# Reverse Engineering and FEM Analysis for Mechanical Strength Evaluation of Complete Dentures: A Case Study

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## 1. Introduction

Complete dentures are used in social healthcare of the seniors. These frequently deteriorate, due to the fragility and structural defects of the materials from which are realized, and also due to the accidents produced because of the patients disabilities. The loss of teeth impairs patients' appearance, mastication ability and speech, thus upsetting the quality of their social and personal life (Mack F., 2005). The selection of materials used in complete dentures technology is crucial, because this directly relates to its performance and life span. Generally, the complete dentures bases are made from acrylic resins – heat curing, light curing, casting, injection, microwaves technologies. Processing technology of these materials sometimes lead to complete dentures with small defects, which can initiate cracks; these are responsible for failure of the complete denture before the expected lifetime. The relative short lifetime of the complete dentures has led researchers to investigate the causes of fracture by studying the stress distribution upon mastication and to find ways to improve their mechanical performance. The finite element method (FEM) has been used for five decades for numerical stress analysis (N. Faur, 2002). The advent of 3D FEM further enables researchers to perform stress analysis on complicated geometries such as complete dentures, and provides a more detailed evaluation of the complete state of stress in their structures.

### 1.1 The aim of the work

Due to developing technologies of acrylic resins, the complete dentures have a high degree of porosity (defects). These defects in material structure, together with brittle fracture behavior, can cause failure of the complete denture before the expected lifetime.

The aim of this paper is to perform a numerical analysis which emphasize the high risk of denture degradation due to presence of defects. Numerical analysis was performed by applying finite elements method on a three-dimensional geometric model resulted by 3D scanning of a real denture. The scanned model, as a point cloud, has been processed and converted into a solid geometric model using „reverse engineering" techniques. Through the subject approached, this paper wants to inform about the reverse engineering tehniques and also presents their usefulness by a numerical analysis.

Based on FEM analysis have been investigated the stress distribution and structural integrity of a maxillary complete denture. The study focused on fracture resistance evaluation of dentures, in the presence of structural defects of materials, which initiates denture's cracking or fracture, before the estimated lifetime. Also, was analysed, through defectoscopy method, the porosity degree of dentures depending on the material they are made, and the influence of the defect size and location in denture, on the stress and strain state.

## 2. Material and methods

### 2.1 Mechanical properties of the material

For this study, have been selected maxillary complete dentures from different acrylic resins obtained by two technologies: heat-curing material - Meliodent (Heraeus Kulzer, Senden, Germany) and light curing material - Eclipse Resin System (Dentsply International Inc.- DeguDent GmbH, Hanau Germany). The dentures were non-destructively evaluated using an Olympus stereomicroscope, Type SZX7, locating the defects and micro-cracks resulted from their technology, fig. 1-a, b. In most of dentures assessed, defects were located in the area indicated in Figure 1. Using an image processing system, QuickphotoMicro 2.2, was made an assessment of defects size, fig. 1-b. In the next step of the study, was performed an experimental program to determine the mechanical properties of the materials involved in the analysis. The materials have been prepared in accordance to the manufacturer's recommendations, Table 1. The mechanical properties were determined by tensile tests on a testing machine, model Zwick Roell (Zwick GmbH & Co. KG, Ulm, Germany), according to ISO 527 standard and bending tests according to ASTM D 790 standard. The test results showed a brittle fracture behavior, which may indicate some vulnerabilty of this materials in the presence of defects.



