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Finite Element Analysis of the Main Structure for a New Conceptual Aircraft Passenger Vertical Seat Design

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ABSTRACT

Standing cabin is a new design concept of aircraft passenger cabin whereby passengers are transported in the standing position throughout flight as opposed to current seated position. An important element of this cabin concept is the design of the vertical seat to support the passengers, which has to be in compliance with requirements of aviation regulation. In commercial aircraft applications, weight of passenger seat is a significant factor that can affect flight performance of the aircraft. Meanwhile, the seat's structure should have adequate strength to ensure proper safety provision to passengers. Hence weight and strength are potentially two conflicting design requirements for the vertical seat, and the optimum structural design should have the best compromise with regards to these two requirements. In this study, parametric study on primary structural design of the proposed vertical seat concept is done to obtain an optimized design that satisfies the strength requirements for safety of passengers without causing high penalty to the overall aircraft weight and performance. The simulation analysis for the main structures of the vertical seat design is conducted through finite element method using ABAQUS software. From the results of the analysis, main structural parts made from aluminium alloy with diameter 90 mm and thickness 3 mm are selected for the optimum vertical seat design. This standing seat design has also been shown to have adequate strength and can satisfy the safety regulation requirement without failure. The maximum stress on the seat's structure under 9-g forward loading is found to be 147.5 MPa, which is lower than ultimate strength of aluminium. Moreover, the seat's weight is estimated to be 9.5 kg and the maximum deflection of its main structures under forward 9-g loading is 28.42 mm. All in all, the stress analysis results highlight that the structural strength of the optimal vertical seat design can satisfy the requirements of the governing aviation regulations to provide safety to passengers.

1. Introduction

Passenger standing cabin has been one of the proposed solutions to reduce the operational flight costs per passenger. In this novel cabin concept, aircraft passengers are envisioned to be transported in their standing position instead of current seated position as illustrated in Figure 1. By having larger

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numbers of passengers per flight, the costs per passenger and subsequently passenger's flight ticket price could be reduced, making flight services more affordable to the public [1]. Moreover, this cabin concept is also anticipated to create a new market segment of aircraft passengers, similar to the way low-cost airlines have revolutionized the airlines industry before. Even though this cabin design idea has already been around for a while, it is rather unfortunate that the number of reported or published design engineering studies related to it in public domain is very scarce or close to none. This is despite that there has been a patented design of standing cabin by Airbus, which is one of the world's leading aircraft manufacturers, and also expressed strong interests over the years from several airlines such as Spring Airlines (China), Ryanair (United Kingdom), Tiger Airways (Singapore) and also VivaColumbia (Columbia) [2]. All these indicate that there exists a great potential and interest for this new aircraft cabin concept within the airlines industry.

The heart of any passenger cabin design is the seat. In general, aircraft passenger seat is not just designed for comfort but also to provide appropriate safety level to the passengers during flight [3]. Similarly, for the standing cabin concept, aircraft passengers will be supported by what is called as a vertical seat as shown in Figure 1. In previous published design work by the authors, several potential designs of the vertical seat to be used in the standing cabin concept have been generated, taking into account all the established design requirements [4,5]. The best vertical seat design among these few alternatives has been chosen through application of multi-attribute decision making method with the involvement of several stakeholders and the selected design concept is depicted in Figure 2.

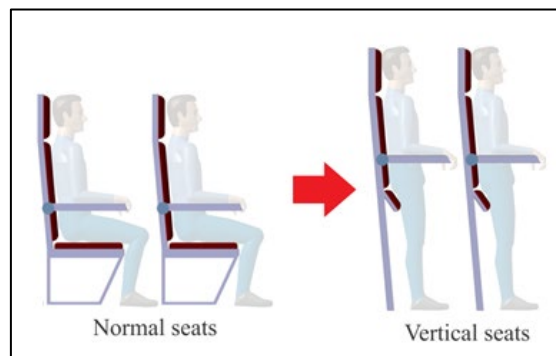


Fig. 1. Conventional versus standing cabin [6]



