NUMERICAL ANALYSIS OF A LAMINATED PLATE BASED ON X-RAY COMPUTED TOMOGRAPHY IMAGES

Virgil TUDOSE[1], Daniela-Ioana TUDOSE[2], Anton HADĂR[3], Stefan Dan PASTRAMĂ[4]

The paper presents a method for obtaining the numerical model of a laminated plate made of polyester resin, using the X-ray computed tomography. Finite element analyses were undertaken in order to obtain the stress and displacement fields in the case of three point bending. Validation of the numerical model was done using experimental measurements by the strain gauge technique. The obtained results can be used to estimate the lifetime of the structure and for a correct prediction of the in-service behavior and bearing capacity of the structure.

Keywords: X-ray computer tomography, finite element method, strain gauge technique.

1. Introduction

Inner defects existing in different structures can modify both their mechanical behaviour and the carrying capacity. Since the causes of appearance of discontinuities are multiple and difficult to avoid, their effect on the mechanical behavior should be studied in order to establish the risk that appears in service due to such flaws.

The first step in such a study is a quantitative and qualitative evaluation of the structure [1,2]. Such a goal can be accomplished with the help of adequate non-destructive techniques (ultrasonic techniques, thermography, X-ray computer tomography etc. [3,4]. These techniques are used to determine the existence of defects, and, when they are detected, it is possible to obtain their precise shape, dimensions and position. All this information can be further used to obtain the geometric and calculus models of the desired structure.

The next step is to choose the calculus method. A first choice is to use analytical calculations which are usually very time consuming and sometimes

[1] Lecturer, Department of Strength of Materials, University POLITEHNICA of Bucharest, e-mail: virgil.tudose@upb.ro
[2] Assistant professor, Department of Strength of Materials, University POLITEHNICA of Bucharest, e-mail: daniela.tudor@upb.ro
[3] Professor, Department of Strength of Materials, University POLITEHNICA of Bucharest, e-mail: anton.hadar@upb.ro
[4] Professor, Department of Strength of Materials, University POLITEHNICA of Bucharest, e-mail: stefan.pastrama@upb.ro *(corresponding author)*

impossible to apply. The most easy-to-use are numerical methods and, especially, the finite element method which is also a very powerful numerical tool [5,6].

A final experimental validation of the numerical results is necessary in order to accept the results of the finite element analyses [7]. For this, the strain gauge technique, photoelasticity or other experimental methods may be used.

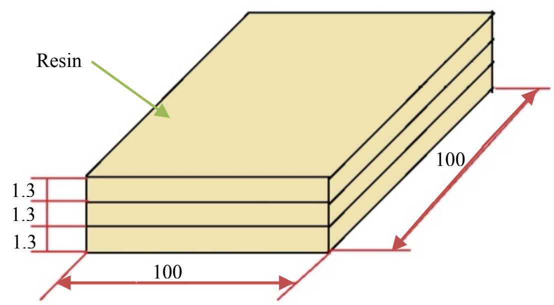
One of the techniques used to quantitatively investigate mechanical structures is the X-ray computed tomography. This technique is a non-destructive one and it uses X-rays to obtain 2D images taken around an axis of rotation. These images are further digitally processed in order to obtain a 3D image of the studied structure. Finally, the 3D geometrical model can be converted into input data for subsequent numerical analyses using dedicated software, [8].

Several researchers used X-ray computed tomography in order to analyze the mechanical response of different structures. For example, microtomography was used in order to evaluate the evolution of cracks in structures made of aluminum alloys casted under pressure [9, 10]. The obtained experimental information was further used to obtain numerical models for characterization of the initiation of cracks starting from the manufacturing defects. High Resolution Synchrotron Radiation Computed Tomography was used by Scott et al., [11], to detect fiber damage progression in a carbon–epoxy notched laminate loaded till failure. Sharma et al. obtained effective tensile moduli of 3D carbon/carbon composites using image-based finite element [12] simulations and experiments. The non-destructive evaluations were undertaken with X-ray tomography. The goal of this research was to characterize the behavior of the structure in the presence of cracks, voids, and fiber bundles distortion. A 3D finite element model containing such defects was obtained and analyzed. Tudor et al. [13] presented a combined research using both X-ray computed tomography and ultrasonic imaging in order to establish the position, shape and size of the defects that appeared during the manufacturing process in a layered plate made of polyester resin. A three-dimensional model was obtained from the X-ray tomography using specific software for data processing and further used to evaluate the effect of defects on the integrity of the analyzed structure, by comparing the numerical results with the ones for a similar plate without defects. Investigation of defects in fiber-reinforced polymers, textile composites or layered foams using X-ray tomography were described also by other researchers [14-16].

