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Failure analysis of FML plates with cutouts: Experimental and finite element approaches

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1. Introduction

At the end of decade 1970s, the idea of using two materials for conquest of defects of both materials was suggested [1]. Metal structures have high strength and resistance against impact and are easily repairable, while composite materials possess features such as high fracture resistance and high stiffness. By mixing the two types of materials, all of these properties could be achieved [2]. In 1978, metal laminate materials known as ARALL in institute of aerospace engineering in Delft University were introduced. These materials were composed of thin layers of aluminum alloys and unidirectional and bidirectional fibers of curing aramid with resin (prepreg) [3]. GLARE laminate materials are also from family of FML materials which is made of glass fibers room-temperature-curing epoxy resin and sheets of aluminum alloys. The great difference between GLARE and ARALL is that, GLARE is made of glass fibers rather than aramid [4]. FML plates are from family of hybrid materials which usually composed of thin metal layers and fibers curing with epoxy resin. Because of employing metal in the structures of these materials, they show plastic behaviors [5]. Therefore, the elastic/plastic analyses of them are important. These materials have good properties against impact, fracture, and corrosion. Moreover, other physical advantages such as high strength, resistance against fire, and weight-saving compared with metal alloys, lead to widespread use of them in aerospace and military industries. Manufactured materials which are composed of metals and composites have complicated mechanical properties and unpredicted behaviors, therefore, there have been many studies on this subject, of which we can mention to researches on the mechanical properties of a special kind of FMLs known as steel/aluminum/GRP laminate, which was carried out by Khalili et al [6]. Tensional and fatigue properties of fiber metal laminates with different fiber materials were studied and compared by G. Reyes and H. Kang [7]. The effect of angle of fibers arrangement and existence of fibers of glass and Kevlar on tensional properties of FMLs were investigated by S. Ebrahim Mousavi-Torshizi [8].

In the field of investigating the tensional behavior of FMLs, some articles are available in the literatures. P. Soltani et al [9] studied finite element nonlinear tensional behavior of in-plane loaded GLARE plates and compared with experimental results which had been presented by Wu G. and Yang [10]. In both papers, the behaviors of in-plane loaded sheets of FML have been presented. Numerical and experimental fatigue analyses in FML panels with cutouts have been performed by E. Armentani. In this research, a metal barrel of trunk of Airbus A330/300 was considered as reference structure for designing, and panels with cutout have been manufactured on this basis and subjected to multi-directional loading [11]. The effect of geometry on behavior of FML plates in linking joints has been numerically studied by R. M. Frizzell [12]. In this analysis effect of delamination between layers, plastic behavior of Aluminum layers and damage in fibers cured by resin in FML plates with cutouts while subjecting to shear and tensional loading was investigated. The results of this research have been compared with previous experimental paper of the author [13]. Modeling of delamination and damage in joints made by FML's has been studied by R. M. Frizell et al. [14]. The thermoplastic behavior of FMLs under tension, bending and impact loading has been performed by J. G. Carrillo et al. [15]. The effect of the existence of cutouts and type of them on stress concentration factor in FML plates has been carried out by Yazdani and Rahimi [16].

In the load-displacement diagram two important points can be observed. First point is relevant to plastic collapse load which is not the necessary load for physical collapse of the structure. In fact, plastic strains take place significantly at this point. Second point is relevant to the maximum load which could be tolerated by the structure, which is named by plastic instability load. Both the points are shown in Fig. 1. To find plastic collapse load, two commonly methods, Twice-elastic-slope (TES) method and Tangent-intersection (TI) method, were suggested in papers. [17, 19]

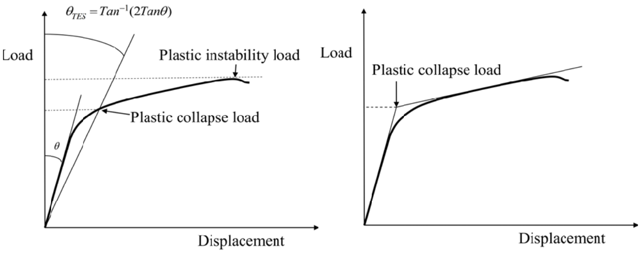

Fig. 1 The way of finding plastic collapse load by two methods TI and TES

The present paper describes the results of experimental and numerical investigation into the failure and large deflection of FML plates with different types of cutout. The study is included finite element models and elastic compensation method to determine the effect of types of cutouts and increment of their size on strength of the structures. In addition, results of experimental and finite element methods are compared with the results of elastic compensation method.

