APPLICATION OF RAPID PROTOTYPING TECHNOLOGY IN DESIGNING ROBOTS AND PERIPHERAL DEVICES

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The Department of Robotics at the Technical University of Ostrava has disposed of the Rapid Prototyping technology (hereinafter as RP) since 2009. From the very beginning, there were efforts to print not only models to present various concepts and prototypes to the public, but primarily functional technical solutions. Over the time, there have been a large number of printed parts as well as functional units with the print share reaching up to 80%. Related to the need to adjust the models for printing in order to achieve the best results, both for own and commercial production, there have been many doubts how to suitably solve certain construction elements. The paper describes some of problems that have arisen and tries to find adequate solution using experimental methods. The paper is designed as a review of the solved issue aiming at providing a set of findings which can be subsequently used in designing parts produced by the RP technology, on condition that professional production systems and polycarbonate materials with mechanically removable support are used.

KEYWORDS
rapid prototyping, polycarbonate, Stratasys, bend tests, tensile tests, screw connection

1. INTRODUCTION

The 3D-printer used at the department is Stratasys FORTUS 360 mcL [Stratasys 2014] with print type FDM [Chua 2003, Spisak 2014] and software Insight, which commonly offers a wide range of print parameters setting as well as own predefined print possibilities of internal structure of fibres of the printed objects. It particularly includes Solid, Sparse, or Double Sparse. The construction material is polycarbonate PC-10 from printer's producer.

During production of each layer, the first element to be created are the contours, whose number can be set as well as their width within the range of currently used nozzle. Subsequently, the internal space is filled. [Beniak 2014] The way of its filling can also be set, but the following three predefined options are used the most.

Solid is a type of 3D-print where a cross-section of the part is printed using the maximum density of the material from which it is made. First the perimeter of the part is printed then the inner space is filled layering the fibres in a pre-defined position.

Sparse is an economical method of 3D-print, where the part isn´t in a solid cross-section. This way of printing saves on material and weight. An analysis of the print shows that it is similar to solid print, but it is different in that when filling the inner space there is constant separation between the fibres in each layer. By changing the position of the fibres in each layer, the cross-section of the structure is altered.

Double Sparse, like Sparse, is an economical 3D-print procedure which, however, uses twice as much material as Sparse for internal structure filling. This is achieved so that, rather than only being oriented in one direction like in Solid and Sparse, the fibres are laid crosswise to form a chequered pattern with a gap in the centre. As a result, the structures are mutually displaced in the various layers.

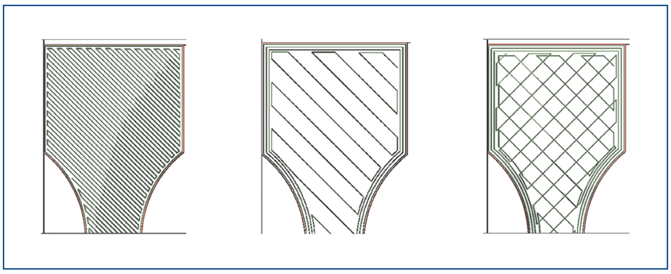

Figure 1. Mapping of commonly selected structures on sample parts for a tensile test (from left) Solid, Sparse, Double Sparse

Parameter	Value	Parameter	Value
Contour width	0.508 [mm]	Nozzle type	T 16
Slice height	0.254 [mm]	Extruder temperature	368 [°C]
Part sparse fill air gap	2.286 [mm]	Heated-bed temperature	145 [°C]

Table 1. Print parameters

Parameter	Value	Parameter	Value
Tensile Strength	68	Flexural Strength	104 [MPa]
Tensile Modulus	2 280 [MPa]	Flexural Modulus	2 200 [MPa]
Heat Deflection	138 [°C]	Tensile Elongation	5 [%]

Table 2. Selected mechanical properties of PC-10 material provided by the producer – Stratasys

As stated above, with respect to the implemented projects, whose production was primarily secured by the RP technology, such as an effector with an end arm [Lipina 2011] or a mobile robot Kraken (Fig. 2), several basic construction findings have been gathered.

