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ANALYSIS OF A NEW STANDING PASSENGER SEAT DESIGN FOR COMMERCIAL TRANSPORT AIRCRAFT

Ahmad Redzman Mohamad Nor and Fairuz Izzuddin Romli
Department of Aerospace Engineering, Faculty of Engineering, Universiti Putra Malaysia, Serdang, Selangor, Malaysia
E-Mail: fairuz_ir@upm.edu.my

ABSTRACT

In order to have profitable flight operations, many airlines have used high-density passenger cabin design and arrangement. By doing this, more passengers can be accommodated inside the cabin per flight, hence reducing the overall flight costs per passenger. With conventional aircraft seats, the seat pitch is progressively reduced over the years to accommodate additional passengers into the cabin and this has created high flight comfort issues among the passengers. Reduced seat pitch also means that available legroom at each seat becomes smaller, which leads to discomfort due to inadequate space for many passengers in their sitting positions. For short-haul flights, the standing passenger cabin concept has been explored and proposed to help resolve this issue. Since passengers will require less legroom space in their standing positions, it is possible to have reduced seat pitch (hence more passengers) and acceptable comfort. A proposed standing passenger seat design is studied in this work to establish and support its suitability to be used in the standing passenger cabin concept. Finite element analysis is conducted to demonstrate its ability to fulfill the strength requirements imposed by the aviation authority. Furthermore, several design improvements have also been made to minimize its weight while still satisfying the strength requirements. The final standing passenger seat design has been shown to have adequate structural strength to cope with the requisite 9-g loading and a mass of about 11.7 kg which is lower than most conventional aircraft seats. All in all, this indicates that the proposed standing seat design has a good potential to be applied for air transportation and further supports the future implementation of the standing cabin concept. The final design from this study can be further refined in future studies to improve its characteristics.

Keywords: standing cabin, finite element analysis, standing passenger seat, aircraft cabin, aircraft passenger seat.

INTRODUCTION

Many airlines today have resorted to high-density cabin design configurations for their aircraft passengers' cabin in order to accommodate more onboard passengers per flight. More flying passengers can help to lower operational flight costs per passenger, thus enabling airlines to further reduce their flight ticket price and make their offered services more attractive to potential passengers [1]. This strategy has been proven to be successful for most low-cost airlines. However, current conventional high-density cabin configurations also generally means reduced seat pitch and available legroom, which leads to ongoing issues of in-flight discomfort among aircraft passengers [2]. This situation can be taken to imply that the usual strategy to increase the number of passengers inside the cabin by reducing the seat pitch between rows of passengers has potentially reached its limit. The inadequate legroom due to unsuitably small seat pitch can considerably affect the level of comfort and also safety of passengers [3]. For this reason, there is a need to explore different designs of high-density aircraft cabin such that an adequate level of passengers' comfort, is able to be provided, especially when comfort has become a major factor for passengers' loyalty and intention to reuse the airlines' services [4].

One of the proposed ideas of high-density aircraft cabin is the concept of standing passenger cabin. As illustrated in Figure-1, passengers are envisioned to be transported in the standing position in this new revolutionary concept instead of the usual sitting position. It should be noted that standing cabin concept is not recently new as it has been pursued by aircraft manufacturers and airlines since last decade. A few low-cost airlines have shown a keen interest to convert their passenger cabin into this standing cabin concept and Airbus, one of the leading aircraft manufacturers in the world, has also filed a patented design of a standing cabin [5]. All these indicate that this new cabin concept has great potential and interest within the air transportation industry. Unfortunately, this cabin concept has yet to be implemented in commercial transport aircraft today and hardly any scientific researches have been published in the public domain with regard to its development and implementation. This realization calls for a closer look into the feasibility and viability studies of this new cabin concept. Nonetheless, it is noted that the standing cabin concept is principally legal by the current standard of major governing aviation authorities, which do not specify that the passengers have to be in their sitting position during take-off and landing phases, or enforce specific standard for seat comfort or seating configuration onboard the cabin. As per current regulations, it is sufficient to prove that a proper certified mechanism is used to secure the passengers, even if they are standing during take-off and landing phases.

