Warta Ardhia 2023, 49 (2): 87-95

Optimization of Double Hole Composite Plate on the Floater Compartment of Amphibious Aircraft Using Taguchi Method

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Diterima: 9 Mei 2023, disetujui: 27 November 2023, diterbitkan online: 29 Desember 2023

Abstract

A floater or pontoon is one of the most important components of amphibious aircraft to assist the take-off and landing operation. The inner structure of the floater consists of compartments to carry some payload and to reinforce the structural strength due to water and aerodynamic load that occurred during the aircraft operation. The composite material is chosen instead of metal to reduce the weight of the floater. One of the problems on the composite panel is the existence of some holes due to joint with another part or also to minimize its weight. In this study, the optimization of the composite plate with the existence of a double hole is done using the Taguchi Method. The objective of this optimization is to minimize the stress that happens due to the tensile load. The Finite Element Method is used to calculate the maximum stress and stress distribution on the plate. Tsai-Hill failure criterion is used to make sure that the optimum design does not fail. This optimization considers open hole configuration, the ratio between diameter, and hole distance, as well as the fiber orientation as the control factors. The Taguchi L9 Orthogonal Array is used to make 9 design variations from 3 control factors and 3 levels. This process also considers the thickness of the lamina and material strength as noise factors. The optimization process results in the optimum composite design as follows: 1st double hole configuration (in line with the load direction), the ratio between diameter and hole distance is 0.5, and the fiber direction is [0/90/45/-45]s. The maximum in-plane stress of the optimum design is 39.56 MPa with the Tsai-Hill value is 0.23, so the design does not fail. This optimum configuration of the composite plate can be used to make design considerations for an amphibious aircraft floater compartment.

Keywords: composite structure, optimization, Taguchi method, finite element method

Abstrak

Optimisasi Plat Komposit Lubang Ganda pada Kompartemen Floater Pesawat Amphibi dengan Menggunakan Metode Taguchi: *Floater atau ponton merupakan salah satu komponen paling penting pada pesawat amphibi untuk membantu operasi lepas landas dan mendarat. Struktur internal floater terdiri dari kompartemen untuk membawa beberapa muatan dan untuk memperkuat kekuatan struktural akibat beban air dan aerodinamika yang terjadi selama operasi pesawat. Material komposit dipilih daripada logam untuk mengurangi berat floater. Salah satu masalah pada panel komposit adalah adanya beberapa lubang akibat sambungan dengan bagian lain atau juga untuk meminimalkan beratnya. Dalam penelitian ini, optimisasi plat komposit dengan adanya lubang ganda dilakukan menggunakan Metode Taguchi. Tujuan dari optimisasi ini adalah untuk meminimalkan tegangan yang terjadi akibat beban tarik. Metode Elemen Finit digunakan untuk menghitung tegangan maksimum dan distribusi tegangan pada plat. Kriteria kegagalan Tsai-Hill digunakan untuk memastikan bahwa desain optimum tidak gagal. Optimisasi ini mempertimbangkan konfigurasi lubang terbuka, rasio antara diameter dan jarak lubang, serta orientasi serat sebagai faktor kontrol. Taguchi L9 Orthogonal Array digunakan untuk membuat 9 variasi desain dari 3 faktor kontrol dan 3 tingkat. Proses ini juga mempertimbangkan ketebalan lamina dan kekuatan material sebagai faktor noise. Proses optimisasi menghasilkan desain komposit optimum sebagai berikut: konfigurasi lubang ganda pertama (sejajar dengan arah beban), rasio antara diameter dan jarak lubang adalah 0,5, dan arah serat adalah [0/90/45/-45]s. Tegangan in-plane maksimum dari desain optimum adalah 39,56 MPa dengan nilai Tsai-Hill sebesar 0,23, sehingga desain tidak gagal. Konfigurasi optimum dari plat komposit ini dapat digunakan untuk mempertimbangkan desain kompartemen floater pesawat amphibi.*