The design load capacity of the effector is 3 kg at its own weight of 5 kg. The jaw drive is secured by engine MAXON RE-35 90W with gearbox GP-32 HP, which uses a gear transmission to achieve the power of 633 N in the jaws. The design incorporates common construction elements, such as Linear motion system THK or plain bearings IGUS.

The mobile robot is primarily designed for the remote inspection of parked cars chassis – specifically for the search of explosives. The use determines the robot design. Its low height allows the robot to fit under the chassis of most cars. The robot's drive is ensured by the thin actuators Dunkenmotoren. A camera head containing a colour camera, a LED light with adjustable intensity and a laser rangefinder is fitted at the head of the robot. It is possible to rotate the camera head up and down around a horizontal axis for the purpose of chassis inspection. The second fixed camera is positioned at the rear of the robot chassis in order to facilitate reversing. The pictures of both cameras are transmitted wirelessly to the robot control application running on a laptop or PC.

Firstly, it concerns implementation of certain construction parts, such as full printing of the gear set, which didn't need further machining or implementing of driving unit, or of the linear motion into the skeleton produced by the RP technology.

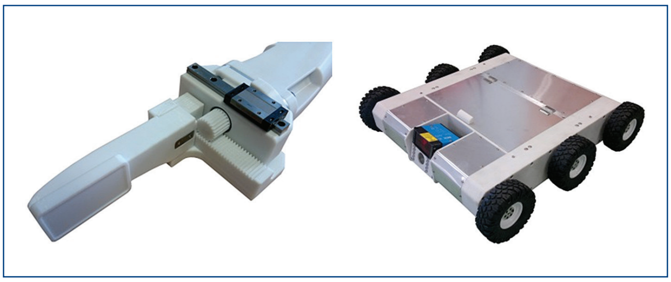

Figure 2: Left –partially dismantled end effector with a visible printed pinion and a rack, right – mobile six-wheel inspection robot Kraken.

Secondly, it concerns implementation of construction parts which need further machining due to producer's requirements, such as plain bearings IGUS, whose shape is precisely defined as well as the dimension of the opening to press the bearing in. If the opening is not adjusted to the predefined dimension, there is a danger that the constant pressure of the pressed-in bearing on the part produced by the RP technology will cause permanent damage to the part in the bearing's surroundings.

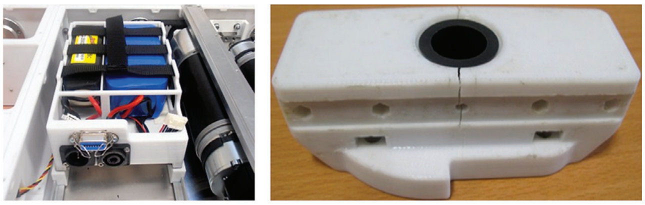

Figure 3. Left – implementation of the driving unit and a battery box in the mobile robot Kraken, right – da mage of the part by an incorrectly placed plain bearing

Thirdly, those are factors that are completely unknown. Starting from properties that can, at first, appear to be as mere banalities, such as correct design of the screw connection or implementation of threads into parts produced by the RP technology, which finally relates to the effort to increase the load capacity of screw connections in general. Despite construction unknowns, such as print accuracy related to implementing lock connections, for parts whose length exceeds the working area of the printer and thus the need to use appropriate glues to keep compactness of the whole connection. The final issue that was mentioned at the beginning, i.e. material properties of the construction material and the related question of selecting a suitable internal structure of the printed part with respect to its anticipated use and applied forces, which gives us the choice between the predefined structures and own proposal.

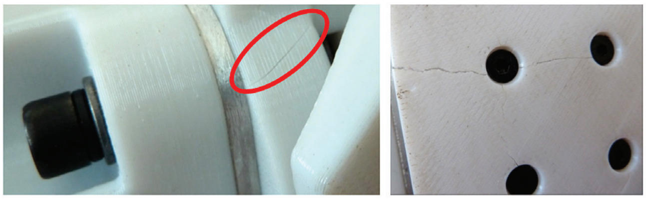

Figure 4. An example of spontaneous spreading of cracks in the area of screw connections over time

2. METHODS AND PROCEDURES OF PERFORMED MEASUREMENTS

2.1 Screw connections

In order to test screw connections, we used a series of samples both from full material and honeycomb to find out the influence of different internal structure on the connection load capacity. The sample was designed in order to enable tests where there is a gap between the sample and the tightened washer and vice versa, i.e. the gap is eliminated when the sample is rotated. This design was implemented in order to verify a presumption that when orienting the sample, when there is no gap between the sample and the washer, the load capacity of the connection is higher than in opposite case. Sample dimensions are given in Fig. 5, where the central opening diameter in the sample depends on the type of the used thread and connection (pass-through opening or thread form).

