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Influence of Size of Open Hole on Stability of Compressed Plate Made of Carbon Fiber Reinforced Polymer

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ABSTRACT

This manuscript concerns the investigation of the influence of the open hole on stability of the compression plate made of carbon-epoxy composite. Experimental tests carried out on the real plate resulted in a postcritical path from which the critical load value was determined using appropriate approximation method. In parallel, an independent study was carried out based on a numerical analysis using the finite element method (FEM). Investigations were conducted in terms of a linear eigenproblem analysis, from which the value of the bifurcation load was determined for the FEM model of the plate. Its values resulting from the numerical analyses were validated against the experimental results, thus confirming the adequacy of the designed FEM model of the plate. The paper shows that the incremental increase of the hole in the plate monotonically influences the decrease in the critical load of the plate. The largest decrease was observed for the specimen with the largest hole analysed and was 13.5% compared to a plate without a hole. The newness of the paper is the application of interdisciplinary investigation methods to describe the influence of the open hole compression (OHC) on the stability of composite plates. ABAQUS® was used as the tool with which the numerical analyses were realised.

Keywords: critical load, buckling, CFRP, FEM.

INTRODUCTION

Fiber-reinforced polymer (FRP) composites, known for their high strength and light weight, have gained prominence among engineers in many industries [1]. In particular, materials of this type have found widespread use in thin-walled structures. Thin-walled elements, are the special type of load-bearing elements that exhibit high level strength and stiffness ratios relative to the weight. It is these properties that determine the application of such thin-walled elements as load-bearing structures in aerospace [2–4], space [5], automotive [6–8] or sport industries [9], where there are quite high requirements for structural behavior under compound loading conditions. A disadvantage of thin-walled load-bearing elements is that their components may be subject to loss of stability under certain loading conditions. For this reason, it is important not only to know the strength of such components, but also the stiffness that protects structures against early failure through loss of structural stability [10–12]. To describe the work of a structure in this way, it is necessary to know the critical load at which such a structure loses stability. This is a very important issue, since there are cases in which the critical load is treated as a limit load that causes the structure to failure [13, 14]. There are many papers in the literature on local buckling of thin-walled structures [15–17]. Numerical and experimental studies of the stability of columns with an complex section were the subject of articles [18, 19]. Many cases have been described in the literature where a thin-walled structure demonstrates the ability to carry a load after losing stability [20–23]. Therefore, it becomes important to study in the postcritical state up to the destruction of the construction, which concerned the description of limit loads on the structure [24–26].

For mounting purposes, it is necessary to drill holes in structural elements. These holes could work on the structure as stress-concentrating notches, which could lead to damage propagation and failure. Therefore, the existence of a hole in composite structures has become an object of study for many researchers [27]. Such scientific work can be divided into two groups of studies: OHC open hole compression and OHT open hole tension. The failure and damage of the OHT structure of carbon fibre-reinforced polymer composites is described in the papers [28, 29]. The papers [30–32] analysed the limit load and failure behaviour of the OHC structure obtained from both theoretical analysis and testing. Majority of OHC papers describe the failure of composite structures excluding the critical state. For this reason, the authors of this paper investigated the buckling state of the OHC of a thin-walled composite structure.

This paper investigates the influence of the size of the open circular hole on the stability of the plate element made of laminate. The study covered linear and nonlinear numerical study of the structure using the FEM (finite element method) and experimental verification. The newness of the paper is the application of interdisciplinary investigation methods (numerical analysis of linear and non-linear stability problem and approximation method for determining the critical load) to describe the influence of the open hole compression (OHC) on the stability of composite plates. It is interesting to note that numerical methods are now very often used for the analysis of real structures [33–39].

OBJECT OF THE RESEARCH

The object of the study was a thin plate with a open circular hole made of CFRP (carbon fiber reinforced polymer) [40, 41]. The mechanical and strength properties of the test material shown in Table 1. The plate was made of laminate, which was a stack of eight layers in a symmetrical position of the layers with respect to the composite's center plane with a total thickness of 1.048 mm (each individual layer had a thickness of 0.131 mm) [42, 43]. The arrangement of the composite layers was adopted from the literature [44]. It represented a popular laminate configuration in the form of: [0/90/0/90]s.