2. Experimental procedures

2.1. Manufacturing procedure

The plates were composed of 5 layers, including 3 aluminum alloy sheets with thicknesses of 0.4 mm and 0.3 mm (to consider the effect of thickness on structural behavior) and two woven E-glass layers with approximate thickness of 0.25 mm for each layer. Aluminum sheets and woven plies with length $a = 104$ mm and width $b = 100$ mm were cured with epoxy resin, and for manufacturing them the lay-up method was applied. The properties of aluminum sheets and composite layers which were used for producing samples have been represented in Table 1.

Table 1

Material properties of the layers [18]

Material	E, GPa	v	E_T, GPa	E_L, GPa	v_{LT}	G_{LT}, GPa
AL	71	0.33	-			
Woven/glass epoxy	-		15.8	15.8	0.25	2.8

The samples were pressured in room temperature during 24 hours. Therefore, FML plates with approximate thicknesses of 1.4 mm and 1.7 mm were obtained. Schematic view of plates' lay-up is shown in Fig. 2.

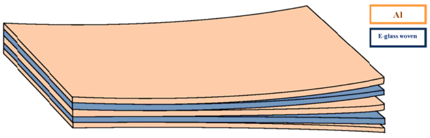

Fig. 2 Schematic view of GLARE lay-up

To create cutout in FML plates, the waterjet machine was used, in order to prevent the delamination and damages in layers. Circular and elliptical cutouts were created at the center of the plates. Circular cutouts had two different radii. Radius of first type of circular cutout was 7 mm, and of the second type was 14 mm. Moreover, for creating elliptical cutouts, major and minor diameters of ellipse considered being 28 and 14 mm, respectively. In one type of the samples the major diameter, and in the other ones minor diameter was aligned in the load direction. In Table 2, the samples which were tested are introduced with numbers 1 to 8, and in this paper these names are used in reporting the results.

Fig. 3 shows the specimens.

FML plates have complicated mechanical properties; the global mechanical properties of plates obtained by Yazdani [16] are used in the FEM analysis.

Table 2

Sample's specification

Sample's name	Thickness, mm	Cutout type
Sample 1	1.4	Circular – 7 mm radius
Sample 2	1.4	Circular – 14 mm radius
Sample 3	1.4	Elliptical – major diameter aligned in load direction
Sample 4	1.4	Elliptical – minor diameter aligned in load direction
Sample 5	1.7	Circular – 7 mm radius
Sample 6	1.7	Circular – 14 mm radius
Sample 7	1.7	Elliptical – major diameter aligned in load line
Sample 8	1.7	Elliptical – minor diameter aligned in load line

Fig. 3 Samples with cutout

2.2. Testing procedure

Plates with different cutouts were subjected to static tensional in-plane loading. The loading was performed by Instron 5500 machine with capacity of 200 kN and a constant cross head speed of 1.3 mm/sec. In order to prevent plates to be exposed to shear, special fixtures were designed and were used in the testing procedure and are shown in Fig. 4.

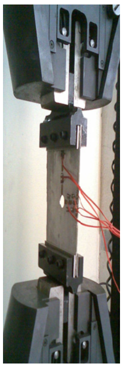

Fig. 4 Tensile test of FML plates with cutout

3. Finite element simulation

3.1. Finite element model of FMLs

In FEM analysis, ABAQUS commercial software was used. One quarter of the laminates were modeled because of the symmetry of the geometry, loading, and boundary conditions. Dimensions which were used in the simulation had the same sizes in the experimental work to compare results of the two methods. The size of plates and type of cutouts are presented in section 2.1. Global mechanical properties obtained by Yazdani and Rahimi [16] were used in finite element analysis and the plates were considered being homogenous.

