

METHOD TO REDUCE THE INDEPENDENT CONSTANTS OF ORTHOTROP MATERIALS IN RAPID PROTOTYPING

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Abstract: *Sequential engineering is the method of production in a linear format. The different steps are done after each another, with all attention and resources focused on one task. In concurrent engineering, different tasks are tackled at the same time, and not necessarily in the usual order. Concurrent engineering is a method by which several teams within an organization work simultaneously to develop new products and allows more flexible approach. The concurrent engineering is a non-linear product or project design approach during which all phases of manufacturing operate at the same time. Usage of rapid prototyping gain developers, designers and engineers more time and money and save more resources.*

Key words: *orthotrop material, material science, FullCure 720.*

1. Introduction

Nowadays it takes less and less time to launch a new product, therefore the planning phase needs less time, too. While a large number of methods have been established for numerous problems, many challenges remain to be solved. New tasks emerge requiring the development of new methods or processing schemes. Moreover, with the earliest possible elimination of the errors in planning, the costs of errors can also be significantly decreased. Rapid prototyping is an approach which allows crucial design decisions as early as possible. A rapid prototyping system should support maximal re-use and

innovative combinations of existing methods, as well as simple and quick integration of new ones. On the basis of all these it is obvious that the role of prototypes has increased considerably, especially that of the functional prototypes, with the help of which the parts can be examined under the later working conditions and furthermore real workload analysis can be done. On the one hand, prototyping helps to identify adequate methods and optimal parameters. This enables developers to make crucial design decisions as early as possible in the knowledge discovery process. Costly redesign and useless use of human

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resources at later stages can be avoided [1]. On the other hand, prototyping helps to control several risks and inefficient use of resources. Most importantly, the performance of the envisioned system can be estimated beforehand. This gives the customer an impression of the final result and its limitations. It also helps to clarify misunderstandings concerning the envisioned outcome. Another important aspect is to estimate computation time, cost and resources of the final system. Especially for applications with tight constraints on these resources (e.g. real time systems), such an estimation is essential in order to decide to which extent knowledge discovery can be applied [2]. In this paper authors have investigated the change in resource requirements due to the use of rapid prototyping..

2. The role of prototypes

Formerly the prototypes were manufactured only at the end of the planning cycle and they were rather expensive and wasting lots of human resources, as the tools needed during the manufacturing were not available. Whereas nowadays the prototypes appear in a fairly early phase of planning. Sequential engineering is the term used to describe the method of production in a linear format. The different steps are done one after another, with all attention and resources focused on that one task. After it is completed it is left alone and everything is concentrated on the next task. In concurrent engineering, different tasks are tackled at the same time, and not necessarily in the usual order. Concurrent engineering is a method to develop new products and services by doing task simultaneously. Both product and process design run in parallel and occur in the same time frame. Product and process are closely coordinated to achieve optimal

matching of requirements for effective cost, quality, and delivery. Decision making involves full team participation and involvement. Usage of rapid prototyping gain developers, designers and engineers more time and money and save more resources [3].

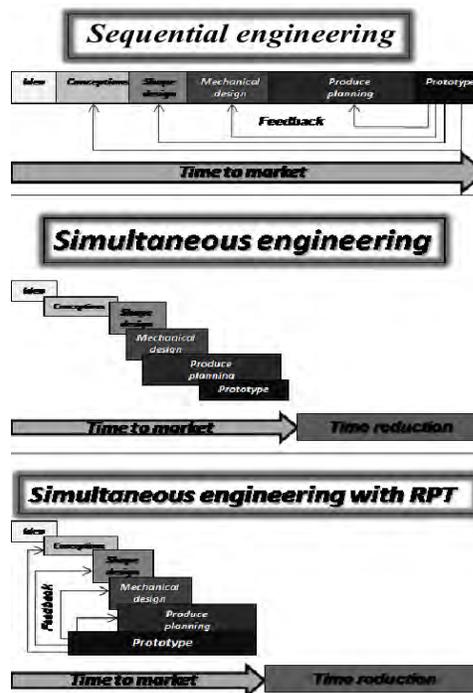


Fig. 1. Comparison of sequential, concurrent engineering and rapid prototyping (source: [4])

