BUDAPEST UNIVERSITY OF TECHNOLOGY AND ECONOMICS
FACULTY OF TRANSPORTATION ENGINEERING AND VEHICLE ENGINEERING

Numerical and experimental stress analysis of rapid prototyping

Ph.D. THESIS PRESENTATION

Péter Ficzere

M.Sc. mechanical engineer

Scientific leader:
Lajos Borbás Ph.D.

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1. Introduction

1.1. A Background and actuality of research study

The first steps of a product lifcycle is determines its future. **[Ming13]** Therefore very important to choose the best concept from the ideas. Used the rapid prototypes we can realise more concepts in short time what helps to select the best one. Very important to decrease the time to market. This is an advantage on the market In many cases we can realise the problems only after the manufacturing the prototype and we have to re-plan the models to modify. **[Sass06].** Usually to manufacture the prototypes we have no tools, like this the first part is always very expensive. In the traditional design method we can start the planing of the manufacturing only after the final appropriate prototype tests. On this area is a great innovation the rapid prototyping process. The essence of this additive manufacturing method, that we build the geometry layer by layer. **[Gin13], [Her01]**. Using this method arbitrarily complex geometries can be produced without tools. Thanks to the spread of technology fields of application are expanding, often used for example like medical prothesis. **[Bibb10], [Win05], [Pet99], [Bus13]**, **[Wan10],** or in small series manufacturing, where should be to expensive planning and manufacturing tools. In such cases, however, we need to know whether the parts is it suitable to carry the loads. To do this usually we need simulation. In my dissertation the main goal was to determine the required parameters to simulations.

1.2. Objective of the research

The aim of my dissertation is to scientifically prove my hipotheses. My hipotheses are:

- I assume that with the use of rapid prototyping could lead to significant time saving during the production design and planning process. Owing to this and the other advanteges of this technologie (it can manufacturing without tools) cost reduction can be achieved against the traditionally manufacturing methods.
- The geometrical properties (accuracy, surface roughness) of the rapid prototypes are not treated in a unified system.
- The rapid prototype parts have not isotropical properties but orthotrops against the available datas.
- The material properties are the same in printed layer (in a plane).
- The combined use of the optical photoelastic investigation and the numerical analysis is suitable to validate material laws and material properties

1.3. Delimitation of the theme

There are a variety of implementation possibilities of the additive manufacturing. All the material properties of the procedure is not intended to examine because the application of an appropriate test method we can be able to investigate all the same analogy. Therefore, it was necessary to choose one procedure and further carry out its.

There are more aspects of the selection, therefore after the literary review and consultations with manufacturers I make the decision.

At the selection was an important aspect of the usability in the future of my experimental results. First step of the refining was choosing the method which resulting parts for functional prototype, small sereies product or medical applications. In such applications the model has to have appropriate stiffness and material properties.

In addition it was essential also that the parts can be manufactured with sufficient accuracy.

In many cases the relevance of the proceedings will decide the price. It includes both the cost price of the production equipment well as the cost of used raw materials, furthermore the operating and service costs.

They will also be affected by distribution the use of parts of certain procedures. In addition to the previously mentioned price and ability of manufactured models properties the dissemination is determined by the given machine handling (what level of expertise is required), the installation requirements (space requirement noise pollution, etc.) is a korábban említetteken túl.

In view of these aspects from the rapid prototyping technologies restricted myself to the OBJET technology's materials, because this method offers the most opportunity to use. Ezzel az eljárással többféle különböző merevséggel rendelkező alkatrészt lehet készíteni. It is fast, it ensures a sufficent accuracy with an equipment clean and silent mode which allows up to office use as well. **[Gurr12]** To usability as a functional prototype is very much influenced by the stiffness.

As to further limitation to aim of my dissertation I choosed from these technologies the OBJET proceeding FullCure 720 called material investigations were done which has the maximum stiffness from the available materials with this procedure.

During a detailed literature review I searched and analyzed from scientific papers the principle of the Rapid Prototyping, areas of it's use, the known methods, the available properties, accuracy, stiffnesses.

In the next step I dealt with the determination of the numerical simulation required material properties as well as the needed test method to investigate the materials.