The analysed plate was characterised by overall dimensions: height: 140 mm, width: 20 mm and thickness: 1.048 mm – Fig. 1a. Open holes were drilled in the specimens to investigate their effect on buckling and critical load of the composite structure. Four specimens were prepared for testing and 3 of them were weakened with a hole – Fig. 1b–e. The hole sizes were characterized by varying diameters from Ø2 mm (Fig. 1c), Ø4 mm (Fig. 1d) and Ø8 mm (Fig. 1e).

METHODOLOGY

Two independent test methods were used to describe the critical state of an axially compressed thin-walled composite plate with an open oval hole. The purpose of the research was to study the influence of the circular hole made in plate on the critical load. The range of the manuscript covered conducting experimental tests on a real plate in which holes with Ø2 mm, Ø4 mm and Ø8 mm were made. The conducted experimental tests on the manufactured composite plate made it possible to observe real behaviour of the plate

Table 1. CFRP – mechanical and strength properties

Tensile strength	F_{TU}	0°	1867 MPa
		90°	26 MPa
Tensile modulus	E_1	0°	131.71 GPa
	E_2	90°	6.36 GPa
Poisson's ratio	n_{12}	0°	0.32
Shear strength	F_{SU}	±45°	100.15 MPa
Shear modulus	G_{12}	±45°	4.18 GPa
Compression strength	F_{CU}	0°	1531 MPa
		90°	214 MPa

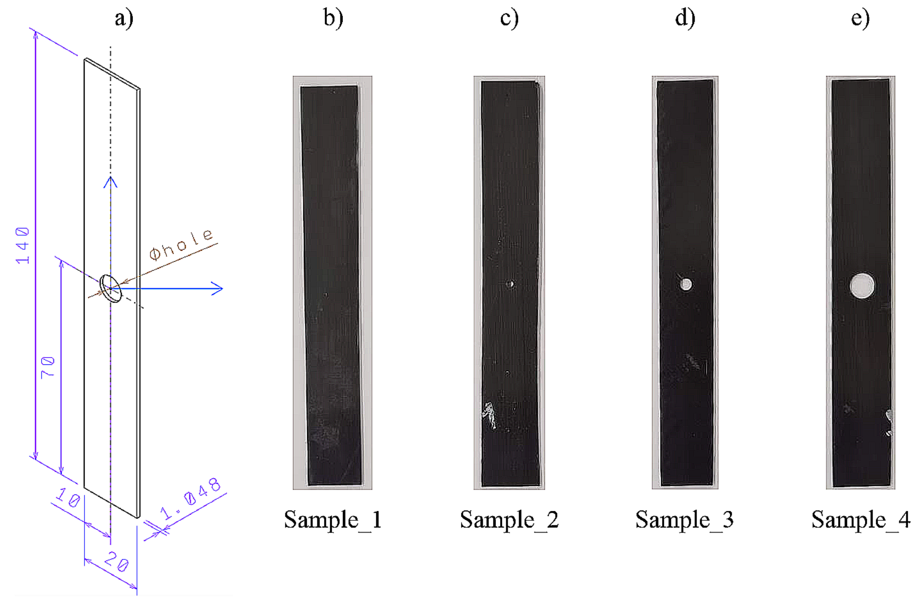


Fig. 1. Subject of the study: (a) CAD model with dimensions in mm, (b) plate, (c) plate - Ø2 mm hole, (d) plate - Ø4 mm hole, (e) plate - Ø8 mm hole

in the critical and weak-critical states. This approach made it possible to identify the buckling mode and, at the same time, to determine the critical load value. The second independent research method was numerical simulation using the FEM. The numerical analyses carried out were aimed at creating adequate experimentally verified FEM models. This approach enabled the stability issues of thin-walled composite structures to be modelled, adequately representing in particular the behaviour of a real OHC plate. Experimental testing of the compressed composite plate was carried out on the universal static machine with the constant crosshead displacement speed of 1 mm/min – Fig. 2a. The main view of the fixed plate on the test stand is shown in Fig. 2b.

