CFD Letters 13, Issue 11 (2021) 87-94

CFD Letters

Journal homepage:
https://semarakilmu.com.my/journals/index.php/CFD_Letters/index
ISSN: 2180-1363

Effect of Cut-Out Shape on the Stresses in Aircraft Wing Ribs under Aerodynamic Load

Jaffar Syed Mohamed Ali[1,*], Wan Muhammad Hafizuddin W. Embong[1], Abdul Aabid[2]

[1] Department of Mechanical Engineering, Kulliyyah of Engineering, International Islamic University Malaysia, 53100, Selangor, Malaysia
[2] Department of Engineering Management, College of Engineering, Prince Sultan University, PO Box 66833, Riyadh 11586, Saudi Arabia

ARTICLE INFO

Article history:
Received 27 August 2021
Received in revised form 19 October 2021
Accepted 22 October 2021
Available online 21 November 2021

Keywords:
Simulation; Stress Analysis; Wing ribs; Cut-outs; ANSYS

ABSTRACT

Ribs in aircraft wings maintain the airfoil shape of the wing under aerodynamic loads and also support the resulting bending and shear loads that act on the wing. Aircrafts are designed for least weight and hence the wings are made of hollow torsion box and the ribs are designed with cut-outs to reduce the weight of the aircraft structure. These cut-outs on the ribs will lead to higher stresses and stress concentration that can lead to failure of the aircraft structures. The stresses depend on the shape of the cut-outs in the ribs and thus in the present work, the commercial software ANSYS was used to evaluate the stresses on the ribs with different shapes of cut-outs. Four different shapes of cut-out were considered to study the effect of cut-out shape on the stresses in the ribs. It was found that the best shape for the cut-outs on the ribs of wings to reduce weight is elliptical.

1. Introduction

Aircrafts are constructed primarily from thin metal skins that are capable of resisting in-plane tension and shear loads. The skins are stiffened by longitudinal stringers that resist the in-plane compressive loads. Besides, the frames and ribs resist concentrated loads in transverse planes and transmit them to the stringers and the spars. Wing ribs maintain the shape of the wing section and assist in transmitting external loads to the wing skin and reduces the column length of the stringer. They are frequently of unsymmetrical shape and possess webs which are continuous except for lightness holes and openings for control runs. The design of a wing depends on many factors, such as the size, weight, speed, rate of climb, and application of the aircraft. The stress analysis of the wing rib requires a complete identification of all the loads acting on its structure. Generally, the wing rib is mainly subjected to aerodynamic loads, including lift force, drag force, pitching moment, and stringers axial force components and the load coming from the body forces in the form of gravitational forces and inertia forces. These types of loads are important for the design of the wing. Hence, several studies have been reported in the literature for the design and analysis of wing and

* *Corresponding author.*
E-mail address: jaffar@iium.edu.my (Jaffar Syed Mohamed Ali)

https://doi.org/10.37934/cfdl.13.11.8794

other parts of aircraft structures. The present literature review is more focused on the wing structural design and analysis using different methods and techniques.

Bindu and Ali [1] used finite element analysis, to study the effect of circular holes in the ribs on the static and buckling strength of the ribs. Yang *et al.,* [2] used the functionally graded material plate (FGMP) which was a unique idea to reduce the weight in the aircraft wing structure. Two-dimensional stress distribution of circular hole on a FGM plate was studied. The numerical results are presented for the FGMPs for a given radial Young's modulus and Poisson's ratio. It was found that as the radial Young's modulus is increased, the stress is decreased and it is less influenced by the variation of the Poisson's ratio. Thus, it was concluded that the stress around the circular hole in the FGMP can be effectively reduced by choosing the proper change of the radial elastic properties. Sandeep and Rao [3] presented the development of a parameterized automated generic model for the structural design of an aircraft wing using finite element method. They used the Topology Optimization techniques for detailed sizing and shape optimization of wing components with stability constraints.