In this paper, an example of using X-ray computed tomography to obtain the numerical model of a three-layered laminated plate made of polyester resin is presented. This model is further analyzed with the Finite Element Method (FEM) to obtain the stress and displacement fields in the case of three point bending. The numerical model was validated experimentally by undertaking measurements with the strain gauge technique [17].

2. The nondestructive evaluation of a plate

For this study, a square plate made of polyester resin and having a side of 100 mm was analyzed. The plate was obtained by successive casting of three layers of material (Fig. 1), each layer having a thickness of 1.3 mm. Several circular defects were artificially inserted in the middle layer.



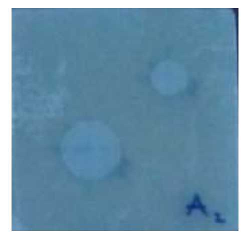


Fig. 1.Multilayered plate with defects in the middle layer

A nondestructive evaluation of the plate was performed using X-ray computer tomography. This method was chosen since it offers the possibility to obtain images of successive sections that can be further assembled in a tridimensional image of the examined object. A helical CT Scan spiral computer tomography device was used.

The results were processed in two stages. In the first one, the presence of defects, the shape, position and dimensions were established. Then, segmentation of planes and reconstruction of the volume of the plate were accomplished.

The following methodology was used, [1]:

- From the series of transversal sections obtained by X-ray scanning, the ones with maximum span of the defect were chosen. For this, two planes of interest - vertical and horizontal were defined;
- The chosen section is rebuilt in frontal plane (Fig. 2, b) and sagittal plane (Fig. 2, c) , using the defined planes;
- In the frontal section, the shape of the defect, the overall dimensions of the plate and the defects and the position of defect are defined;
- In the sagittal plane, the thickness of the plate and the depth of the defect are monitored.

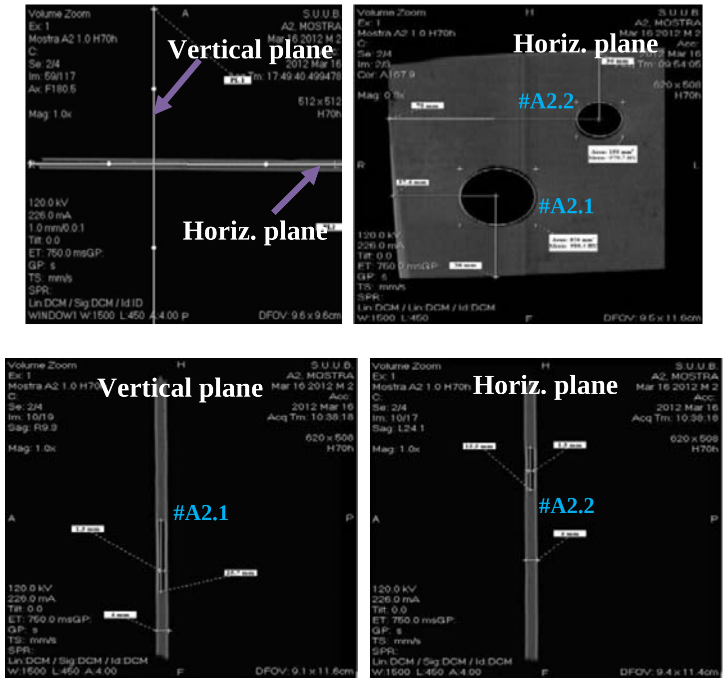


Fig. 2. Computer tomography evaluation of the studied plate

The second stage of processing of images is 3D reconstruction of the plate volume (Fig. 3) with the following steps [1]:

- Calibration of the series of images (transversal sections) obtained by scanning;
- Definition of objects through the attenuation coefficient;
- Definition of regions of interest (ROI);
- Auto-segmentation of surfaces, based on the differences between the densities found by the X-ray scanning process;
- Reconstruction of the 3D volume using the segmented surfaces.

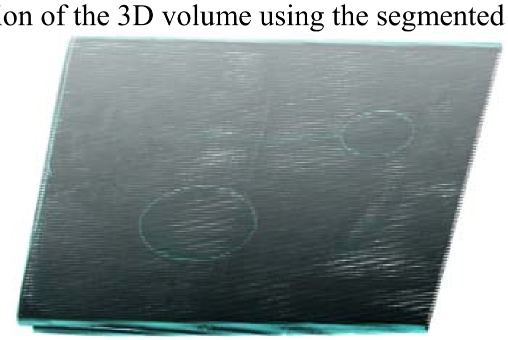


Fig. 3. 3D reconstruction of the volume of the plate

3. Numerical modeling of the flawed plate

This section presents a numerical evaluation of the studied plate, using the finite element method. The numerical model will be further validated by experimental investigations using the strain gauge technique.

