Journal of Solid and Fluid Mechanics (JSFM), 13, (1):1-4, 2023

Shahrood University of Technology

Journal of Solid and Fluid Mechanics (JSFM)

DOI: 10.22044/JSFM.2023.12491.3678

Manufacturing Engineering of Iran

Thickness optimization of the airplane wing box components by the design of experiments method

B. Shahriari[1], A. Mahdian[2], M. Shirani[3], M. Sahraei[4], M. Ismailian[5]

[1]Assist. Prof., Faculty of Mechanics, Malek Ashtar University of Technology, Isfahan, Iran.
[2]Assoc. Prof., Faculty of Mechanics, Malek Ashtar University of Technology, Isfahan, Iran.
[3]M.Sc., Faculty of Mechanics, Malek Ashtar University of Technology, Isfahan, Iran.
[4]Ph.D, Iran Aircraft Manufacturing Ind. Co., Isfahan, Iran.
[5]Ph.D, Faculty of Mechanics, Malek Ashtar University of Technology, Isfahan, Iran

*Corresponding author: shahriari@mut-es.ac.ir

Received: 12/09/2022 Revised: 03/13/2023 Accepted: 05/01/2023

Abstract

Structure optimization in aerospace industries is of particular importance due to the need for light structures to reduce costs and increase flight performance. The main components of an airplane wing consist of spars, ribs and skin. At first, in this research a wing structure with two I-shaped spars, 6 ribs and a shell with specific geometric characteristics is modeled. By choosing aluminum alloy as the material of the structure and using the finite element method, the wing structure has been subjected to static loading and the maximum amount of stress and displacement of the wing box area has been obtained. Then, according to the results of the analysis and the optimization capability, the wing structure has been divided into three parts in order to optimize the thickness of the components along the length of the wing. By defining the thickness of the wing box components in all three parts as factors and stress and weight as the answers to the optimization problem through the method of designing experiments, which in this problem is the static analysis of the structure, the thickness of the components of the wing box area according to the goal of the lowest weight and the highest stress Optimization is allowed. The obtained results indicate that after the optimization, the weight of the wing box has decreased by 46.5%.

Keywords: Airplane wing structure; Wing box; Analysis; Optimization; Design of experiments.

1. Introduction

The main components that suffer the most severe loads during flight are generally located in the wing section of the aircraft. Wings are the main components providing thrust and are aerodynamically designed to provide the required thrust. Longitudinal poles in the wing are called spars and rib blades. An airplane wing has a cross-section called an airfoil in order to generate lift. The wings are attached to the fuselage, rooting the joint. The wing structure is composed of component structures including spar, rib, shell and longitudinal reinforcement components. To the front part of the wing that directly splits the air and is the first part that meets the air at the beginning of the flight and participates in the production process, the leading edge and to the trailing part of the wing and the last points where the air goes up and down from the surface. It passes through it, it is called the escaping edge. The building of each wing may consist of one or more independent spars, in this situation both spars can create an independent and strong structure called a spar box or a wing box, in which case the components of the substructure of the attack edge and escape edge are connected to it. Is. be. In this research, this important part of the wing structure has been analyzed and optimized.

2. specifications

In this research, the wing structure that is investigated in the wing box area has two I-shaped spars, six ribs and a shell. The distance between the ribs is 1040 mm and the wing length is 5200 mm. The height of the spars, the distance from the leading edge to the front spar, the distance from the trailing edge to the rear spar, and the distance between the two spars are shown in Figure 1.

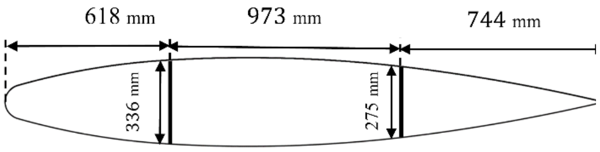


Figure 1. Airfoil wing

In an I-shaped spar, its upper and lower parts are called cap and its vertical section is called web. The cross-sectional dimensions of the I-shaped spars and the thickness of the wing structural components are shown in Table 1.