Global mechanical properties of plates are presented in Table 3.

For elastic/plastic analysis of the samples, the measurements of yield stress and plastic strain obtained from experimental work were used in FEM analysis.

Table 3

Global mechanical properties of FML plates [16]

Plate thickness	E, GPa	v
1.4 mm	49.905	0.25
1.7 mm	54.622	0.25

3.2. Mesh, loading, and boundary conditions

The element (S8R) was used which is an 8-node element and has the capability of distributing stress in thickness direction. The arrangement of elements was changed several times to achieve precise results. In addition, finite element mesh was refined near the cutouts.

In all the simulations points along the x axis were constrained in the y direction and points along the y axis are constrained along x direction. Moreover, in the edge which plates are subjected to loading, all degrees of freedom were removed from them, except displacement in x direction.

An incremental load-displacement analysis is performed by using the arc-length RIKS method in the ABAQUS software. Moreover, Von-Mises yield criterion and non-linear analysis were performed. The RIKS method uses in geometrically nonlinear static problems, where the load-displacement response shows a negative stiffness and the structure must release strain energy to remain in equilibrium. The RIKS method uses the load magnitude as an additional unknown; it solves simultaneously for loads and displacements [20].

4. Elastic compensation method

Elastic Compensation Method is a continuum finite element based method for evaluation of lower bound limit load of the structure. By using the iterative elastic analysis, considering E_i^e as the module of elasticity in the previous step of loading; E_{i+1}^e as the modulus of elasticity in the current step; σ_i^e as the maximum stress in each element (Von-Mises stresses which were obtained in FE was used in this paper); and σ_n as nominal or average value of stress the elastic modulus is modified after each iteration according to Eq. (1) [21]:

$$E_{i+1}^e = E_i^e \frac{\sigma_n}{\sigma_i^e} . \tag{1}$$

Where subscript *i* is the present iteration number. Eq. (1) is continued until the convergence in results, and for the convergence criteria, following equation is assumed [22]:

$$\frac{\sigma_{i+1}^e - \sigma_i^e}{\sigma_{i+1}^e} \le k , \qquad k \approx 10^{-4} . \tag{2}$$

Above linear method mentioned, was used for calculating the lower bound limit load which is enough for yielding. By considering Eq. (2), at the end of the analysis, maximum value of σ_i^e was calculated and used to obtain the limit load P_{Li} based on the Eq. (3):

$$\frac{P_{Li}}{\sigma_Y} = \frac{P_n}{max_e\left(\sigma_i^e\right)} \to P_{Li} = P_n \frac{\sigma_Y}{max_e\left(\sigma_i^e\right)} . \tag{3}$$

In this method global mechanical properties which had been obtained by Yazdani and Rahimi [16] were used. By the method mentioned, limit load of each specimen was calculated and is presented in the next section.

5. Results and discussion

The behavior of FML plates with cutouts under tensional in-plane loading was considered. Results are expressed as load-displacement curves which were resulted from experimental work and finite element analysis. The load-displacement diagrams of samples 1 to 8 are shown in Figs. 5-12, respectively.

Based on the results of above study, some important points were concluded. First, the effect of using aluminum sheets on the behavior of FMLs while subjecting to in-plane loadings. By comparing Figs. 5-8 with Figs. 9-12 it is observed that the thinner plates have more displacement in elastic region than the thicker ones under the same applied loadings. Moreover, due to the more ratio of composite to metal in the plates with 1.4 mm thickness, more applied load was supported by these specimens in almost all the cases and more displacement was achieved.

Metals have better behaviors in elastic region than composites. Therefore, increment in the thickness which is related to aluminums sheets causes more volume ratio of metal to composite in plates with thickness of 1.7 mm. By doing so, their behavior was improved by notifying the slope of load displacement diagrams in the elastic regions.