To describe the critical and postcritical state of the plate, not only the load values were

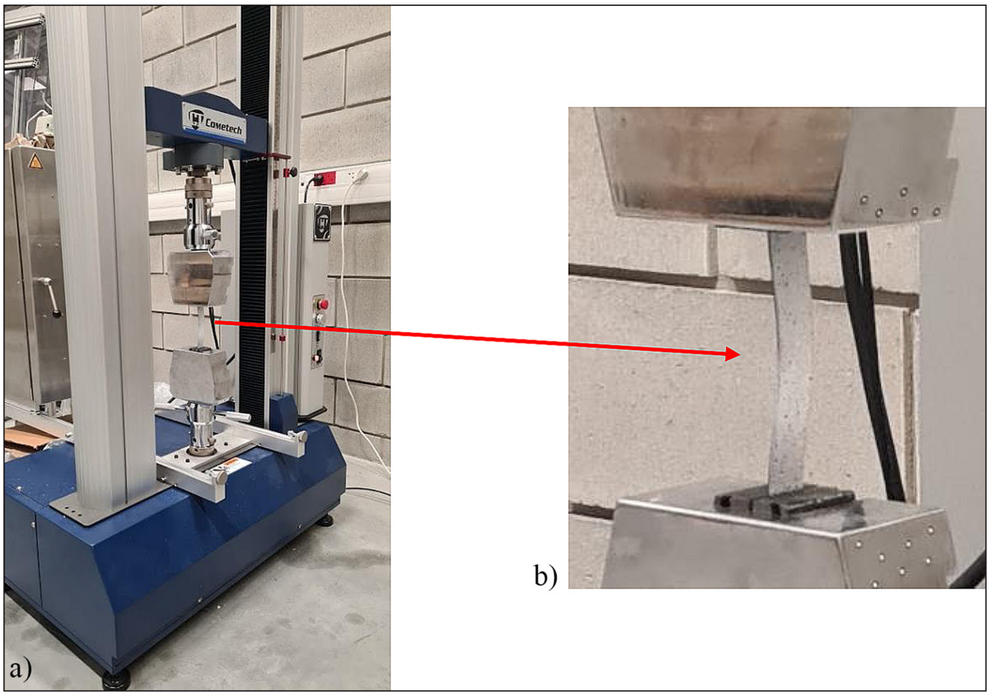


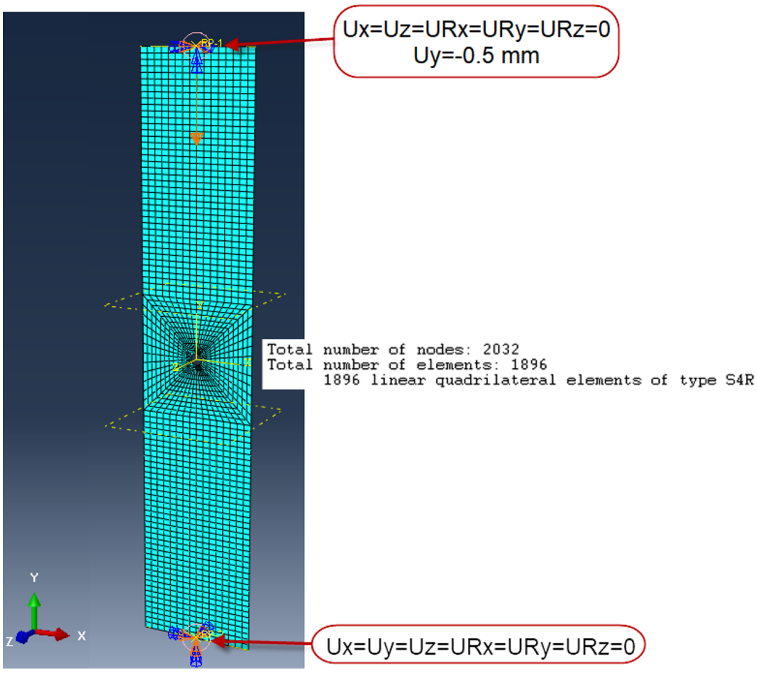
Fig. 2. Experimental stand: (a) test machine, (b) plate fixing

recorded, but also the displacements in the longitudinal direction of the plate. During measurements, the following were recorded: the test time, compressive load on specimen, and displacement of crosshead, i.e. shortening of a specimen. As a result, measurements were obtained from which the characteristics of the plate were determined, making it possible to assess the critical state. In order to investigate the effect of the hole on the stability of the compressed composite plate, it was necessary to determine the experimental critical load. To determine the experimental value of the critical load, a method known from the literature for approximation straight-lines intersection method was selected and used [45, 46]. This method makes it possible to approximate the critical load from the obtained load-displacement characteristics (sample shortening).