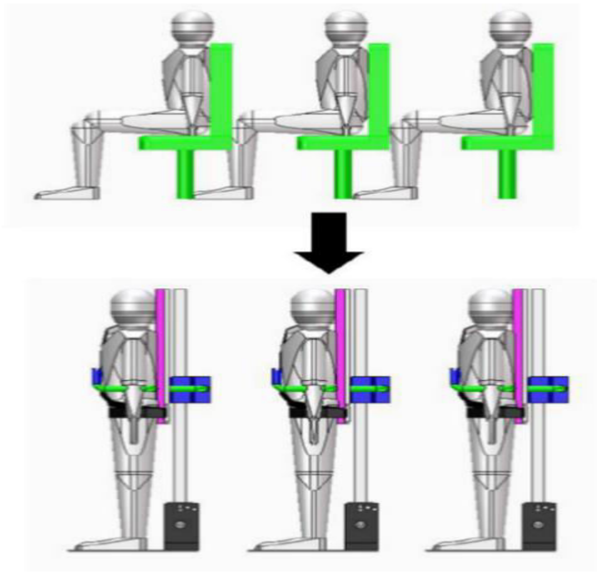

Figure-1. Standing passenger cabin concept [6].

Due to the nature of standing, this cabin concept is only proposed for use in short range flights between one to two hours. By having the passengers standing instead of sitting during flights, the seat pitch could be reduced between the rows of passengers with appropriate comfort level since less legroom is required when passengers are standing instead of sitting. Furthermore, a conducted ergonomic study on the standing cabin has also indicated that no notable increase in health risk for passengers is anticipated to be posed by the standing posture as compared to the sitting posture in short flights but it is proposed that passengers should be properly supported while standing [7]. The need for proper support is also in line with the requirements of the regulations that entail passengers to be able to be properly secured for their safety during the flights.

In standing cabin concept, the passengers' support while they are standing is typically referred to as vertical support or standing passenger seat. Similar to a conventional sitting cabin, the seat design is often taken as the heart of the cabin since it significantly dictates the cabin design arrangement and the provision of comfort and safety to the passengers. It is believed that, in order for the standing cabin concept to be successfully realized into commercial transport aircraft, a good standing passenger seat design has to be developed first. Under this notion, the research work presented here is focused on the development of the standing passenger seat design that fulfills the requirements, particularly in regards to the governing regulations.

PREVIOUS WORKS ON THE STANDING CABIN DESIGN CONCEPT

The authors have published several previous works with regards to the study of standing passenger cabin concept for commercial transport aircraft. In order to establish potential market demands and acceptance of this new cabin concept, an initial market survey has been conducted among aircraft passengers. The survey is carried out at two major low-cost airport terminals in Malaysia (i.e. Sultan Abdul Aziz Shah Airport and Kuala Lumpur International Airport 2) and on the whole, 1000 responses are obtained. In short, the survey results show that 47% of the respondents are willing to try the standing cabin concept if the price of the flight ticket is considerably reduced and majority of them are between the age of 23 to 25 years old [8]. This finding is rather expected as the standing cabin is predicted to be more appealing for the younger air travelers and a reduced flight cost is a major factor in making their air travel decision. Overall, although the implementation of standing cabin concept might have a limited appeal for certain categories of aircraft passengers only, it still has adequate market demands especially when the option is offered with much reduced flight ticket prices.

As discussed before, a successful implementation of the standing cabin concept into commercial transport aircraft is greatly dependent on the design of standing passenger seat. In conjunction to this, establishment of design requirements for the standing passenger seat has been accomplished with involvement of related stakeholders, either through survey or face-to-face interview session. Apart from air passengers, local aviation authorities and experts from local aerospace manufacturing companies are also included in the process. This ensures that the established design requirements take into account the perspectives of different stakeholders such as passengers, airlines, authorities and also manufacturing companies. Among others, several design criteria that have been concluded to be of great importance for the design of the standing passenger seat include safety, strength, weight and stability [9]. All identified essential design criteria from this requirements analysis process act as the main reference in creating potential design concepts of standing passenger seat.

A number of design alternatives for standing passenger seat are previously generated and assessed to determine the best concept with respect to these design requirements. As shown in Figure-2, the selected best design concept for the standing passenger seat is consisted of backrest support and body handle support that are both attached to a single main structural beam. These supports will help the passengers to maintain their standing posture during flight. Moreover, the seat design concept is also equipped with a 3-point seat belt to further secure and ensure passengers' safety, particularly during take-off and landing phases. Figure-3 illustrates the vision of the standing cabin arrangement with this standing passenger seat design concept, which is based on estimated Boeing B737-300 aircraft cabin dimensions.