The second is related to the effect of existence of the inevitable cutout and the type of it on the strength of the plates. It is obvious that the strength of all kinds of specimens with cutouts is less than complete ones. There-

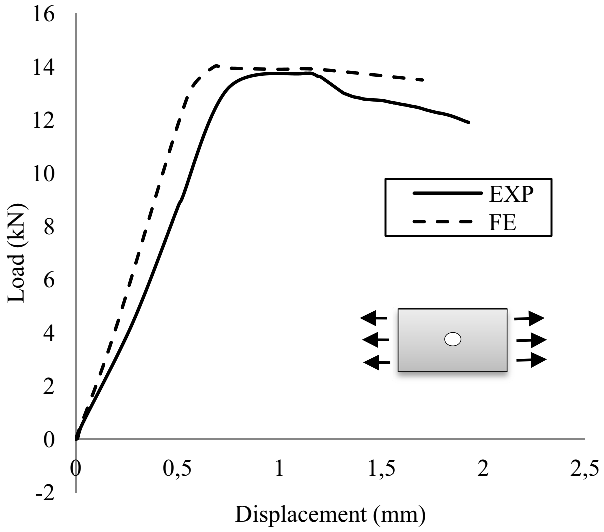

Fig. 5 Load-displacement of sample 1

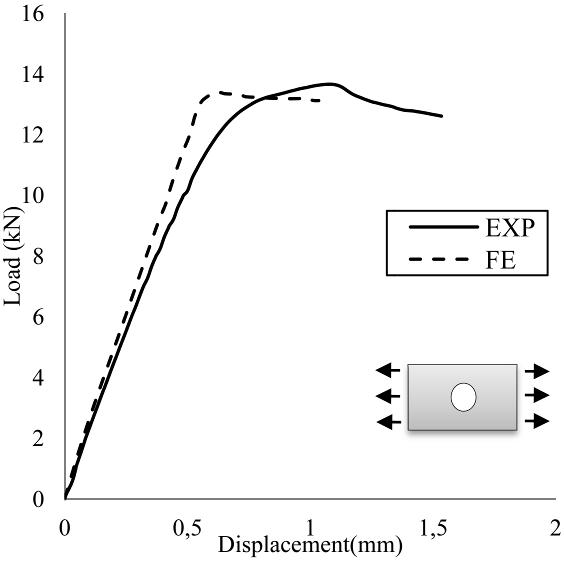

Fig. 6 Load-displacement of sample 2

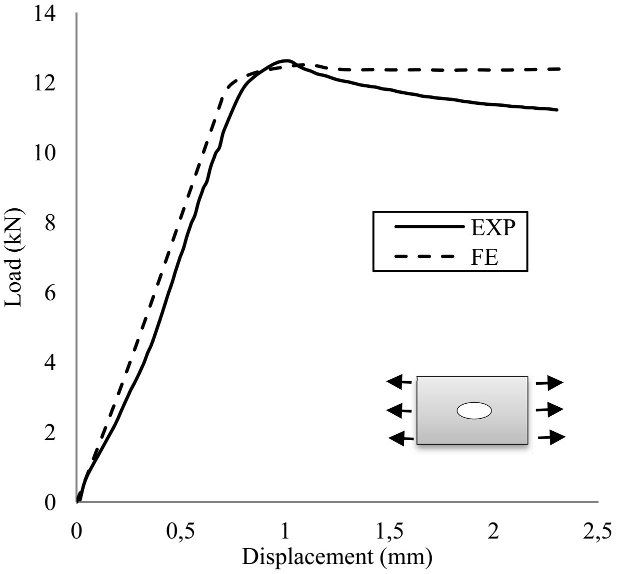

Fig. 7 Load-displacement of sample 3

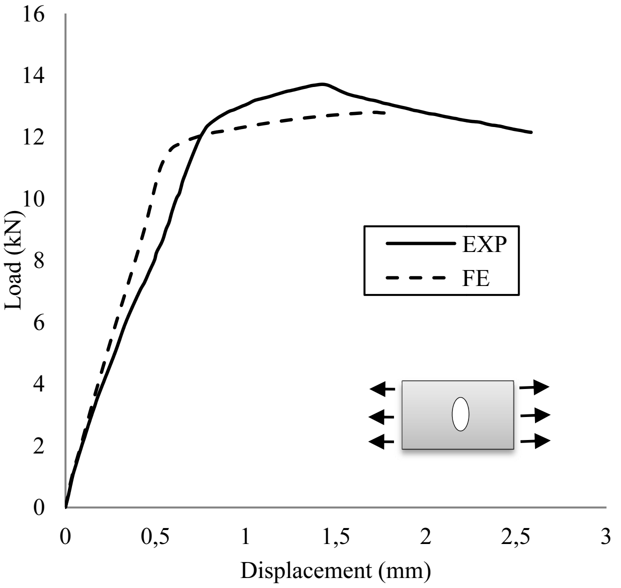

Fig. 8 Load-displacement of sample 4

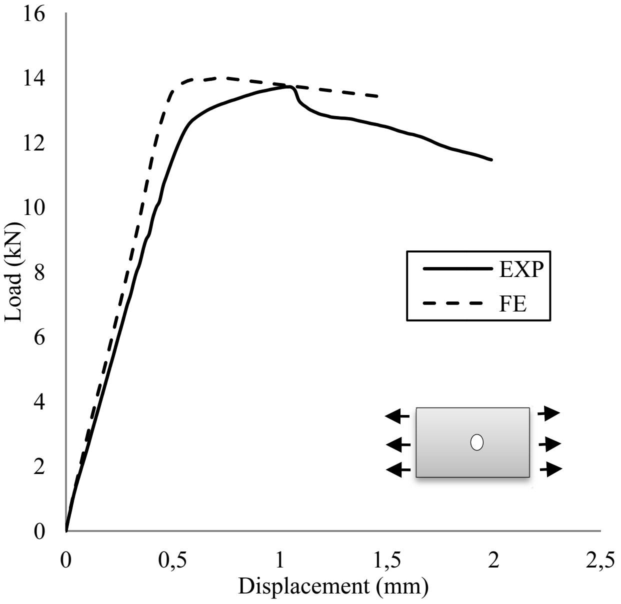

Fig. 9 Load-displacement of sample 5

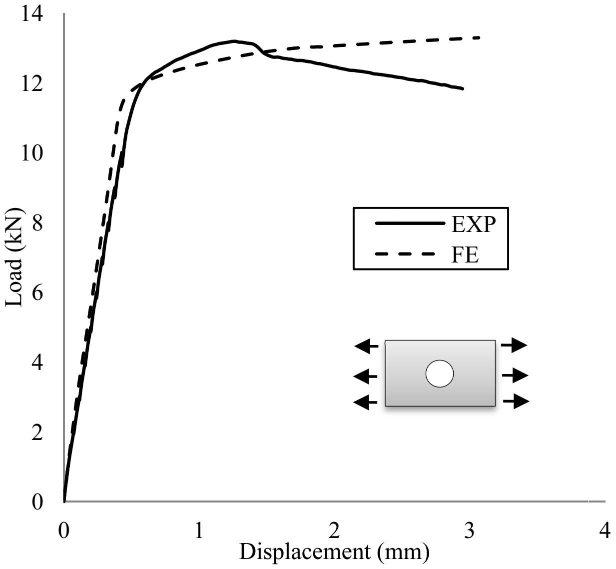

Fig. 10 Load-displacement of sample 6

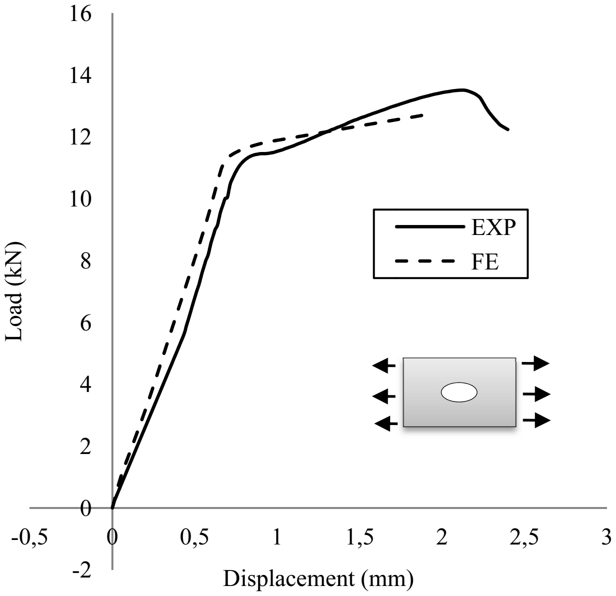

Fig. 11 Load-displacement of sample 7

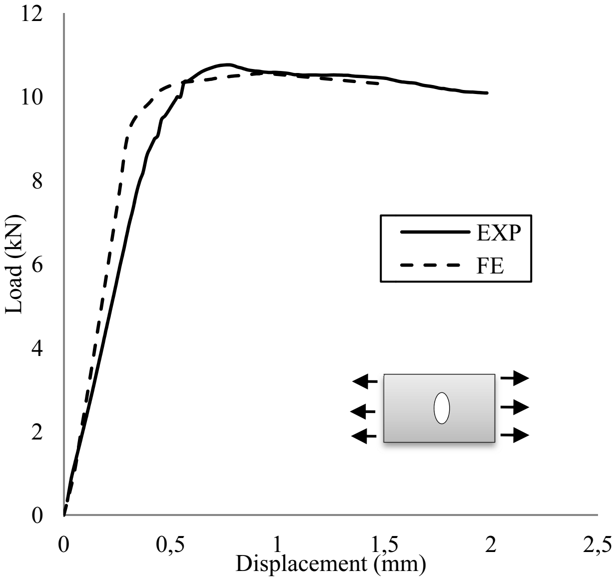

Fig. 12 Load-displacement of sample 8