The numerical analysis was based on the finite element method in ABAQUS [47, 48]. The critical state of the plate was analysed using linear stability analysis, allowing the critical load of the compressed plate to be determined and corresponding to the first (lowest) mode of buckling [49]. The critical load corresponded to the bifurcation load, that is, it represented an idealized plate that had no inaccuracies. The numerical analysis was extended to the solution of a non-linear stability problem, where the calculations were performed on a model with an initial geometric imperfection that corresponds to the lowest buckling mode of the plate model. To discretize the plate, SHELL-type shell finite elements with 6 degrees of freedom at each node were used. This type of numerical element used for this was a 4-node shell element with reduced integration – S4R (Fig. 3). The composite was designed using the Layup-Ply modelling technique, with which the configuration of the laminate layers was modelled. Composite material properties were described by defining an orthotropic model of the material in a plane stress state - Table 1. Boundary conditions corresponded to realization of fixing the end surfaces of the composite plate in the grips of the testing machine. This was realized on the basis of reference points, which were linked to the end edges of the plate in such a way that all degrees of freedom were transferred to them. Boundary conditions of reference points were defined as presented in Figure 3. Loading of the model was realized by displacing the upper reference point by -0.5 mm opposite to the Y axis orientation – Fig. 3. The adopted method of defining boundary conditions and loading of model corresponded to conditions of experimental testing.

DISCUSSION OF RESULTS

The test data results allow a qualitative and quantitative analysis of the influence of the hole on the critical state of the compressed CFRP plate



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Total number of nodes: 2032
Total number of elements: 1896
    1896 linear quadrilateral elements of type S4R
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Fig. 3. FEM plate model

based on recorded test parameters. The identification of the critical state of the plate was carried out on the basis of the buckling mode obtained, which is the lowest mode of loss of stability, and the corresponding value of the bifurcation (critical) load [50]. The resulting lowest buckling mode of the tested hole composite plate was shown in Figure 4.

Qualitative analysis of results confirms the correspondence of numerically determined modes of buckling of the numerical model with the experimental deformation form of the plate - Fig. 4. The quantitative investigation of the numerical results makes it possible to determine the value of the bifurcation (critical) load corresponding to the obtained first mode of buckling of the CFRP plate with a hole.

Based on the experimental studies of displacements as the function of external load, approximate values of a critical load were determined for analysed variants of the plate with a hole. The process of determining an experimental value of critical force using the approximation straight-lines intersection method was presented in Figure 5. Microsoft Excel software was used in the approximation process and the determination of the coefficients $R^2>0.9$. The determined experimental value of the critical load formed the basis for verifying the results of numerical analysis [51]. The relative error was calculated using the formula:

$$\delta = \frac{|\mathrm{FEM} - \mathrm{EXP}|}{\mathrm{FEM}} \cdot 100\% \tag{1}$$

Table 2 summarizes the experimental (EXP) and numerical (FEM) critical load values of the tested plates with a hole. The smallest relative error of the results was obtained for sample 3 and was 7.2%, while the largest for sample 2 (8.3%). The determined results all show a quantitative agreement between the critical load values of the numerical calculations and the experimental values.