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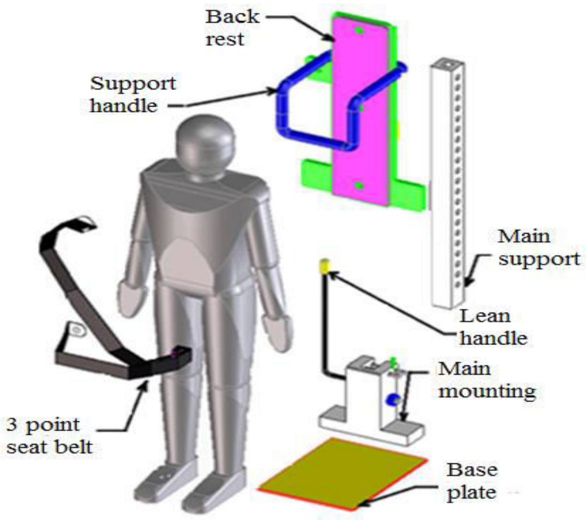

Figure-2. Selected standing passenger seat design.

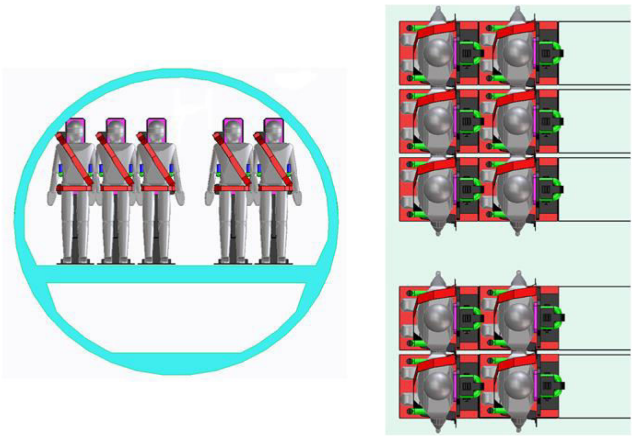

Figure-3. Envisioned standing cabin arrangement.

As can be observed from the selected design concept for the standing passenger seat, its strength heavily depends on the main single structural beam that holds and provides the standing support to the passengers. In the meantime, weight of this seat can also be primarily contributed to this primary seat structure. All in all, this main structure must be able to provide ample strength to support the standing passengers without being too heavy such that it gives weight penalty to the overall aircraft flight performance. Weight is definitely a major issue for aircraft and has significant influence on its overall performance and cost development [10]. In view of standing cabin, the standing seatsshould be lighter than the conventional seats since a higher number of them will need to be installed inside the aircraft cabin to accommodate the additional passengers. Therefore, there is a need for suitable compromise between strength and weight for the design of the standing passenger seat. To achieve this, analysis study is conducted on the selected standing passenger seat design concept with a primary focus on its main structure.

METHODOLOGY

The key design requirements for the standing passenger seat are imposed by the governing aviation regulations. For the static structural analysis, which can be taken as adequate for this conceptual design stage, the strength of the standing seat has to be able to withstand static loadings as prescribed in Figure-4 without breaking. Moreover, at this early design stage, the analysis is focused on the utmost requirement that is the 9-g forward force. It can be safely presumed that the seat's main structure has adequate strength to withstand the other lower force requirements if it can satisfy the 9-g force. The mass of an average passenger has been often estimated in the aircraft design process to be between 90 kg to 110 kg [11, 12].In this study, assuming that the average passenger weighs around 95 kg and gravitational acceleration can be taken as 9.81 m/s^2, the approximate force under 9-g is then calculated to be 8.4 kN. Under Joint Aviation Requirements (JAR), the load needs to be multiplied by a safety factor of 1.33 to further determine the required strength of the seat. As a result, the loading to be applied under the 9-g condition for analysis of the standing passenger seat is taken as 11 kN.