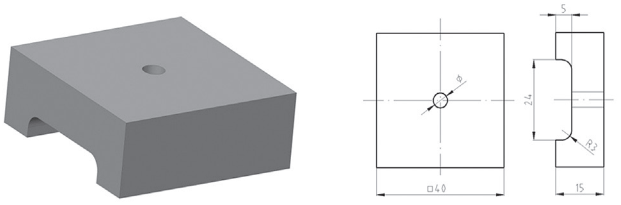

Figure 5. Model and basic dimensions of the test sample

The principle of the measurement procedure is as follows. The individual samples have been tightened by certified torque screwdriver (range 1 ÷ 6 Nm, step 0.1 Nm) or by torque wrench (range 5 ÷ 25 Nm, step 0.25 Nm) to the sturdy plate. The measurements were carried out from the lowest adjustable value of torque wrench, step by step, to the moment when the thread or the insert was destroyed. The values of torque were then read and used for calculation of the force at the axes of the screw

2.1.1 Threads

In order to find out the load capacity of threads [Lipina 2013] created in parts produced by the RP technology, a series of tests on M6 threads cut right into the parts was carried out. At the same time, other possibilities of creating a thread in the part were considered, particularly sticking a rivet nut [Sariv-Nemcik 2014] and use of thread inserts Helicoil [Helicoil 2009]. Individual types of threads and their placement towards the tightened washer are depicted in the following figure.

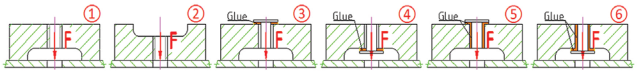

Figure 6. Placement of treads in the test sample

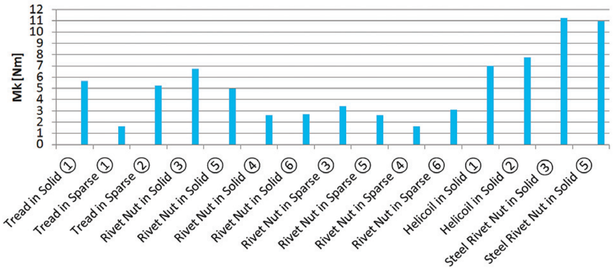

Figure 7. Placement of treads in the test sample

Type of Thread in Material	Mk [Nm]	F [N]	Type of Thread in Material	Mk [Nm]	F [N]
Tread in Solid ①	5.650	5 231	Rivet Nut in Sparse ⑤	2.600	2 407
Tread in Sparse ①	1.600	1 481	Rivet Nut in Sparse ④	1.600	1 481
Tread in Sparse ②	5.233	4 846	Rivet Nut in Sparse ⑥	3.100	2 870
Rivet Nut in Solid ③	6.750	6 250	Helicoil in Solid ①	7.000	6 481
Rivet Nut in Solid ⑤	5.000	4 630	Helicoil in Solid ②	7.750	7 176
Rivet Nut in Solid ④	2.600	2 407	Steel Rivet Nut in Solid ③	11.250	10 417
Rivet Nut in Solid ⑥	2.700	2 500	Steel Rivet Nut in Solid ⑤	11.000	10 185
Rivet Nut in Sparse ③	3.400	3 148	*(Placement Fig. 6)*		

Table 3. The measured and calculated values of the force acting at the axes of the screw.

