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COMPOSITES THEORY AND PRACTICE

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STATIC COMPRESSION OF GFRP PLATE WITH HOLE - 3D SCANNING COMPARATIVE EVALUATION

A wide range of non-contact measurement methods is used in many fields of industry. 3D scanning technology is one of the modern techniques of geometry registration for reverse engineering, inspection or structure deformation analysis. The aim of the study is a comparative evaluation of square composites plates with holes under compression loading. The evaluation was performed on the basis of results from hand-held 3D laser scanner measurements. An essential element of the presented evaluation is analysis of the wall thickness of the plates. The range of this paper covers: presentation of 3D laser scanning measurement methodology, experimental tests and 3D scanning comparative evaluation of the specimens. The geometry of the composite plates with two kinds of holes: elliptical and cylindrical are compared. Higher values of wall thickness deformations for the plates with the elliptical holes were observed.

Keywords: 3D laser measuring scanners, composite plates with holes, static compression, deformations, failure

ŚCISKANIE STATYCZNE PŁYTY Z OTWOREM - OCENA PORÓWNAWCZA Z UŻYCIEM SKANINGU 3D

Szeroki zakres bezkontaktowych metod pomiarowych jest używany w wielu dziedzinach przemysłu. Technologia skaningu 3D jest jedną z nowoczesnych technik rejestracji geometrii do celów inżynierii odwrotnej, inspekcji lub też analizy deformacji struktury. Celem prezentowanej pracy jest analiza porównawcza kwadratowych płyt kompozytowych z otworami, poddanym obciążeniom ściskającym. Ocena została dokonana na podstawie wyników pomiarów wykonanych przenośnym skanerem laserowym 3D. Zasadniczym elementem analizy jest porównanie zmiany grubości uśrednionych modeli płyt. Zakres pracy obejmuje: przedstawienie technologii pomiarów skanerem laserowym 3D, testy eksperymentalne i analizę porównawczą próbek w oparciu o skanowanie 3D. Porównano płyty kompozytowe z dwoma typami kształtów otworów: cylindrycznymi i eliptycznymi. Zaobserwowano wyższe wartości deformacji w kierunku *z* dla płyt z otworami eliptycznymi.

Słowa kluczowe: laserowe skanery pomiarowe 3D, płyty kompozytowe z otworami, statyczne ściskanie, deformacje, zniszczenie

INTRODUCTION

Nowadays, laminated composite structures are frequently used in many fields of industry. Due to their properties (e.g. high stiffness, wear resistance, strength-to-weight ratios etc.), composite plates are widely used among others in mechanical, civil and aerospace engineering applications. Especially glass reinforced composites have become more popular in civil applications (e.g. parts of composite covers for ice sledges) because of their price. Additionally, composite plates often have cut-outs of different shapes due to practical engineering requirements, for example in mechanical joints. However, holes in composite plates drastically reduce the mechanical properties of the laminate. Therefore, composite plates with holes are more widely analyzed by researchers, especially their buckling behaviour and optimization [1-4]. The heterogeneous properties of composite materials and the wide range of their reinforcements and matrices are the reasons that experimental tests play a significant role in the analysis of composite structures. Although, analytical and numerical models are useful guides for the experiment planning, nevertheless, these calculations might omit important elements of the structure behavior. On the one hand, experimental tests play a significant validation role of the numerical calculations. On the other hand, particularly in the engineering applications of thin walled structures, experiments enable observation of the combined effects of all the imperfections that affect the results [5]. One of the popular approaches to composite experimental tests is structure deformation registration using strain gauges, extensometers and other systems of deformation measuring techniques. Additionally, in the compression experimental tests of thin walled structures, especially those prone to buckling failure in real conditions, optical measurement techniques are often used to observe buckling behavior, such as an automated laser scanning system [6].

Currently, the development of measurement solutions which can be used in laboratory testing as well as in commercial applications can be observed. An example of the rapid development of the technology is the 3D optical scanning method [7]. The broad spectrum of technical solutions of structural light and laser scanners gives new possibilities for a variety of applications (deformation analysis, data acquisition, rapid prototyping, reverse engineering, quality inspections) [8, 9]. Hand-held laser scanners give the opportunity to register the shape of the structure changes without contact. There are several advantages which have led to the more common use of 3D laser scanning technology, such as the possibility to obtain high density acquisition in a single scan, non-contact measurement, self-positioning on the target location etc. [9]. The number, kind and shape of light sources (from single point to many lines) have an influence on the parameters of the 3D scanning measurement, e.g. data acquisition speed, spatial resolution and accuracy [10, 11].

