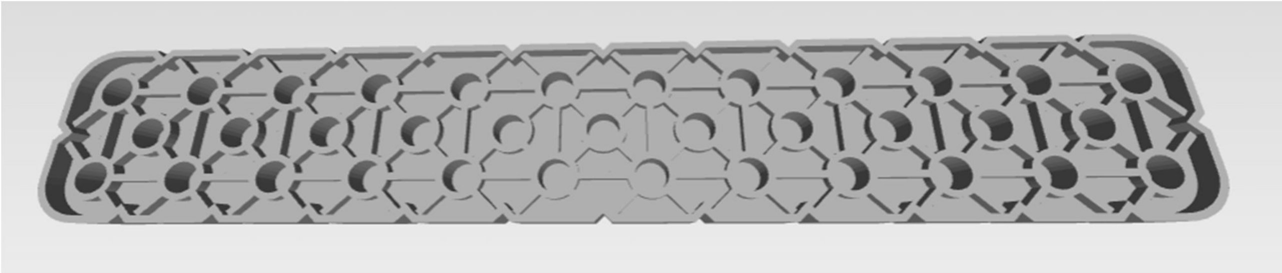

***Fig. 2** Modifyied item 2x12 Beam (228-2500-026) VEX*

2 Selection of printer

Printability in the conditions of primary and secondary schools and the requirement of easy printing (beginner level) defines printers using FDM (Fused deposition modeling) technology. During the research, it was found that the Prusa Research [3-4] 3D printer platform is currently the most used 3D printer platform in primary and secondary schools. The most frequently found printers from Prusa Research in Czech schools were the following:

- Original Prusa MINI+,
- Original Prusa i3 MK3S+,
- Original Prusa MK4.

The last variant of the printer was chosen, namely the Original Prusa MK4. The proof was the fact that it is a newer version and its evaluation is very positive compared to the others listed. Last but not least, this printer is owned by the Faculty of Mechanical Engineering at Jan Evangelista Purkyně University, where the individual prints were realized [1].

3 Filament selection and print settings

The decisive parameters for choosing the filament material are ease of printing, excellent mechanical properties of the print, minimal post-processing, quality of the filament from a verified manufacturer, so that the print succeeds on the first try and the nozzle does not become clogged, etc. Last but not least, due to the financing of Czech education, price is also a determining parameter. The monitored manufacturers were Prusament filament, Fiber3D and Filament PM. PLA (easy printing, worse mechanical properties, no post-processing), PET-G (easy printing, better mechanical properties, minimal post-processing), ABS were selected from the materials that are available on the market and meet the monitored criteria (more demanding printing, excellent mechanical properties, easy postprocessing) and ASA (replacement for ABS due to toxicity and easier printing) [2-7].

All the listed materials were selected in the final decision for experimental measurement and testing by destructive tests. In terms of printing, a printout with 100% density and straight fill will be made depending on the requirement of printing simplicity. Slicing is done in PrusaSlicer 2.7.4., and in the print settings, the height between the printing plate and the nozzle tip of the 3D printer is chosen for higher details due to the shape complexities of the model 0.10 to 0.20 mm, which also slows down the printing, which is desirable. From the point of view of printing speed, the setting on the first layer is decisive, which also determines the success of printing, the setting corresponds to a value of 10 mm/s [8-14]

4 Implementation and results of experimental measurements and testing

4.1 Tensile load test

Measurement conditions:

- Measurement date: 14. 05. 2024,
- Temperature: 22.2 °C,
- Air pressure: 997.7 hPa,
- Humidity: 34.8 %.

The aim of the testing is to compare and evaluate the mechanical properties of the original VEX IQ part and parts printed from materials: 1 x PLA (Filament-PM PLA MarbleJet light marble 0.5kg), 1 x PET-G1 (Fiber3D PETG Beige beige 1kg), 1 x PET -G2 (Prusament PETG Jungle Green 1kg), 1 x ASA (Prusament ASA Sapphire Blue 850g) and 1 x ABS (SunLu ABS Filament Yellow 1kg) on the Original Prusa MK4 3D printer. The experimental test will be performed using a tensile load test. The assumed place of fracture of the test prints is the part with two holes, or her immediate surroundings. We monitor the material that comes out the best from the test, while further experimental measurements and tests will then be carried out on the given material depending on the specific 3D printing settings.

Description and measurement procedure

- Preparation of test prints - visual inspection, removal of possible stringing for PET-G, and marking of test prints according to the table below.
- Setting of the tearing machine and software parameters (selection of the machine – Hegewald & Peschke inspect 100, selection of

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suitable clamping fixtures, pulling speed 10 mm/min, starting load F_0=2 N).