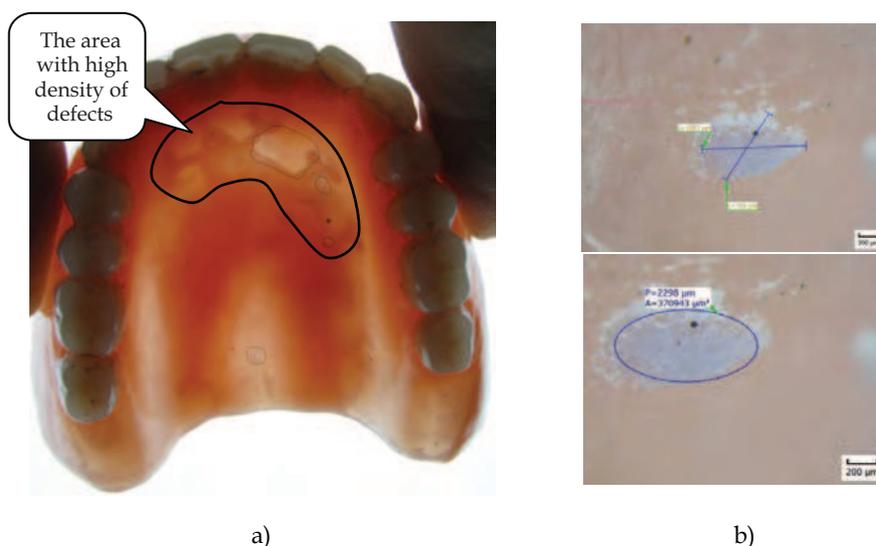a)                                                                    b)

Fig. 1. Non-destructive evaluation of maxillary complete dentures: a) locating defects in denture; b) measurement of localised defects.

| Brand Name | Polymer: monomer ratio | Batch No. (polymer/monomer) | Description | Polymerization procedure |
|---|---|---|---|---|
| Meliodent Heat Cure | 34g:17mL | 64713213/64713308 | Heat polymerized | 7 hrs at 70° C and 1 hr at 100° C |
| Eclipse Prosthetic Resin System | Base plate supplied as pre-packed material | 030822 | Light – activated | Visible blue light |

Table 1. The characteristics of acrylic resins included in this study

## 2.2 Geometric modeling of the upper complete denture

Finite element analysis was performed on geometric models, resulted after the complete dentures' 3D scanning (with 3D laser scanner LPX1200, Roland) and image processing by „reverse engineering", taking into consideration the located defects. A thin layer of green dye (Okklean, Occlusion spray, DFS, Germany) was sprayed on the surface of the denture to increase its contrast for scanning. The denture was positioned on the rotating table of the 3D scanner and scanned with a scanning pitch of 0.1 x 0.1 mm.

Scanning technique used is that of triangulation which is based on using a 3D non-contact active scanner. Non-contact active scanners emit some kind of radiation or light and exploit a camera to look for the location of the laser dot. Depending on how far away the laser strikes a surface, the laser dot appears at different places in the camera's field of view. This technique is called triangulation because the laser dot, the camera and the laser emitter form a triangle, fig. 2.
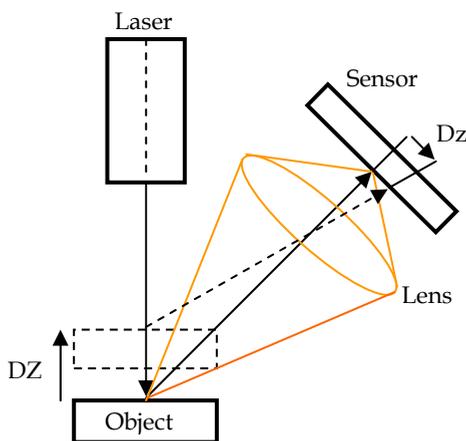


Fig. 2. Principle of laser triangulation sensor

The results of scanning process may be a point cloud (fig. 3) or a polygon mesh (fig. 4) having the shape of the scanned object. In a polygonal representation, the registered points are connected by straight edges forming a network of small plane triangular facets. After 3D scanning, the point cloud or polygon mesh are processed by reverse engineering technique and converted into a solid geometric model, fig. 5.
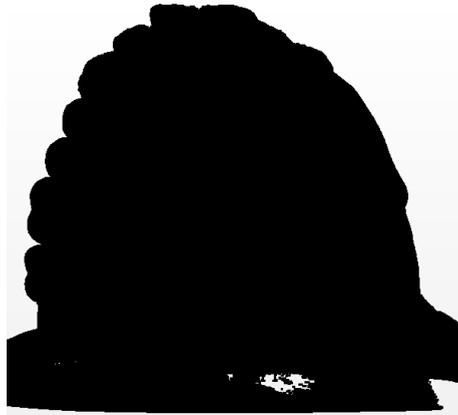
Fig. 3. The point cloud resulted from 3D scanning of the maxillary denture