Yang *et al.,* [4] have studied on a three-dimensional stress state using 3D elements and it was found that the maximum stress concentration occurs at the midplane of the plate when the plate is a thin flat plate. From their studies, it has been found that the stress and strain concentration factors of the finite thickness plate are different even if the plate is in an elasticity state except at the notch root of the plate surface. Moreover, they stated that the location of the maximum concentration moves away from the midplane of the plate with increasing plate thickness. Similar to this, Dhanjal and Arora [5] analyzed a rectangular plate with a circular hole at the centre using finite element analysis (FEA). For tensile loading, it was reported that as the ratio of plate thickness to hole diameter increases the stresses reduced. Mekalke *et al.,* [6] analysed a plate subjected to uniform stress with a circular hole and observed the difference in the results which is obtained from multiple meshes using the NASTRAN/PATRAN program with meshing algorithm and found that the Middle-Ruled mesh offers a symmetric response in the plots whereas the other meshes don't offer that symmetry of solution to a desirable extent. More and Bindu [7] studied the effects of element size on accuracy of simulations using FEM for static and buckling analysis of plates and concluded that an element size of 40 mm is required for accurate static analysis.

Shabeer and Murtaza [8] determined an effective model for optimal design by modelling the wing structure that blends composite skin with isotropic materials of the other wing components. By measuring stress and displacement, the optimum design for each wing with different ply orientations was obtained. Kavya and Reddy [9] studied the bending, buckling and vibration analysis of composite wings made of S Glass, Kevlar 49, and Boron Fibre composite materials using ANSYS software. Wang *et al.,* [10] used finite element model of the wing reduced by using the equivalent strength and stiffness method. Three-step optimization was used to improve structural efficiency. Static strength and buckling are used as a constraint in this optimization strategy.

The composite wing rib optimization analysis, where an optimization of the amount of ply and stacking sequence resulting in an optimum design weight was obtained by Kandemir [11]. Besides, Panettieri *et al.,* [12] applied global/local modelling techniques of structural analysis to optimize structural wing box configuration of the civil aircraft for least weight. Zakuan *et al.,* [13] investigated the static and modal analysis of a three-dimensional wing using ANSYS finite element package. Recently, Basri *et al.,* [14] studied the stress analysis of wing made of NACA4415 under an aerodynamic load generated using Schrenk's approximation.

From the above literature survey, it can be noted that the stress analysis of aircraft wings using modern tools is an active field of research and the effect of cut-outs made on such aircraft structures is of primary interest as it can lead to high stress concentration. Bairavi and Balaji [15] and recently Dharmendra *et al.,* [16] has analyzed the effect of different cut-out shapes on the stresses in the ribs using Finite Element Analysis. In both the above studies, the ribs alone were analyzed as a two-dimensional body without considering the actual structure of the wing. In the present work the ribs are taken as an integral part of the wing and the aerodynamic lift load are applied on the wing to know the actual effect of complex loading on the stresses in the rib with different cut-out shape. Thus, in the present study the effect of various shapes of cut-outs on the resulting stress on the ribs of an aircraft wing is analysed using ANSYS software.

2. Modelling and Simulation

In this work, SolidWorks software was initially used to model the wing with different cut-out shapes and then ANSYS software was used to mesh and analyze for stresses. The effect of four different cut-out shapes viz. circular, triangular, square and elliptical, on the stresses on the rib were analyzed and compared. The wing rib material was taken to be Aluminium 2024-T3 which is used in aircraft structure because of its high strength and fatigue resistance properties. The model was imported from SolidWorks to ANSYS, then the model with the wing ribs was meshed before applying the boundary condition and loading conditions. The properties of the material used for the rib is as shown in Table 1.

Table 1
Material properties

Properties	Aluminum 2024-T3
Density	2770 kg/m³
Yield strength	280 MPa
Ultimate strength	440 MPa
Young's modulus	71000 MPa
Poisson's ratio	0.33
Bulk Modulus	69608 MPa
Shear modulus	26692 MPa

The shape of the ribs was taken to be as of NACA 4415 airfoil. The position and size of the cut-outs on the ribs are taken from the data of typical existing aircraft wing ribs. In the present study, in each rib, three different sizes of cut-outs were made, with 22698 mm² for the biggest one, 15393 mm² for the medium, and 9503.32 mm² for the smallest size as shown in Figure 1, for the wing ribs with circular cut-outs. Similarly for all other cut-out shapes, three different size cutouts were made with the same areas as defined for circular cut-out.