- Clamping the test print.
- Test execution – a total of 4 tests were carried out for each group of materials, which corresponds to 24 tests. The reason for such a sample was 2 factors, namely, the time requirement and workload of the laboratory of destructive tests of materials at the Faculty of mechanical engineering at Jan Evangelista Purkyne University, and the fact that the resulting force did not change significantly and the materials showed similar behavior. For this reason, the test was terminated with 4 results and was not continued.
- Analysis of results – location of fractures, maximum loading force until breaking of prints.

Tab. 1 *Measured values from the tensile load test*

Original item VEX		**Material PLA**		**Material PET-G1**	
Designation of the printout	*F_{max} [N]*	*Designation of the printout*	*F_{max} [N]*	*Designation of the printout*	*F_{max} [N]*
orig_1	2028	PLA_1	2611	PETG1_1	3906
orig_2	1927	PLA_2	2601	PETG1_2	3968
orig_3	1977	PLA_3	2579	PETG1_3	3917
orig_4	2090	PLA_4	2658	PETG1_4	3774
Arithmetic mean	**2005.5**	*Arithmetic mean*	**2612.25**	*Arithmetic mean*	**3891.25**

Tab. 2 *Measured values from the tensile load test*

Material PET-G2		**Material ASA**		**Material ABS**	
Designation of the printout	*F_{max} [N]*	*Designation of the printout*	*F_{max} [N]*	*Designation of the printout*	*F_{max} [N]*
PETG2_1	3568	ASA_1	2986	ABS_1	2674
PETG2_2	3513	ASA_2	3110	ABS_2	3020
PETG2_3	3458	ASA_3	2963	ABS_3	3032
PETG2_4	3609	ASA_4	2129	ABS_4	2946
Arithmetic mean	**3537**	*Arithmetic mean*	**2797**	*Arithmetic mean*	**2918**

Tab. 3 *Calculation of the standard deviation of the loading force of the original part from the tensile load test*

Original item VEX			
Designation of the printout	*F_{max} [N]*	*ΔF_i*	*$(\Delta F_i)^2$*
orig_1	2028	22.5	506.25
orig_2	1927	-78.5	6162.25
orig_3	1977	-28.5	812.25
orig_4	2090	84.5	7140.25
Arithmetic mean	**2005.5**	**0**	**14621**
The standard deviation of the loading force F_{max}			**45.7**
The resulting value of the loading force F_{max} and its standard deviation			**2005.5 ± 45.7 N**

Tab. 4 *Calculation of the standard deviation of the loading force of the PLA material from the tensile load test*

Material PLA			
Designation of the printout	*F_{max} [N]*	*ΔF_i*	*$(\Delta F_i)^2$*
PLA_1	2611	-1.25	1.56
PLA_2	2601	-11.25	126.56
PLA_3	2579	-33.25	1105.56
PLA_4	2658	45.75	2093.06
Arithmetic mean	**2612.25**	**0**	**3326.74**
The standard deviation of the loading force F_{max}			**21.8**
The resulting value of the loading force F_{max} and its standard deviation			**2612.25 ± 21.8 N**

Tab. 5 *Calculation of the standard deviation of the loading force of the PET-G1 material from the tensile load test*

Material PET-G1			
Designation of the printout	*F_{max} [N]*	*ΔF_i*	*$(\Delta F_i)^2$*
PETG1_1	3906	14.75	217.56
PETG1_2	3968	76.75	5890.56
PETG1_3	3917	25.75	663.06
PETG1_4	3774	-117.25	13747.56
Arithmetic mean	**3891.25**	**0**	**20518.74**
The standard deviation of the loading force F_{max}			**54.14**
The resulting value of the loading force F_{max} and its standard deviation			**3891.25 ± 54.14 N**

Tab. 6 *Calculation of the standard deviation of the loading force of the PET-G2 material from the tensile load test*

Material PET-G2			
Designation of the printout	*F_{max} [N]*	*ΔF_i*	*$(\Delta F_i)^2$*
PETG2_1	3568	31	961
PETG2_2	3513	-24	576
PETG2_3	3458	-79	6241
PETG2_4	3609	72	5184
Arithmetic mean	**3537**	**0**	**12962**
The standard deviation of the loading force F_{max}			**43.03**
The resulting value of the loading force F_{max} and its standard deviation			**3537 ± 43.03 N**

Tab. 7 *Calculation of the standard deviation of the loading force of the ASA material from the tensile load test*