The geometrical model of the plate was obtained using information yielded by the CT non-destructive evaluation. The plate was loaded in three point bending and the constraints and loading were defined taking into account the parameters of the testing machine used in the experimental analysis (Fig. 4).

The load was applied as a uniformly distributed pressure in order to avoid the effect of load concentration, in five different loading cases, (Fig. 5). The values of the force and corresponding pressures for the considered loading cases are presented in Table 1. The surface on which the pressure was applied is equal to the one of the loading roller used in the experimental validation of the proposed numerical model (see next paragraph)

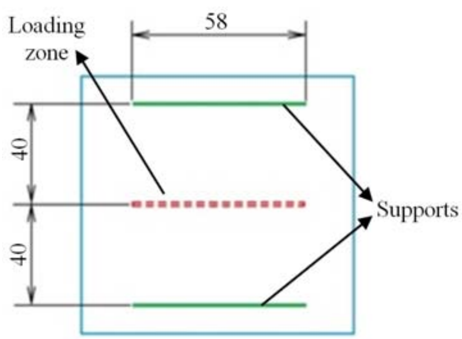


Fig. 4. Constraints and loading of the studied plate

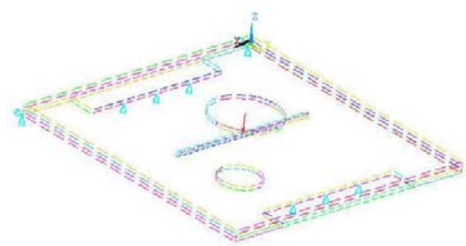


Fig. 5. Numerical modeling of the loads and constraints

Table 1

Values of the applied forces and pressures

Force [N]	*10*	*20*	*30*	*40*	*50*
Pressure [MPa]	0.172	0.344	0.517	0.689	0.862

The structure was meshed using tetrahedral elements. The maps of longitudinal strains are presented in Fig. 6 for all loading cases. The maximum strains obtained using the finite element method are listed in Table 2.

Table 2

Maximum strains

Force F, [N]	*10*	*20*	*30*	*40*	*50*
Strain, ε_l^{num}, [μm/m]	120	240	360	480	600