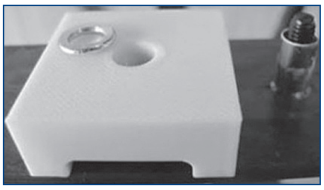

Fig. 8. Al. Rivet Nut in Solid

Fig. 9. Rivet Nut in Sparse

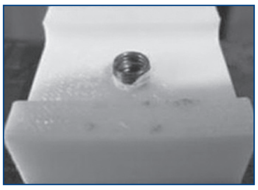

Fig. 10. Helicoil

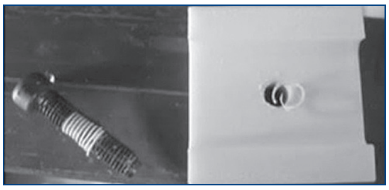

Fig. 11. Thread in Solid

2.1.2 Pass-through openings

In order to find out the load capacity of a screw connection [Lipina 2013] created in parts produced by the RP technology, a series of tests on samples produced with a pass-through opening was carried out (see Fig. 5) for screw connections with thread M4 and M6 with diameters of 4.5, respectively 6.6 [mm]. Having found out the influence of the area by which the force incurred from the torque impacts on the sample, the area was enlarged by inserting a washer under the screw head. The measurement was then carried out both for the screw head area and washers of standard and large sizes. Standards of the used standardised parts and their areas impacting on the sample are listed in the following table.

Screw	Indication in text	Standards	Area [mm²]
M4	Screw M4	SCREW M4 x 30 ISO 4762	2.36
	Washer S (Standard)	WASHER 4.3 ISO 7090	2.90
	Washer L (Large)	WASHER MB M4 ISO 7093	6.04
M6	Screw M6	SCREW M6 x 30 ISO 4762	3.14
	Washer S (Standard)	WASHER 6.4 ISO 7090	3.61
	Washer L (Large)	WASHER MB M6 ISO 7093	9.10

Table 4. Standards and impact area

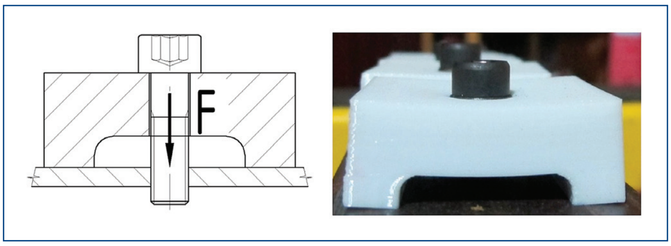

Figure 12. Screw connection in pattern, on down side is shown bent sample (solid M6 – washer S) during testing

Screw	Type of print	Screw		Washer S		Washer L	
		[Nm]	[N]	[Nm]	[N]	[Nm]	[N]
M6	Solid	20.625	19 097	17.563	16 262	17.000	15 741
	Sparse	2.467	2 284	2.267	2 099	3.200	2 963
M4	Solid	9.417	13 079	6.917	9 606	7.083	9 838
	Sparse	0.967	1 343	1.167	1 620	1.767	2 454

Table 5. Measured and calculated values

2.1.3 Pass-through openings – long-term load capacity

The test of a long-term load capacity [Lipina 2014b] follows up the previous test. The objective of the experiment was to determine how big torque can be applied to a screw connection applied in a part produced by the RP technology from a polycarbonate material without causing any damage to the part with respect to long-term forces impacting on the connection.

The measured values for samples of type Solid M6 (see Tab. 5) from the previous chapter were calculated in descending order in 10% intervals from 90% of the maximum measured values to 40%. Subsequently, the samples were subjected to a long-term test during which they were tightened to the washer by a predetermined torque for the period of 5 months (155 days). During the period, the samples were monitored for any mechanical changes of the structure on the surface.

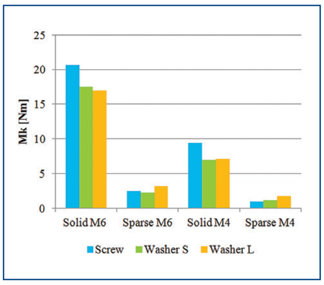

Figure 13. Average measured values of maximal torque

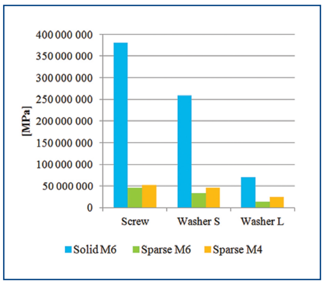

Figure 14. Pressure force applied to the sample

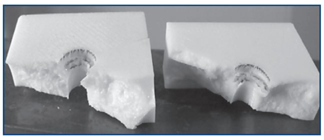

Figure 13. Subsequent destruction of sample shown in Fig. 12 with visible imprint of screw head