The wing ribs have been extruded to a thickness of 1 mm. The model of ribs shown in Figure 1 and Figure 2 is based on the configuration of the actual wing ribs. The position and the way the wing ribs were connected to the wing spars were exactly similar to those made on the actual the aircraft wings. With the data from the NACA 4415 airfoil, the wing ribs were sketched as shown in Figure 1. Ten ribs are considered, and they are located with a distance of 500 mm between them.

The wing spars were modelled separately and then the spars were attached to the ribs using Boolean features. This process is very important which enables the wing ribs and the spars to become as one integral part. This is to ensure that the force applied to the wing ribs will also be transmitted to the spars. These steps were repeated for other different shapes of cut-outs.

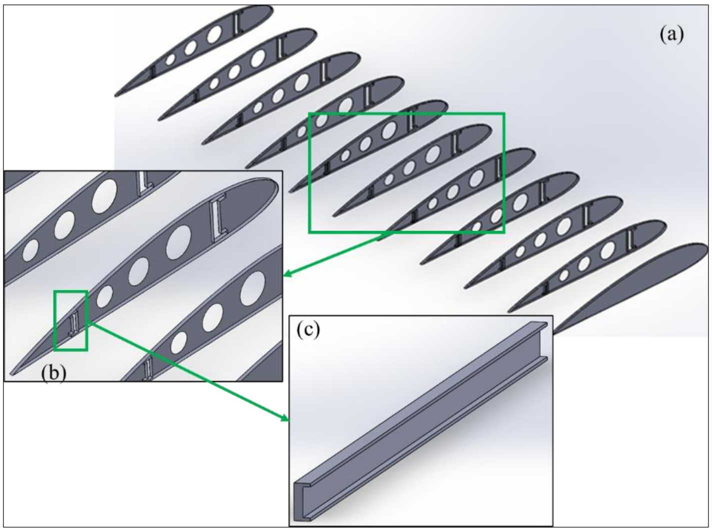


Fig. 1. Finite element model (a) Wing ribs (b) Wing ribs design for attachment of wing spars (c) Model of wing spars

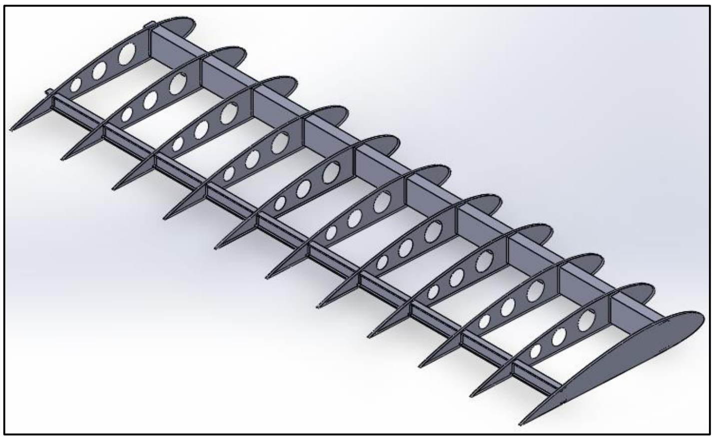
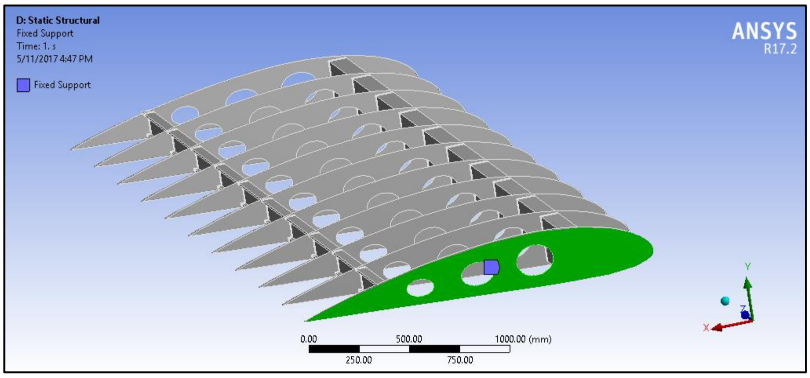
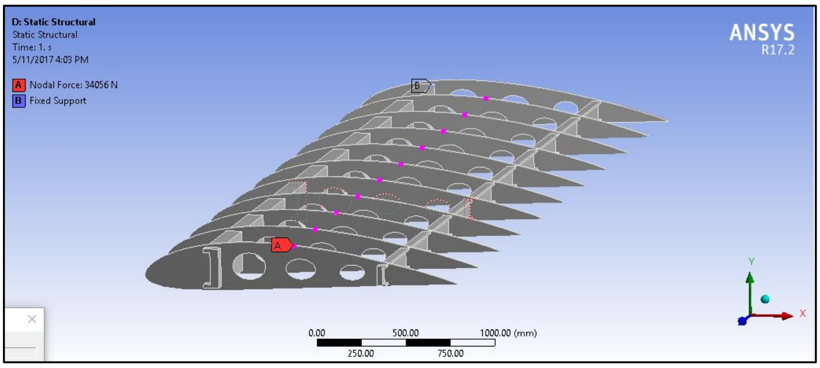