Fig. 2. Selected vertical seat design concept

It is well-known that safety is always a prime consideration in aviation and passenger seat design to be applied inside the commercial aircraft cabin is subject to requirements as outlined in governing regulations by the regulatory bodies [7]. In terms of the requirements on passenger seat's structural strength, this is mainly to ensure that passengers would be adequately protected in the event of any flight incidents or accidents. At this moment, no passenger seat design for the standing cabin concept has been certified for commercial aircraft use and a crucial initial step towards that is to demonstrate the capability of the vertical seat design to provide a proper support to the passengers during flight. Following this notion, the presented research work in this paper is focused on the structural analysis of the selected vertical seat design. In this study, the main interest for the FEA simulation analysis is the main support structure, which highly contributes to the overall strength and acts as the backbone of the vertical seat design.

2. Methodology

In the design of aircraft passenger seat, there is a potential conflict between its structural strength and weight. Having a greater structural strength is preferred for passengers' safety but this is usually linked to heavier structural weight. To arrive to an acceptable compromise, a design parametric study is conducted by using computer-aided design (CAD) model of the chosen vertical seat design concept for simulation analysis of its weight and strength. It should be noted that parametric study has been a frequently applied method in various engineering product design and development processes, for instances, in the design of blade distributor [8], antenna [9] and also jet actuator [10]. For this study, the interested design parameters to be varied are thickness and diameter for the main structures of the vertical seat since both have a direct effect on its resultant strength and weight. The thickness is varied at three levels whereas the diameter is considered at five different values. Additionally, three materials are also studied for the main seat structures: aluminum, stainless steel and titanium, which are the common materials used in current aircraft passenger seat structures. All in all, based on full-factorial design of experiment (DoE) approach, a total of 45 different simulation case settings needs to be analyzed in this parametric study. This also means 45 variations of the CAD model for vertical seat design concept are required for the simulation analysis, which is done using CATIA software tool.

While structural weight for each variation of the vertical seat design can be directly estimated in CATIA, the maximum deflection under the prescribed loadings of the regulation is simulated through the finite element analysis (FEA) using ABAQUS software tool. FEA is a widely-accepted method that is used to estimate the deflection and stresses of a structure under loadings. Some examples of FEA application include for vehicle's crash investigation [11], aeroelastic effects on the aircraft's wing [12] and design of automotive seat frame [13]. It is noted that no specific aviation regulation for standing passenger seat design exists as of now and therefore, current regulation for conventional passenger seat design is applied in this study. Figure 3 shows the specified critical loads in the forward, sideward, downward, rearward and upward directions that must be considered in the structural analysis and testing of the aircraft passenger seat. It can be noted from the figure that the most constraining load is in forward direction, which is of 9-g magnitude. For conceptual design development of new aircraft seat, it is often focused on satisfying the most critical 9-g forward certification loading. This is based on the notion that, if the seat structure can sustain a maximum forward 9-g force, it will also be able to withstand those lower forces at different directions without breaking. Furthermore, the resultant deflection of the seat structure under the forward inertia load is critical to dictate the allowable pitch between the rows of seats.

The current aviation regulations do not require passengers to be transported onboard the aircraft in a seated position as long as they are appropriately secured by certified safety mechanism. In view

of this, the vertical seat design must be equipped with effective safety mechanism. Due to standing position of the passengers during flight for the standing cabin concept, a four-point lap and shoulder harness system has been deemed more appropriate. According to Advisory Circular by the Federal Aviation Administration (AC No. 21-34), for assessment of the three-point lap and shoulder harness system in a static test, the loading distribution could be defined as 40% to the shoulder harness and the other 60% to the lap seat belt. Adopting a similar assessment requirement for the four-point lap and shoulder harness system, and referencing to the SAE 8049 Static Test Set Up for passenger seat, the defined loading for FEA simulation analysis is indicated in Figure 4.