Then, I have analyzed the possible methods for the validation of material properties. Afterwards as a result I present with the help of coating layered optical photoelastic investigation the validation of material properties which I have determined earlier. I'll show you on a part which has a different shape that if it is loaded by known boundary condition then the results of the numerical analysis and the emerging stress and strain values on the real parts are comparable. In addition, I explain below that the parts printed in different position are how will deform as a a result of the same loads.

Finally, I summarize my new scientific results as well as the possibilities of application and I suggest possible directions for further developments.

In my dissertation I intended to determine the experiments and test methods wich required to numerical simulations. Using these experiments and test methods can be performed the simulations on all parts which made by additive manufacturing.

1.4. Method of the research

The available laboratory of the Budapest University of Technology and Economics Department of Vehicle Elements and Drives (Today's name is Department of Vehicle Elements and Vehicle-Structure Analysis), and my scientific leader Lajos Borbás Ph.D. (Leonardo awarded material scientist) created favorable conditions to develop the research theme in national and international environment. In the dissertation I used in accordance with the goals a wide range of classic research methods. I highlight the literature of mechanical modelling of the composite materials which are very close to the material properties of the model what manufactured layer by layer. **[Sasson14]**.

On the base of international and national literature I discovered and evaluated the informations required to numerical simulations of Rapid Prototypes. Then I focused those well known experiments which can help verifying my hypothesis. I paid particular attention to industrial usability of the applied measurments **[Has12]**, ensuring the practical applicability of the methods. I made tensile tests in the well-equipped, accredited laboratory of the Cooperation Research Center for Biomechanics, Budapest University of Technology and Economics managed by Lajos Borbás Ph.D. with the help of Gábor Szebényi Ph.D.. The required specimens are provided to me by Varinex Inc..

In order to determine certain parameters new test method development was needed. The compliance of these new test methods are demonstrated by finite elemnet analysis.

I regularly consulted about the results of the measures and methods, their development opportunities. My results was publicated continously in international journals and on international conferences (experimental mechanics). Hybrid (photoelastic coating technique **[Koc82], [Franz01]** and finite element analysis applied together) method was developed by me to validation of the determined material properties. The required measurements I had doneat the laboratory of the BME Department of Vehicle Element and Drives. I have built up a close relationship with software developers in order to identify options to mumerical simulations.

2. Summary of research activities – New scientific results

In my work I dealt with the mechanical investigation of functional models, prototypes made by Rapid Prototyping. I have found how to get economic benefits as a result of the analysis of production technologies. Probably because of the novelty of the process and even immaturity caused problems during my examinations that datas from different manufacturers may be comparable only after certain adjustments.

Against my hypothesis (the additive manufacturing technology results orthotrop material properties) the manufacturers are not currently dealt with at an appropriate attention to give exacts material properties. My results proved the mechanical properties of the Rapid Prototyping models are depends on the printed directions, the printed positions, i.e. the printed direction, the printed position determines the mechanical behavior of the subsequent product.

To determine all of the material constants at materials which has a behavior described by orthotrop material law I had to develop new measuring procedure. After that, I had to veryfing these procedures. On the base of the determined constants it was important the investigations for validation. I developed a hybrid method which applies two well known method (photoelastic coating technique and finite element analysis) together to validation material properties.

Due to the results of my research in the case of individual parts the optimization can be performed to an appropriate accuracy what has a significant importance.

A number of questions can be asked in the context of the above. Furthermore it would be determined how can loadable by dynamic loads and what is the answer to fatigue test the parts made by additive manufacturing technology.

A significant number of them are made of special polymers so typical of plastics time-dependent creep parameters are missing.

Should be examined even the change of mareial properties depend on temperature as well as it should be dealt with aging susceptibility of materials.

2.1. New scientific results

2.1.1. It has been proved, that the material properties of the pieces produced by OBJET technology are not independent of the printing direction, so the method results in orthotropic material properties.

That to what extent the parts can be loaded is basically determined by their material properties. So the choice of material model used in modelling considerably influences the accuracy of modelling. As it was mentioned, the E and the υ material properties have to be specified for the finite element analysis (static strength test). For this the most widespread method is the tensile test.