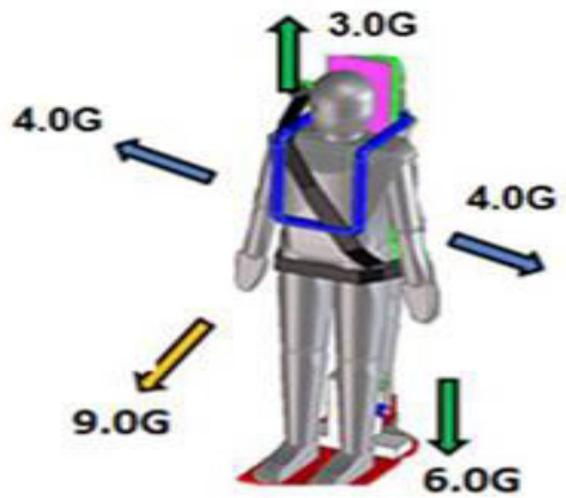

Figure-4. Required static condition loadings on aircraft passenger seat for strength testing based on regulations.

Additionally, due to the selected cabin arrangement and seat pitch used, there is a constraint regarding the maximum permissible deflection for the standing seat structure. It has been expected that the cabin seat pitch can be comfortably reduced down to 20 inches with the standing cabin concept. As illustrated in Figure-5, with a seat pitch of 20 inches and the selected standing seat design, the simple calculation of travel distance between the initial and deflected states of the standing seat indicates that the maximum travel distance of the standing seat between front and back passenger is about 100 mm. Hence maximum deflection for the standing seat should be less than this or else the passengers might injure themselves by knocking themselves to the front seat during worse case scenario.

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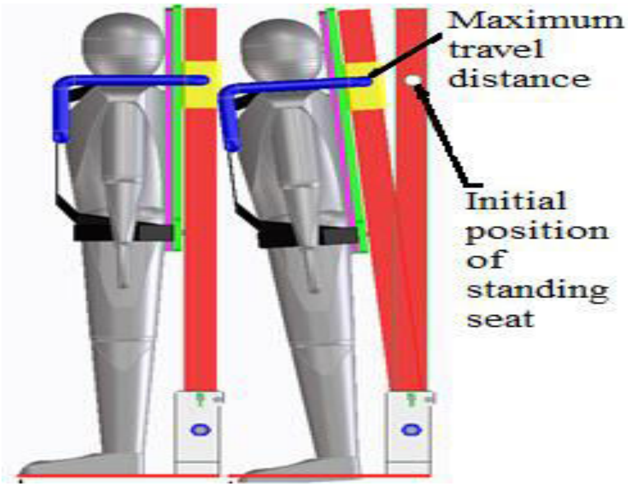


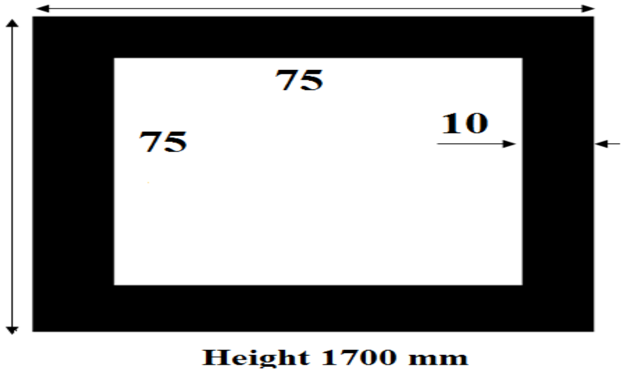
Figure-5. Maximum seat deflection requirement.

To ensure that the standing seat design can satisfy these strength requirements, simulated stress analysis through the finite element method (FEM) is conducted. Finite element analysis (FEA) has been widely used to model the stresses on an engineering design, which include applications on the structural analysis such as for mobility robot footrest [13], water fetching aid [14] and also aircraft wing [15]. For this study, the computer-aided design (CAD) model of the main structure for the standing passenger seat is created in CREO PARAMETRIC software and is then imported to ABAQUS software for the analysis. Several design parameters of the standing seat's main structure have been considered, which include cross-section shape, material and dimensions. The analysis results are then used to determine the best design settings for the standing passenger seat. In this case, the best design will have an aptly light weight while able to satisfy the strength requirements. For reference, mass of advanced conventional aircraft passenger seats is about 12 kg.