The next stage of the research was to analyse the influence of the open hole on the stability of the compressed composite plates. For this purpose, the determined critical loads for all cases were compared with each other and presented graphically in Figure 6. Plates weakened with a hole sample 2, sample 3 and sample 4 were compared with a plate without a hole – sample 1. The conducted tests show that increasing the diameter of the open hole monotonically decreases the critical load of the plate. Maximum decrease in critical load occurred for a plate with an 8mm diameter hole was 13.5% (experimental tests) compared to a plate without a hole. In the final step, the FEM model was experimentally verified in the nonlinear state [52, 53]. Nonlinear load-shortening characteristics were determined, allowing to determine

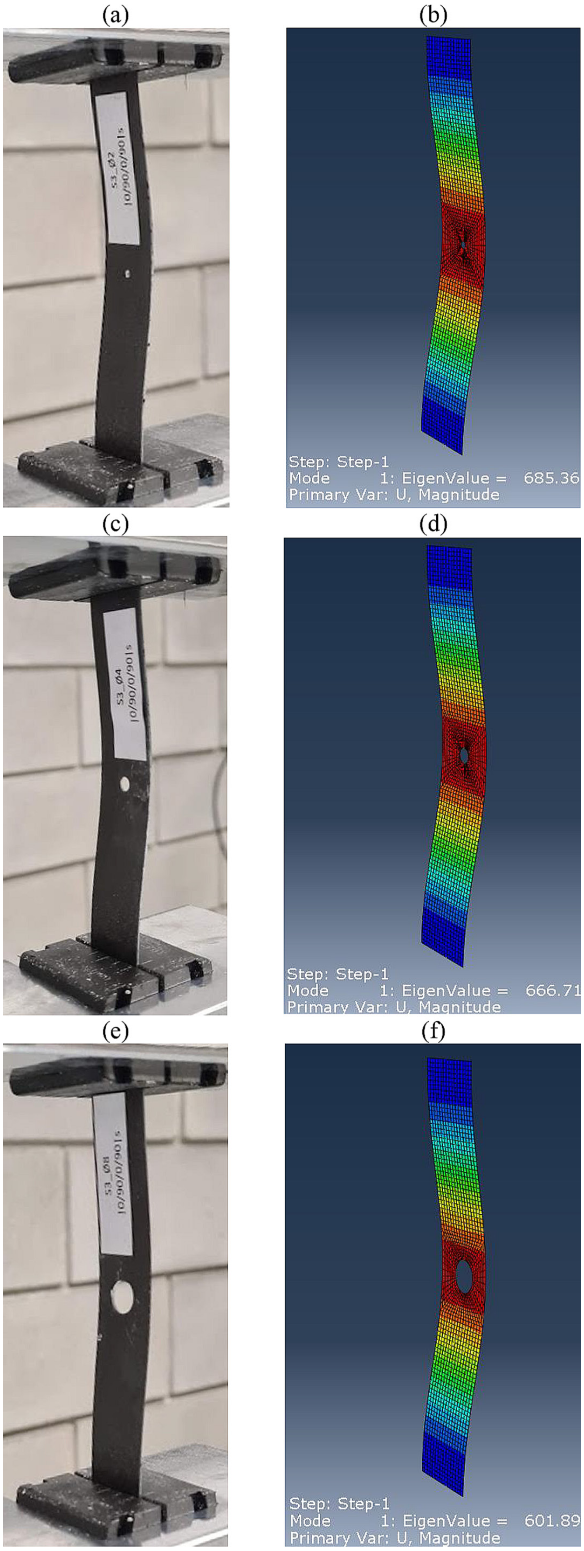

Fig. 4. Numerical and experimental first mode buckling of a plate with a hole: (a, b) sample 2, (c, d) sample 3, (e, f) sample 4