From the OBJET technology, where the acrylic-based photopolymer used as basic material polymerizes the drops by UV light, we can presume isotropic material properties.

The tensile specimen is standard size, it is 4 mm thick and the material it is made of is the above-mentioned acrylic-based photopolymer.

The tensile specimen was manufactured by Varinex Zrt. in two building directions (*Figure 1*) that are parallel with the longitudinal axe but are perpendicular to each other, in two different „thicknesses” of layer (16 and 30 μm).

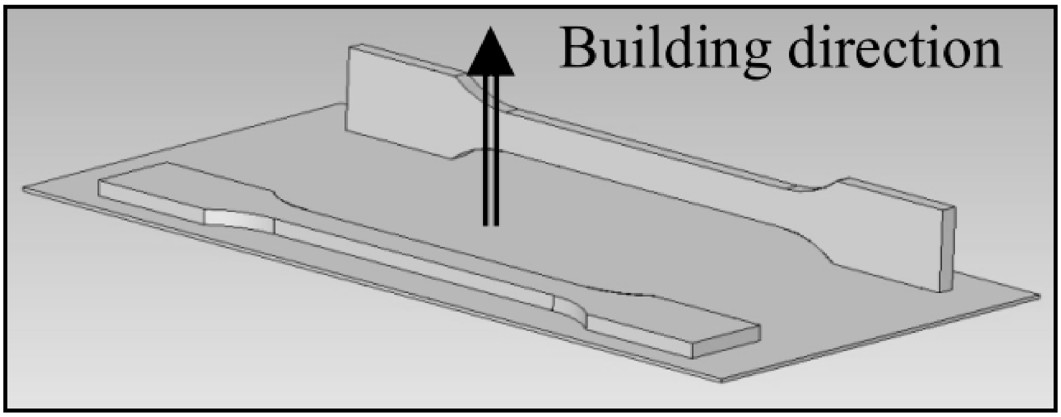

Figure 1. **The building of a standing and a lying specimen**

We carried out a tensile test on 5 specimens in both directions in both thicknesses.

From the tensile test results it can be pointed out that the tensile strength of the specimens built in a standing position has not changed with the thickness of the layer. In the case of the specimens made in a lying position the elongation at rupture has grown two times bigger than in the case of the standing specimens and the deviation of both the tensile strength and the elongation at rupture was very big. In this case the increasing of the thickness of the layer had practically no effect at all. The results of the tests are given in Table 1.

Table 1. **A The results of the tensile test**

	Average Young's modulus (MPa)	Average tensile strength (MPa)	Average elongation at rupture (%)
standing 16 µm	2302±32	57±0,3	8,4±0,7
standing 30 µm	2376±41	60±0,6	5,8±0,3
lying 16 µm	2095±74	49±2,5	11,1±4,5
lying 30 µm	2068±19	48±0,8	12,6±5

In the flexible range of the results the measurements (Elastic modulus) can be reproduced well. At the end of the tensile (the part of the uniform expansion) the tensile strength gives similar figures in the case of the same building directions but the deviation is bigger in the case of the specimens made in a lying position. The deviation of the elongation at rupture of the specimens printed in a standing position is significantly smaller than that of the specimens made in a lying position. In the case of the test bodies printed in a lying position the elongation at rupture shows a stochastic character.