Fig. 4. The polygon mesh resulted from 3D scanning of the maxillary complete denture

The first step in converting a point cloud is processing and polygonization. This stage may include operations such as:

- Filter noise – removing the points placed in undesirable regions due to measurement errors, this can be done automatically;
- Filter redundancy – uniformly reducing the number of points in a point set where the points are too close or overlapped each other;
- Triangulation 3D – this operation converts a point cloud to a polygonal model.

If an object is scanned from several angles and resulting in more scanned surfaces, they must be registered and merged in a single polygon mesh.

After 3D scanning of a maxillary complete denture, a point cloud (fig. 3) was imported into the Pixform Pro software (INUS Technology, Seoul, Korea), and processed to create a fully closed polygon mesh. To create a continuous polygon mesh the point cloud of the scanned denture was triangulated and converted into a polygonal model. This polygonal model has
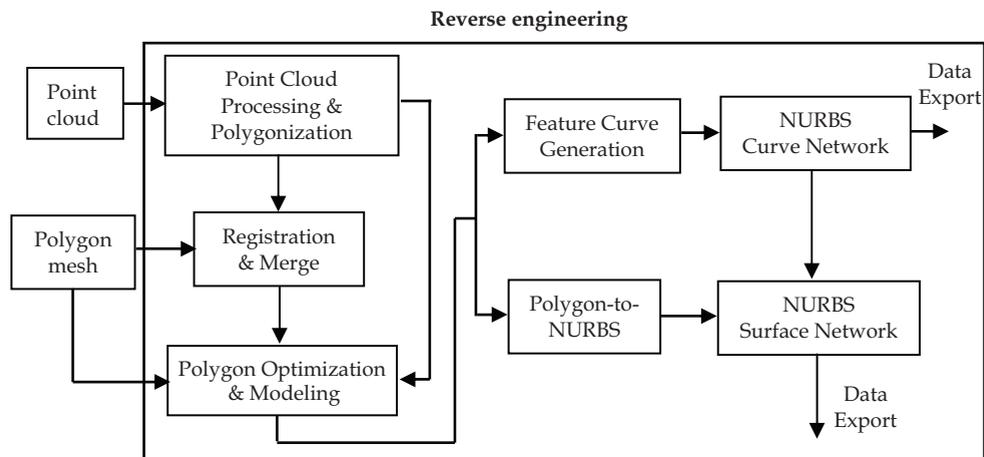
**Reverse engineering**



Fig. 5. The work process of reverse engineering technique

gone through a set of operations in the order they are listed: cleaning abnormal polygon meshes, refining the surface by smoothing and fill holes.

The smooth operation smoothes the surface of the polygonal model by changing the coordinates of the input vertices. The operation can be done automatically and provides three methods: Laplacian, Loop and Curvature. The Laplacian method is a tool for enhance global smoothness wile Loop method is a kind of local smoothing tool for keeping details of model. The Curvature method is used for curvature based smoothing. For this work was chosen the Laplacian smoothing method because it has the smallest deviations from the scanned model.

Another important operation in polygon mesh optimization is to fill holes in a model that may have been introduced during the scanning process. This operation can be done automatically or manually and constructs a polygonal structure to fill the hole, and both the hole and the surrounding region are remeshed so the polygonal layout is organized and continuous (Pixform Pro, 2004).

The result of polygon mesh optimization stage is a fully closed model (fig. 6) ready to generate NURBS (Non-uniform Rational B-Spline) curves or surfaces network.

The surface creation process begins by laying down curves directly on the polygonal model to define the different surfaces to be created. The curves network created on model (fig. 7) can be the basis for subsequent realization of the surfaces.