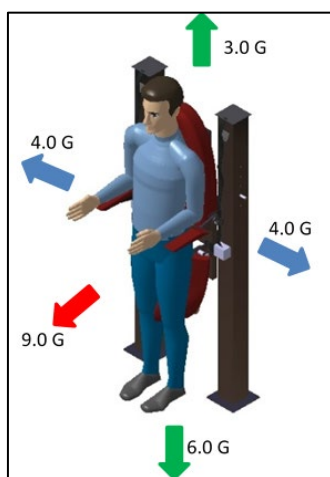


Fig. 3. Static loading conditions for stress analysis as specified by the aviation regulation

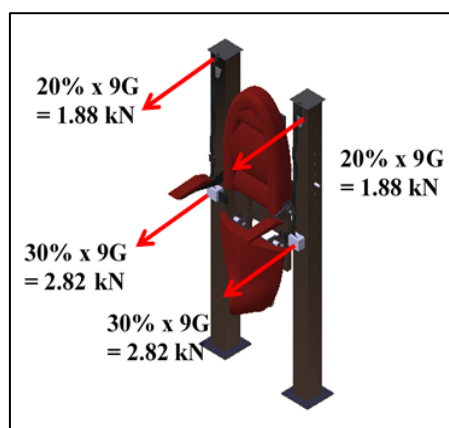


Fig. 4. Defined loading for FEA simulation and acting points for the force loading with four-point restraint system

In reference to the typical estimations of passenger's mass that are suggested for use in aircraft conceptual design process, an average mass of 80 kg is taken as the estimated mass of the passenger for the simulation analysis. This is in agreement with the Federal Aviation Regulation (FAR) and Joint Aviation Requirements (JAR) that both specify a minimum passenger's mass of 77 kg for certification. Under JAR and FAR regulation, the safety factor of 1.33 should be multiplied to the load to determine the required strength of the seat. This means that the mass is approximated to be 106.4 kg for every

passenger by including the safety factor. Subsequently, the final magnitude of this force is calculated as 106.4 kg multiplied by 9 times gravitational acceleration of 9.81 m/s², which gives 9.4 kN. The 9-g force condition is applied here since this is the most extreme loading case as per regulation and it is important that the main support structure does not significantly deflect under such loading since the seat pitch is preferred to be as small as possible to accommodate more seats within the cabin.

As indicated before, two main design considerations in commercial transport aircraft application are taken into account in the optimization of this vertical seat design, which are strength and weight of the seat. In this study, the strength factor is represented by the maximum deflection of the seat's main structure. Moreover, the optimization process should also include any design constraints that have to be satisfied, which can be formulated to ensure that the optimized vertical passenger seat is competitive against its market competitors. The first considered constraint is in terms of its structural weight. It is known that current typical conventional aircraft passenger seat in economy class usually weighs between 12 kg to 13 kg. It is therefore preferred that weight of the vertical seat to be lighter than these conventional seats. Considering that seat cushions and other non-structural parts of the seat will take around 1 kg of mass, the constraint for the structural weight of the vertical seat is set to be less or equal to 12 kg. Meanwhile, the second constraint is set for the maximum deflection of the main seat's structure under the standard test loadings, which reflects on the structural strength of the seat. In this case, following the proposed seating arrangement for the standing cabin concept [14], the seat pitch of 508 mm is targeted. It should be noted that the initial sizing of the vertical seat has been tailored to suit the Malaysian anthropometry measurements, which results in an allowance of 415 mm for the backrest seat cushion's thickness and the head's diameter of the seat's occupant. This leads to a design constraint for maximum seat deflection to be less or equal to 93 mm, which is the allowable forward deflection before passengers could hit the back of the seat in front of them.

For the design optimization process, since both seat's weight (or mass) and maximum deflection are to be minimized, a single objective function equivalent to the product of these two values can be formulated and used. Using the FEA simulation analysis result and also estimated mass from CATIA for each design case, a mathematical model that relates the objective function with the two varying design parameters (i.e. thickness and diameter of the vertical seat's main structures) can be derived using Response Surface Methodology (RSM). The widespread application of RSM in product design optimization process has been evident in numerous studies including in the design of flapping wings of micro air vehicles [15], airship [16] and automotive rubber bumpers [17]. In this study, derivation of the mathematical model (also known as response surface equation or meta-model) is done using statistical software, MINITAB. Once the objective function model is derived, the setting for structural design variables (i.e. diameter and thickness) that is corresponding to optimum value of the objective function can be determined.