Table 1. Dimensions and thickness of wing structure components

Structural components	Dimensions and thickness	Quantity(mm)
spar	Front spar width	100
	Rear cap spar width	100
	thickness of the front spar cap	10
	Rear spar cap thickness	12
	Front web spar height	316
	Rear web spar height	251
	thickness of the front web spar	4.5
	Rear web spar thickness	4
shell	shell thickness	5
rib	Rib thickness	2.5

3. Static analysis

The material used in this wing structure is AL7075 (T651) with a modulus of elasticity of 71700 MPa and a yield stress of 503 MPa. First, the wing structure is designed with the help of Katia software. Then, in Abaqus software, through the standard Abaqus solver, the wing structure was meshed using shell element and static analysis was performed on it. To determine the boundary conditions, the cross-section of the spars at the root of the wing is taken (with all degrees of freedom closed). For loading, reference points are established on the elastic center of mass, which is 10% closer to the wing's leading edge. Then, using the coupling clause, the reference points on each rib are coupled to the four common points of the components. Finally, the loads applied to the wing structure have been applied to the reference points of the ribs.

According to the obtained results, the maximum stress value in the wing structure and the wing box is the same, so the wing box bears the highest stress in the wing structure. Also, considering that in the areas far from the root, very little stress is applied, and in the areas close to the root of the wing, the maximum stress value is equal to 354.1 MPa and is far from the yield stress of the material, which is equal to 503 MPa, the ability to optimize the thickness Wing box components are present along the length of the wing. Figure 2 and Figure 3 show the stress distribution in the wing and wing box structure.

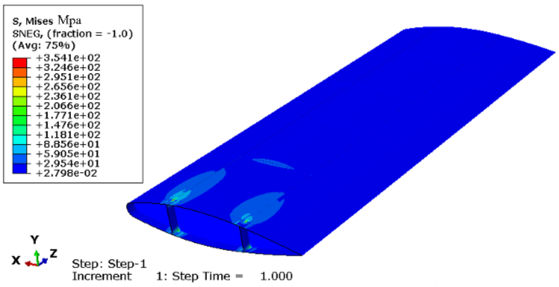
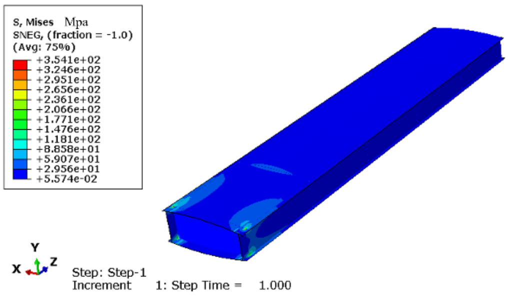


Figure 2. Stress distribution in the wing structure



Wing box

Figure 3. Stress distribution in the wing box structure

4. Optimization

Optimizing dimensions will include improving the cross section or thickness of specific elements of the structure. In this research, in order to optimize the thickness of the wing box components, the wing structure is divided into three equal parts according to Figure 4.

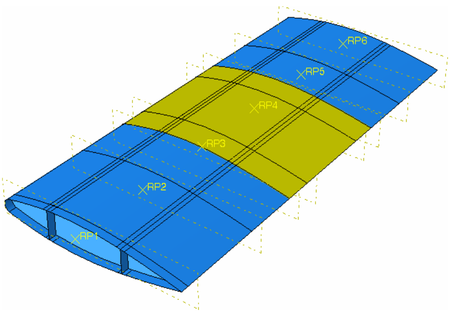


Figure 4. Dividing the wing structure into three equal parts

Optimization factors and constraints for each part of the wing box are stated in Table 2. There is a total of 12 thickness factors.

Table 2. Optimization factors with constraints

Wing box area						
Factor	near the root	Range (mm)	middle of the wing	Range(mm)	near the tip	Range(mm)
Rib thickness	Rib1	1.5 - 2.5	Rib2	1.2 - 2	Rib3	1 - 1.5
Skin thickness	Skin1	2.5 - 5	Skin2	2 – 3.5	Skin 3	1.5 - 3
Shell thickness	Cap Spar1	9 - 12	Cap Spar2	8 - 11	Cap Spar 3	7 - 10
Cap thickness	Web Spar1	2.5 – 4.5	Web Spar2	2 – 3.5	Web Spar 3	1.5 - 3

The objective functions or the responses considered to optimize the thickness of the wing box components are stress and weight. In this research, the goal is to minimize the weight of the wing box without exceeding the maximum allowable stress criteria. In this problem, the maximum allowable stress is calculated based on the reliability factor of 1.5, which is often considered in aerial structures, and the yield stress of the selected material is calculated through the formula (allowable stress / yield stress = reliability factor). Therefore, the goal of optimizing the wing box is to have the lowest weight and the highest Von Mises stress, which is obtained by putting the confidence factor in the formula equal to 335.33 MPa.