fore, four types of cutout were created on the center of plates to investigate the effect of types of cutout on plate's failure. By comparing load-displacement diagrams in plates with 1.4 mm and 1.7 mm thicknesses, it is observed that the maximum loads were attained in plates with small circular cutout. Moreover, by comparing Fig. 6 with Fig. 8 and Fig. 10 with Fig. 12, the big circular cutout supports more load than the elliptical cutout which minor diameter aligned to the load direction.

As can be observed, the curves in finite element analysis follow the same behavior and lead to almost close results to the experiments. However, the differences can be attributed to neglecting the delamination effects and approximations of using the global mechanical properties in both the finite element simulations and elastic compensation methods.

By using two methods TES and TI, plastic collapse load of the structures were calculated for experimental and finite element analysis, and the results are presented in Table 4.

Table 4

Plastic collapse load using TI and TES method

Specimens	Plastic Collapse Load, N			
	TES Method		TI Method	
	EXP	FEM	EXP	FEM
Specimen 1	12761.5	13901.23	13002.73	13723.81
Specimen 2	13148.58	13121.2	12737.875	12953.136
Specimen 3	11751.02	12166.5	12053.588	11918.089
Specimen 4	13174.59	12541.4	12390.633	11861.093
Specimen 5	13173.54	13826.3	12965.382	14043.169
Specimen 6	13128.26	12495.5	12144.268	11943.542
Specimen 7	13115.62	12369.2	11865.676	11911.054
Specimen 8	10594.03	10417.1	10866.134	10075.453

As it is shown in Table 4, the plastic collapse load of the samples with more thicknesses has been increased, except in the sample 8, and the values calculated of both methods have close results. In addition, in average, the minimum plastic collapse load is attributed to the sample 8, and the maximum is related to the sample 5. Plastic instability load which is the maximum load that could be attained for both experimental and finite element methods are obtained and are presented in Table 5.