In the present paper, the possibility to observe the deformations of composite plates with different cut-outs is investigated.

3D LASER SCANNING MEASUREMENT METHODOLOGY

Changes in the composite plate shape can be registered by optical measurements in order to observe structure deformations defined as changes in the shape of the analyzed structure under loading. Structure surfaces are registered in the form of measurement points by devices such a hand-held 3D laser scanner. In contrast to 3D structural light scanners, 3D laser scanners require positioning markers. The base of the positioning targets allows for the registration of all the points in form of "measurement point clouds" in one coordinate system. On the basis of this shape registration, the virtual model of the structure is created. However, registration of the points causes irregularities in 3D data scans, which make the use of additional software dedicated for data processing necessary. The set of measurement points is registered in the form of range image $z = f(x,y)$, where z is the object depth for a location with (x,y) coordinates in the sensor image plane. Parameter z is specified according to the triangulation rule [10]. The data from the 3D scanning measurement are independent of the complex shapes of the measured structures. Simplifications of scanning data processing algorithms have been developed in several studies [11].

In the present analysis, the 3D scanning measurements were performed using a hand-held 3D laser scanner REVscan manufactured by the Creaform company [11]. The correct 3D laser scanning procedure covered several stages: sensor calibration, preparation of the scanned structure, implementing the scanning process, cleaning noise data and redundant measurement points, model translation to STL format, and data analysis [11].

There are two ways of placing the positioning targets, shown in Figure 1. In the most popular method positioning targets are placed on the structure. The second technique, called "black box", relies on sticking the positioning targets in the area of the measured structure. It enables registration of the 3D shape of plates without any contact. In the present paper, the "black box" technique is used for placing positioning targets. The model in form of an editable polygon mesh (facet mesh) is helpful to determine the thickness, compare the shape, obtain the deformation or inspect the quality.

a) b)

Fig. 1. Placing positioning target: a) on structure, b) "black box"

Rys. 1. Umiejscowienie bazy znaczników: a) na powierzchni struktury, b) „black box"

MATERIALS AND METHODS

The research examined composite plates with holes under compression loading. The investigated structures are composed of 8 layers of plain woven 0/90 glass fabric and manufactured by means of the vacuum bag method. The nominal geometries of the specimens are shown in Figure 2.

a) b)

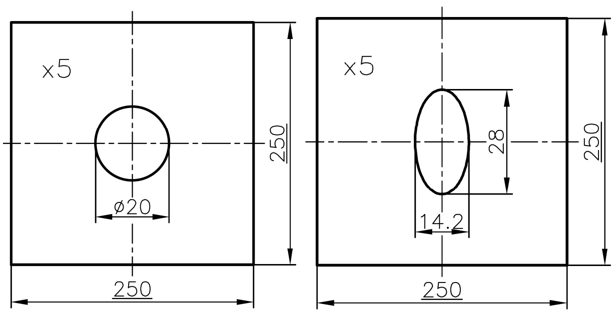

Fig. 2. Geometries of plates with holes: a) circular, b) elliptical

Rys. 2. Geometrie płyt z otworami: a) okrągłymi, b) eliptycznymi

The material properties of the considered composite structure are given in Table 1. The cut-out shapes were obtained using a milling machine with numerical control after the manufacturing process. Although 10 specimens of each type of geometry were prepared, only the composite plates with the highest quality were tested.

TABLE 1. **Mechanical properties of composite plates [12]**
TABELA 1. **Właściwości materiałowe płyt kompozytowych [12]**

Young's modulus	Young's modulus	Shear modulus	Poisson's ratio	Density	Minimum thickness of layer
E_1 [GPa]	E_2 [GPa]	G_{12} [GPa]	ν_{12}	ρ [g/cm^3]	[mm]
38.6	8.27	4.14	0.26	1.8	0.125

Composite plates with different shapes of holes were measured after proper preparation with the use of the 3D laser scanner in order to receive the virtual models. Next, selected specimens with compatible dimensions (Fig. 3a) were placed in a special holder (Fig. 3b) in order to achieve uniform distribution of loading.