3. Results and Discussion

Example outputs of the FEA simulation analysis in ABAQUS are depicted in Figure 5 and Figure 6, which are for stress and deflection plots, accordingly, for the aluminum design cases with a diameter of 90 mm and thickness of 5 mm. On the other hand, summary of simulated outputs for all 45 design cases of the vertical seat are tabulated in Table 1. In addition, estimated mass obtained from CATIA for each of these 45 design cases is also included in Table 1. Recalling the two design constraints for this vertical seat design, which indicate that its structural weight must be less or equal to 12 kg and its maximum deflection must be 93 mm, it could be observed from Table 1 that the most likely design to be able to simultaneously fulfill these two conditions is among those using the aluminum material. It can be observed that the structural mass penalty from using stainless steel and titanium materials

has been too heavy, even though their performance in terms of maximum deflection is much better than that for aluminum. Based on this assessment, aluminum is decided to be the material for main structures of the vertical seat design.

Subsequently, data for all aluminum design cases is statistically analyzed for design optimization process using the statistical software, MINITAB. The backward elimination method is applied for the regression model fitting in MINITAB, which starts with the full or saturated model and the predictor variables are eliminated from the regression model in iterative process one by one. This ensures that all possible variations of the predictor variables have been considered first before being eliminated from the final constructed regression model if they are deemed insignificant. In this study, two-sided confidence interval of 95% and alpha-to-remove of 0.1 are used, which are recommended standard settings in MINITAB.

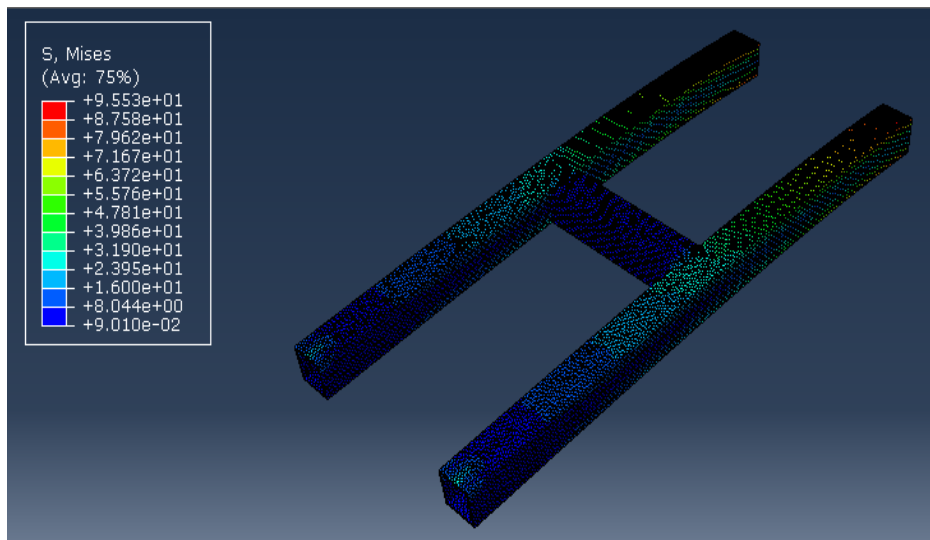


Fig. 5. Stress plot from FEA analysis for aluminum design case with diameter of 90 mm and thickness of 5 mm