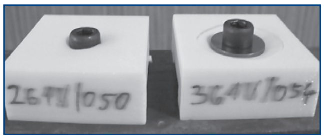

Figure 14. Destruction of sample Sparse M6 – Screw (on the left)/Sparse M6 – Washer L

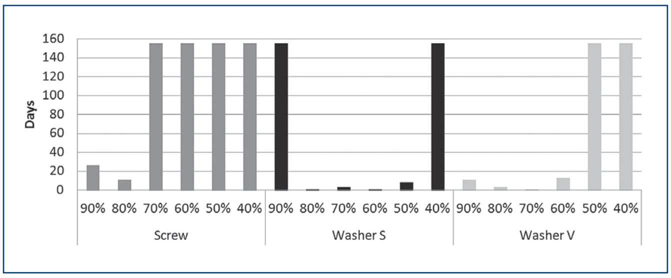

Figure 15. Graph of load capacity of individual samples under a percentage load in days

2.2 Tensile tests

The tensile test was carried out on 2 samples of basic dimensions. The first type (see Fig. 16) was printed as Solid, Sparse and Double Sparse. Samples Solid was printed both in horizontal position, when the material achieves bigger strength, and vertically. The sample was also used for testing locks with glue. The samples were printed both in vertical and horizontal position in order to find out the influence of the print position on mechanical properties. In order to compare mechanical properties in tensile stress between printed and manufactured parts, panels of manufactured polycarbonate MARLON FSX Longlife were cut out in exactly the same dimensions as in the case of printed material.

The second type of a sample takes basis from the dimensions of the tensile test sample. However, its width was extended due to application of two different internal structures. The use of own designed structure is limited to the hatched area, but with respect to the fact that the tests did not provide results that could be comparable with commonly offered possibilities, those test are not dealt with in this paper in detail.