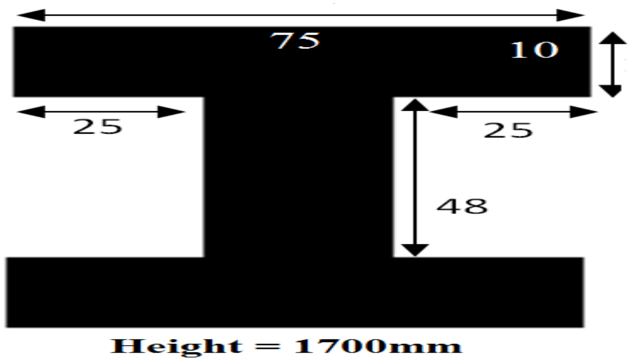
RESULTS AND DISCUSSIONS

Firstly, three cross-section shapes are considered for the main support structure of the standing passenger seat design as shown in Figure-6. These different cross-section shapes are commonly used in engineering structures. In this initial analysis, the material for the main standing seat's structure is designated as steel. It should be noted that the dimensions of each cross-section is chosen such that their volume is the same, and thus all of them correspond to the same weight. Table-1 summarizes the FEA results for all these different cross-section designs in terms of deflection and von mises stress. As a general rule, the structure design will fail if the maximum value of the von mises stress induced exceeds the yield strength of the material [16]. From the result presented in both Table-1 and Figure-7, the cross-section shape with the lowest deflection value is found to be the square-hollow, which has a maximum deflection of 34.6 mm. This is lower than the 100-mm limit that has been previously established, hencemain structure design with this square-hollow cross-section can be taken as safe for use with 20-inch seat pitch cabin arrangement. Moreover, its resultant von mises stress is also much lower than the yield strength of steel material, which is 690 MPa.

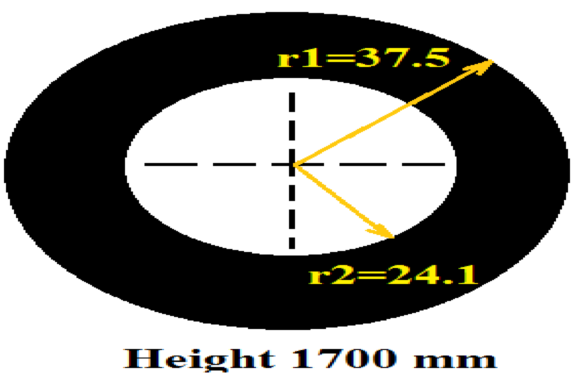
However, it is known that steel material is often heavy in weight. For a potential weight reduction, it is good to also explore other types of typical materials that are applied for aircraft cabin equipment or structures. Three materials have been shortlisted: steel ASTM A514, aluminum alloy 2014-T6 and titanium Grade 5, which all can be found in existing aircraft seat design. With the selected square-hollow cross-section as in Figure-6(a), FEA simulation analysis is donein ABAQUS with the different materials and the results are summarized in Table-2 and presented in Figure-8.



(a) Square-hollow cross-section



(b) I-shape cross-section



(c) Circular-hollow cross-section

Figure-6. Considered cross-section shapes for the main structure of standing passenger seat(all dimensions are in milimeters).

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Table-1. FEA simulation results for different considered cross-section shapes.

Cross-Section Shape	Maximum Deflection (mm)	Maximum Von Mises Stress (MPa)
Square-hollow	34.6	354.4
I-shape	37.8	342.2
Circular-hollow	39.7	364.5