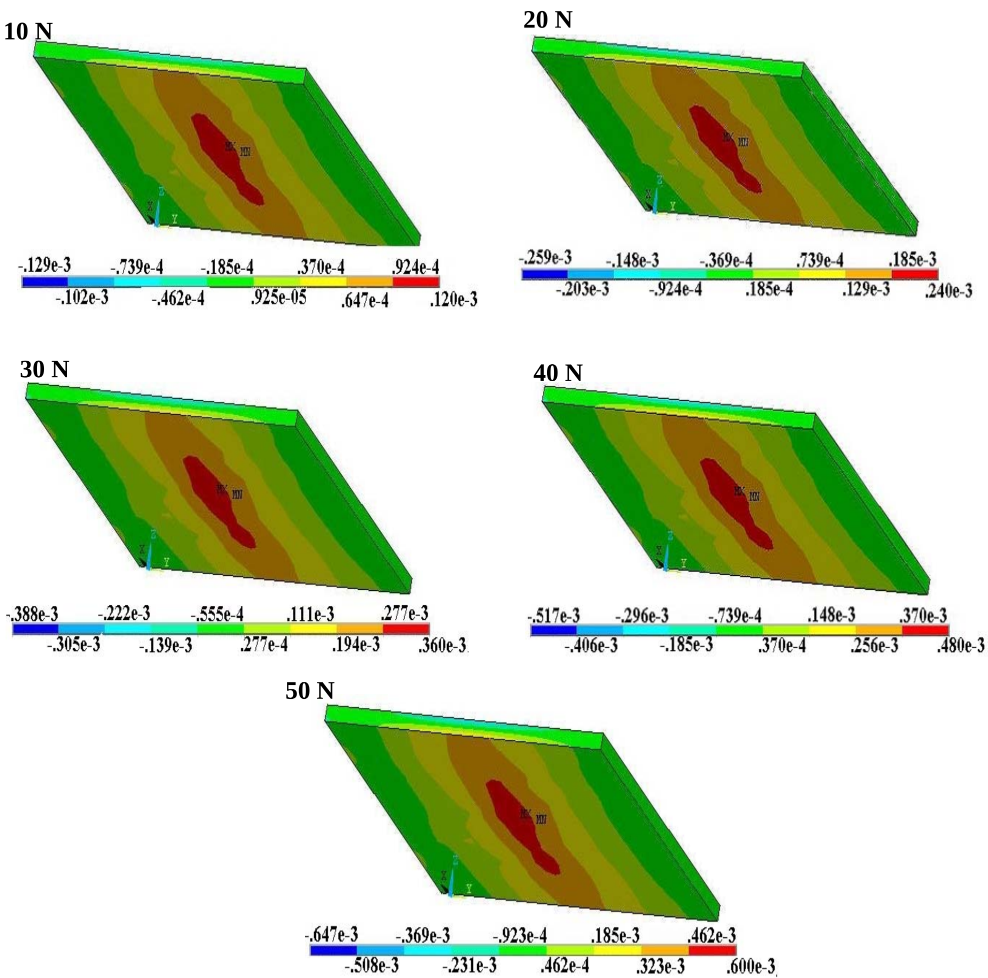


Fig. 6. Contour maps of longitudinal strains [mm/mm]

4. Strain gauge measurements

A strain gauge experimental analysis was performed on the studied flawed plate for the experimental validation of the numerical model.

In order to measure local strains, a strain gauge was glued on the longitudinal direction on the top surface of the studied plate. The gauge has a constant k_t = 2.05 and a gauge length of 10 mm. A Spider 8 multi-channel amplifier was used for acquisition and processing of the experimental data (Fig. 7).

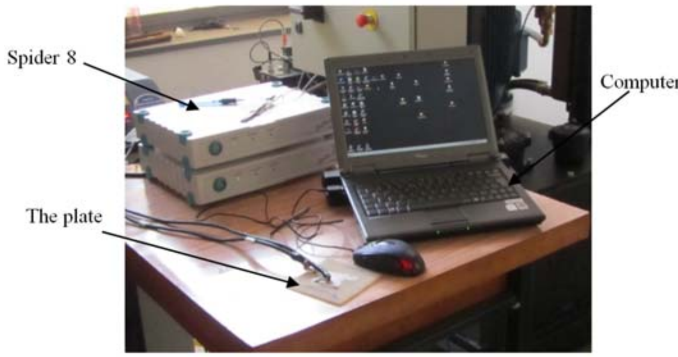


Fig. 7. The strain gauge experimental set-up

The same three point bending load was applied using an Instron 8801 testing machine. A schematic view of the constraints, loading and place of strain gauge is shown in Fig. 8.

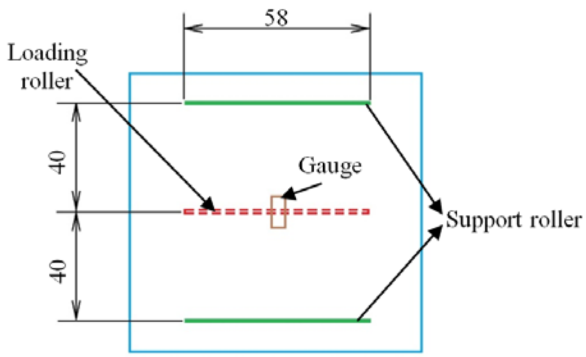


Fig. 8. Placement of gauge

Strains were determined for all five considered loading cases. The comparison between the numerical and experimental results is presented in Table 3.

Table 3

Experimentally obtained strains and errors versus numerical strains

Strains	Force [N]				
	10	20	30	40	50
ε_l^{exp} [μm/m]	108.2	218.6	331.5	499.5	637.5
Relative error, $\|\boldsymbol{E}\| = \frac{\varepsilon_l^{exp} - \varepsilon_l^{num}}{\varepsilon_l^{exp}} \cdot \mathbf{100}$, [%]	10.90	9.78	8.60	3.90	5.88

Since differences between the experimental and numerical results are acceptable, the numerical model is validated and can be further used in similar calculations.

5. Conclusions

A combined numerical-experimental analysis of the mechanical response of a layered plate made of polyester resin and loaded in three point bending was presented in this paper. In the first part of this research, it has been shown that processing of data obtained by X-ray computer tomography can lead to an accurate geometrical model of the analyzed structure. The presence, shape and position of defects were emphasized in the achieved model. Further, a three dimensional finite element model was analyzed in order to obtain the stress and strain fields that could allow the user to assess the mechanical influence of defects in the considered structure.

Since an analytical approach is impossible in the case of structures having inner defects, the numerical methods and especially the finite element method remain a very convenient alternative. Nevertheless, in the case of a numerical model, an experimental validation is usually required. For the structure analyzed in this paper, strain gauge measurements were undertaken for this purpose. A good agreement was obtained between the numerical and experimental results, confirming thus the accuracy of the proposed model.