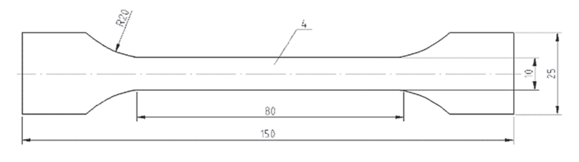

Figure 16. Dimensions of the test sample with a standard structure

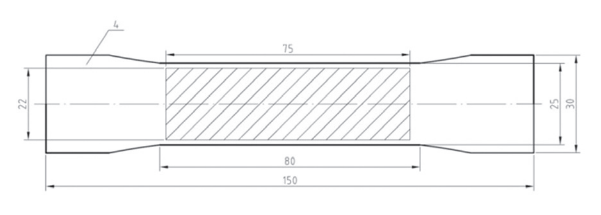

Figure 17. Dimensions of the test sample with own designed structure

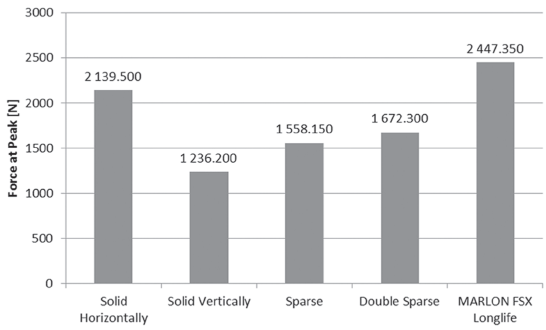

Figure 18. Force at peak for the tested samples

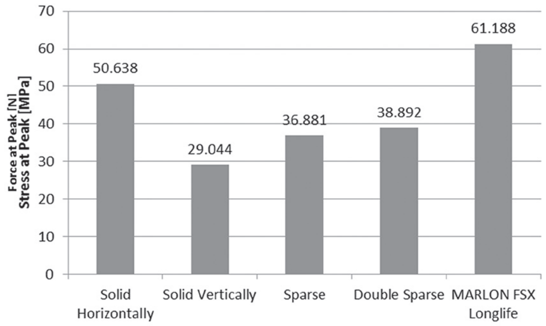

Figure 19: Stress at peak for the tested samples

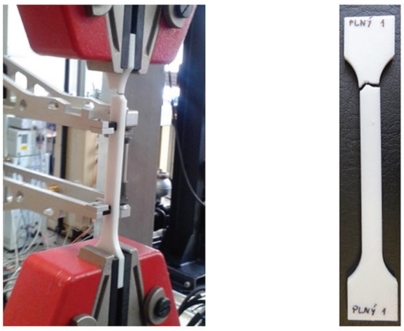

Figure 20. Tensile test of the Solid sample, horizontal

The tests were conducted on a M500-50CT bench-top twin-column universal materials testing machine, which is capable of exerting forces up to 50 kN and measuring sample elongation with a precision of 0.001 mm. The machine was connected to and controlled by a computer using WinTest Analysis software. The reported parameters are averages obtained from sample sections.

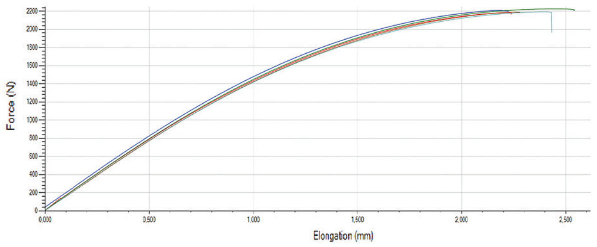

Figure 21. Plot from the tensile test of the Solid sample, horizontally

A possible way to implement connections of parts produced by the RP technology is usage of glue or designing shaped locks [Lipina 2014d] on individual parts. This method enables us to create smooth part connections without increasing the weight of the whole unit due to the use of a screw connection.

In order to determine the tensile strength of a part, a series of samples (see Fig. 16) was printed from solid material. The samples were printed in two pieces and the connections were secured by various types of locks which perfectly match and thus increase connection coherence. With respect to the fact that different lock shapes have different area for glue layer, a series of a sample with a so-called "blunt" connection was designed. The samples had areas for the glue at their maximum in order to find out the influence of the glue on the connection strength. The connection used three types of glue from various producers, namely Den Breaven Mamut Glue, Loctite 401, and UHU CA 103.

Sample numper	❶	❷	❸	❹	❺	❻	❼
Connection mapping							

Table 6. Types of individual connections

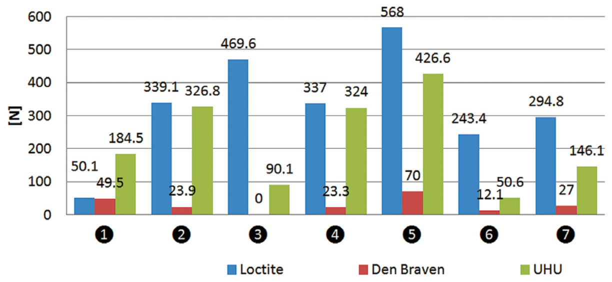

Figure 22. Average measured values for individual connections and glues

2.3 Bend tests

A bend test [Lipina 2015b, Lipina 2015c] follows up and extends previous tensile tests and it has three objectives. Firstly, it concerns the need to find out the bend size of samples printed according to standard structures offered by SW Insight. Secondly, a series of samples, whose internal structure anticipates forces applied, was designed. Thirdly, it concerns printed samples combined with another material. The design of internal structures was done in software Creo 2.0, where solid material was clearly defined in the thickness corresponding to tuples of the contour width.

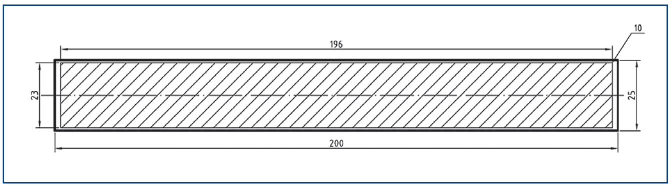

Figure 23. Basic dimensions of a sample for a bend test

Subsequent setting of the number of contours in SW Insight resulted in achieving the desired print trajectory in order to get the highest strength of the sample in the direction of applied tensile forces. Most of the samples were printed in the same basic dimension and they only differ in internal structuring, or they were assembled into the basic dimension by connecting partial segments. The dimensions of the internal structure are shown as the hatched area in the following figure. (not valid for Solid and Sparse).

