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The Use of Computed Tomography and Ultrasonic Imaging for Assessment of Defects in Plates Made of a Polyesteric Resin

Daniela Ioana TUDOR, Stefan Dan PASTRAMA, Anton HADAR

University Politehnica
Department of Strength of Materials
Faculty of Engineering and Management of Technological Systems
Splaiul Independentei 313, Sector 6, 060042, Bucharest, Romania
e-mail: stefan.pastrama@upb.ro

The paper presents an experimental assessment of defects in a layered plate made of a polyesteric resin (plastic material). Two non-destructive methods were used: X-ray computed tomography and ultrasonic imaging. The main purpose of this work was to establish the position, shape and size of the defects that appeared during the manufacturing process. A three – dimensional model was obtained from the X-ray tomography using specific software for data processing. The model was used in order 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. Some considerations on the efficiency of the two used experimental methods are also presented.

Key words: X-ray computed tomography, ultrasonic imaging, finite element method, defects.

1. Introduction

Nowadays, polyesters (plastic materials) tend to replace classic materials in many fields, either due to functional or to economic reasons. In order to produce high performance structures made of plastic materials, it is very important to manufacture them without defects that could affect the behavior in service, otherwise the quality conditions may not be fulfilled. A quantitative evaluation of the possible defects that may appear during the manufacturing process or in service should be performed periodically. Usually, such a check is done by non-destructive methods. *The non-destructive control* represents a type of control in which dismantling or destruction of the structure is not necessary. Nowadays, it plays a very important role in the structural integrity assessment of industrial parts or assemblies, mainly due to the possibility of detection and measurement of defects. Periodic control avoids premature failure of components with bad or even catastrophic consequences, emphasizing the state of integrity of structures both during the manufacturing process and in service. A very important feature of such methods is the possibility of obtaining information regarding the existence, dimensions and shape of defects. This can be used as input data in numerical calculations regarding the structural integrity or lifetime in service of a component.

Non-destructive methods based on ultrasound properties have seen a spectacular development in the last years. *Ultrasonic imaging* is a non-invasive technique based on the principles of spectral analysis, allowing the user to capture images that can emphasize microstructural details at a scale comparable with the one of metallographic analysis [1, 2]. Ultrasounds propagate on large distances in metallic materials, reflect and/or refract at the interface between two environments with different acoustic impedance. The propagation speed depends on the mass density and Young's modulus of the propagation environment. The most important property of ultrasounds is reflection at the interface of two environments, and in particular, on the surface of a defect. Ultrasound examination is used nowadays for metallic components as laminated semi products, plates, metal sheets, rails, casted, forged or welded products, pipes, tanks, etc. It is used also for measurements of thickness in parts that are accessible only on one side.

The X-ray computed tomography is a non-destructive technique that uses X-rays to obtain 2D images taken around an axis of rotation and digital processing to generate a 3D image of the inside of an object from the 2D images. The 3D reconstruction of the structure can be converted into input data for subsequent numerical analyses using proper software [3].

Several researchers have used these non-destructive methods to assess the structural integrity of machine parts and especially to investigate the initiation and development of cracks.

The automatic detection of internal defects in composite materials using non-destructive techniques is described in [4]. The authors propose two steps for interpreting ultrasonic data: the pre-processing technique necessary to normalize the signals of composite structures with different thicknesses and the classification techniques used to compare the ultrasonic signals and detect classes of similar points. The efficiency of the ultrasonic technique was evaluated by Garnier *et al.* [5], in the case of detection of in site defects resulting from impact or in-service damages in complex aeronautical structures such as wings or rods. The authors evaluated also two other techniques (InfraRed Thermography and Speckle Shearing Interferometry) in order to find the most suitable one from the point of view of precision and quickness and reported that ultrasonic testing enables the depth of a defect to be determined while the other two techniques offered a shorter detection time. For improved detection of defects in plastic pipes, and especially when such flaws are close to the interfaces, a new approach in ultrasonic inspection, based on a combined application of non-linear deconvolution and the Hilbert–Huang transform was proposed by Kazys *et al.* [6]. Pau *et al.* [7], proposed a technique, based on the analysis of the reflection of high frequency ultrasonic waves from the wheel-rail interface, which was used to obtain graphic maps used to determine the shape of the contact area, to measure its size, and also to collect qualitative information about the distribution of the wheel-rail contact pressure.