Once the curves network is created, the model is ready to generate NURBS surfaces (fig. 8). This can be done automatically or manual. Automatic surface generation doesn't need to draw a curve, while manual surface generation can completely maintain the flow line of the original polygon surface. Manual generation of surfaces is related to the network of curves.

For this case, because the scanned denture has a complex geometry, was chosen automatic generation of NURBS surfaces on the polygonal model. To obtain the geometric model of the maxillary complete denture the NURBS surfaces network was exported in initial graphics exchange specification (IGES) format and then imported into Solid Works 2007 for conversion into a solid model, fig. 9.
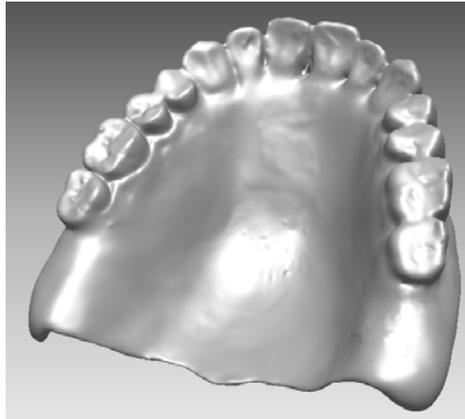
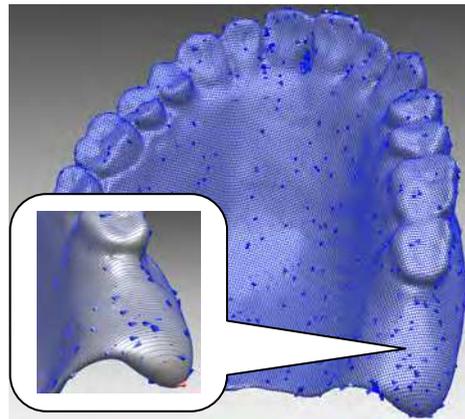Fig. 6. A closed polygon mesh resulted after the optimization stage



Fig. 7. The NURBS curve network generated on polygonal model
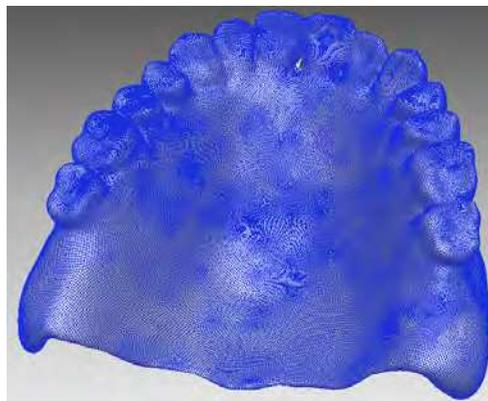


Fig. 8. The NURBS surface network generated on polygonal model

Fig. 9. The solid geometric model of complete denture

The NURBS tools (curves and surfaces) are commonly used in computer-aided design (CAD) and also found in various 3D modeling and animation software packages. They allow representation of geometrical shapes in a compact form. NURBS surfaces are functions of two parameters mapping to a surface in three-dimensional space. The shape of the surface is determined by control points.

## 2.3 The FEM analysis

Using the FEM software package, ABAQUS v6.9.3, on the geometric model of complete denture, was performed an analysis of the stress and strain field, taking into consideration different located defects. Based on non-destructive evaluation were carried out four models of analysis. At each model was considered a defect as a material hole with a diameter of 2 mm and 1 mm depth, in the area indicated in figure 1.

In the first model the fault was introduced near the midlle of the denture thickness, fig. 10. In the second and third model the faults were considered near the top surface of the denture and bottom respectively, fig. 11 and 12, and the fourth model shows a situation with a fault located in the thickness of the denture, with an irregular shape and a total surface twice that the faults defects of previous models, fig. 13. The fault depth of the fourth model is about 1 mm.

All four models were analyzed in two situations, in the first case we consider that the material of maxillary denture is Eclipse and the second case when the material is Meliodent.