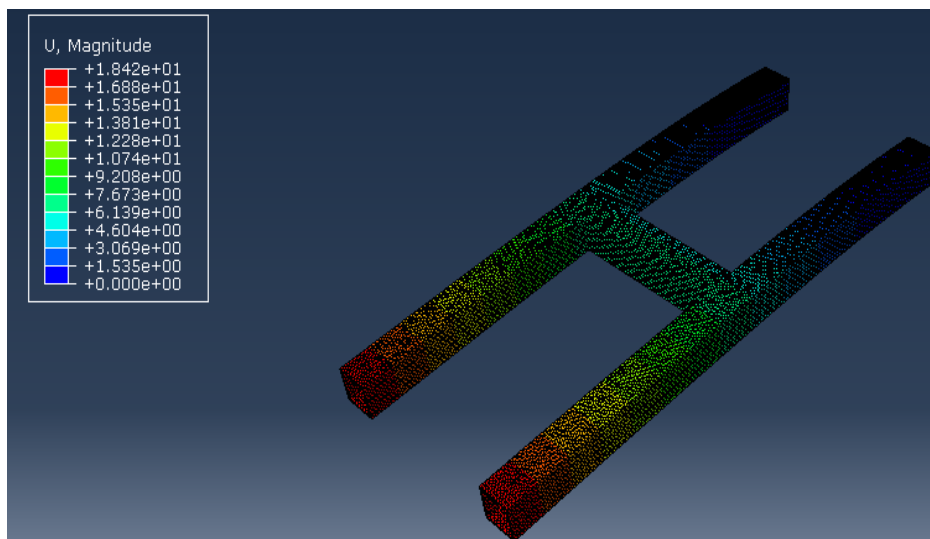


Fig. 6. Deflection plot from FEA analysis for aluminum design case with diameter of 90 mm and thickness of 5 mm

Table 1
 Simulation outputs for considered design cases

Material	Diameter (mm)	Thickness (mm)	Estimated mass (kg)	Maximum deflection (mm)	Maximum stress (N)	Objective function (kg.mm)
Stainless	90	5	44.86	6.89	97.130	309.09
Steel, AISI 304	90	4	36.31	8.29	115.40	301.01
	90	3	27.55	10.63	148.50	292.86
	80	5	39.70	9.88	122.50	392.24
	80	4	32.19	11.87	145.70	382.10
	80	3	24.46	15.14	186.90	370.32
	70	5	34.51	14.99	164.70	517.30
	70	4	28.03	17.90	198.00	501.74
	70	3	21.34	22.89	249.60	488.47
	60	5	29.29	24.37	227.30	713.80
	60	4	23.86	28.93	270.80	690.27
	60	3	18.21	36.41	529.10	663.03
	50	5	24.03	43.21	344.50	1038.34
	50	4	19.65	50.62	401.30	994.68
	50	3	15.06	62.84	526.30	946.37
Aluminum Alloy 7075-T6	90	5	15.47	18.42	95.53	284.96
	90	4	12.52	22.18	114.80	277.69
	90	3	9.50	28.42	147.60	269.99
	80	5	13.69	26.42	121.80	361.69
	80	4	11.10	31.73	145.50	352.20
	80	3	8.43	40.49	186.80	341.33
	70	5	11.90	40.05	164.30	476.60
	70	4	9.67	47.85	197.20	462.71
	70	3	7.36	61.15	248.90	450.06
	60	5	10.10	65.07	226.90	657.21
	60	4	8.23	77.25	270.20	635.77
	60	3	6.28	97.26	514.40	610.79
	50	5	8.29	115.30	343.10	955.84
	50	4	6.78	135.10	425.80	915.98
	50	3	5.19	167.80	523.40	870.88
Titanium	90	5	25.46	11.53	95.53	293.55
	90	4	20.61	13.88	114.80	286.07
	90	3	15.63	17.79	147.50	278.06
	80	5	22.53	16.54	121.80	372.65
	80	4	18.26	19.87	145.50	362.83
	80	3	13.88	25.35	186.80	351.86
	70	5	19.58	25.07	164.30	490.87
	70	4	15.91	29.96	197.20	476.66
	70	3	12.11	38.29	248.90	463.69
	60	5	16.62	40.74	226.90	677.10
	60	4	13.54	48.37	270.20	654.93
	60	3	10.33	60.89	514.40	628.99
	50	5	13.64	72.21	343.10	984.94
	50	4	11.15	84.61	425.80	943.40
	50	3	8.55	105.10	523.40	898.61