Microtomography was used in order to evaluate the evolution of cracks in structures made of aluminum alloys casted under pressure [8, 9]. The obtained experimental information was further processed to obtain numerical models aiming at characterizing the initiation of cracks starting from the voids. Scott *et al.* [10], used High Resolution Synchrotron Radiation Computed Tomography to detect fiber damage progression in a carbon-epoxy notched laminate loaded to failure. Sharma *et al.* obtained effective tensile moduli of 3D carbon/carbon composites using image-based finite element simulations and experiments [11]. The non-destructive evaluations were conducted using X-ray tomography in order to explore cracks, voids, and fiber bundles distortion and to reconstruct 3D finite element meshes containing most of these defects. Investigation of defects in fiber-reinforced polymers, textile composites or layered foams using X-ray tomography were described also by other researchers [12–14].

The techniques of ultrasonic imaging and X-ray computed tomography were compared and evaluated to investigate artificial defects made using very small drill bits in aluminum castings [15]. The authors showed that defects smaller than 0.3 mm could not be detected by ultrasonic tests, but could be emphasized using X-ray tomography, without obtaining precise dimensions.

When non-destructive testing is to be used, it is very important to properly establish the most adequate method. The choice is based on several factors, as: type of material, presumed dimensions of the investigated structures, type of defects (surface or embedded), costs, etc.

This paper presents the non-destructive evaluation of a layered plate made of polyesteric resin. Both X-ray computed tomography and ultrasonic imaging were employed in order to establish the position, shape and size of the defects that appeared during manufacturing of the plate. A numerical model was obtained further to the experimental investigations and proper processing of the collected data. The model is presented as an example of how 3D models obtained using non-destructive techniques can be 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.

2. Experimental work

2.1. The specimen

The analyzed plate was obtained by successive casting of two layers of polyesteric resin and has a rectangular shape (Fig. 1). Each layer has a thickness of 1.3 mm. The purpose of the non-destructive evaluation was to detect possible casting defects at the interface between the layers (lack of adherence, voids, etc.) and to obtain a 3D model of the flawed plate in order to evaluate the mechanical influence of defects using the finite element method.

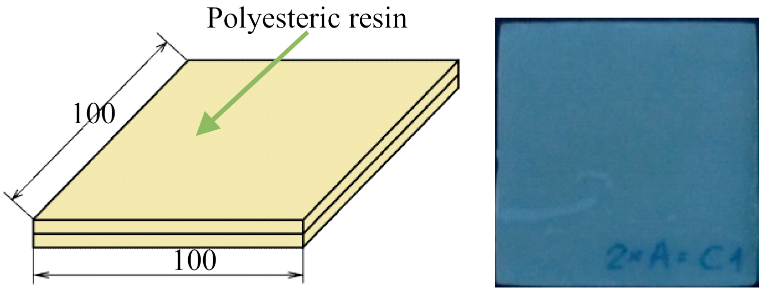

Fig. 1. The specimen.

Two non-destructive methods were used for the assessment of defects, namely X-ray computed tomography and ultrasonic imaging. The use of two procedures was justified on one side by the possibility of validation of some results by comparison between the data yielded from each method and, on the other side, by the limitations of each method. Information obtained from each method can lead to a more precise image of the shape, dimensions and location of the detected defects [16].

2.2. Experimental investigations using X-ray computed tomography

X-ray computed tomography is based on the measurement of the degree of attenuation of the electromagnetic radiation that travels through the examined object and reconstruction of the 3D image of the object using the 2D projections of the cross sections. Through this non-destructive method, one can get important information regarding the materials of the investigated structures and the interior shape, and, last but not least, a 3D reconstruction of the analyzed object can be obtained.

The studied specimen was investigated using a helical CT scan (Fig. 2). High quality images can be very quickly achieved due to the state-of-the art detector technology. The typical CT image is composed of 512 rows, each of 512 pixels.