Material ASA			
Designation of the printout	*F_{max} [N]*	*ΔF_i*	*$(\Delta F_i)^2$*
ASA_1	2986	189	35721
ASA_2	3110	313	97969
ASA_3	2963	166	27556
ASA_4	2129	-668	446224
Arithmetic mean	**2797**	**0**	**607470**
The standard deviation of the loading force F_{max}			**294.59**
The resulting value of the loading force F_{max} and its standard deviation			**2797 ± 294.59 N**

Tab. 8 *Calculation of the standard deviation of the loading force of the ABS material from the tensile load test*

Material ABS			
Designation of the printout	*F_{max} [N]*	*ΔF_i*	*$(\Delta F_i)^2$*
ABS_1	2674	-244	59536
ABS_2	3020	102	10404
ABS_3	3032	114	12996
ABS_4	2946	28	784
Arithmetic mean	**2918**	**0**	**83720**
The standard deviation of the loading force F_{max}			**109.36**
The resulting value of the loading force F_{max} and its standard deviation			**2918 ± 109.36 N**

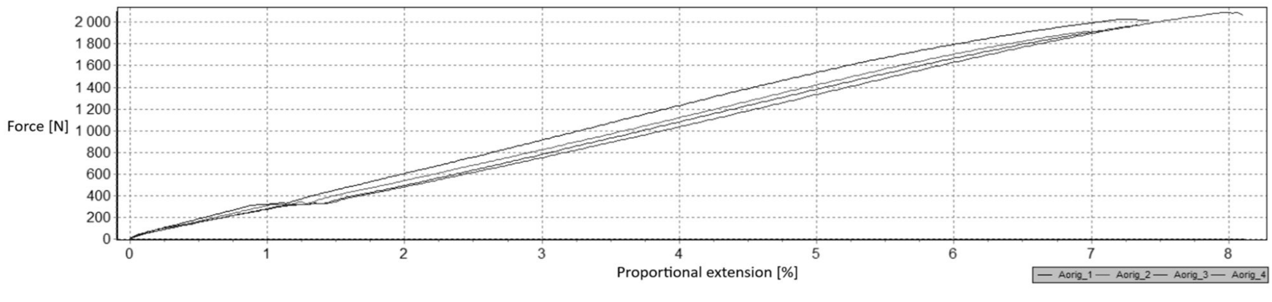

Fig. 3 *Tensile load test - multiple representation of load force curves - Original*

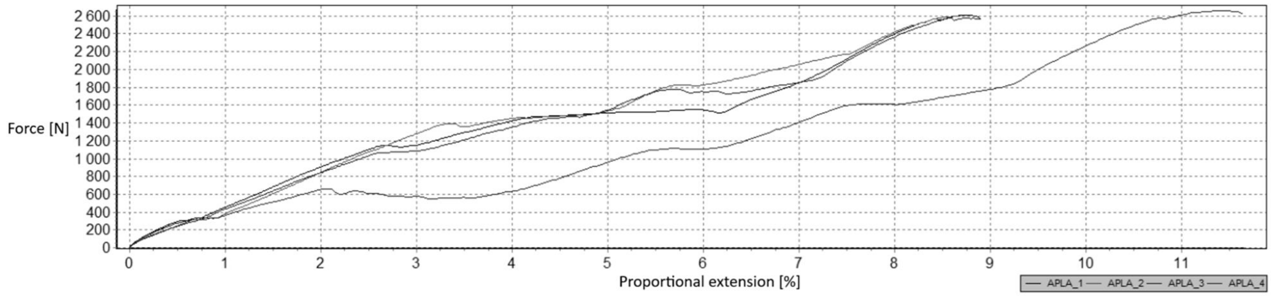

Fig. 4 *Tensile load test - multiple representation of load force curves – PLA*

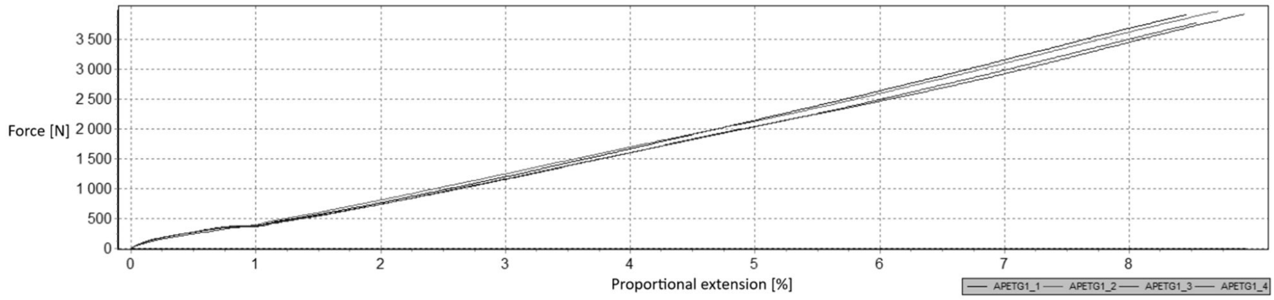

Fig. 5 *Tensile load test - multiple representation of load force curves – PET-G1*