Fig. 2. Spars were assembled to the ribs

After the completion of the wing ribs modelling in the SolidWorks, the mesh is generated using the auto mesh option in the ANSYS workbench. Then the process was proceeded by placing the support and loading on the ribs. The material was selected from the general engineering data for Aluminum alloy through the ANSYS workbench data. Clamped boundary conditions were applied on one end of the wing as shown in Figure 3(a), and the pink dot color in Figure 3(b) indicates the nodal center of the wing ribs about which the aerodynamic forces have been applied.



(a)



(b)

Fig. 3. (a) Fixed support boundary conditions (b) Nodes for applying aerodynamic force

3. Results and Discussion

To calculate the aerodynamic load on the wings, the aircraft was taken to be in cruise phase of flight, where the aircraft will be in steady level flight with lift equal to the weight, thus the force acting on the wings is equal to the weight of the aircraft. The force acting on the wing was calculated as follows: the weight of a typical aircraft is taken from the literature, such as Boeing 737 with a mass of 85139.3 kg (851392.8 N), thus for the semispan wing considered for analysis, the loading on one wing is 425696.44 N which was then equally divided by the 10 ribs, thus 42569.6 N of load is applied at every rib at the nodal center of the wing ribs (the pink dot color) in Figure 3(b). The wing is considered to be a cantilever; thus, one end of this wing has been fixed i.e., with all 6 Degree of Freedom (DOF) were arrested as shown in Figure 3(a).

3.1 Convergence Study

The effect of mesh size was studied before proceeding to the investigation of different cut-outs. The number of elements was varied until convergence was achieved. The value of Von-Mises stress at the hole was considered for investigation and the results obtained are presented in Table 2 which shows for different element sizes. Based on Table 2 the element size of the mesh can be concluded. The mesh size that would be used is 150mm size as the value of the result has only 0.1% difference between each other and it will also take less computational time to run the simulation.