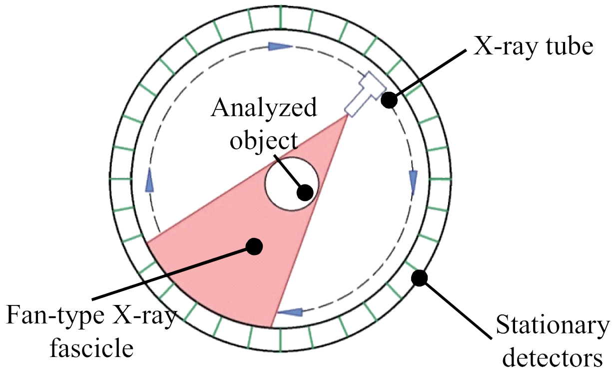

Fig. 2. Working principle of the CT scan.

Results of the scanning procedure were processed using the software eFilm Workstation (trial version) [17], an application used for viewing and manipulating medical images, that works in two consecutive stages: i) the presence, shape, position and dimensions of discontinuities were established first and ii) segmentation of planes was then realized having as final result the 3D reconstruction of the plate.

In the first stage, results were processed using the following steps:

- The 2D sections obtained using X-ray scanning were analyzed and the section with the maximum size of a found defect was chosen;
- Two planes of interest were defined for this section: a horizontal (frontal) and a vertical (sagittal) plane;
- Using the dedicated software and the defined planes, the chosen section is reconstructed in each plane
- In the frontal plane, one can emphasize: the shape of the defect, the overall dimensions of the plate, the dimensions of the defect and the position of the defect in this plane.
- In the sagittal plane, the thickness of the specimen and the depth of the defect are put in evidence.

A series of tomographic images were achieved for the studied plate, emphasizing several defects. The main one was a lack of adherence between the layers with a maximum length $L_{\max} = 37$ mm, a maximum width $W_{\max} = 5$ mm and a maximum depth $h_{\max} = 1.1$ mm. Other defects with smaller dimensions could be observed on the tomographic images (Fig. 3).

The second stage is dedicated to the processing of the 2D slices in order to reconstruct the 3D image of the specimen. This model was further used in the numerical simulations in order to establish the influence of defects on the in-service behavior of the structure. Here, the following steps were undertaken:

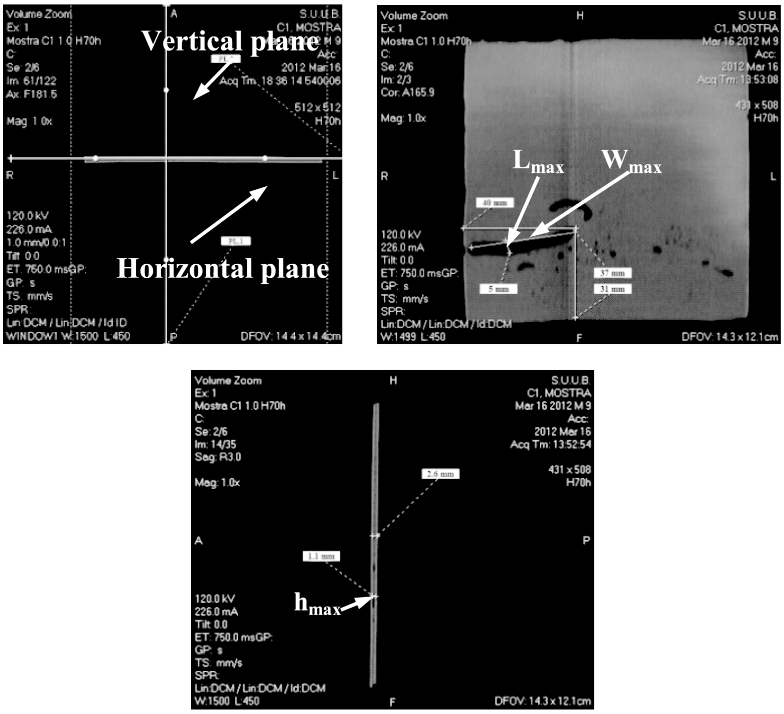

FIG. 3. Processing of the tomographic images.

- Calibration of the 2D images obtained following the X-ray scan;
- Definition of objects through the attenuation coefficient;
- Definition of regions of interest;
- Auto segmentation of the surfaces, based on the differences between the mass densities (shades of grey from the images);
- Reconstruction of the 3D volume using segmented surfaces.