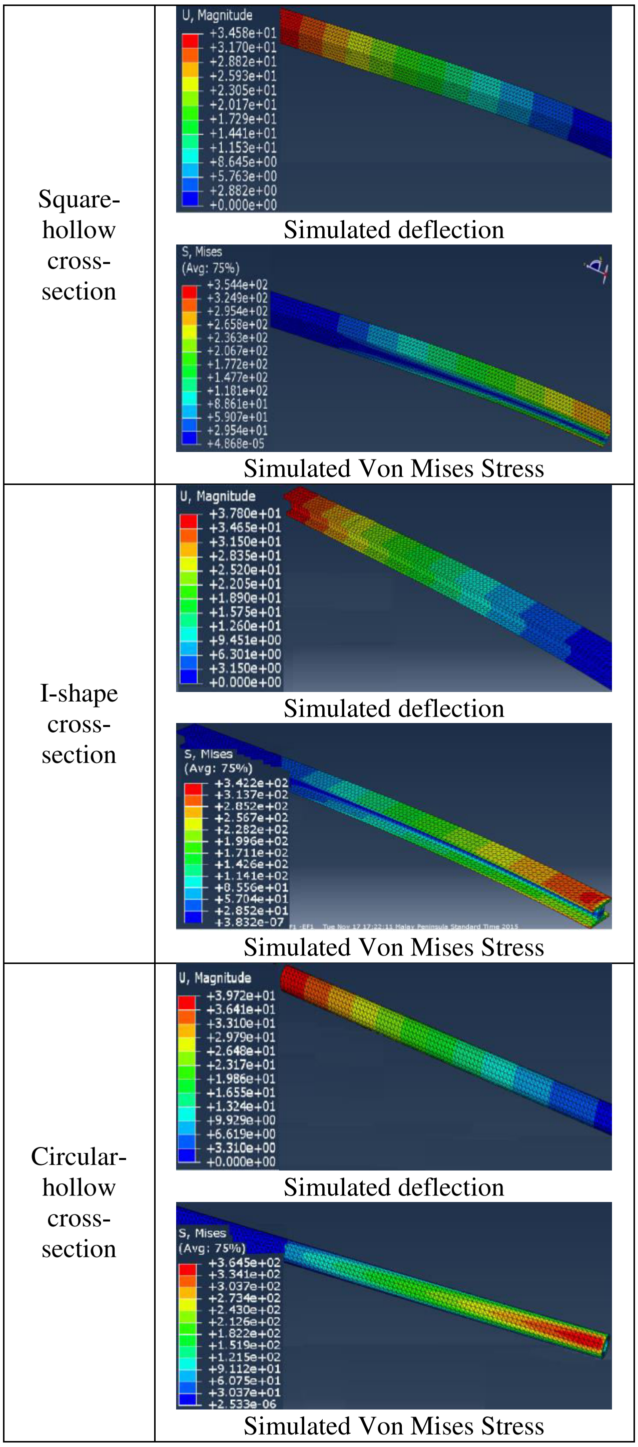

Figure-7. FEA results of different cross-section shapes.

Table-2. FEA simulation results for different considered materials with square-hollow cross-section.

Material	Maximum Deflection (mm)	Maximum Von Mises Stress (MPa)	Weight (kg)
Steel	34.6	354.4	34.5
Aluminum	105.2	354.4	12.3
Titanium	62.1	349.8	18.5