The fitted regression model for relationship between the objective function value and the design parameters (i.e. diameter and thickness of the main seat's structure) in aluminum cases is presented in Table 2. This model has corresponding R^2 value of 99.99%, which means that it has good goodness-of-fit measure and properly captures the variation of the objective function values that is collectively explained by the seat's diameter and thickness parameters. Based on this model, main effects plot

for the design parameters is shown in Figure 7. It can be noted that the curves for both diameter and thickness parameters have a slope, which means that both have significant effects on the objective function value. Finally, through the available “Response Optimizer” feature in MINITAB that assists in finding the optimal point of a mathematical model, the vertical seat’s main structure design can be optimized using the fitted regression model. In this case, optimum setting for the diameter and thickness of the vertical seat’s main structure is found to be 90 mm and 3 mm, respectively.

Table 2
 Fitted regression model in MINITAB

Term	Coefficient value
Constant	4240
Diameter (mm)	-128.29
Thickness (mm)	211.70
Diameter*Diameter (mm ²)	1.4644
Diameter*Thickness (mm ²)	-4.831
Diameter*Diameter*Diameter (mm ³)	-0.005916
Diameter*Diameter*Thickness (mm ³)	0.02857

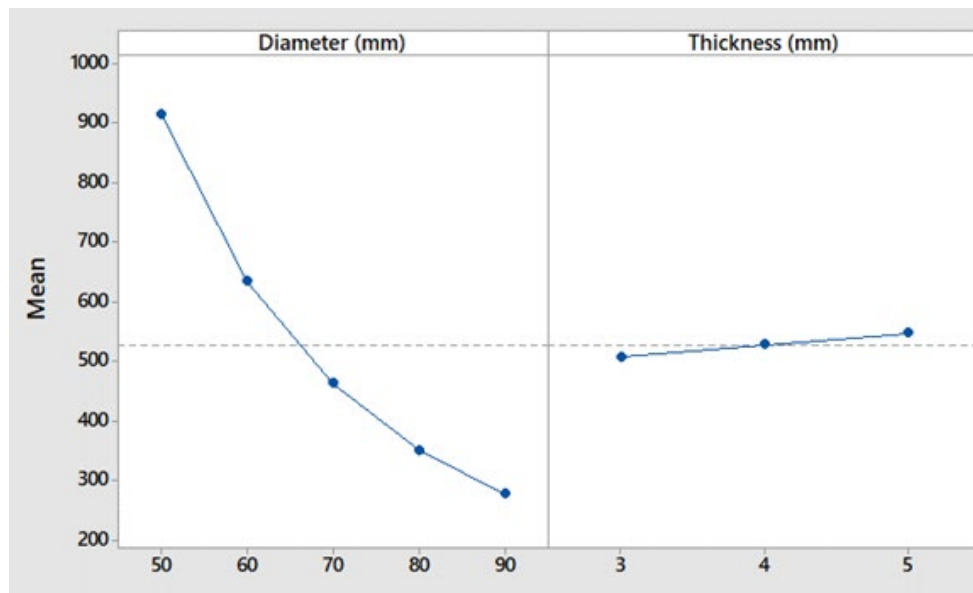


Fig. 7. Main effects plot for the objective function value using aluminum material

In accordance with the results of the structural analysis and design optimization process, the final vertical seat design is illustrated in Figure 8. The material for its main structural frame is aluminum, with diameter and thickness of 90 mm and 3 mm, respectively. It is established that the certification requirements for aircraft passenger seat design based on the current aviation regulations necessitate it to be able to withstand the most critical 9-g forward loading without failure. As inferred by the FEA simulation output from ABAQUS for this optimal vertical seat design in Figure 9, resultant maximum stress on the seat’s main structures is 147.5 MPa, which is much lower than the ultimate strength of aluminum that is 570 MPa. This means that the seat’s structures will be able to withstand 9-g forward loading without failure. Furthermore, since the certification loadings in the other directions are less than 9-g as indicated in previous Figure 3, this implies that the seat structures should be able to satisfy those certification requirements as well.