Kata kunci: struktur komposit, optimisasi, metode Taguchi, metode elemen finit

1. Introduction

The development of 19-passenger commuter aircraft allows for changing the aircraft from land-based operation into water-based operation. This 19-passenger aircraft will be changed into an amphibious aircraft that can take off and land either land-based or water-based [1]. The development of amphibious aircraft will be dedicated to supporting the water-based tourism sector and increasing the economic growth in Indonesia. This aircraft also can be used as be water ambulance that can access the most remote areas in the Indonesian archipelago. This is because of this aircraft's capability to land from island to island [2].

doi: http://dx.doi.org/10.25104/wa.v49i2.520.87-95
0215-9066/ 2528-4045
Nomor akreditasi: (RISTEKDIKTI) 786/AU1/P2MI-LIPI/11/2017 (Sinta 2).

There are two types of amphibious aircraft: float plane and flying boat. Float planes use twin floaters to assist the aircraft during the water phase. This twin floater is usually fitted on the bottom side of the fuselage. The flying boat uses the bottom area of the fuselage that is modified its shape is like the hull of the boat. On the flying boat, there are no part additions but so much modification of the fuselage structure. The float plane aircraft is likely to be chosen rather than a flying boat for the alteration of commuter aircraft into amphibious aircraft. It's better to develop floaters of light aircraft in terms of less modification and easier certification process.

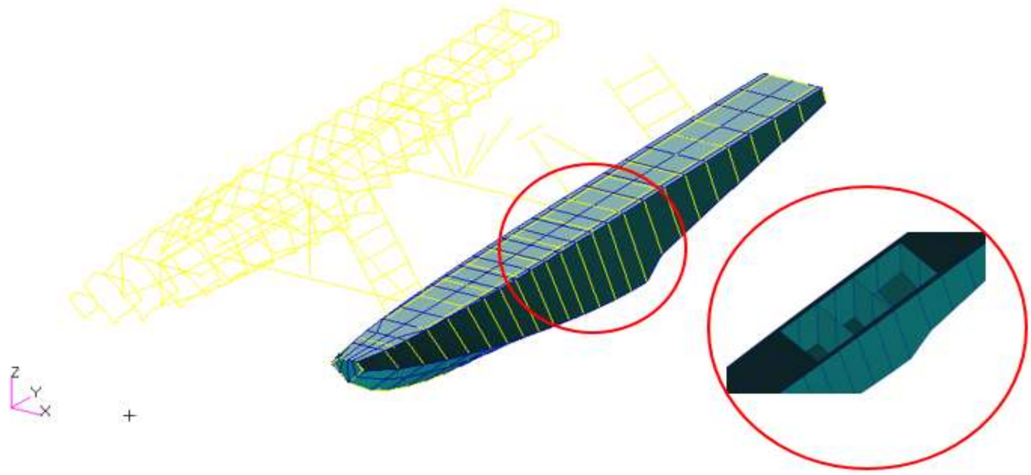

Figure 1. Twin Float Compartment
Source: Analysis Results, 2022

The utilization of composites to replace the conventional use of aluminum materials in the basic N219 aircraft is imperative. This is due to the weight increase resulting from the replacement of the landing gear with floaters [3]. To address this, the float components must employ composite materials to achieve a weight reduction of 200-300 kg. The floater amphibious aircraft is built from a skin structure on the outside and joined into the bottom side of the fuselage using a strut and ladder at the bulkhead area. The inside of floater compartments is built from bulkhead, frame, and intercoastal. The floater structure uses a composite material that is manufactured using Vacuum Assisted Resin Infusion (VARI) process. The presence of holes and the interaction of multi holes in the composite plate floater compartment is need to evaluated and optimized to prevent the failure of the structure. The compartment model of the twin float can be seen in Figure 1.

Dr. Genichi Taguchi from Japan developed some design optimization based on robust design. It is a tool that is powerful to improve the performance of a product or process. The purpose of this method is to increase the performance and to decrease performance variation [4].