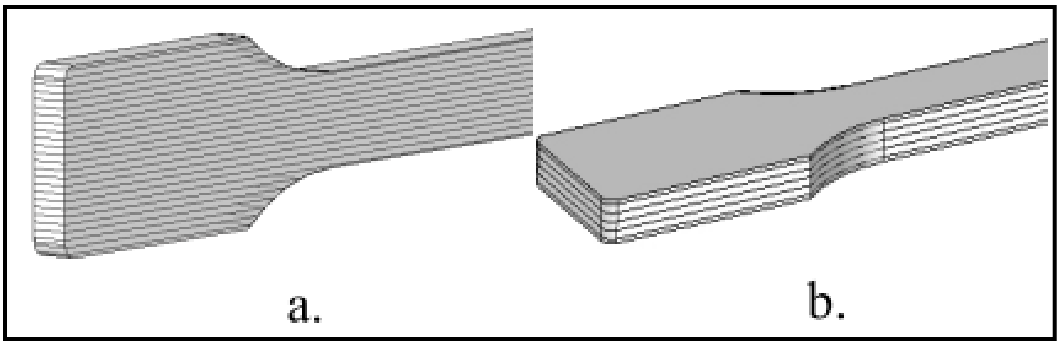

Figure 2. **The lamination of the standing (a) and the lying (b) specimens**

The results of the tensile tests show that, the rapid prototype materials made by OBJET technology are not isotropic, so we have to be very careful when applying the material laws used for numerical analysis. Since the direction of the tensile was perpendicular to both building directions (*Figure 2*), it can be presumed that the material may also give a different result when it is built in another direction which is perpendicular to these building directions.

Related publications: **[Ficz09], [Ficz10b], [Ficz11c], [Ficz11b]**

2.1.2. It has been verified, that the material properties in each direction are same within a layer (in one plane) printed by OBJET technology.

Previously, I demonstrated that the model what I have chosen can be described by the orthotrop material law. The orthotropical materials are special type of the anisotropical materials. There are 2 or 3 principal directions, which have different material properties. **[Jon75], [Lov98]** The generalized Hooke law for orthotropical materials is

$$\begin{Bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \varepsilon_3 \\ \gamma_{23} \\ \gamma_{31} \\ \gamma_{12} \end{Bmatrix} = \begin{bmatrix} S_{11} & S_{12} & S_{13} & 0 & 0 & 0 \\ S_{21} & S_{22} & S_{23} & 0 & 0 & 0 \\ S_{31} & S_{32} & S_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & S_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & S_{55} & 0 \\ 0 & 0 & 0 & 0 & 0 & S_{66} \end{bmatrix} \begin{Bmatrix} \sigma_1 \\ \sigma_2 \\ \sigma_3 \\ \tau_{23} \\ \tau_{31} \\ \tau_{12} \end{Bmatrix} \quad (1)$$

where ε_1, ε_2, ε_3 are the strains into the 1,2,3 directions,
γ_{ij} ($i \neq j$) represents engineering shear strain (i,j = 1, 2, 3)
σ_1, σ_2, σ_3 are the normal stresses,
τ_{ij} ($i \neq j$) are the shear stresses (i,j = 1, 2, 3)
S_{ij} is the compliance matrix,

$$[S_{ij}] = \begin{bmatrix} \frac{1}{E_1} & -\frac{\nu_{21}}{E_2} & -\frac{\nu_{31}}{E_3} & 0 & 0 & 0 \\ -\frac{\nu_{12}}{E_1} & \frac{1}{E_2} & -\frac{\nu_{32}}{E_3} & 0 & 0 & 0 \\ -\frac{\nu_{13}}{E_1} & -\frac{\nu_{23}}{E_2} & \frac{1}{E_3} & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{G_{23}} & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{1}{G_{31}} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{1}{G_{12}} \end{bmatrix} \quad (2)$$

where:

In the compliance matrix E_1, E_2, E_3 are the Young modulus
υ_{ij} is the Poisson's ratio for transverse strain in the j-direction when stressed in the i-direction (i,j = 1, 2, 3) ($i \neq j$)
G_{ij} are the shear modulus
in addition: $S_{ij}=S_{ji}$

This shall be assisted by further understanding of *Figure 3*.

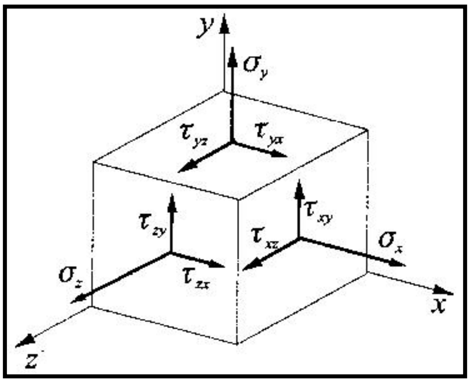

Figure 3. **Stress Directions** [Bha80]