The reconstructed object is shown in Fig. 4.

FIG. 4. The reconstructed volume.

2.3. Experimental investigations using ultrasonic imaging

The second step of this research is the analysis of the studied plate using ultrasonic imaging. For this purpose, an equipment Nuclear MicroSonic-01 was used. The experimental set-up, shown in Fig. 5, is a complex equipment for automatic ultrasonic examination of rectangular or cylindrical samples in order to detect and characterize flaws in the analyzed structure [18]. The equipment allows ultrasonic examination with different incidence angles, both using longitudinal and transversal waves. The area under examination is automatically scanned with a high resolution ultrasonic fascicle, using mechanical devices for displacement and a data acquisition system for amplitude and flight time data, measured on the echo signals, synchronous with the scanning of the investigated domain. The obtained data, saved in amplitude and time of flight files depending on the used coordinates (circumferential or radial) allow construction of C-scan or B-scan ultrasonic images of the scanned area. From the pair of C-scan representation in amplitude and time of flight corresponding to each incident angle, a B-scan representation depth of defect – radial position can be achieved for a section through the sample. Such images are extremely useful since they contain all information regarding the found defects: shape, dimensions and orientation.

Fig. 5. The experimental set-up for ultrasonic imaging.

The considered plate was analyzed by ultrasonic imaging in the following conditions: immersion in demineralized water through automatic scanning of bottom echo and defect echo. A flaw detector USIP12-Krautkramer type A312 with the nominal frequency of 10MHz was used. The ultrasonic images of the detected defects are presented as amplitude image (Fig. 6) and time of flight image (Fig. 7).

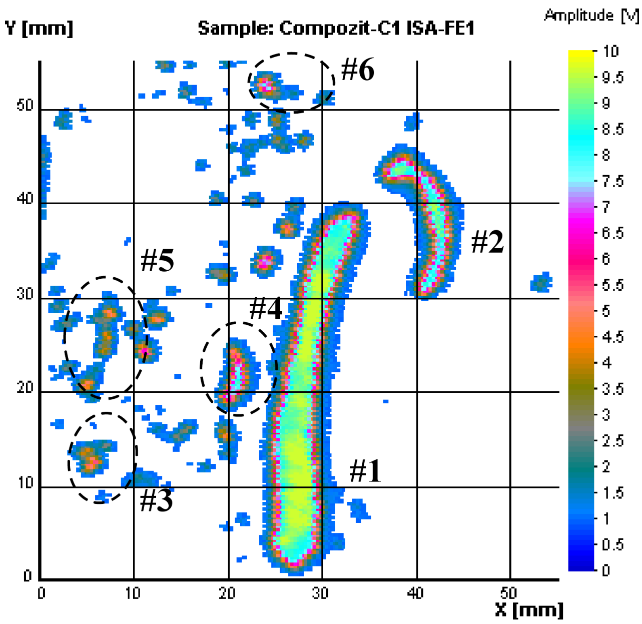

FIG. 6. Ultrasonic image in amplitude.

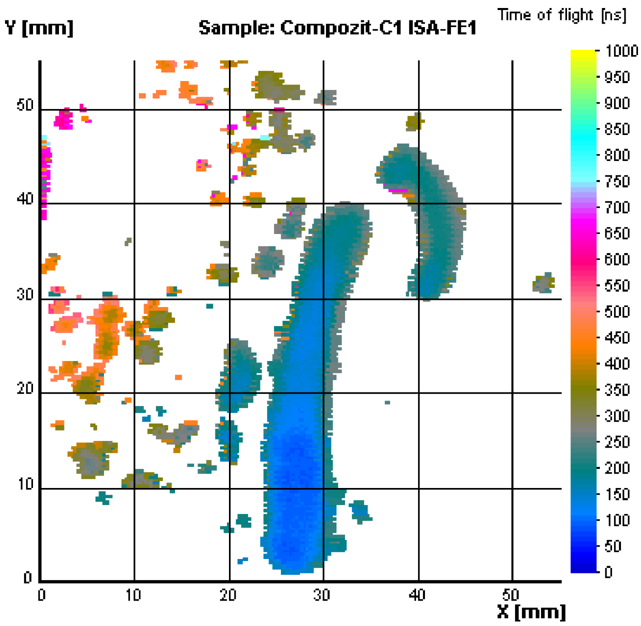

FIG. 7. Ultrasonic image in time of flight.