Table 2
Convergence study results

Element size (mm)	Stress value (MPa)
150	226.09
130	226.31
110	226.39

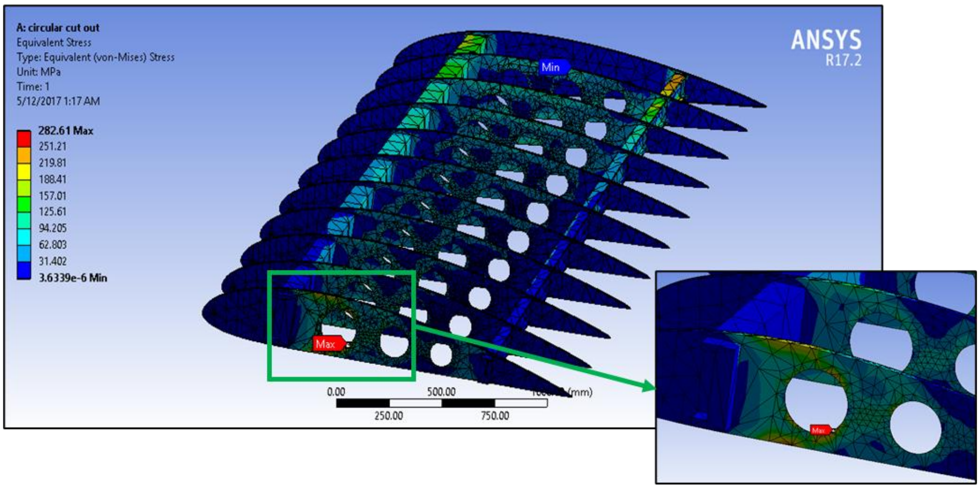
3.2 Stress Analysis of Wing Ribs

The load was applied at the center of the wing ribs as mentioned previously. One end of this wing has been fixed with all 6 Degree of Freedom (DOF) arrested. Thus, the maximum stresses will occur on the rib at the root of the wing. Table 3 gives the results of the maximum Von-Mises stresses around the cut-out for all four cut-out shapes on the rib at the root of the wing. As mentioned earlier, of the three sizes of cut-out on every rib, the highest stresses reported here are from the biggest cut-out on the rib at the root of the wing.

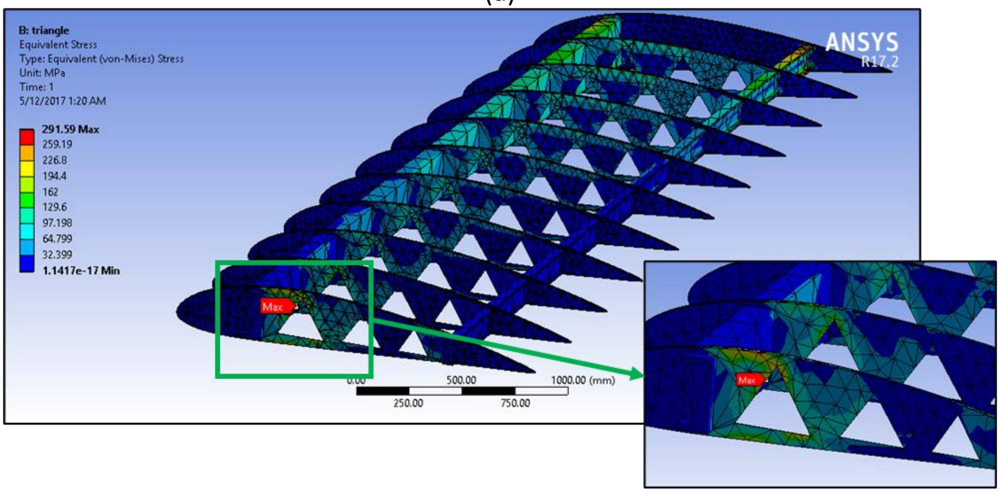
Table 3
Stress values at different shapes of the cut-out

Cut-out shape	Maximum Stress (MPa)
Circular	282.61
Rectangular	284.56
Triangular	291.59
Elliptical	205.48