Some previous researches study hole interaction on a composite plate and optimization based on Taguchi methodology [5][6][7][8]. Özaslan et al. have studied hole interaction at carbon-epoxy composite laminate both experimental and numerically. To predict the strength of the specimen, point stress criteria were used. Mesh refinement was applied at the area around the hole to focus on investigating the stress. The stress concentration factor was evaluated by varying the holes' angle. The biggest stress concentration factor occurred at a hole angle of 22.50 [9]. Previously, Özaslan et al. studied both the experimental and numerical of composite plates with single holes. The study is done by varying the ratio between specimen width and hole diameter. Based on this research, it can be concluded that the stress concentration factor was increased up to 15% by decreasing the ratio of specimen width over hole diameter from 6 to 3 [10].

Salleh et al. studied the tensile properties of kenaf composite and kenaf/fiber hybrid composite laminate. This research was driven by a drilling process that induced a high rate of composite parts rejection. The strength and failure of open hole kenaf composite were investigated according to notch sensitivity [11]. Nasir et al. have done a parametric study in terms of tensile strength on natural fiber composite after the drilling process. This experimental study used the Taguchi method to minimize the number of experiments. ANOVA (analysis of variance) was used to determine which parameter was statistically significant to residual tensile strength [12]. Pandivelan et al. used the Taguchi L9 orthogonal array to identify the best combination of parameters to increase the formability of the wall angle test [13].

Nurrohmad et al. have done the optimization and parametric study to identify which parameter significantly affects the performance of composite plates with a single hole. The number of numerical simulations on combinatoric parameters was reduced by the Taguchi L9 orthogonal array. This research concluded that the fiber direction is the most significant parameter [14]. Le-manh and Lee have done the optimized stacking sequence on the maximum strength of laminated composite plates using genetic algorithm and isogeometric analysis [15].

The purpose of this research is to optimize the design of a composite plate with two interacted holes. The Tsai-Hill failure criterion was used to investigate whether the plate failed or not. The Taguchi method was used to determine which combination must be simulated using the finite element method [16]. The optimized design will be proposed for the design of the floater compartment. The significance of each parameter will be considered on the design process of the amphibious composite floater.

2. Methodology

Methods used in this research consist of several steps. First of all, the design parameter of the composite plate with a double hole was defined. After that, Taguchi's orthogonal array L9 was generated to reduce the number of simulations [17]. All of the numerical modeling was done using Simulia Abaqus. In the final steps, after the data was obtained, the calculation of Signal to Noise and ANOVA (Analysis of Variance) was conducted to determine the best configuration of the design parameter that gives the best performance and to know the significance of each design parameter.

The Taguchi method's primary goal is to improve product or process quality by eliminating variability and identifying the most relevant elements influencing system performance. The S/N Ratio is used as a performance measuring criterion in the Taguchi Method, where "signal" is the average of the target values and "noise" is the variability or deviation from the target. This method aids in the identification of optimal parameters that give stable performance while minimizing variability. The following is the algorithm or steps in carrying out the Taguchi method:

1) Determine factors that may influence the performance of design and identify the possible levels of each factor
2) Generate the experimental or simulation design utilizing Taguchi matrix / Taguchi Orthogonal Array
3) Specify the response variable to be measured to evaluate system performance
4) Perform several numerical simulations or experimental test
5) Calculate the Signal-to-Noise Ratio (S/N Ratio) for each experiment
6) Determine the optimal settings for the tested factors based on the S/N Ratio. Select the combination of levels that yields the highest S/N Ratio.
7) Verify the optimal results by conducting additional experiments/simulations

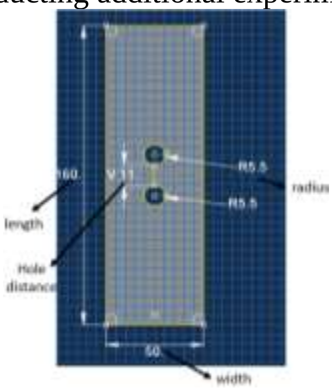

Figure 2. Model geometry
Source: Analysis Result, 2022

The geometry of the model can be seen in Figure 2. The specimen has 160 mm of its length and 50 mm of its width. The diameter of the hole is 11 mm and the distance between the hole is 11 mm. This specimen was made from composite material with some fiber stacking sequence. This model will be varied into several configurations following the Taguchi method. First of all, the control factors for the optimization process were defined. The selected control factors are hole configuration, the ratio between hole diameter and hole distance, and fiber orientation. The selection of these variations aims to achieve the optimum configuration in determining the design of double holes in composite plates. The hole diameter, spacing between holes, and fiber arrangement will undoubtedly influence the strength of the composite material's structural integrity. Each control factor has three levels that also will be varied. The complete control factor and each level are shown in Table 1.