The image in amplitude was used to measure the position and dimensions of defects while the image in time of flight was used to obtain the depth of defects.

In this way, a characterization of all defects in the plate was achieved in terms of position and dimensions. The results for the six defects emphasized in Fig. 6 are presented in Table 1.

Table 1. Position and dimensions of defects.

No.	Position		Dimensions		
	X-coordinate [mm]	Y-coordinate [mm]	Length on X [mm]	Length on Y [mm]	Depth [mm]
1	24.6–33.6	1.7–39.0	9.0	37.3	1.2–1.5
2	36.6–43.5	30.6–45.1	6.9	14.5	1.3–1.5
3	19.2–22.2	18.8–24.5	3.0	5.7	1.3–1.4
4	23.1–24.9	33.1–34.9	1.8	1.8	1.4–1.5
5	6.0–8.4	24.0–29.1	2.4	5.1	1.6–1.8
6	23.1–25.2	51.5–53.3	21	1.8	1.4–1.6

Analyzing the dimensions of the most important defect (No. 1) on can see that its span on the OY axis, found using ultrasonic imaging (37.3 mm) is very close to the length determined by X-ray computed tomography (37 mm). Also, dimensions and position of other defects, with smaller importance were obtained.

3. Numerical results

The 3D reconstruction of the studied plate using X-ray tomography was used further in order to obtain a numerical model, analyzed with the finite element method [16]. The two biggest defects (No. 1 and No. 2) were taken into account and inserted in the 3D model (Fig. 8). Also, a calibration model (without defects) was analyzed in order to compare the stresses in order to assess the influence of the considered defects on the mechanical behavior of the plate.

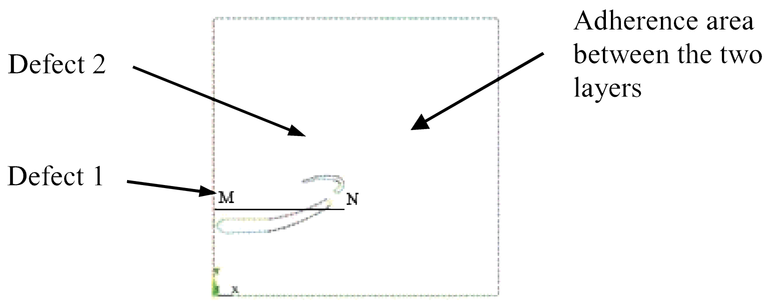

Fig. 8. The 3D model obtained from reconstruction.

Before the numerical analysis, a traction test was performed in order to establish the stress-strain curve of the considered plastic material. A universal INSTRON 8801 testing machine was used for testing nine specimens with rectangular cross section at room temperature and with a rate of 0.1 mm/min. The results were averaged, resulting the stress-strain curve from Fig. 9. Although in the studied literature referring to the CT-scans of samples made of or containing polymers [10–14] it was not found any mention to the possible modifications of the mechanical characteristics due to X-ray exposure, the authors verified this hypothesis. For this, after the CT-scan tests, specimens made of the material of the scanned plate were manufactured and tested in traction. Differences from the stress-strain curve of the material between the non-exposed and exposed specimens were insignificant, showing thus that the influence of the X-ray exposure on the mechanical characteristics of the used material is negligible.