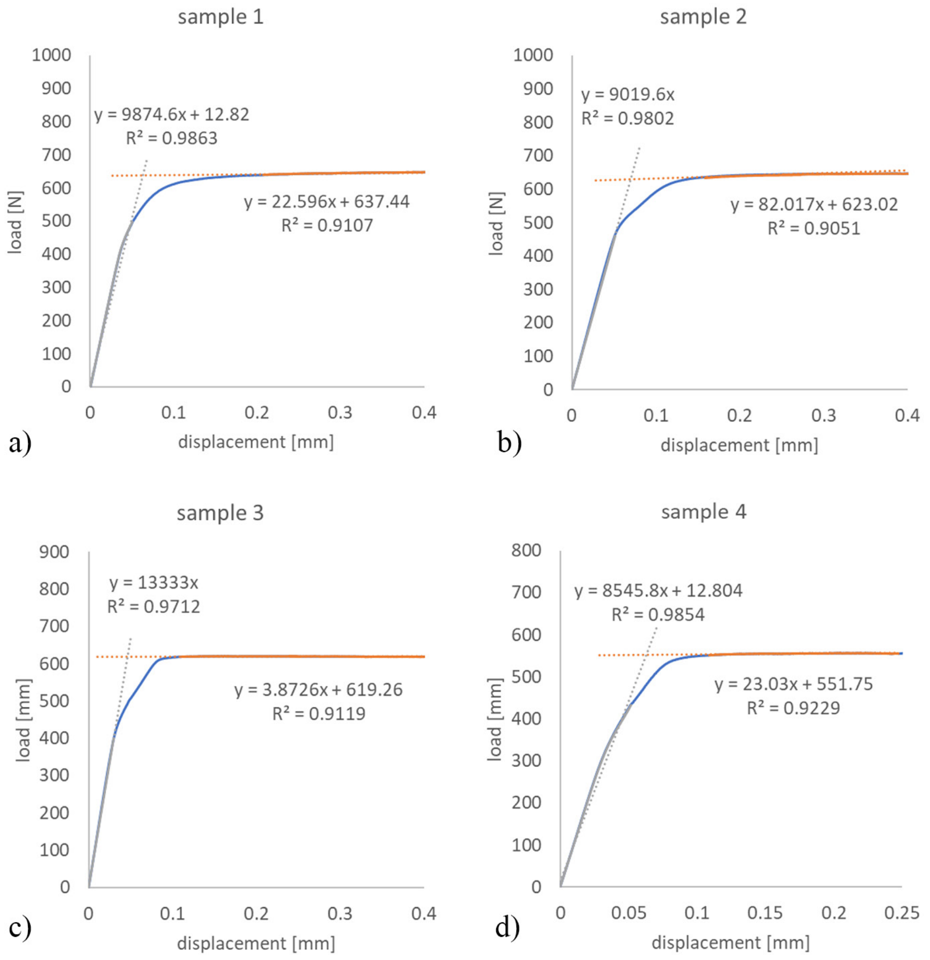

Fig. 5. Example of result obtained by straight-lines intersection method: (a) sample 1, (b) sample 2, (c) sample 3, (d) sample 4

Table 2. Experimental and numerical values of the critical load

Parameter	Unit	Sample 1	Sample 2	Sample 3	Sample 4
FEM	*[N]*	694	685	667	601
EXP	*[N]*	639	628	619	553
Relative error	*δ [%]*	7.9	8.3	7.2	8