A sample of type "Sandwich" was designed by assembling several segments (printed as Solid) up to the height of 25 mm, namely "Sandwich 5/4" is composed of 5 segments, each with edge height of 4.45 mm, and "Sandwich 8/7" of 8 segments (see Fig. 25), each with edge height of 2.75 mm. Individual segments were then connected to each other into the desired height by interlaying a corresponding number of double coated adhesive tape 3M VHB 5925-F [3M 2014] with a layer height of 0.64 mm.

Samples with polyurethane filling were printed in two types, namely as an external casing of 1 mm thick wall, where the smallest walls remained open for filling in the inside by a polyurethane compound, or with the biggest wall open, where the inside of the sample was filled with ribbing of 45° angle (see Fig. 80), which was finally filled with the polyurethane compound. The polyurethane compound „Dukarit C 46A : G226 : Durasil 80 " [Torten 2014] was prepared in two variants of concentrations, namely 1:1:0.5 or 1:1:1, where the last number means the ratio of the filling in the compound, which has a significant influence on the final mechanical properties.

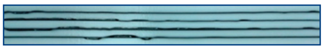

Figure 24. Sample type „Sandwich 5/4" ready for the test.

Figure 25. Printed sample ⑭ (Ribs 1:1:0,5) filled with polyurethane

Three-point bend test. Bend tests were performed on a desk two-column universal pull-test machine MC500-50CT. The pull test machine exerts a force of 50kN with a precision of measurement of sample elongation of 0.001mm. The machine is operated by a computer through WinTest Analysis software.

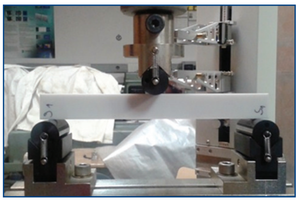

Figure 24. Process of three-point test in flexion, sample ① (Solid).

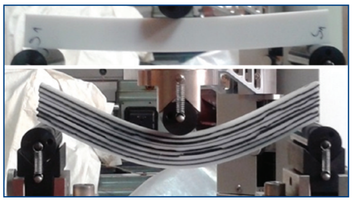

Figure 25. Course of the test in sample type (from top) Solid and Sandwich 8/7

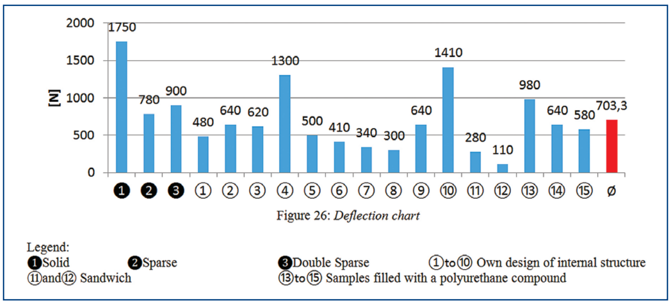

Figure 26: *Deflection chart*

Legend:
❶Solid ❷Sparse ❸Double Sparse ①to⑩ Own design of internal structure
⑪and⑫ Sandwich ⑬to⑮ Samples filled with a polyurethane compound

3. CONCLUSION

Based on the issue related with design, production, and operation of parts produced by the RP technology, the introductory part implied several difficulties that accompany this technology. Those were then divided and experimental solutions helped to find corresponding possible outcomes. The objective of this paper is to provide a set of advice and recommendations which would simplify the process of construction designs of parts for printing. However, it must be taken into consideration that the below-mentioned overview of the results and recommendations corresponds with the used technology and material.