Table 1. Control Factors and parameters of each level

Control Factor	Level	Parameter
Hole configuration	1	Upper - lower
	2	Side by side
	3	Diagonal
Hole diameter: Hole distance	1	0.5 (22 mm)
	2	1 (11 mm)
	3	1.5 (7.3 mm)
Fiber orientation	1	(0/90/0/90)s
	2	(45/-45/45/-45)s
	3	(0/90/45/-45)s

Source: Analysis Results, 2022

Taguchi orthogonal array is a tool that is used to decide the combination that will be run using a numerical method. From the three control factors and three levels, the Taguchi orthogonal array L9 was used so there are 9 running, as can be seen in Table 2. From this approach, the number of simulations can be reduced from 27 to 9 variations.

Table 2. Taguchi Orthogonal Array L_9

Running	Control Factor 1	Control Factor 2	Control Factor 3
A	1	1	1
B	1	2	2
C	1	3	3
D	2	1	2
E	2	2	3
F	2	3	1
G	3	1	3
H	3	2	1
I	3	3	2

Source: Analysis Results, 2022

The detailed design of the simulation can be seen in Table 3. This variation will be running using numerical simulation by considering noise factors. The noise in this optimization process pertains to material strength and lamina thickness, both of which are uncontrollable variables. Each noise factor is assigned variations of 95%, 100%, and 105% of the values present in the database or as per the design.

Table 3. The design the n of the Simulation follows Taguchi Orthogonal Array L_9

Running	Hole Configuration	Ratio of Diameter: Hole Distance	Fiber Direction
A	Upper and lower	0.5	(0/90/0/90)s
B	Upper and lower	1	(45/-45/45/-45)s
C	Upper and lower	1.5	(0/90/45/-45)s
D	Side by side	0.5	(45/-45/45/-45)s
E	Side by side	1	(0/90/45/-45)s
F	Side by side	1.5	(0/90/0/90)s
G	Diagonal	0.5	(0/90/45/-45)s
H	Diagonal	1	(0/90/45/-45)s
I	Diagonal	1.5	(45/-45/45/-45)s

Source: Analysis Results, 2022

The specimen used in the simulation is a fiber-reinforced polymer. To give clear information about these specimens, the stacking sequence can be seen on Figure 3. To avoid the coupling between the bending moment and axial load, the solid laminate is designed to be balance-symmetric. The material of the composite can be seen on Table 4.

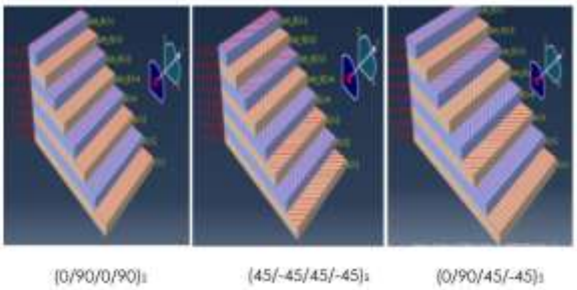

Figure 3. Stacking Sequence
Source: Analysis Results, 2022

Table 4. Material database

Material	Carbon Fiber Composite
Thickness of lamina	0.2 mm
E1	126 GPa
E2	11 GPa
E3	11 GPa
Nu	0.29
G12	6.6 GPa
G13	6.6 GPa
G23	3.93 GPa
Allowable Shear Strength	60 MPa
Allowable Compressive Strength	655 MPa
Allowable Tensile Strength	855 a

Source: Analysis Results, 2022

3. Result and Discussion

The results of numerical simulation using finite element analysis canine seen on Figure 4. The stress distribution on tch specimens showed the location of maximum stress that occurred. All of the specimen has a maximum stress at the edge of the hole. From this evaluation, the biggest stress value occurred at specimen number I with 312.6 MPa and the lowest was at specimen number C with 37.71 MPa. The better design will give a smaller value of maximum stress. The complete review of the maximum principle stress of all running including its noise factor can be seen on Table 5.