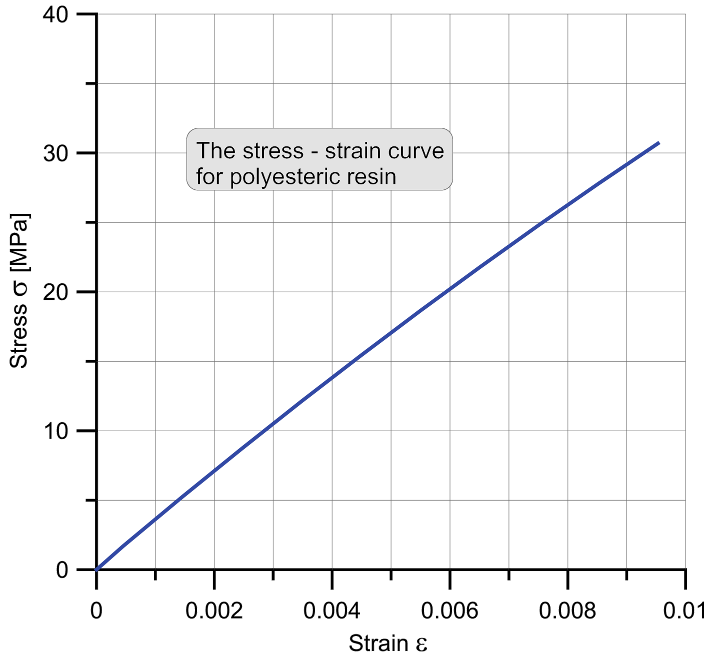

FIG. 9. The average stress-strain curve of the polyesteric resin.

A Young's modulus of 3482.2 MPa was obtained by drawing the tangent to the curve in origin. Since a small non-linearity can be observed on the curve, data obtained from the tensile test were inserted in the input file of the finite element study in order to perform a non-linear analysis. A common loading case was considered for the layered plate: bending load through a uniformly distributed force for the plate simply supported on the edges. For this loading case, both the flawed and the calibration plate were analyzed using a model with eight nodded isoparametric solid elements. Both plates contained the same number of nodes and elements, the difference in the two meshes being only the fact that, for the plate with defects, the nodes were decoupled in the area of discontinuities in order to simulate two independent surfaces and to model thus the lack of adherence between the layers. The finite element model is shown in Fig. 10.

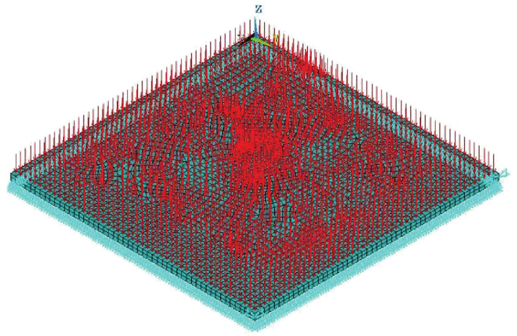

Fig. 10. The finite element model.

The most interesting results in terms of stresses are those for the middle section that is at the bonded surfaces of the two plates, where the defects were discovered at the non-destructive tests. The map of the von Mises equivalent stress in the middle section is presented in Fig. 11 for both the flawed and calibration plate. It should be mentioned that the contour maps are presented with values of the stress in non-dimensional form σ_{eq}/p_0 where p_0 is the applied uniform pressure, whose absolute value was chosen as to yield stresses lower than the 0.2 offset yield limit found from the stress-strain curve.

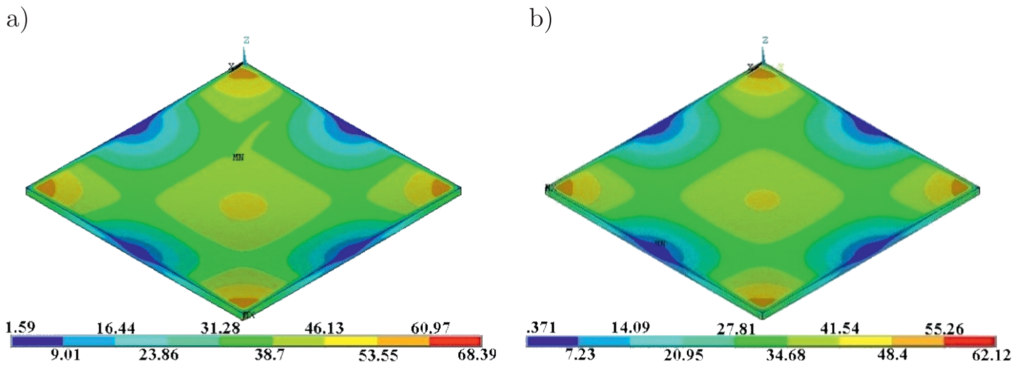

Fig. 11. Contour map of the non-dimensional von Mises equivalent stress: a) flawed plate, b) calibration plate.