There are the so-called digital prototypes, which are 3D models used by CAD/CAM/CAE software. Through these models the shape can be seen, and we can perform finite element analysis on them regarding the possible constraints and loads. Also we can perform checking interference and production simulations (turning, milling and drilling) on them. 3D printing is a form of additive manufacturing technology where a three dimensional object is created by laying down successive layers of material. 3D

printers are generally faster, more affordable and easier to use than other additive manufacturing technologies. 3D printers offer product developers the ability to print parts and assemblies made of several materials with different mechanical and physical properties in a single build process. Advanced 3D printing technologies yield models that closely emulate the look, feel and functionality of product prototypes. A 3D printer works by taking a 3D computer file and using and making a series of cross-sectional slices. Each slice is then printed one on top of the other to create the 3D object. Three-dimensional printing makes it as cheap to create single items as it is to produce thousands and thus undermines economies of scale. The polyJet prototyping technology or Objet's patented PolyJet inkjet technology works by jetting state of the art photopolymer materials in ultra-thin layers (16μ) onto a build tray layer by layer until the part is completed. The intuitive Objet studioTM software manages the process. Each photopolymer layer is cured by UV light immediately after it is jetted, producing fully cured models that can be handled and used immediately, without post-curing. The gel-like support material, which is specially designed to support complicated geometries, is easily removed by hand and water jetting.

In the area for surface accuracy improvement and build time reduction, there have also been researches during the past decade on the optimization of build orientation and adaptive slicing. As a part is built up layer by layer with RP processes, a staircase effect is a major factor affecting the surface smoothness. Its influence is determined by the layer thickness and the local part geometry. If the layer thickness is computed based on the local geometry, the staircase effect can then be controlled to a user-specified tolerance level. In general, there are two

slicing approaches for the determination of the layer thickness, i.e. uniform slicing and adaptive slicing. Uniform slicing is the simplest approach for slicing a part at equal intervals. It is widely used for commercial RP systems in industry today. It is however a compromising issue in determining the layer thickness. If the layer thickness is small, one obtains a smooth part but it results in many layers and long build time. On the other hand, if the layer thickness is large, the build time is short, but one may end up with a part having a large staircase effect. For resolving the above compromising issue, adaptive slicing has been proposed to generate a variable layer thickness based on the local surface geometry and a pre-specified smoothness requirement [5] [6].

3. Finite element analysis (FEA)

Realising that the demand for functional prototypes and the use of built-in rapid prototypes in small series production and medical science have increased significantly, it became necessary to be able to decide whether the certain model can be used in its real load conditions. For the FEA (static strength test) a 3D CAD model is needed and are needed to know the constraints and loads, moreover, the material law and properties are needed, in the case of a linearly elastic model, means that the Elastic modulus and the Poisson's ratio should be known [7]. Realising that the demand for functional prototypes and the use of built-in rapid prototypes in small series production and medical science have increased significantly, it became necessary to be able to tell whether the certain model can be used in its application network. In more complicated cases we have to use finite element analysis to carry out this. For the finite element analysis we need a 3D CAD model and we have to know the constraints and loads depending on the environment,

moreover, we need the material law and properties, in the case of a linearly elastic model, means that we have to know the Elastic modulus and the Poisson ratio. To evaluate the non-linear and time dependent behaviour we have to specify further material properties. It is important to mention that in the case of a model with unknown material properties the results have to be verified by experiments carried out on real models, the defined material law can be applied only after this verification.

4. The examination of material properties

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 ν material properties have to be specified for the final 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 drop by drop, we can presume isotropic material properties. The tensile specimen is standard size, it is 4mm thick and the material it is made of is the above-mentioned acrylic-based photopolymer. The tensile specimen was manufactured by Varinex Rt. in two building directions (Fig. 2) that are parallel with the longitudinal axe but are perpendicular to each other, in two different thicknesses of layer (16 and 30 μm). The main goal of this paper is to determine which of the material properties of the rapid prototyping model that has to be used for FEA. Authors found that to the linear elastic area (real working area) need to be investigated, where the Elastic modulus (E) and the Poisson's ratio (ν) should be constant. Experimental investigation shows none of

them are constants. Tensile tests are needed to determine the above mentioned parameters described by the law material properties. Previously, the material was modelled as an isotropic material [8], but other [9] studies have demonstrated that the model have chosen by the authors can be described more precisely by the orthotrop material law.