These relations showed that there are 9 independent constants need to represent an orthotropical material. However, I have assumed due to the layer by layer method that within a single layer (a plane) material properties are the same. For this reason number of the independent parameters can be reduced. For the tensile test two different perpendicular examination prototypes were built. In addition, I looked at a third direction, when the specimens placed diagonally between the lengthwise and across directions with 45°. *(Figure 4).*

The aim of the test was to determine the simplification possibilities. The tensile specimen is standard size, it is 4 mm thick and the material it is made of is FullCure720 acrylic-based photopolymer by OBJET technology. The tensile specimen was manufactured three positions in the same building directions with a thickness of layer 30 μm *(Figure 4).*

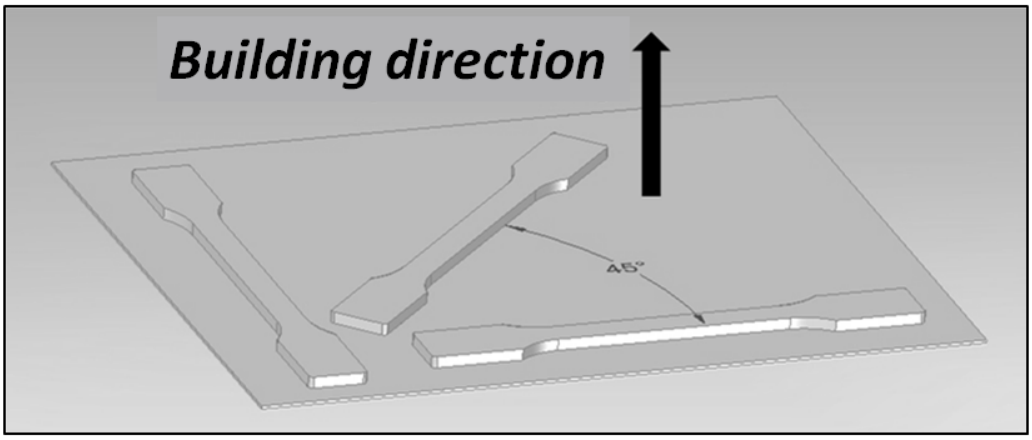

Figure 4. **The building direction of specimens**

Table 2. **Statistical analysis of tensile test**

	Young Modulus printed across {Mpa}	Young Modulus printed lengthwise {Mpa}	Young Modulus printed diagonally {Mpa}	Difference {%}
Average	*2288*±60	*2370*±25	2250±45	±*3%*

As is clearly visible from the results, there is no significant difference in modulus focusing on printing direction. The average results show that is a very small 3% difference. From the above I found that the material properties within a layer (a plane) are the same in all directions. This means that the material properties described previously (2) from the nine independent parameters some are identical. With this the number of independent parameters are reduced. I have determined that material produced with OBJET technology has 2D orthotrop material properties. Also worth to be mentioned the phenomenon that I observed during the tensile tests in several cases at once ruptured the specimen in several places so the test material of specimens were very homogeneous.

Related publications: **[Ficz11c], [Ficz11d]**

2.1.3. A new measurement technology has been developed to determine the shear modulus G using poor tensile test, without applying poor shear external load.

In isotropic case, the basic material properties can be specified by two independent material constants (E, υ). , However, in orthotropic case the shear modulus (G) can no longer be calculated using the constants mentioned above.

In pure shear or torsion state case it can use the following formula to determine the value of the (G):

$$\tau = G\gamma \qquad (3)$$

The interpretation of the following equation, *Figure* 5.

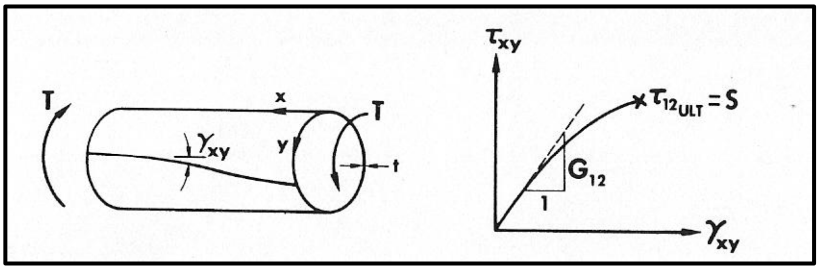

Figure 5. **Interpretation of the shear modulus** [Jon75]