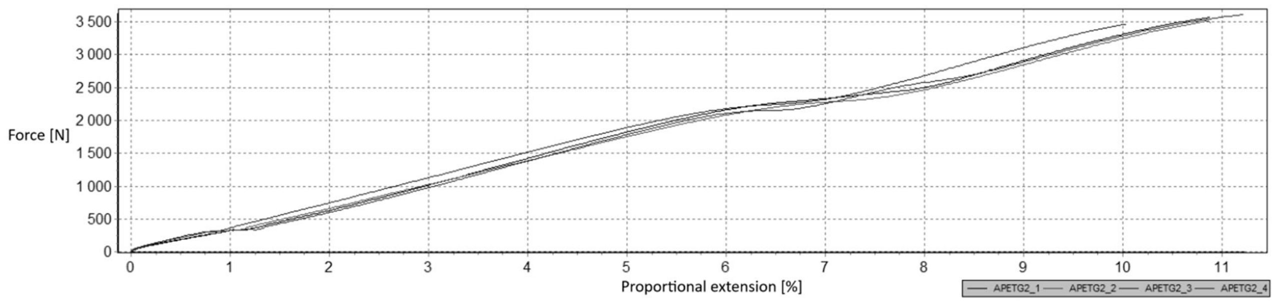

Fig. 6 *Tensile load test - multiple representation of load force curves – PET-G2*

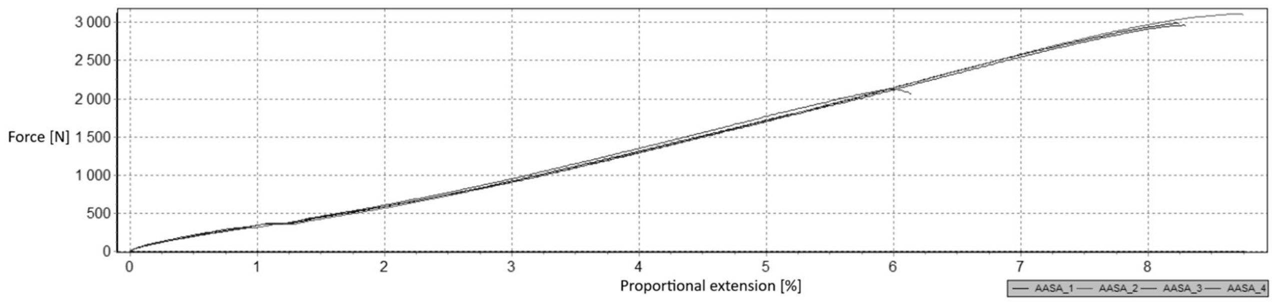

Fig. 7 *Tensile load test - multiple representation of load force curves – ASA*

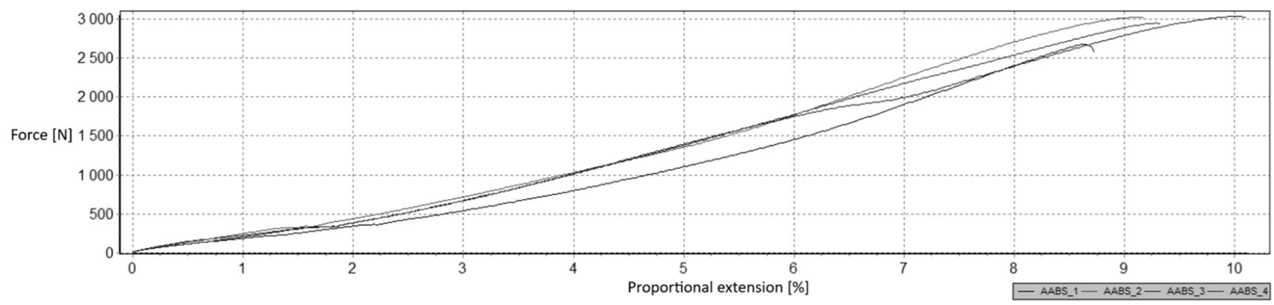

Fig. 8 *Tensile load test - multiple representation of load force curves - ABS*

4.2 Deflection test

Measurement conditions:

- Measurement date: 14. 05. 2024,
- Temperature: 22.2 °C,
- Air pressure: 997.7 hPa,
- Humidity: 34.8 %.