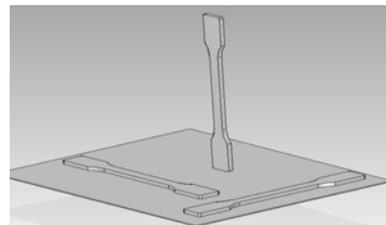


Fig. 2. The building of a standing and a lying specimen (source: [10])

4.1. Orthotropical material properties

The orthotropical materials are special type of the anisotropical materials. There are 2 or 3 principal directions, which have different material properties. The generalized Hooke law for orthotropical materials is (1), (2):

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

Where $\varepsilon_1, \varepsilon_2, \varepsilon_3$ are the strains into the 1,2,3 principal directions,

- γ_{ij} ($i \neq j$) represents engineering shear strain
- $\sigma_1, \sigma_2, \sigma_3$ are the principal stresses,
- τ_{ij} ($i \neq j$) are the shear stresses
- S_{ij} is the stiffness matrix,

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

where:

- In the stiffness matrix E_1, E_2, E_3 are the Young modulus in 1, 2, and 3 directions respectively
- ν_{ij} is the Poisson's ratio for transverse strain in the j -direction when stressed in the i -direction
- G_{ij} are the shear modulus in the ij planes
- in addition : $S_{ij}=S_{ji}$

These relations showed that there are 9 independent constants need to represent an orthotropical material. However, the authors 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. The aim of the test was to determine the simplification possibilities.

5. Results

The tensile diagrams are shown in Fig. 3 and 4.

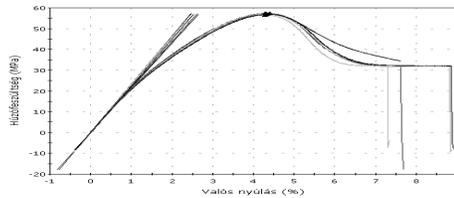


Fig. 3: Tensile diagram (standing specimen, the thickness of the layer is 16 μm)(source: measurement done by the authors)

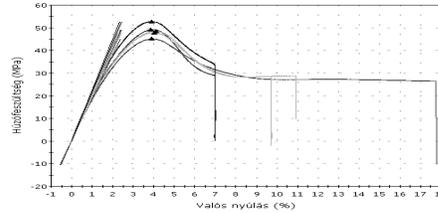


Fig. 4: Tensile diagram (lying specimen, the thickness of the layer is 16 μm)(source: measurement done by the authors)

From the tensile test results it can be pointed out that the tensile strength of the specimens built in a standing position (Fig. 3) has not changed with the thickness of the layer. In the case of the specimens made in a lying position (Fig. 4) 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 tensile tests Table 1.

	Average Young's modulus [MPa]	Average tensile strength [MPa]	Average elongation at rupture [%]
standing 16 μm	2302 \pm 32	57 \pm 0.3	8.4 \pm 0.7
standing 30 μm	2376 \pm 41	60 \pm 0.6	5.8 \pm 0.3
lying 16 μm	2095 \pm 74	49 \pm 2.5	11.1 \pm 4.5
lying 30 μm	2068 \pm 19	48 \pm 0.8	12.6 \pm 5

(source: [9])

In the flexible range of uniaxial stress state the results of the measurements (Elastic modulus) can be reproduced well. At the end of the biaxial stress state (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.

6. Summary

The results of the tensile tests show that, in contradiction to our original presumption, 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, it can be presumed that the material may also give a different result when it is built in another direction which is perpendicular to this building direction. As is clearly visible from the results, there is no significant difference in modulus focusing on printing direction. The average results shows very small 3.5% difference. From the above the authors found that the material properties within a layer (a plane) are the same in all principal directions. This means that the material properties described previously (2) from the nine independent parameters some are identical. So $E_1 = E_2$, $\nu_{12} = \nu_{13}$ and $G_{12} = G_{13}$, with this **the number of independent parameters are reduced**. Authors have determined that material produced with OBJET technology have 2D orthotropic material properties. Also worth to be mentioned the phenomenon observed by the authors during the tensile test in several cases at once ruptured the specimen in several places so the test material of specimens were very homogeneous.

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