We have no torsion tool therefore remains the possibility of determining the shear state. There are several well-known and standardized in-plane shear test but none of them is suitable for the exact determination of the shear modulus of elasticity. Theoretical the γ angle distortion may also be determined on a cube. If the lower face of the cube fixed and the opposite side had got a load which is parallel with the basic plane. The rate of the load (F) induces τ stresses. Important to have a constraint all of the internal points which let only displacement paralell with the load as you can see in *Figure* 6. **[Leg11], [Tóth]**

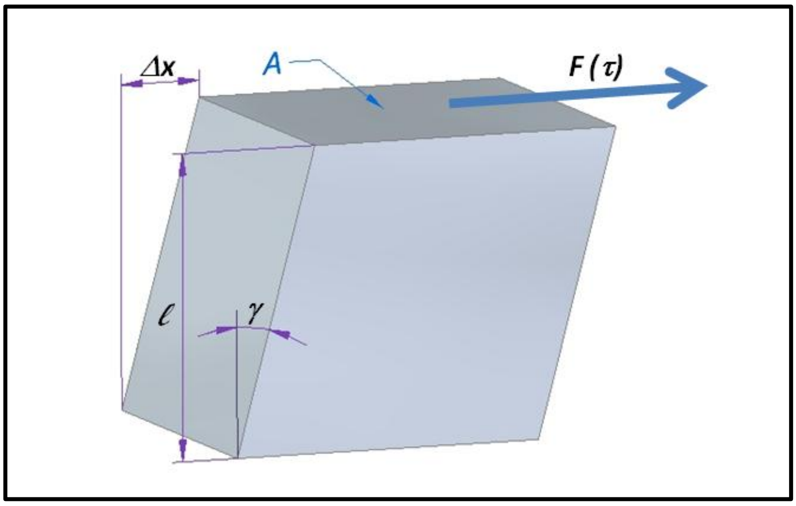

Figure 6. **Pure shear stresses caused deformation**

Therefore I had to develop a method which allows to determine the shear modulus. The result is shown in the following figure.

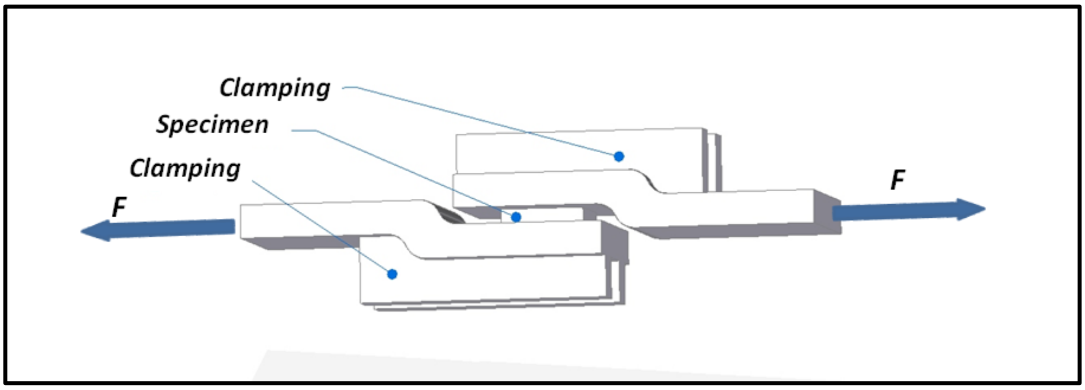

Figure 7. **Compilation of the layout**

The specimen is a 20x20x4 mm square-based prism from the investigated material. This should be fix to clamping. *(Figure 7.)* Fixation happened with a special glue. **[Loctite]**

The stress state will not pure shear stress with this method, but it is computable with the measured correction factor.