The aim of the testing is to compare and evaluate the mechanical properties of the original VEX IQ part and parts printed from materials: 1 x PLA (Filament-PM PLA MarbleJet light marble 0.5kg), 1 x PET-G1 (Fiber3D PETG Beige beige 1kg), 1 x PET -G2 (Prusament PETG Jungle Green 1kg), 1 x ASA (Prusament ASA Sapphire Blue 850g) and 1 x ABS (SunLu ABS Filament Yellow 1kg) on the Original Prusa MK4 3D printer. The experimental test will be performed using a deflection test. The assumption is that individual printed parts will bend or break at the point of pressure of the product. We monitor the material that comes out the best from the test, while further experimental measurements and tests will then be carried out on the given material depending on the specific 3D printing settings.

Description and measurement procedure

- Preparation of test prints - visual inspection, removal of possible stringing for PET-G, and marking of test prints according to the table below.
- Setting of the tearing machine and software parameters (selection of the machine – Hegewald & Peschke inspect 100, selection of suitable clamping fixtures, pulling speed 10 mm/min, starting load F_0=2 N).
- Clamping the test print.
- Test execution – a total of 4 tests were carried out for each group of materials, which corresponds to 24 tests. The reason for such a sample was 2 factors, namely, the time requirement and workload of the laboratory of destructive tests of materials at the Faculty of mechanical engineering at Jan Evangelista Purkyne University, and the fact that the resulting force did not change significantly and the materials showed similar behavior. For this reason, the test was terminated with 4 results and was not continued.
- Analysis of results – location of fractures, maximum loading force until breaking of prints.

Tab. 9 *Measured values from the deflection test on 5/14/2024*

Original item VEX		***Material PLA***		***Material PET-G1***	
Designation of the printout	*F_{max} [N]*	*Designation of the printout*	*F_{max} [N]*	*Designation of the printout*	*F_{max} [N]*
orig_1	146	PLA_1	180	PETG1_1	330
orig_2	144	PLA_2	168	PETG1_2	328
orig_3	125	PLA_3	182	PETG1_3	300
orig_4	134	PLA_4	192	PETG1_4	274
Arithmetic mean	**137.25**	*Arithmetic mean*	**180.5**	*Arithmetic mean*	**308**

Tab. 10 *Measured values from the deflection test on 5/14/2024*

Material PET-G2		***Material ASA***		***Material ABS***	
Designation of the printout	*F_{max} [N]*	*Designation of the printout*	*F_{max} [N]*	*Designation of the printout*	*F_{max} [N]*
PETG2_1	292	ASA_1	212	ABS_1	242
PETG2_2	282	ASA_2	222	ABS_2	240
PETG2_3	290	ASA_3	234	ABS_3	227
PETG2_4	290	ASA_4	226	ABS_4	233
Arithmetic mean	**288.5**	*Arithmetic mean*	**223.5**	*Arithmetic mean*	**235.5**

Tab. 11 *Calculation of the standard deviation of the loading force of the original part from the deflection test*

Original item VEX			
Designation of the printout	F_{max} [N]	ΔF_i	$(\Delta F_i)^2$
orig_1	146	8.75	76.56
orig_2	144	6.75	45.56
orig_3	125	-12.25	150.06
orig_4	134	-3.25	10.56
Arithmetic mean	**137.25**	**0**	**282.74**
The standard deviation of the loading force F_{max}			**6.36**
The resulting value of the loading force F_{max} and its standard deviation			**137.25 ± 6.36 N**

Tab. 12 *Calculation of the standard deviation of the loading force of the PLA material from the deflection test*

Material PLA			
Designation of the printout	F_{max} [N]	ΔF_i	$(\Delta F_i)^2$
PLA_1	180	-0.5	0.25
PLA_2	168	-12.5	156.25
PLA_3	182	1.5	2.25
PLA_4	192	11.5	132.25
Arithmetic mean	**180.5**	**0**	**291**
The standard deviation of the loading force F_{max}			**6.45**
The resulting value of the loading force F_{max} and its standard deviation			**180.5 ± 6.45 N**

Tab. 13 *Calculation of the standard deviation of the loading force of the PET-G1 material from the deflection test*

Material PET-G1			
Designation of the printout	F_{max} [N]	ΔF_i	$(\Delta F_i)^2$
PETG1_1	330	22	484
PETG1_2	328	20	400
PETG1_3	300	-8	64
PETG1_4	274	-34	1156
Arithmetic mean	**308**	**0**	**2104**
The standard deviation of the loading force F_{max}			**17.34**
The resulting value of the loading force F_{max} and its standard deviation			**308 ± 17.34 N**