The maximum force of mastication at a patient with complete denture is between 60-80 N (Zarb G, 1997). For this study was considered a mastication force of 70 N distributed on palatal cusps of the upper teeth, fig. 14. The areas with distributed force are about 46.666 mm$^2$ and the result is a normal pressure of 1.5 MPa. To fix the model, there have been applied supports on surfaces shown in fig. 15.

The supports from denture channel allow a 0.2 mm displacement in vertical direction and stop the displacements in horizontal plane. Also, the supports from palatal vault allow a 0.1 mm displacement in vertical direction and stop the displacements in horizontal plane. Allowed displacements were considered to replace the deformations of the oral mucosa.

Fig. 10. The first analysis model: the fault is considered near the midlle of the denture thickness



Fig. 11. The second analysis model: the fault is considered near the top surface of the denture



Fig. 12. The third analysis model: the fault is considered near the bottom of the denture
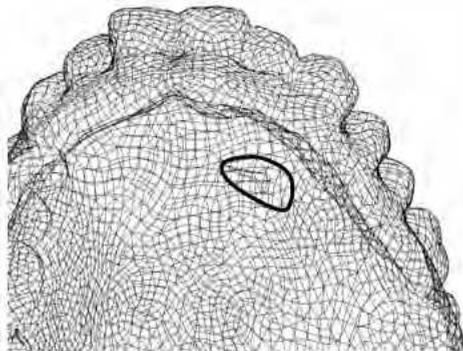
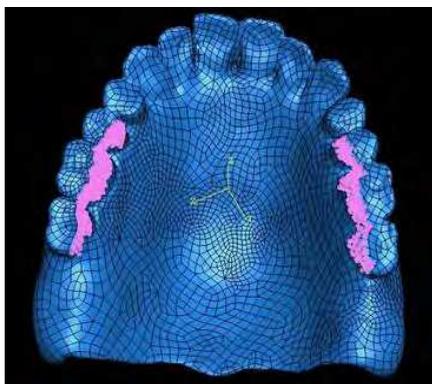Fig. 13. The fourth analysis model: the fault is considered in the thickness of the denture



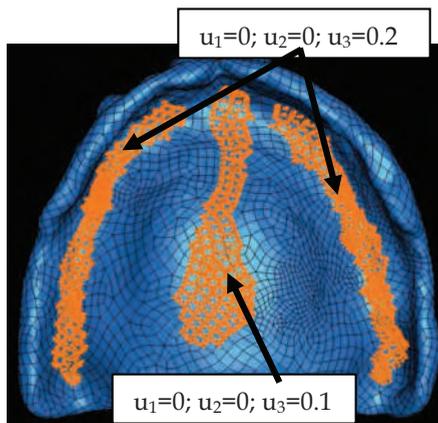Fig. 14. The applied pressure on palatal cusps



Fig. 15. Applied boundary conditions on complete denture model

All the analysis models have been meshed in tetrahedral finite elements, C3D4, accounting for a total of 243032 elements and 49154 nodes.

## 3. Results

In most assessed dentures was observed that the faults occurs mainly in the area where the thickness of denture is high, as indicated in figure 1. It was also noticed that, in the Eclipse dentures the density of defects may be higher than in the Meliodent dentures, but the defects in Eclipse may be smaller in size than those in Meliodent. This is due to different technologies for developing materials (heat curing polymerization – Meliodent and light curing polymerization – Eclipse).

The mechanical properties resulted after the experimental programs were given in table 2. The results show that, Eclipse Base Plate has a better elasticity compared to Meliodent and also a better fracture strength.

| Material | Ultimate Tensile Strength $\sigma_{uts}$ [MPa] | Tensile Young's modulus, E [MPa] | Total Elongation $A_t$ [%] | Flexural Strength $\sigma_f$ [MPa] |
|----------|------------------------------------------------|----------------------------------|----------------------------|------------------------------------|
| Eclipse | 80.16 | 3390 | 4.06 | 127 |
| Meliodent | 68.62 | 1215 | 8.76 | 118 |

Table 2. Mechanical properties of the materials used for FEM analysis

For finite element analysis were considered four analysis models, each of them having a defect located in different areas of the denture. For all these cases have been evaluated the stress and strain states (fig. 16 - 24).