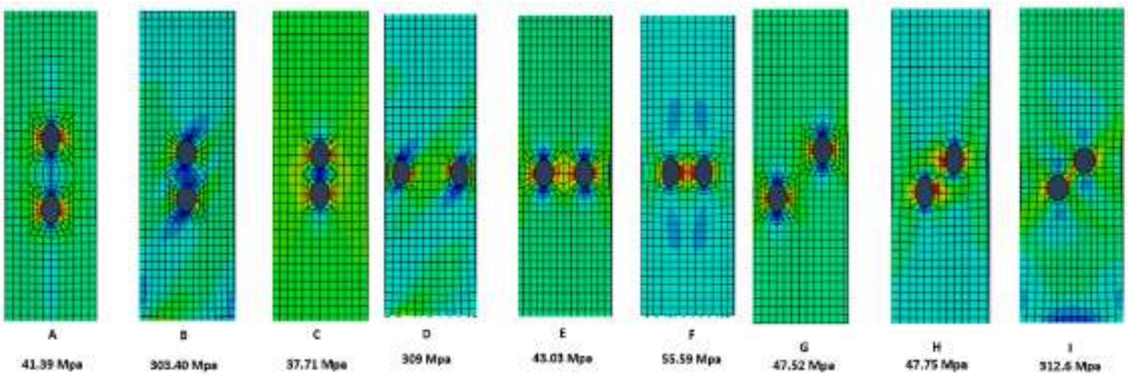

Figure 4. Maximum Principle Stress of each running
Source: Analysis Results, 2022

Table 5. Maximum Principle Stress value of all running with its noise factor

Number of Simulations	Control Factor			Maximum Principle Stress (Mpa)		
	Hole Configuration	Ratio of Diameter: Hole Distance	Fiber Direction	Noise 1	Noise 2	Noise 3
A	Upper and lower	0.5	(0/90/0/90)s	43.58	41.39	39.42
B	Upper and lower	1	(45/-45/45/-45)s	319.2	303.4	289.1
C	Upper and lower	1.5	(0/90/45/-45)s	39.69	37.71	35.91
D	Side by side	0.5	(45/-45/45/-45)s	325.3	309.0	294.3
E	Side by side	1	(0/90/45/-45)s	45.29	43.03	40.98
F	Side by side	1.5	(0/90/0/90)s	58.53	55.59	52.93
G	Diagonal	0.5	(0/90/45/-45)s	50.02	47.52	45.26
H	Diagonal	1	(0/90/0/90)4s	50.26	47.75	45.47
I	Diagonal	1.5	(45/-45/45/-45)4s	329.0	312.6	297.8

Source: Analysis Results, 2022

To give better information on the specimens, failure analysis must be done. Tsai-hill failure criterion is one of the appropriate criteria to evaluate the failure of the composite material [18]. The composite structure will fail if the Tsai-Hill value is equal to or bigger than 1. From Table 6, we can see the performance of the specimens. The orange color indicates that this specimen failed according to numerical analysis.

Table 6. Tsai-Hill Value off all specimens

Number of Simulations	Control Factor			Tsai-Hill Value		
	Hole Configuration	Ratio of Diameter: Hole Distance	Fiber Direction	Noise 1	Noise 2	Noise 3
A	Upper and lower	0.5	(0/90/0/90)s	0.429	0.387	0.351
B	Upper and lower	1	(45/-45/45/-45)s	1.502	1.355	1.229
C	Upper and lower	1.5	(0/90/45/-45)s	0.236	0.213	0.193
D	Side by side	0.5	(45/-45/45/-45)s	2.024	1.826	1.656
E	Side by side	1	(0/90/45/-45)s	0.283	0.256	0.232
F	Side by side	1.5	(0/90/0/90)s	0.633	0.571	0.517
G	Diagonal	0.5	(0/90/45/-45)s	0.285	0.257	0.233
H	Diagonal	1	(0/90/0/90)4s	0.481	0.434	0.393
I	Diagonal	1.5	(45/-45/45/-45)4s	1.953	1.763	1.599