Tab. 14 *Calculation of the standard deviation of the loading force of the PET-G2 material from the deflection test*

Material PET-G2			
Designation of the printout	F_{max} [N]	ΔF_i	$(\Delta F_i)^2$
PETG2_1	292	3.5	12.25
PETG2_2	282	-6.5	42.25
PETG2_3	290	1.5	2.25
PETG2_4	290	1.5	2.25
Arithmetic mean	**288.5**	**0**	**59**
The standard deviation of the loading force F_{max}			**2.9**
The resulting value of the loading force F_{max} and its standard deviation			**288.5 ± 2.9 N**

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***Tab. 15** Calculation of the standard deviation of the loading force of the ASA material from the deflection test*

Material ASA			
Designation of the printout	F_{max} [N]	ΔF_i	$(\Delta F_i)^2$
ASA_1	212	-11.5	132.25
ASA_2	222	-1.5	2.25
ASA_3	234	10.5	110.25
ASA_4	226	2.5	6.25
Arithmetic mean	**223.5**	**0**	**251**
The standard deviation of the loading force F_{max}			**5.99**
The resulting value of the loading force F_{max} and its standard deviation			**223.5 ± 5.99 N**

***Tab. 16** Calculation of the standard deviation of the loading force of the ABS material from the deflection test*

Material ABS			
Designation of the printout	F_{max} [N]	ΔF_i	$(\Delta F_i)^2$
ABS_1	242	6.5	42.25
ABS_2	240	4.5	20.25
ABS_3	227	-8.5	72.25
ABS_4	233	-2.5	6.25
Arithmetic mean	**235.5**	0	141
The standard deviation of the loading force F_{max}			**4.49**
The resulting value of the loading force F_{max} and its standard deviation			**235.5 ± 4.49 N**