Since the materials have a brittle fracture behavior it was considered for this analysis the fracture criterion which takes into account the Maximum Principal Stress.

In all analyzed models, the presence of the faults has increased the stress and strain state, compared to the situation they are not considered. Moreover, this defects increased the fracture risk of denture. Thus, in case of model I the fracture risk of denture has increased by almost 29 % due to present defect, in the second model the fracture risk increased by almost 14 %, in the third case was an increase of almost 90 % and in the latter case (the fourth model) the fracture risk increased with 18 %. The increased rates of fracture risk of denture were determined reporting the actual stress states to the stress state of the same



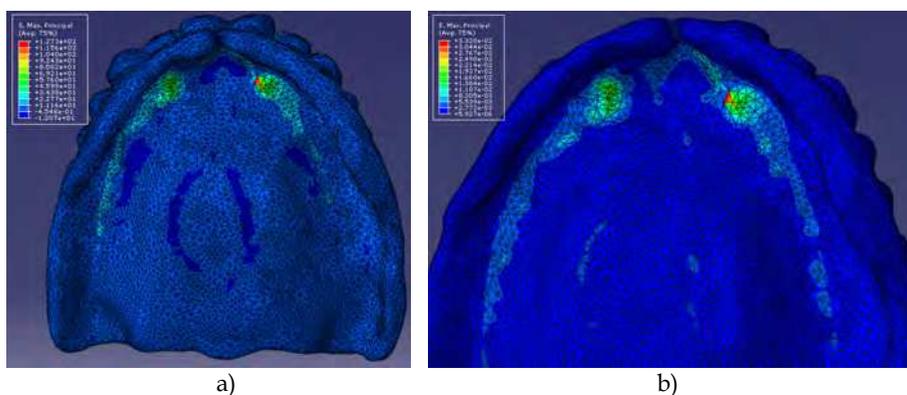a)                                          b)