The results obtained in Table 5 shows that the maximum plastic instability load is related to plate with thickness 1.4 mm and circular cutout with radius 7 mm, and the minimum is corresponding to the plate with thickness 1.7 mm and elliptical cutout which minor diameter is aligned in the load direction. Elastic compensation method results are expressed in Table 6.

Table 5

Plastic instability load in experimental and FE analysis

Specimens	Plastic Instability Load, N	
	EXP	FEM
Specimen 1	13752	14100
Specimen 2	13659.23	13390.5
Specimen 3	12623.48	12521
Specimen 4	13699.76	12791.1
Specimen 5	13718.13	14006.3
Specimen 6	13195.63	13014.3
Specimen 7	13504.97	12734.7
Specimen 8	10761.84	10563.1

As it was observed in Table 6, limit loads which are obtained in this method are closer to plastic instability loads of the experiment.

Table 6

Limit load in elastic compensation method

Specimen	Limit Load, KN
Specimen 1	13.32
Specimen 2	13.18
Specimen 3	12.26
Specimen 4	12.73
Specimen 5	13.83
Specimen 6	13.07
Specimen 7	13.11
Specimen 8	10.14

6. Conclusion

The failure analysis of FML plates with different types of cutout have been studied and discussed. For this purpose, experimental, finite element and elastic compensation methods were used. It shows that the results in both numerical methods follow the same behaviors as experiments. In numerical analysis, the delamination of layers was neglected but in the experiment it is observed that the layers in plastic region of loading started to show negligible delamination. It was concluded that in small circular cutout the value of maximum plastic instability load was more than the plates with elliptical cutouts. The thinner plates with 1.4 mm carried out more load than the thicker ones; it can be attributed to the higher ratio of the composite to the metal. Moreover, due to the higher ratio of the metal in the layers of thicker plates, they have been shown a better plastic collapse loads and less displacements under the applied load.

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LAKŠTINIO METALO KOMPOZITO PLOKŠTELIŲ SU IŠKIRTIMAIS SUIRIMO ANALIZĖ EKSPERIMENTINIU IR BAIGTINIŲ ELEMENTŲ METODAIS

Reziumė

Šiame straipsnyje eksperimentiškai ir skaitmeniniu būdu atlikta lakštinio metalo kompozito plokštelių su iškirtimais suirimo analizė. Lakštinio metalo kompozitas yra medžiaga susidedanti iš metalo, dažniausiai aliuminio, lakštų ir sustiprinta epoksidinės dervos sluoksniais. Pagamintuose bandiniuose buvo iškirsti elipsės ir apskritimo formos profiliai. Šių bandinių mechaninės savybės buvo nustatomos atliekant tempimo bandymus. Analizė atlikta baigtinių elementų metodu naudojant ABAQUS komercinę programinę įrangą. Šiai analizei atlikti buvo naudojamas „lanko ilgio“ RIKS metodas skirtas netiesinių sistemų analizei. Eksperimentiniai ir baigtinių elementų metodu gauti rezultatai buvo lyginami su tampriųjų kompensacijų metodo rezultatais.

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FAILURE ANALYSIS OF FML PLATES WITH CUTOUTS: EXPERIMENTAL AND FINITE ELEMENT APPROACHES

Summary

In this paper, the experimental and numerical failure analysis of Fiber Metal Laminates (FML) with different types of cutouts, were investigated. Fiber metal laminates are types of materials which are consist of combination of metal sheets, especially aluminum ones, with fiber reinforced epoxy layers. At first, specimens were manufactured and elliptical and circular cutouts were created in them. Then subjected to in-plane tensional loading to carry out the behaviors, also, finite element analysis was carried out with ABAQUS commercial software. RIKS method was used in this analysis. Finally, experimental and finite element results were compared with results of elastic compensation method.

Keywords: Failure analysis, Large deflection, Finite element analysis, FML plate.

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