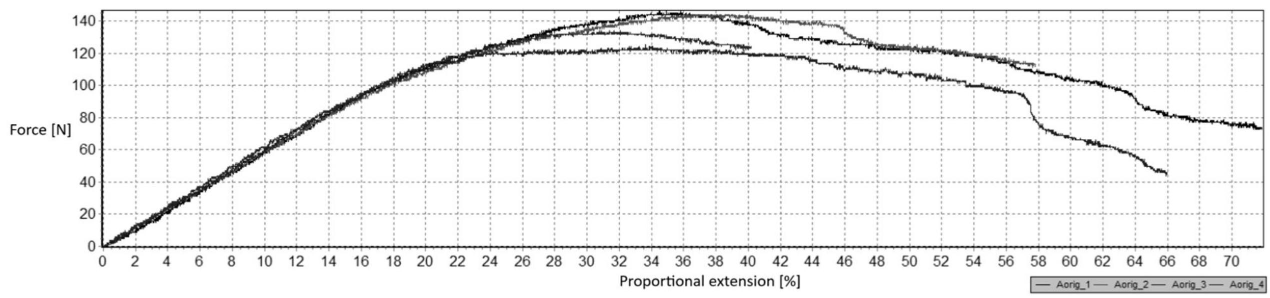

***Fig. 9** Deflection test - multiple representation of load force curves - Original*

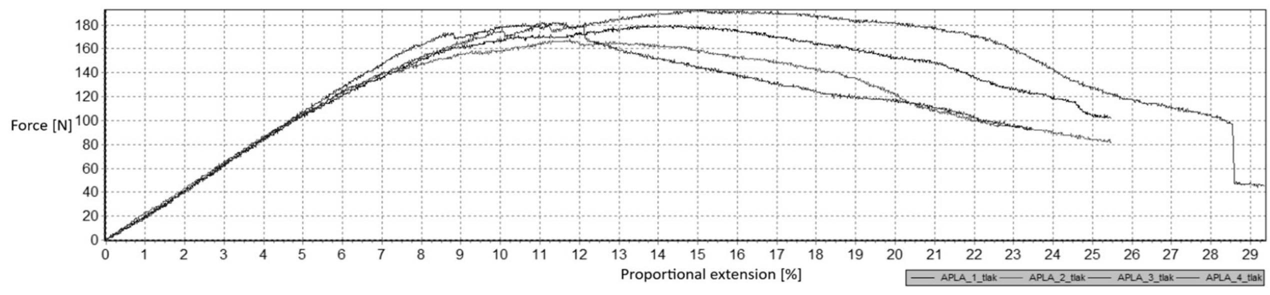

***Fig. 10** Deflection test - multiple representation of load force curves - PLA*

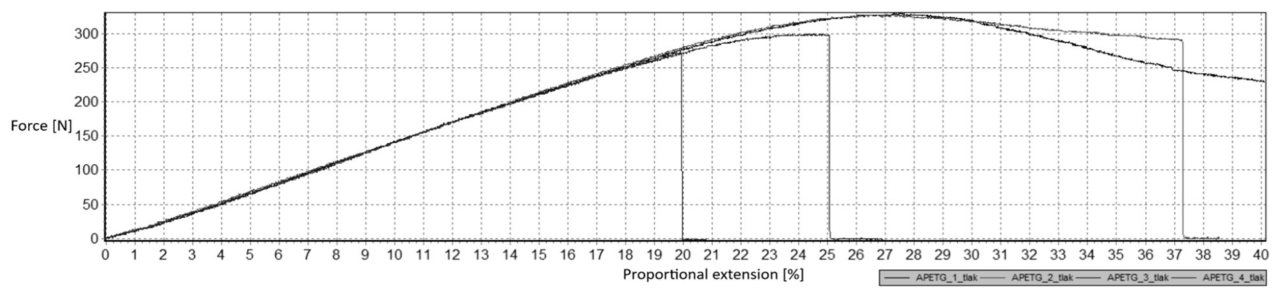

***Fig. 11** Deflection test - multiple representation of load force curves – PET-G1*

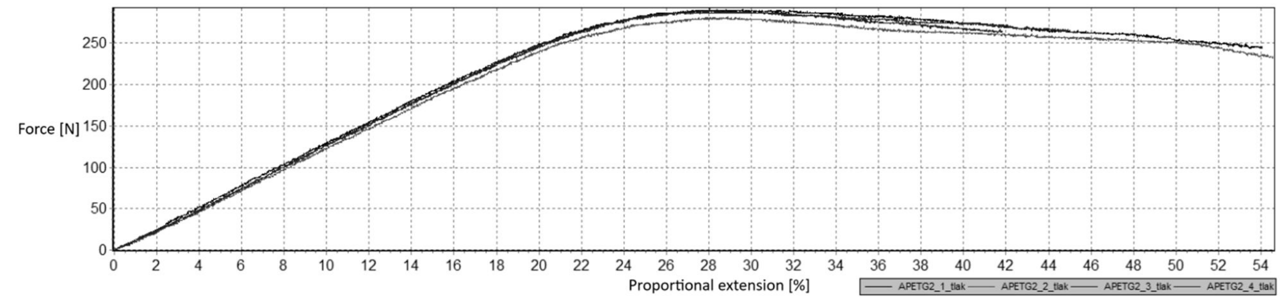

Fig. 12 *Deflection test - multiple representation of load force curves – PET-G2*