Fig. 16. The Maximum Principal Stress (a) and Maximum Principal Strain (b) state in the first analysis model for denture with Eclipse material
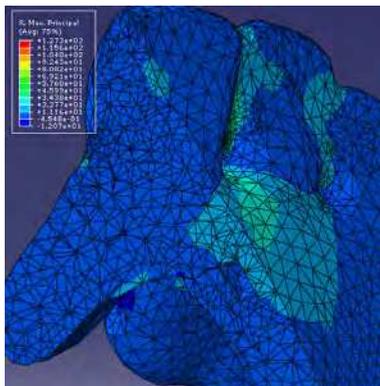
Fig. 17. The Maximum Principal Stress around the defect in the first analysis model for denture with Eclipse material
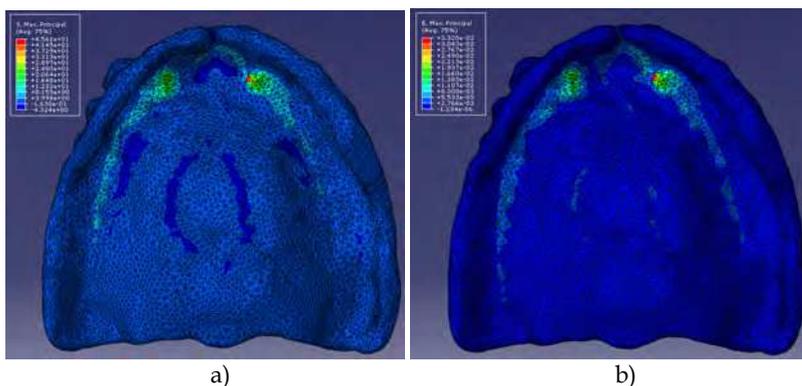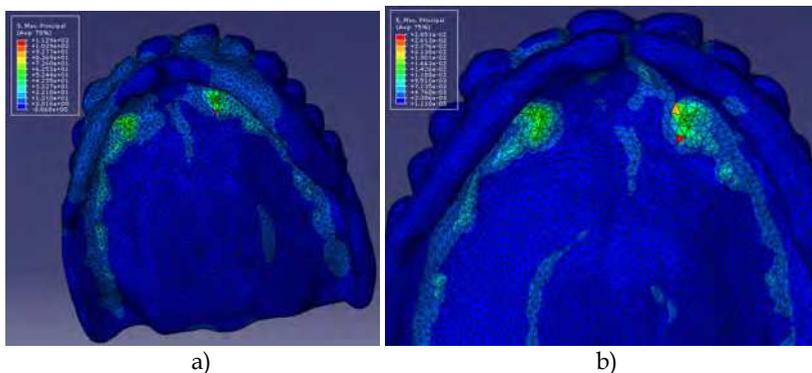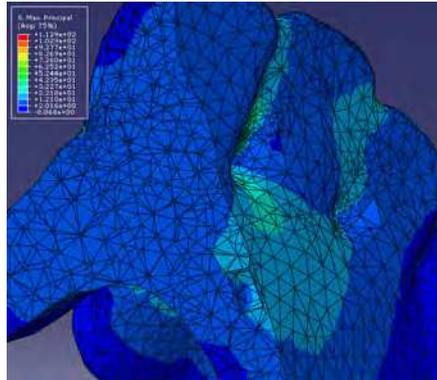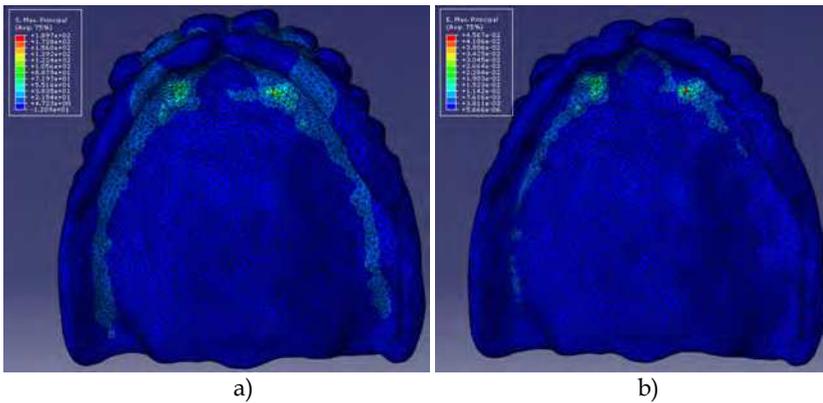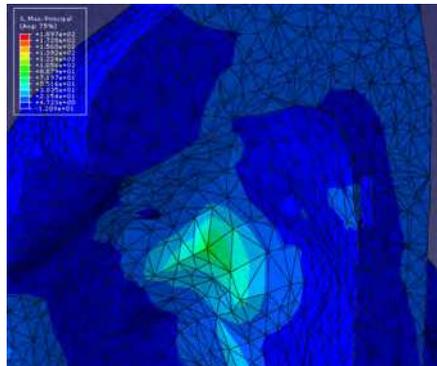


a)              b)

Fig. 18. The Maximum Principal Stress (a) and Maximum Principal Strain (b) state in the first analysis model for denture with Meliodent material



a)              b)

Fig. 19. The Maximum Principal Stress (a) and Maximum Principal Strain (b) state in the second analysis model for denture with Eclipse material