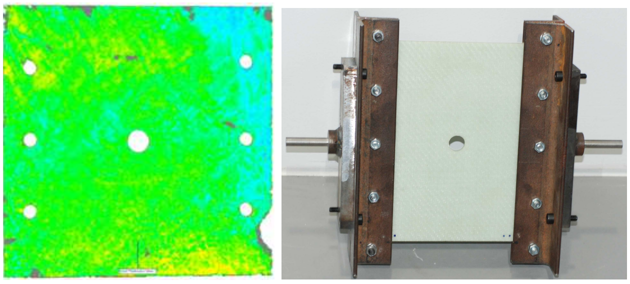

Fig. 3. Composite plate with hole: a) wall thickness distribution, b) encased in special holder

Rys. 3. Płyta kompozytowa z otworem: a) rozkład grubości, b) w specjalnym uchwycie

The compression strength test was performed with the use of a universal testing machine (MTS Landmark). Rectangular composite plates with cut-outs were placed between the top and bottom base in the universal testing machine (Fig. 4). The crosshead speed was 1 mm/min. Additionally, in order to register the structure buckling mode values, the displacement sensor was placed perpendicular to the middle of the structure in the vicinity of the hole.

Fig. 4. Experimental testing stand for plates with holes

Rys. 4. Stanowisko do badań płyt z otworami

The geometry and failure modes of the tested composite specimens with different cut-outs are presented in Figure 5.

a) before failure b) after failure c) before failure d) after failure

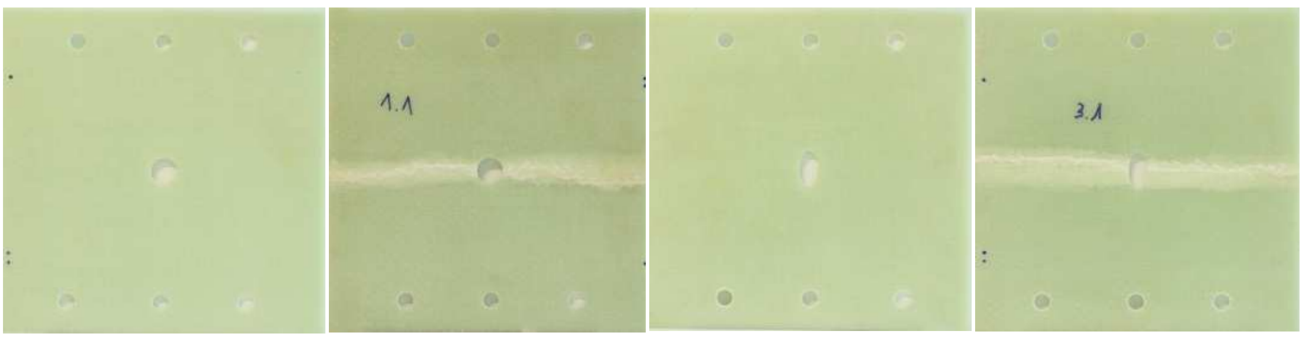

Fig. 5. Composite specimens before and after failure with: a, b) circular holes, c, d) elliptical holes

Rys. 5. Płyty kompozytowe przed i po zniszczeniu z otworami: a, b) okrągłymi, c, d) eliptycznymi

Figure 6 presents the compression behavior of the selected composite plates with circular and elliptical holes. For each of the examined composite plates with cut-outs, the received force-displacement curves are characterized by stable growth at the beginning of the compression test. Until exceeding the yield point, the force increases in time in a stable manner with only slight differences. The load, which causes the force-displacement curves to deviate from linearity, determines the critical buckling load. Further compression of the composite structures causes the force to increase at a definitely slower pace. Critical stress causes a drastic decrease in the force and load carrying properties [13]. The achieved average critical loading for the composite plates with circular cut-outs was 103.6 kN, and for the specimens with elliptical holes it was 101.1 kN.