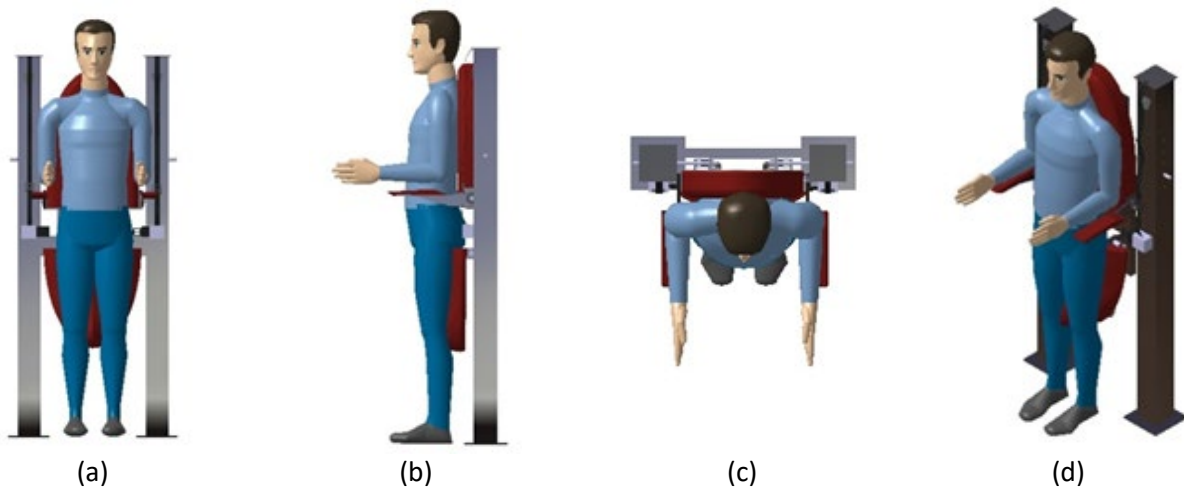


Fig. 8. Illustration of final vertical seat design (a) front view (b) side view (c) top view (d) isometric view

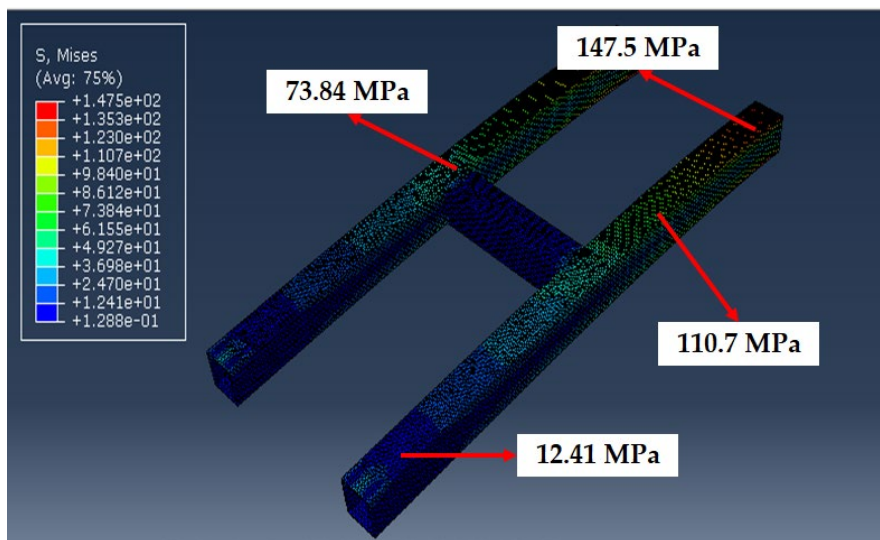


Fig. 9. Structural stress plot for optimal vertical seat design

In addition, it is noted that the yield strength of aluminum is 500 MPa, which is also still much higher than maximum stress of 147.5 MPa from the 9-g loading. This implies that the seat's structures can return to its original shape once the forward loading is relieved without any permanent structural deformation or deflection since this loading situation is still within its elastic region. This capability is very important for the provision of safety to the passengers and the maximum deflection under the forward loading is used to determine the appropriate seat pitch between the seat rows. As shown in Figure 10, maximum deflection recorded for the main structure of the optimal vertical seat design is found to be only 28.4 mm, which comfortably satisfies the design constraint of less or equal 93 mm for the maximum deflection. This also means that it is possible to reduce the seat pitch even further without affecting the level of safety provision to passengers, hence increasing the beneficial impacts of the standing cabin in favor of the operating airlines. Last but not least, the estimated mass of the main structures for the optimal vertical seat design is 9.5 kg, which is below the constraint of 12 kg.