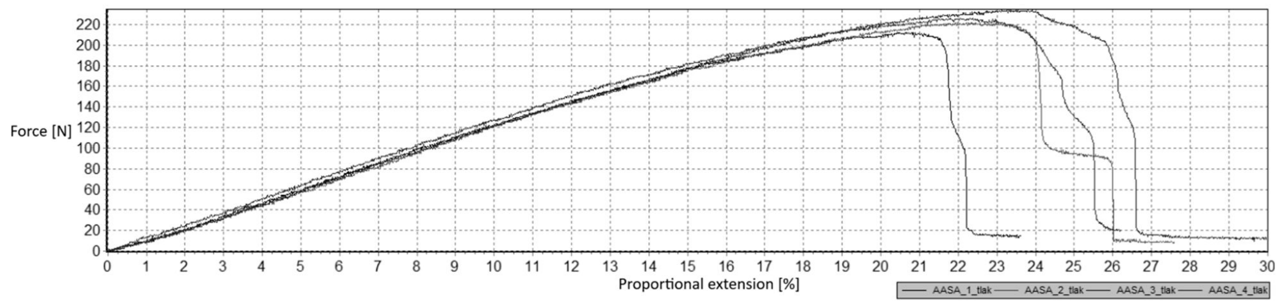

Fig. 13 *Deflection test - multiple representation of load force curves - ASA*

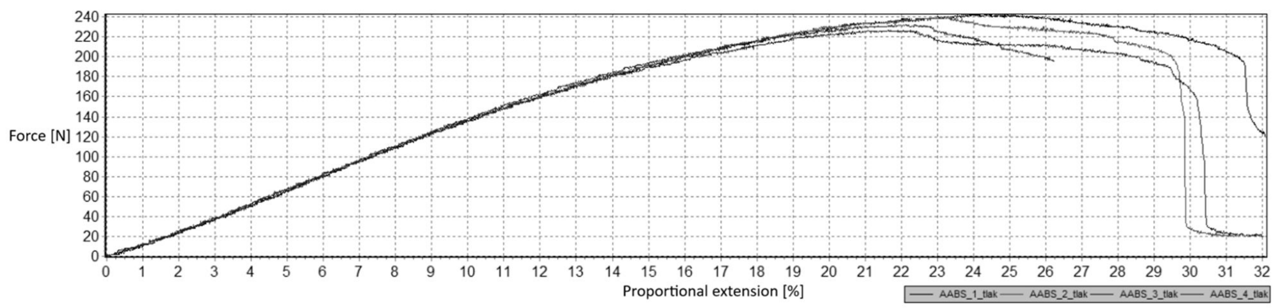

Fig. 14 *Deflection test - multiple representation of load force curves - ABS*

5 Conclusion

As part of the selection of a suitable part from the original parts of the VEX GO and IQ robotic kits, the part 2x12 Beam (228-2500-026) was selected, which is fully satisfactory both in terms of dimensions and in terms of attachment to the Hegewald & Peschke inspect 100 machine incl. clamping devices for the implementation of destructive tests of tensile load and deflection. The choice of these tests corresponds to the principle of stressing this part as part of the application of the robotic kit in primary and secondary school education. The parts are mainly used for construction exercises during the realization of selected robot models and their subsequent disassembly, which corresponds to their method and use for stressing by tensile load and deflection. The 2x12 Beam part (228-2500-026) needed to be slightly adjusted in view of the unnecessarily complicated subsequent post-processing in terms of aligning the bottom side and blocking the pin holes, which led to a reduction in the time burden when removing the supports created during slicing of the model from the printout and a significant reduction in the consumption of filament material. From the point of view of testing, this fact does not have a fundamental effect on the result, as the dimensions and shape of exactly the same parts printed from different filaments are compared.

Choosing a printer for 3D printing parts of a robotic kit in the conditions of primary and secondary schools with the requirement of easy printing (beginner level) led to the choice of a printer using FDM (Fused deposition modeling) technology from Prusa Research. Specifically, it is an Original Prusa MK4 printer. The reason was the fact that Prusa Research printers are very widespread in Czech primary and secondary schools, and it is a newer version, and its evaluation is very positive compared to the other monitored Original Prusa MINI+ and Original Prusa i3 MK3S+. The choice of filament material was determined by the determining parameters. These were easy printing, excellent mechanical properties of the print, minimal post-processing, filament quality from a verified manufacturer and price. Prusament filament and PLA, PET-G, ABS and ASA materials were selected from the monitored manufacturers.

All the listed materials were selected in the final decision for experimental measurement and testing by destructive tests. After carrying out the necessary tests and destructive tests, these evaluations can be stated.

Evaluation of tensile load measurements: In this part, the measured results are evaluated and the subsequent selection of suitable material for the needs of 3D printing in primary and secondary schools. From the measured values, it can be seen that the maximum values of the loading force are higher for all prints than for the original parts, which is due to the filling used and the impassability of the lower part of the model, respectively. Printout due to easier printing and zero post-processing, which could affect the resulting value of the monitored parameters of mechanical tests. In terms of the highest values, the PET-G materials from both companies clearly stand out, while the PET-G2 material from the Prusa Research company, specifically Prusament PETG Jungle Green 1kg, shows a smoother course of load force values and, given its quality, appears to be an ideal choice. Even though the tensile strength values are determined from a print made from a filament with a diameter of 1.75 mm, it can be assumed that the mechanical properties of the PET-G material are precisely those required for the realization of 3D printed parts of a robotic kit in the conditions of primary and secondary schools.

Evaluation of deflection test measurement: In this part, the measured results are evaluated and the subsequent selection of suitable material for the needs of 3D printing in primary and secondary schools. It can be seen from the measured values that the maximum values of the loading force are higher for all prints than for the original parts, which is due to the filling used and the impassability of the lower part of the model, respectively. Printout due to easier printing and zero post-processing, which could affect the final value of the monitored mechanical test parameters. In terms of the highest values, the PET-G materials from both companies clearly stand out, while the PET-G2 material from the Prusa Research company, specifically Prusament PETG Jungle Green 1kg, shows a smoother progression of the loading force values and, given its quality, appears to be an ideal choice. Even though the deflection values are determined from a print made from a filament with a diameter of 1.75 mm, it can be assumed that the mechanical properties of the PET-G material are exactly those required for the realization of 3D printed parts of a robotic kit in basic and medium conditions schools.

Finally, it is recommended to carry out further tests and tests, which will focus on reducing printing costs in terms of filament consumption. The monitored parameters of the prints will be the choice of the appropriate filling pattern and its density, and the effect of the perimeter. Subsequently, other selected materials from the current filament offer will be subjected to tests.

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