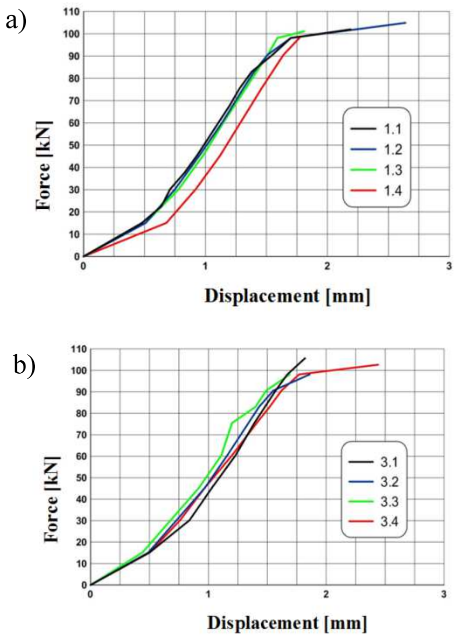

Fig. 6. Force-displacement curve of composite plates with cut-outs: a) circular, b) elliptical

Rys. 6. Wykres siła-przemieszczenie dla płyt kompozytowych z otworem: a) okrągłym, b) eliptycznym

The scanning measurements were done for the tested types of plates after failure. The 3D scan was prepared with a resolution of 0.7 mm. The used 3D scanning method allowed the processing of data point clouds with the accuracy determined by the user. The redundant points were removed and from the remaining ones the surface was created. Finally, the 3D scanning data were analyzed in Geomagic Qualify 2014 software [14].

After filling holes and performing noise reduction, the virtual models in the form of points and facets were obtained. Next, the virtual models were used to analyze the deformation of the loaded structure and to compare the structure with circular and elliptical holes. During the scanning measurements of failure specimens, models of the external surfaces of the plates were produced.

RESULTS

In the 3D comparing analysis the virtual models were created from 500 000 triangular facets each. The data after processing were redefined as the distance between the two external surfaces of the composite plates. The comparison of the average wall thickness of the plates with circular and elliptical holes is presented in Figure 7. One can observe higher values of the wall thickness in the central part of the specimens.

a) b)

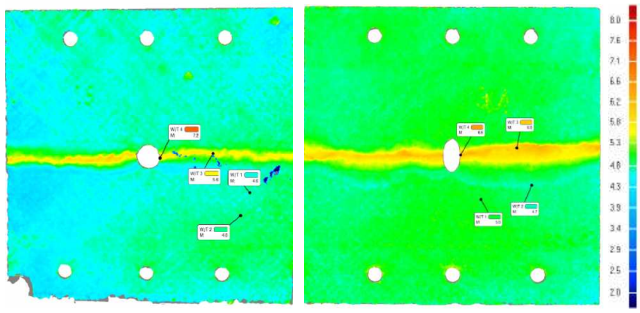

Fig. 7. Comparison of deformations as wall thickness of analyzed structures: a) with circular hole, b) with elliptical hole

Rys. 7. Porównanie deformacji analizowanych struktur: a) z otworem okrągłym, b) z otworem eliptycznym

The comparison of the wall thickness at selected points of the composite plates with different shaped cut-outs is presented in Table 2. Points 1 and 2 (denoted as *W/T1* and *W/T2*) are located in the undamaged area in contrast to points 3 and 4 (denoted as *W/T3* and *W/T)* which are within the damaged region in the middle of the laminate. It should also be noted that point 4 is situated in the neighborhood of the hole. These discrepancies result from the manufacturing process and damage caused by static loads.

TABLE 2. **Average values of wall thickness of composite plates at selected points [mm]**

TABELA 2. **Uśrednione wartości grubości płyt kompozytowych w wybranych punktach [mm]**

Cut-out shape	W/T1	W/T2	W/T3	W/T4
circular	4.6	4.8	5.6	7.2
elliptical	5.0	4.7	6.0	6.6

CONCLUSIONS

On the basis of the presented experimental test and 3D laser scanning measurements, it may be stated that: The virtual models registered by the 3D laser scanner can be useful in obtaining the structure thickness distribution. Moreover, 3D scanning measurements of composite plates with different type cut-outs after failure enabled comparison of the deformations. The manufacturing quality of the composite structures as well as the different shapes of holes in plates determine the behavior under compression.

Higher values of critical loads were obtained for the rectangular GFRP plates with the circular holes than for the same plates with the elliptical cut-outs.

In future works, determination of the influence of the shape and the area of the cut-outs in the composite plates on fatigue limits is planned. For this purpose, the measurement methodology presented herein will be used.

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