A comparative graph of variation of the non-dimensional equivalent von Mises stress σ_{eq}/p_0 in the middle section, on a line passing through the most important defect (line MN in Fig. 8) is presented in Fig. 12. The variation is plotted as a function of the non-dimensional length x/L where x is the distance from point M on the line MN and L is the total length of the plate.

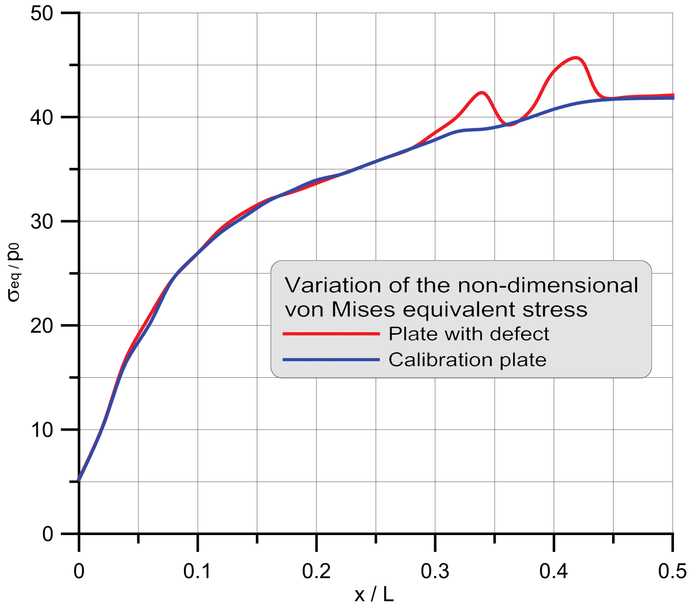

Fig. 12. Comparative variation of the von Mises equivalent stress in the middle section on line MN.

Analysis of the obtained results revealed that the discovered defects produced an increase of the maximum stress in the plate with about 10% but the defect is not dangerous in the sense that the increase does not affect the carrying capacity of the structure. Also, the plot from Fig. 12 shows that in the area of defect, the stresses in the flawed plate are about 10% bigger than those in the calibration plate. This difference appears for the non-dimensional length x/L between 0.3 ... 0.45 this means where the line MN intersects the defect. Such stress concentration is small and, consequently, the growth of the flaw is unlikely to appear.

4. Conclusions

The present paper describes an experimental evaluation of the manufacturing defects in a casted two-layer plate made of a polyesteric resin. Two non-destructive methods were used: X-ray computed tomography and ultrasonic imaging. Thus, the presence, shape and position of macro defects in the analyzed structure were established.

The first method allowed for a 3D reconstruction of the plate and detection of some defects (lack of adherence between the layers). Also, the dimensions of the bigger defects were obtained. The exact characterization of defects using this method is not easy, but a good approximation of their position and dimensions is achieved. The most important advantage of the X-ray computed tomography is the possibility of 3D reconstruction of the studied structures, with all important defects that appear during manufacturing or in service.

Using the ultrasonic imaging, position and dimensions of the most important but also of other smaller defects were emphasized with greater precision. The main dimension of the bigger defect was found in the ultrasonic amplitude image with a difference of less than 0.1% compared to the dimension found with computed tomography. Thus, the 3D model obtained through X-ray tomography can be corrected.

In the paper, an example of use of the reconstructed volume through X-ray tomography in a numerical analysis is also presented. The corrected reconstructed 3D volume of the specimen with the major defects taken into account was used in a non-linear finite element analysis that is an example of how such experimental results may be further used to predict the possible influences of the discovered defects on the carrying capacity of the analyzed structure.

Finally, it should be emphasized that, for a correct prediction of the in service behavior and of the carrying capacity of a structure, the periodic non-destructive evaluation is very important. In this way, defects that may appear in the manufacturing process or in service can be detected. Also, the use of X-ray computed tomography enables the possibility of reconstruction of the volume which can be further used as input data in a numerical analysis that can give a picture of the influence of the defects on the behavior of the structure. Thus, the engineer may take the decision to repair the structure or to continue to use it without the possibility of failure.

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