Designing experiments is a statistical analytical method for modeling and investigating the effect of input variables of a process on one or a number of output variables that are an unknown function of input variables. In this research, the analysis of the structure in Abaqus software is the same as the experiments in the method of designing experiments. After designing and conducting the experiments, variance analysis method is used to analyze the data. In this method, by using variance calculation and hypothesis testing with factorial design test method, the effective factors and also the effect of important interactions are determined, which in this research was done with the help of Mini Tab software. In the method of designing experiments, when the number of optimization factors is large, the number of experiments also increases, and as a result, more time and money must be spent to solve the problem, for this reason, in this method, to reduce the number of experiments, first through the screening method, the factors It is effective on the answers of the identification problem and the optimization of the problem is done with a smaller number of tests. First, 28 tests have been designed in the Minitab software through the Berman platelet screening method. The Berman platelet design is a two-level fractional factorial design with a resolution of 3, and pairwise interactions are not investigated. After analyzing the data, the presented models were checked for stress and weight, and the validity of the model was confirmed based on the stated criteria. Then, according to the Pareto diagrams, the effective factors on the tension and weight of the wing box have been determined. Pareto chart is used to determine the magnitude and importance of the effects. In the Pareto chart, bars that have crossed the reference line are statistically significant or effective. Among the 12 wing box optimization factors, three factors Web Spar1, Skin1 and Cap Spar1 are effective on tension and all twelve factors are effective on the weight of the wing box.

Then, 15 experiments have been designed to optimize the effective factors through the design method of Benken’s box experiment. Benken’s box design is one of the response surface design methods, which is considered due to the smaller number of tests in the design of up to 4 factors. This technique is a three-level factorial design. Since the goal of optimization is to minimize the weight, the non-influential factors on the stress have been placed at their lowest value. After analyzing the data of the tests by Minitab software, the presented models were checked for stress and weight and based on the validation criteria, the validity of the model and the obtained results were confirmed. Bencken’s box tests can be seen in Table 3 and the graphs of the effective parto factors of the tension and weight of the wing box can be seen in Figure 5 and Figure 6.

Table 3. Bencken's box tests

Run	Web Spar1	Cap Spar1	Skin1	Weight (Kg)	Stress (MPa)
1	2. 5	10. 5	2. 50	141	476. 7
2	4. 5	10. 5	2. 50	147	403. 8
3	3. 5	9. 0	2. 50	141	469. 5
4	3. 5	9. 0	5. 00	168	405. 2
5	2. 5	10. 5	5. 00	168	409. 6
6	2. 5	9. 0	3. 75	151	474. 2
7	4. 5	10. 5	5. 00	175	354. 7
8	3. 5	12. 0	2. 50	147	409. 5
9	4. 5	12. 0	3. 75	164	355. 7
10	3. 5	12. 0	5. 00	174	358. 5
11	4. 5	9. 0	3. 75	156	418. 3
12	3. 5	10. 5	3. 75	158	405. 6
13	3. 5	10. 5	3. 75	158	405. 6
14	3. 5	10. 5	3. 75	158	405. 6
15	2. 5	12. 0	3. 75	157	410. 3