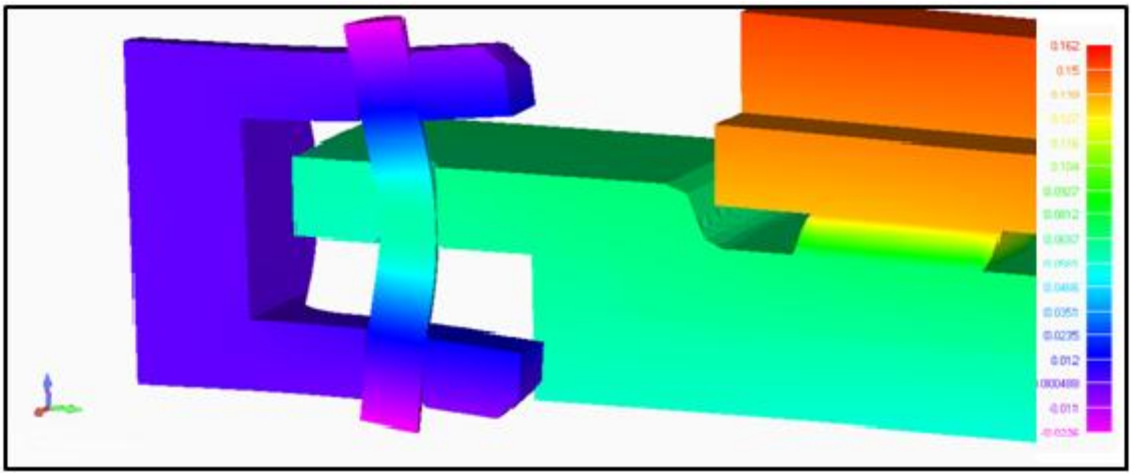

Figure 8. **Clamping deformations (Deformations enlarged for better visibility with a scale 40. Displacement y can be seen on the color bar. Values are in mm)**

(4) $$G = \kappa \frac{Fl}{A(\Delta x_m - \Delta x_{bef})}$$

where κ is the shape factor of the specimen [-], *F* is the force load [N], *l* is the thickness of the specimen [mm], *A* is the loaded face area [mm^2], Δx_m is the measured displacement [mm], Δx_{bef} is the displacement from the deformation of the clamping. The value of Δx_{bef} is changing depend on the loads. It is computable to a given load from the clamping layout characteristic. Thus by this method the shear modulus (G) can be determined by a uneversal test equipment.

Related publications: **[Ficz12d], [Ficz14]**

2.1.4. The material properties (E_1, E_2, E_3, ν_{12}, ν_{23}, ν_{13}, G_{12}, G_{23}, G_{13}) necessary to the static strength analysis of pieces produced from FullCure720 material made by OBJET technology have been determined.

To determine the material properties of the rapid prototypes we made tensile tests on standardized specimens in three different positions. These positions and the tensile tests are shown in fig. 9.

The earlier experiments show us the material law is not isotropic but orthotropic. The Hooke-law – what makes relation between stresses and strains – is more difficult in orthotropic case. By earlier experiments we could reduce the number of independent constants from 9 to 6 because in some directions the material properties are the same (2.1.2.chapter). The Poisson's ratios (υ) were determined by tensile test machine placing strain gauges onto specimens.

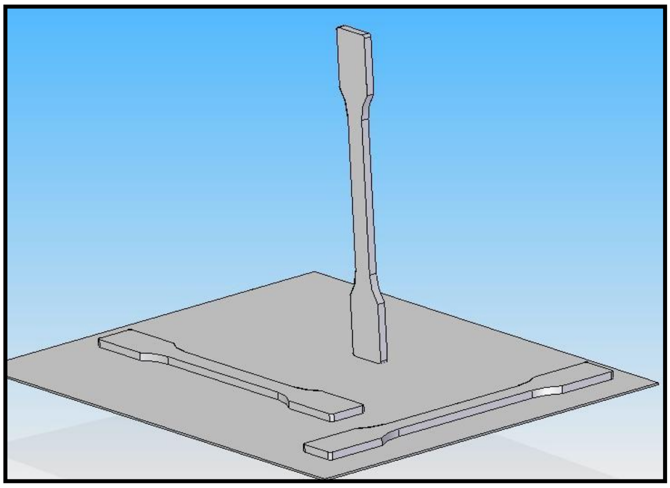

Figure 9. **3 directions manufactured tensile test specimens**

The shear modulus (G) was determined by an own developed in-plane shear test method. It has to use correction factors which depends on the shape, sizes and the used materials.