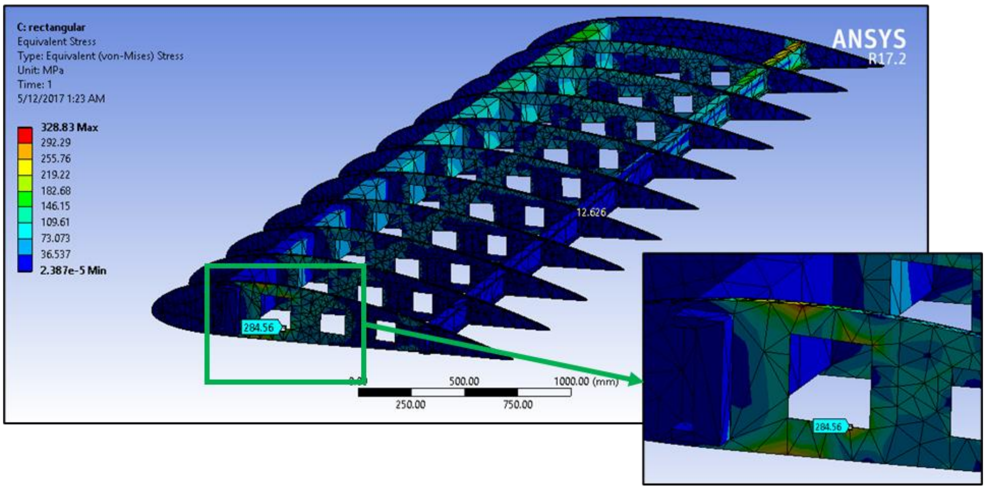
Three-dimensional view of Von-Mises stress distribution for each cut-out can be seen in Figure 4. The variation of Von-Mises stresses with maximum and minimum stress concentration around the surface of the edge is observed and it is found that the location of maximum stress in each cut-out is different depending on its shape.



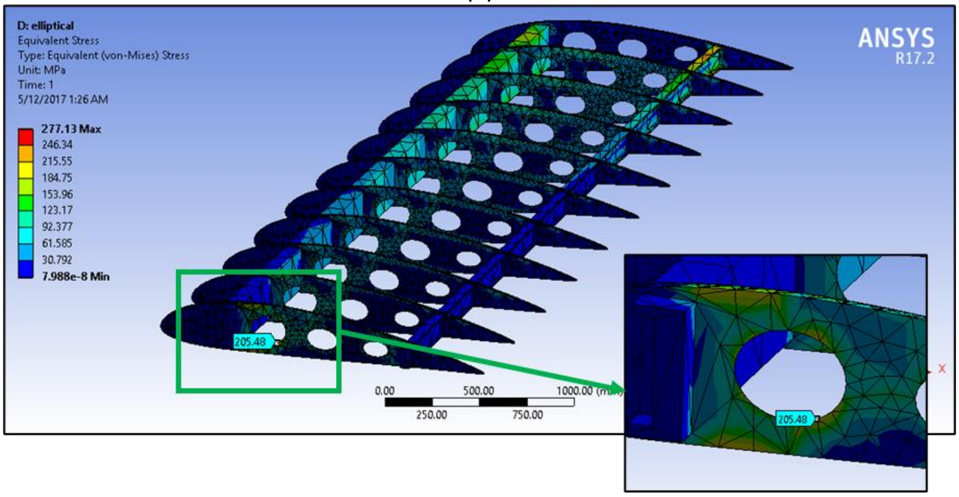
(a)



(b)



(c)



(d)

Fig. 4. Von-Mises Stresses for (a) circular cut-out (b) triangular cut-out (c) square cut-out (d) elliptical cut-out

Based on the present study, the elliptical cut-out shape shows lowest value of Von-Mises stress at the boundaries of cut-out followed by a circular and rectangular cut-out shapes. The cut-out shapes with sharp edges like rectangular and triangular give higher stress values, thus it is understood that the shape of cut-outs with corners (edges) are not suitable to be designed as wing ribs cut-out.

4. Conclusions

The effect of cut-out shape on the stresses in aircraft wing ribs is studied using ANSYS. Framework of the wing with ribs was constructed and assembled using SolidWorks with the dimensions of the cut-outs and their distances taken very similar to that of existing aircrafts. The aerodynamic load of a typical aircraft was used to find the stresses on the ribs. Von-Mises stresses on four different cut-out shapes viz. circular, elliptical, rectangular, and triangular were compared and as expected the shapes with sharp corners lead to higher stresses whereas the circle and elliptic shapes resulted in lower stresses. For the given loading, the maximum value obtained from the stress analysis was between the range of 205.48 MPa to 291.59 MPa for these four shapes of cut-out. The elliptical cut-out resulted in the lowest stress experienced by the wing ribs as compared to other cut-out shapes.

Acknowledgement
This research was not funded by any grant.