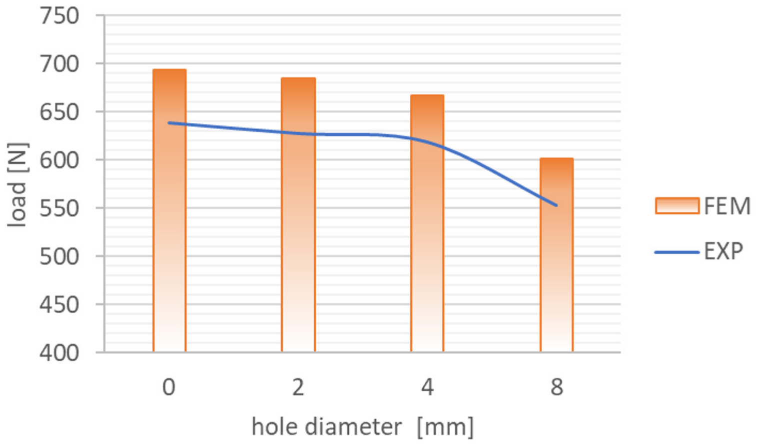

Fig. 6. Influence of the open hole on the critical load of compressed plate

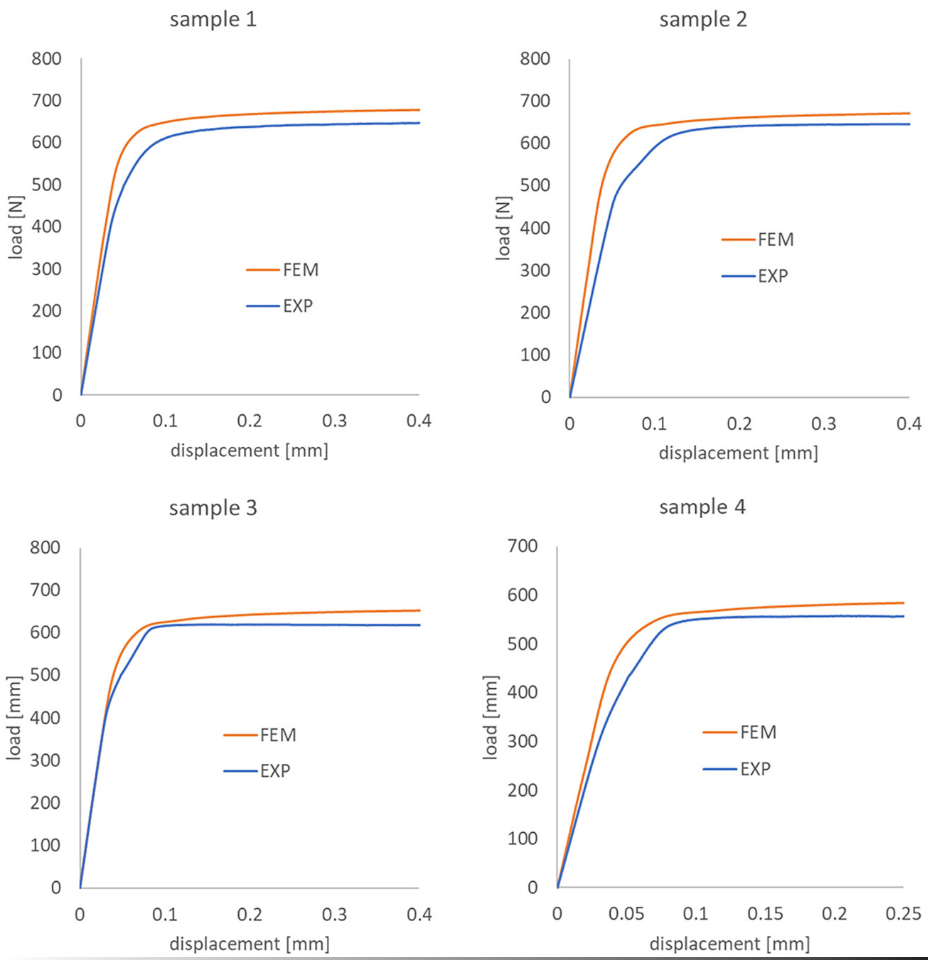

Fig. 7. Numerical and experimental postcritical paths: (a) sample 1, (b) sample 2, (c) sample 3, (d) sample 4

the behaviour of the tested plate with a hole in the weak-postcritical state. Figure 7 compares the postcritical paths obtained by the numerical method with the experimental results.

In all cases, the experimental postcritical path shows less rigidity than the results of numerical computations. This is evidenced by the fact that the real structure is inherently fraught with inaccuracies, while the FEM model is idealized and represents ideal analysis conditions.

CONCLUSIONS

The results obtained enable qualitative and quantitative analysis of the influence of the open hole on the critical state of the compressed CFRP plate. The results of numerical FEM computations presented in the paper were successfully reproduced experimentally. Tests on real plates allowed the determination of critical load values using a dedicated approximation method. The obtained test results quantitatively correspond to the results of numerical computations, their difference did not exceed 8.5%.

The effect of the size of the open hole of the plate did not change the mode of buckling of the plate. The appearance of a single local half-wave was registered in all cases studied. It was shown that the stepwise enlargement of the hole in the plate monotonically affects the decrease in critical load of the plate. Largest decrease was recorded for the specimen characterized by an 8 mm diameter hole and amounted to 13.5% compared to a plate without a hole.

The postcritical characteristics for the real plate and the FEM model show high agreement. In all cases, numerical postcritical path was characterized by the assumed higher stiffness, which is due to the fact that it represented an idealized solution devoid of inaccuracies that may exist in real structures.

At the same time, the quantitative and qualitative correspondence of the calculations of FEM analysis with the results of the experimental tests confirms the adequacy of the designed numerical model, which in the analysed case represents behaviour of the real plate with a hole (OHC).

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