The measured were as follows:

Table 3. **Material properties of FullCure720**

E_1=2350 MPa	ν_{12}=0,39	G_{12}=221 MPa
E_2=2350 MPa	ν_{23}=0,4465	G_{23}=65 MPa
E_3=2000 MPa	ν_{13}=0,4465	G_{13}=65 MPa

Each direction can be identified in the follow figure:

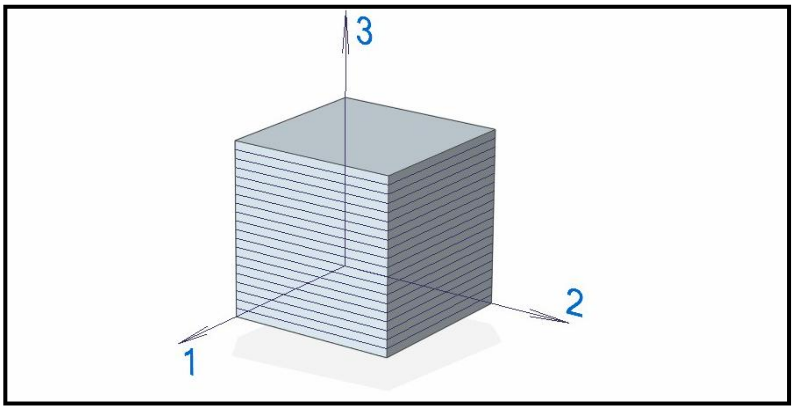

Figure 10. **Principal directions of orthotrop material properties**

Related publications: **[Ficz13c], [Ficz14]**

2.1.5. It has been proved that the joint use of photoelastic coating technique and the numerical finite element analysis is suitable for the validation of static strength properties (E, ν, G) of earlier unknown materials determined in experimental way.

After determining the material properties but before use, must demonstrate their realism as well.

It is not enough only one direction to examine the response to specific loads, the validation shall always be some real experiments to happen.

I made finite element analysis on a selected part which has a different shape. The load was internal pressure to avoid the modelling problem. In this loadcase we can sure the development of complex stress state. Thus, any stress component appears.

We have been manufactured the same geometry from a known material. The part has got a coating layer to the optical photostress investigation. After that the prepared part was loaded an internal pressure and across polarization filters the fringe pattern cause the load was observed. Depending on the test layer can be assigned stress values to fringe pattern. Thus, for a given internal pressure stress values by fringe pattern and the results of the numerical simulation are comparable.

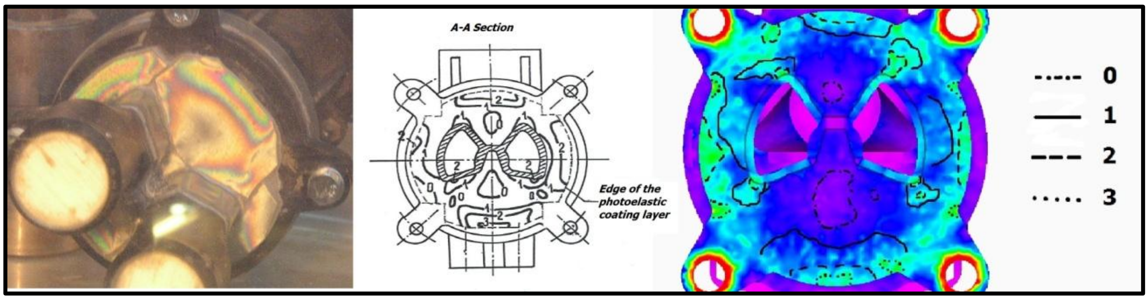

Figure 11. **Results of the optical photoelastic investigation and numeric analysis (m=1 σ_1-σ_2=8.1MPa)**

Based on my results if the stress state results extent and nature also aligns of the two different method then the material properties used in the simulation is considered appropriate.

Related publications: **[Ficz12f], [Ficz13c] [Ficz14]**

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