References

[1] Bindu. H. C., and Muhammad Muhsin Ali. "Design and Analysis of a Typical Wing Rib for Passenger Aircraft." *International Journal of Innovative Research in Science, Engineering and Technology* 2, no. 7 (2013): 3130-3136.
[2] Yang, Quanquan, Cun-Fa Gao, and Wentao Chen. "Stress analysis of a functional graded material plate with a circular hole." *Archive of Applied Mechanics* 80, no. 8 (2010): 895-907. https://doi.org/10.1007/s00419-009-0349-3
[3] Sandeep, Darla, and A. Nageswara Rao. "Optimized design and analysis for the development of aircraft droop nose ribs." *International Journal of Modern Research & Development* 1, no. 7 (2014): 34-41.
[4] Yang, Zheng, Chang-Boo Kim, Chongdu Cho, and Hyeon Gyu Beom. "The concentration of stress and strain in finite thickness elastic plate containing a circular hole." *International Journal of Solids and Structures* 45, no. 3-4 (2008): 713-731. https://doi.org/10.1016/j.ijsolstr.2007.08.030
[5] Dhanjal, Saksham, and Richa Arora. "Stress analysis of a rectangular plate with circular hole using three dimensional finite element model." *International Journal of Engineering, Business and Enterprise Applications (IJEBEA)* 12, no. 1 (2015): 77-80.
[6] Mekalke, G. C., M. V. Kavade, and S. S. Deshpande. "Analysis of a plate with a circular hole by FEM." *Journal of Mechanical and Civil Engineering* (2012): 25-30.
[7] More, Shashikant T., and R. S. Bindu. "Effect of mesh size on finite element analysis of plate structure." *International Journal of Engineering Science and Innovative Technology* 4, no. 3 (2015): 181-185.
[8] Shabeer, K. P., and M. A. Murtaza. "Optimization of aircraft wing with composite material." *International Journal of Innovative Research in Science, Engineering and Technology* 2, no. 6 (2013): 2471-2477.
[9] Kavya, Guguloth, and B. C. Raghukumar Reddy. "Design and finite element analysis of aircraft wing using ribs and spars." *International Journal & Magazine of Engineering Technology, Management and Research* 2, no. 11 (2015): 1443-1455.
[10] Wang, Yu, Xing Ouyang, Hailian Yin, and Xiongqing Yu. "Structural-optimization strategy for composite wing based on equivalent finite element model." *Journal of Aircraft* 53, no. 2 (2016): 351-359. https://doi.org/10.2514/1.C033469
[11] Kandemir, Can. "Weight Optimization of An Aircraft Wing Composite Rıb Using Finite Element Method." *Master thesis, School of Science and Engineering of Hacettepe University* (2020).
[12] Panettieri, Enrico, Marco Montemurro, Daniele Fanteria, and Francesco Coccia. "Multi-scale least-weight design of a Wing-box through a global/local modelling approach." *Journal of Optimization Theory and Applications* 187, no. 3 (2020): 776-799. https://doi.org/10.1007/s10957-020-01693-y
[13] Zakuan, Muhammad Amir Mirza Bin Mohd, Abdul Aabid, and Sher Afghan Khan. "Modelling and Structural Analysis of Three-Dimensional Wing." *International Journal of Engineering and Advanced Technology* 9, no. 1 (2019): 6820-6828. https://doi.org/10.35940/ijeat.A2983.109119
[14] Basri, Ernnie Illyani, Adi Azriff Basri, Mohd Firdaus Abas, Faizal Mustapha, Mohamed Thariq Hameed Sultan, and Kamarul Arifin Ahmad. "UAV NACA4415 wing structural performance analysis subjected to external aerodynamic load using Schrenk's approximation." *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences* 60, no. 2 (2019): 178-190.
[15] Bairavi, S., and Suresh Balaji. "Design and Stress Analysis of Aircraft Wing Rib with Various Cut Outs." *Indian Journal of Applied Research* 6, no. 4 (2016): 511-514.
[16] Dharmendra, P., K. J. Chaithanya, Ayesha Sameera, Khyati Kavathiya, and K. M. Monika. "Design And Analysis Of An Aircraft Wing Rib For Different Configurations." *International Research Journal of Engineering and Technology* 7, no. 6 (2020): 180-192.