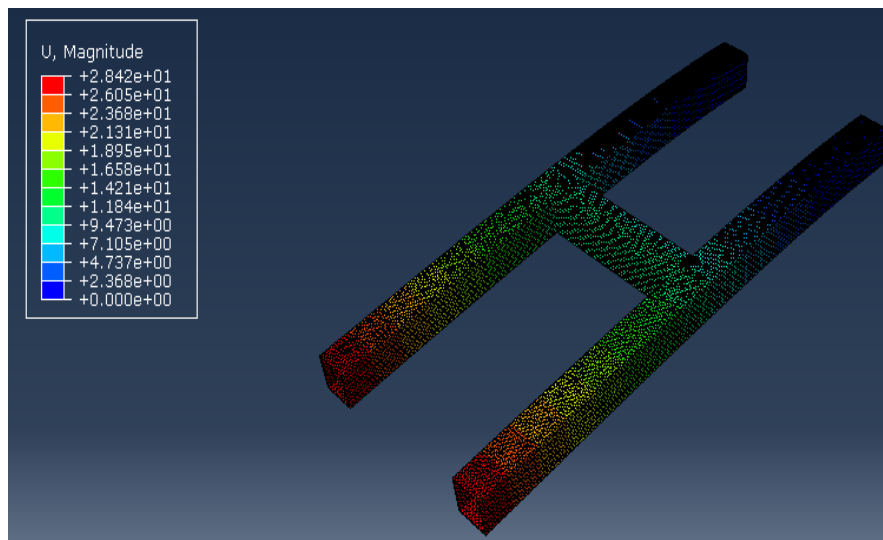


Fig. 10. Structural deflection plot for optimal vertical seat design

4. Conclusion

New solutions or approaches that can reduce flight ticket price have been pursued by airlines to attract more potential passengers. The current trend has progressively moved towards high density cabin designs where more passengers are accommodated into the onboard cabin space. There have been many proposed cabin design concepts to increase the passengers' capacity inside the cabin and one of them is the new standing cabin, which is conceptualized based on the notion that, instead of reducing seat pitch or legroom to accommodate additional rows of seats, it will be more comfortable for passengers to stand during short flights. The heart of this standing cabin concept is a vertical seat design for passengers' support during flight. Continuing the previous works by the authors, this study is focused on FEA analysis on main structures of the chosen vertical seat design. Based on the results, the optimum seat design has aluminum alloy as the material for its structures and its main structural parts have a diameter of 90 mm and a thickness of 3 mm. This chosen optimum seat design has been shown to have adequate strength and satisfy safety regulation requirements. Based on FEA results, the structural design of the vertical seat is able to withstand the required 9-g forward loading without failure. The maximum stress on the seat's structure is 147.5 MPa under 9-g forward loading, which is much lower than ultimate strength of aluminum that is 570 MPa. Furthermore, since the certification loadings in the other directions are less than 9-g, this implies that the seat structures is able to satisfy those certification requirements as well without failure. The seat's weight is estimated to be 9.5 kg and the maximum deflection of its main structures under forward 9-g loading as obtained from the FEA results is 28.42 mm, which is much less than the maximum limit of 93 mm to have the intended 508 mm seat pitch arrangement. The final proposed vertical seat design has also been equipped with four-point restraint mechanism, which offers better safety provision to the passengers. All in all, the stress analysis results highlight that the structural strength of the vertical seat design can satisfy the requirements of governing aviation regulations to provide safety to passengers.

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