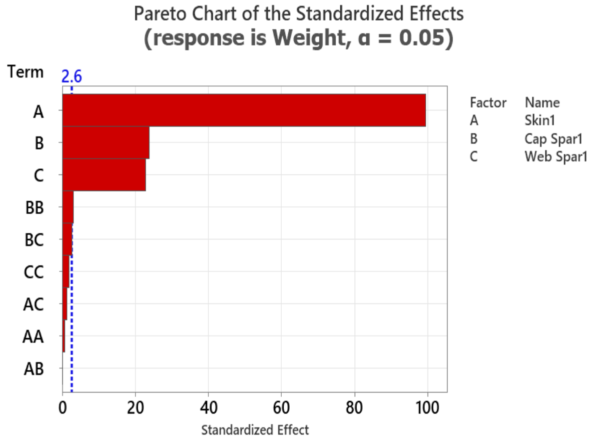


Figure 5. Pareto diagram of the effective factors of weight of the wing

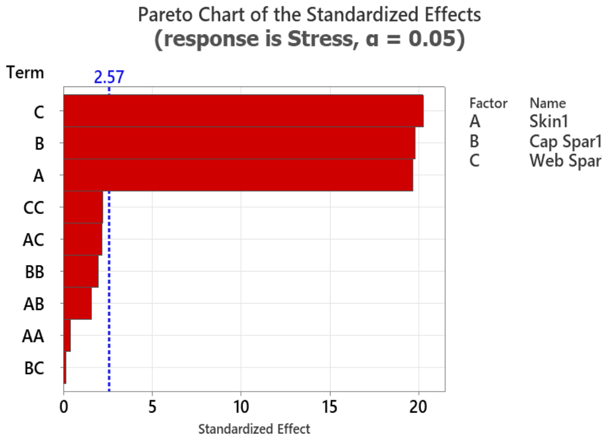


Figure 6. Pareto diagram of the effective factors of tension of the wing box

In this research, according to the optimization goal, which is to reach the maximum allowable Von Mises stress with a value of 335.33 MPa and to minimize the weight of the wing box, the specified goal option for stress and weight minimization has been used in the Minitab software. The optimal values of factors affecting the tension and weight of the wing box, the weight and tension of the optimized wing box can be seen in Figure 7.

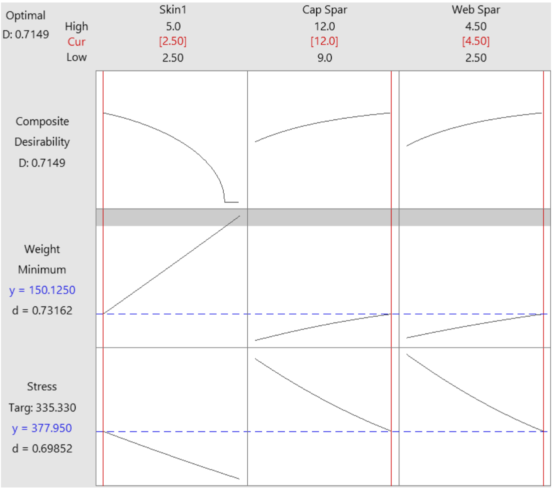


Figure 5. Optimum values of factors affecting stress and weight

5. Conclusions

Although a conclusion may review the main points of the extended abstract, do not replicate the abstract as the conclusion. A conclusion might elaborate on the importance of the work or suggest applications and extensions. Conclusions should include (1) the principles and generalisations inferred from the results, (2) any exceptions to, or problems with these principles and generalisations, (3) theoretical and/or practical implications of the work, and (4) conclusions drawn and recommendations.

6. References

[1] Grihon S, Mahe M (1999) Structhreal and multidisciplinary optimization applied to Aircraft desine. WCSMO-3. Buffalo, NY, USA.

[2] Balabanov V, Garcelon JH (1999) Integrating visuaidoc and genesis for multidisciplinary optimization of a transport aircraft wing. WCSMO-3. Buffalo, NY, USA.

[3] Krog L, Tucker A, Kemp M, Boyd R (2004) Stress analysis and weight optimization of a wing box structure subjected to flight loads. IJES (Vol. 3, pp.33-40).

[4] Guo S, Morishima R, Zhang X, Mills a (2009) *Cutout shape and reinforcement design for composite C-section beams under shear load. Composite Structures* (88, pp. 179-187).

[5] Ainswort J (2010) Airframe wingbox preliminary design and weight prediction. Collier Research Corporation, Published by The Society of Allied Weight Engineers (SAWE) With Permission.

[6] Immanuvel D, Arulselvan K, Maniiarasan P, Senthilkumar S (2014) Stress analysis and weight optimization of a wing box structure subjected to flight loads. *IJES* (Vol. 3, pp.33-40).

[7] Ferroni Soares L (2015) Structural analysis of a wing box. *IRJET* (Vol. 5, pp.23-31).

[8] Pujari C, Patil SF (2016) Stress, fatigue analysis and weight optimization of wing box with splice joint of a transport aircraft. *IJERA* (Vol. 3, Issue 6).