A very important advantage of this methodology is that the 3D shape of the structure can be reconstructed. In this way, a numerical model for parts with complex shapes may be obtained and the precision of the numerical calculation is higher.

Acknowledgement

The work has been funded by the Sectoral Operational Program Human Resources Development 2007-2013 of the Ministry of European Funds through the Financial Agreement POSDRU/159/1.5/S/134398.

REFERENCES

[1] *D.I., Tudor,* Contributii privind evaluarea cantitativa a influentei defectelor de material asupra capacitatii portante a unor structuri (Contributions regarding the quantitative evaluation of the influence of material defects on the carrying capacity of some structures) - PhD Thesis, University Politehnica of Bucharest, 2012 (in Romanian);

[2] ASM Handbook - Nondestructive Evaluation and Quality Control, **vol. 17**, 1997.

[3] *** Computed tomography - Physical Principles, Clinical Applications and Quality Control, third edition, British Columbia Institute of Technology Burnaby, British Columbia, Canada, 2009;

[4] *C.H., Yang, H., Huh, H.T., Hahn,* Investigation of effective material properties in composites with internal defect or reinforcement particles, International Journal of Solids and Structures, **vol. 42**, 2005, pp. 6141–6165;

[5] *L.H., Yam, Z., Wei, L., Cheng, W.O., Wong,* Numerical analysis of multi-layer composite plates with internal delamination, Computers and Structures, **vol.** 82, 2004, pp. 627–637;

[6] *N., Iliescu, A., Hadar, , S.D., Pastrama,* Combined researches for validation of a new finite element for modeling Fiber Reinforced Laminated Composite Plates, Materiale Plastice, **vol. 46**, no. 1, 2009, pp. 91-94.

[7] *D. I., Tudor, I., Părău□anu, A., Hadăr*, Validation of models of plates with discontinuities made of plastic materials, through modal analysis, Materiale Plastice, **vol. 49**, no. 3, 2012, pp. 166-170.

[8] *E. Seeram*, Computed tomography – Physical Principles, Clinical Applications and Quality Control, third edition, Saunders Elsevier, St. Louis, Missouri, 2009.

[9] *E. Ferrie, J.Y. Buffiere, W. Ludwig*, 3D characterisation of the nucleation of a short fatigue crack at a pore in a cast Al alloy using high resolution synchrotron microtomography, International Journal of Fatigue, **vol. 27**, 2005, pp. 1215–1220.

[10] *N. Vanderesse, É. Maire, A. Chabod, J.Y. Buffière*, Microtomographic study and finite element analysis of the porosity harmfulness in a cast aluminium alloy, International Journal of Fatigue, **vol. 33**, 2011, pp. 1514–1525.

[11] *A.E. Scott, M. Mavrogordato, P. Wright, I. Sinclair, S.M. Spearing,* In situ fibre fracture measurement in carbon-epoxy laminates using high resolution computer tomography, Composites Science and Technology, **vol.** 71, 2011, pp. 1471-1477.

[12] *R. Sharma, P. Mahajan, R. Kumar Mittal*, Elastic modulus of 3D carbon/carbon composite using image-based finite element simulations and experiments, Composite Structures, **vol. 98**, 2013, pp. 69–78.

[13] *D.I. Tudor, Ş.D. Pastramă, A. Hadăr* – The use of computed tomography and ultrasonic imaging for assessment of defects in plates made of a polyesteric resin, Engineering Transactions (Rozprawy Inżynierskye), **vol. 62**, nr. 1, 2014, pp.17-31.

[14] *K. Wiesauer, M. Pircher, E. Gotzinger, C.K. Hitzenberger, R. Oster, D. Stifter*, Investigation of glass–fibre reinforced polymers by polarisation-sensitive, ultra-high resolution optical coherence tomography: Internal structures, defects and stress, Composites Science and Technology, **vol. 67**, 2007, pp. 3051–3058.

[15] *M. Blacklock, H. Bale, M. Begley, B. Cox*, Generating virtual textile composite specimens using statistical data from micro-computed tomography:1D tow representations for the Binary Model, Journal of the Mechanics and Physics of Solids, **vol. 60**, 2012, pp. 451–470.

[16] *Z.W. Hua, F. De Carlo*, Noninvasive three-dimensional visualization of defects and crack propagation in layered foam structures by phase-contrast microimaging, Scripta Materialia, **vol. 59**, 2008, pp. 1127–1130.
[17] *N., Iliescu, C., Atanasiu,* Metode tensometrice in inginerie (Methods for stress determination in engineering), AGIR Publishing House, Bucharest, 2006 (in Romanian).