Fig. 20. The Maximum Principal Stress around the defect in the second analysis model for denture with Eclipse material
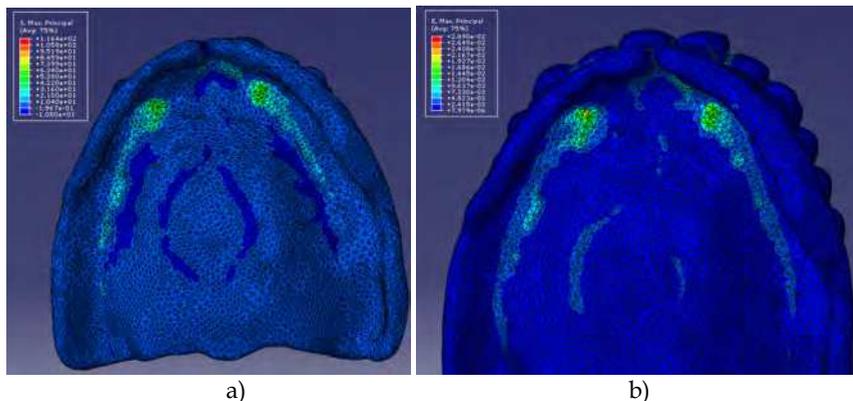


a)                                                b)

Fig. 21. The Maximum Principal Stress (a) and Maximum Principal Strain (b) state in the third analysis model for denture with Eclipse material
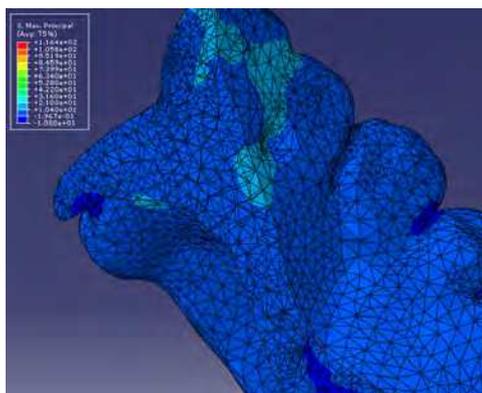


Fig. 22. The Maximum Principal Stress around the defect in the third analysis model for denture with Eclipse material

a)                                         b)

Fig. 23. The Maximum Principal Stress (a) and Maximum Principal Strain (b) state in the fourth analysis model for denture with Eclipse material



Fig. 24. The Maximum Principal Stress around the defect in the fourth analysis model for denture with Eclipse material

denture, loaded in the same way but without defects. These results indicate a greater influence on the stress state when the defect is closer to the bottom of the denture and less if the defect is almost to the upper surface of the denture. Defect in the fourth model, although it has a large surface area, is at the limit of the area indicated as the highest density of defects and because of this it not influence too much the stress and strain state.

In the case of Meliodent denture was observed the same influence of presence defects on stress state and fracture strain.

## 4. Conclusions

The methodology presented in this paper consist in 3D scanning of a real object, processing of the scanned results by reverse engineering and obtaining a digital geometric model and conducting numerical analysis. This methodology can by successfully applied in design optimization, especially in objects with complex geometry.

An important role in fracture strength evaluation of the dentures plays the material's defects and their localization towards the most loaded areas of the denture.

The structural defects located inside the model have a smaller influence on the state of stress than those located on the exterior surface. Also, very relevant for the fracture of the denture is the stress field around the crack, which can either close or open the crack.

The defects in the material's structure may have a negative impact on denture's mechanical resistance. Complete dentures' defects can initiate cracks that are responsible for their failure before the expected lifetime.

## 5. Acknowledgment

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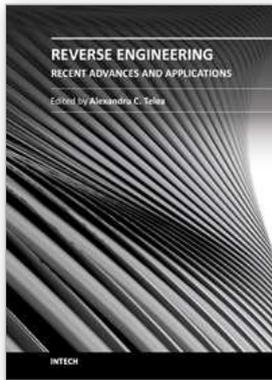
**Reverse Engineering - Recent Advances and Applications**

Edited by Dr. A.C. Telea

Reverse engineering encompasses a wide spectrum of activities aimed at extracting information on the function, structure, and behavior of man-made or natural artifacts. Increases in data sources, processing power, and improved data mining and processing algorithms have opened new fields of application for reverse engineering. In this book, we present twelve applications of reverse engineering in the software engineering, shape engineering, and medical and life sciences application domains. The book can serve as a guideline to practitioners in the above fields to the state-of-the-art in reverse engineering techniques, tools, and use-cases, as well as an overview of open challenges for reverse engineering researchers.

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