Source: Analysis Results, 2022

Table 7. Signal to Noise Ratio Calculation

	Signal to Noise Response		
	Hole Configuration	Diameter: Hole Distance	Fiber Direction
level 1	-37.8575	-38.5805	-33.6277
level 2	-39.1467	-38.6531	-49.8016
level 3	-39.0273	-38.7979	-32.6021
range	1.289181	0.217476	17.19952

Source: Analysis Results, 2022

The best configuration will be evaluated using Signal to Noise Ratio analysis. The biggest value is the best configuration of the design. Figure 5 shows that the best design is: Hole configuration 1, Diameter: hole distance 1, and fiber direction 3.

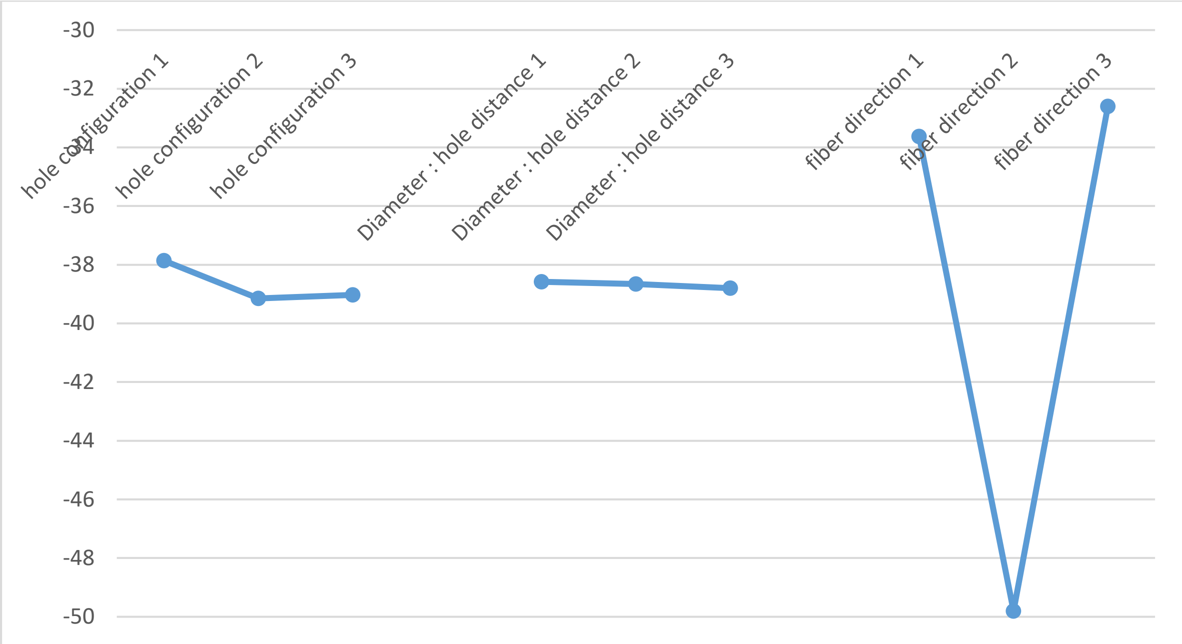

Figure 5. Signal to Noise Ratio
Source: Analysis Results, 2022

4. Conclusion

The Optimum Combination for 2-Hole Composite Plates with Tensile Load is a Top-Bottom Hole Configuration with Hole Distance Ratio of 0.5 using Fiber Direction (0/90/45/-45)s. Of the three simulated factors, the direction of the fiber has the greatest contribution. So the float compartment design must pay attention to Fiber Direction. It was found the Hole Configuration and the Distance between Holes contributed quite significantly.

Acknowledgment

The authors would like to thank the funding by the LPDP (Indonesia Endowment Fund for Education) and the Ministry of Finance of Indonesia.

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