Threads. The best result was achieved with steel rivet nuts that were oriented into the Solid sample by the border towards the impacting force. The Helicoil system proved 69% load capacity compared with steel rivet nuts. An advantage of Helicoil is that it offers self-grip thread inserts. At the same time it was proved that the amount of glue used to attach the rivet nuts into the sample does not play any important role in the nut load capacity. Generally, glue applied to all contact areas between the nut and sample should have an impact on increasing the construction strength. An unquestionable advantage of thread inserts is elimination of thread wear-out in repeated use. Half values of thread inserts were measured in threads cut in the material produced as Solid. Applying threads of any kind cannot be recommended for Honeycomb.

Pass-through openings. The performed measurements determined the maximum torques for given screw connection. Those were then used in tests of long-term load capacity. Another finding was the influence of the area size that impacts on the sample by means of the torque. This was found out by inserting a washer under the screw head, which resulted in enlarging the area through which the force impact son the sample. The presumption than an increase in the area will increase sample load capacity was proved only partially because this presumption as proved only in samples from Honeycomb. Samples from a solid material suffered pressing in the head or the washer into the sample. Thus, higher load capacity was in samples where the force impacted on it only by the area of the screw head. According to the previous findings, with respect to the print accuracy, it is necessary to create the pass-through openings in smooth series according to ČSN EN 20273. This will ensure that the screw can be inserted in the opening without any problems. Moreover, minimizing the gap between the screw and the opening area increases connection load capacity, because tightening the screws results in pressing them in the part. The deformed material in the opening then leans against the screw, which results in strengthening of the whole connection.

Long-term load capacity. Previously realised projects provided findings that deformations appear in the surroundings of screw connections with certain time delay. The main objective was to find out long-term impact of a force incurred by tightening the screw by torque and the maximum possible force value which ensures keeping the surroundings of the screw connection undamaged. The measurements revealed that it is useless to enlarge the area under the screw head, because the best values were achieved in a screw connection without any washers under the head (70% of maximum torque), i.e. with a minimum area. With respect to the fact that the samples remained load even after the determined time period (some of them up to 365 days), and still were under monitoring, it can be stated that the most critical period for a screw connection produced by the RP technology is first 31 days, because after that there were no other surface changes observed in the samples.

Tensile test. The tensile test proved that the strongest structure among the printed samples is Solid printed horizontally, where fibre orientation ensures the best interconnection. The second came structure Double Sparse, reaching up to 80% of the structure strength of Solid horizontally. Quite a surprising result is that structures Sparse and Double Sparse achieved almost identical strength. The worst result was achieved by structure Solid vertically, whose strength correspond to only 58% of structure Solid horizontally. Although the sample is filled with material in its full cross-section, its vertical orientation to the print head causes that the material creates the strongest connection in layers which are layered in a horizontal direction, which causes its weakness in vertical tensile stress. Comparison of manufactured polycarbonate with sample Solid horizontally revealed that Solid horizontally achieves 81% of the strength of classically machined polycarbonate.

Tensile test of lock connections in combination with glue. The performed tests prove that the most suitable glue to connect two parts produced by the RP technology is glue Loctite 401 (This glue was even used to connect rivet nuts with test samples). Concerning the lock profile, the strongest connection is achieved by connection shape of type ❺ (see Tab 6.), or T, which achieved the best combination of strength of the basic material. For completeness, it is necessary to add that achieving a trouble-free connection requires to remove 0.1 mm of the material thickness from at least one of the two connected parts (due to print accuracy).

Bend tests. The highest force in a bend was achieved in sample Solid. The average value was 15 mm, which was the approximate value for 88% of the test results. As a matter of interest, sample Solid exceeds the average bend value only 1.3x. The biggest bend was achieved in samples „Sandwich 5/4“ and „Sandwich 8/7“, which exceed the average value 2.8x, 2.5x respectively. Unlike other samples, those samples were not destroyed during the test, which corresponds to their high value of bend strength at their destruction (for „Sandwich 5/4 almost 12 MPa). With respect to the fact that individual layers of the sandwich can be printed at once, the production time for each layer is low, 0.3 or 0.2 hours, which is 13x lower than the average print time. Division to layers and separate print of individual layers causes increased consumption of support material, which finally achieves only a half of the average value, though. The average value of the module in the band is 1001.6 MPa. Similarly to the bend force, the average value is noticeably exceeded by Solid, namely 1.8x.

The findings are applied in designing parts produced by the RP technology at the Department of Robotics.

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