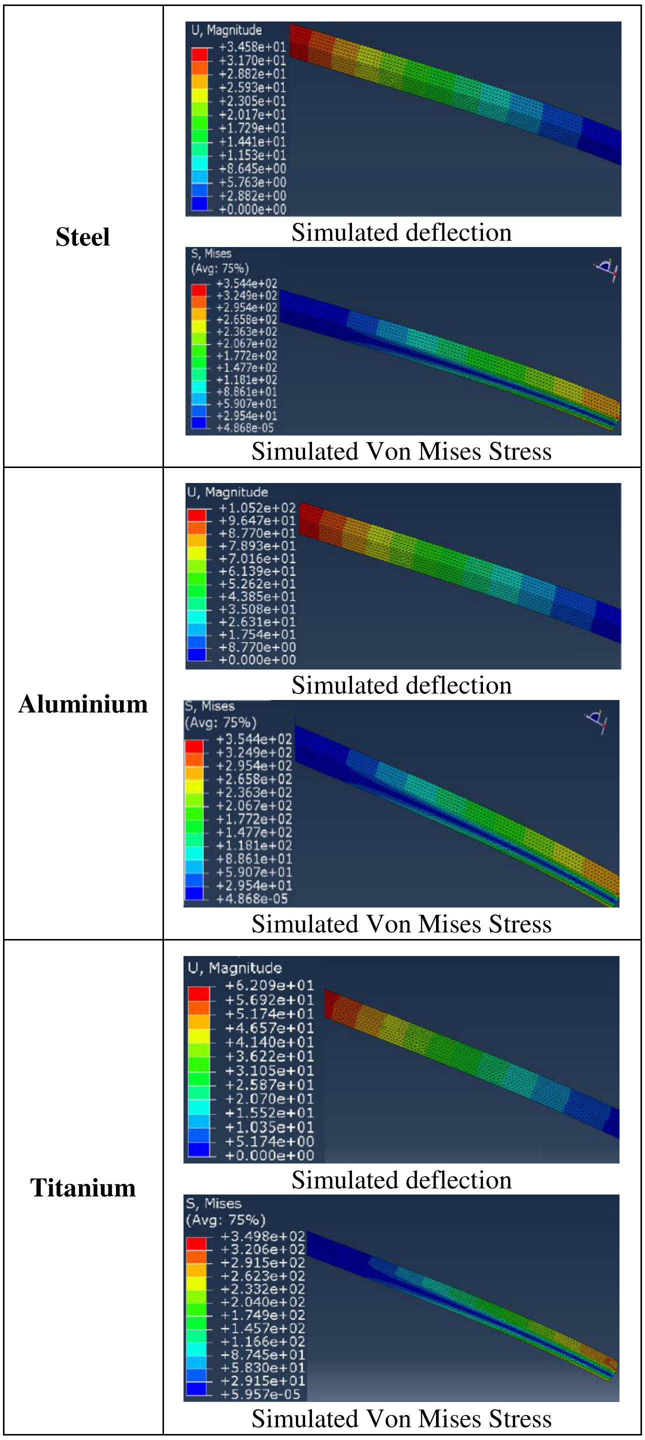

Figure-8. FEA results of different materials with square-hollow cross-section.

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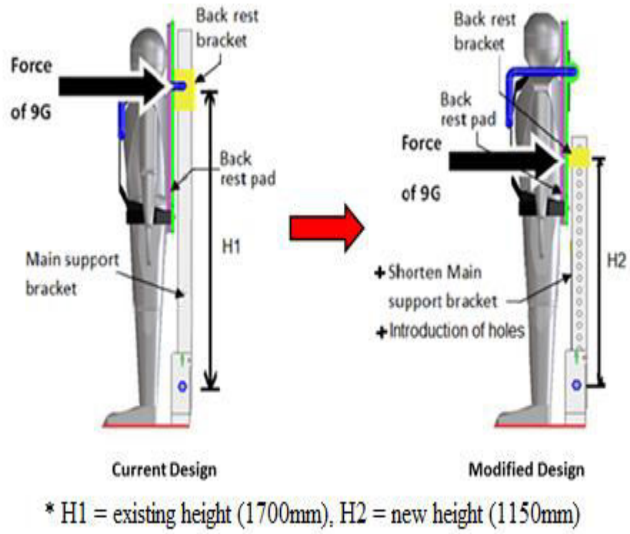
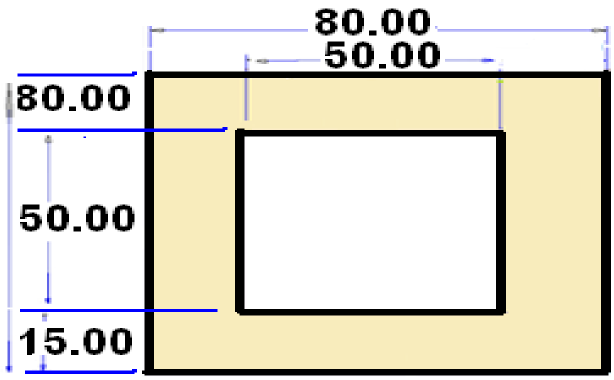
It should be noted that the yield strength for steel ASTM A514, aluminum alloy 2014-T6 and also titanium Grade 5 are 690 MPa, 414 MPa and 970 MPa, respectively. Hence, based on the presented results in Table-2, the simulated von mises stress for all three materials is lower than their yield strength. This means that it is possible to use any one of the materials for the standing seat's main structure. Using steel will lead to the lowest deflection under the applied 11 kN load but the corresponding weight penalty is rather too high. On the other hand, using titanium material gives the overall best strength-to-weight ratio among the options considered, but it should be noted it is also highly expensive. In addition, its corresponding estimated mass is high and it is foreseen to be rather hard to reduce this mass down even by varying the seat dimension or design. Using aluminium as the main support structure's material notably improves the situation regarding the predicted mass but its resultant maximum seat deflection is very high and exceeds the maximum allowable deflection established before. Thus if aluminum material is used with the current design, this limits the possible reduction of seat pitch between rows of passengers and subsequently reduces the number of additional passengers that could be accommodated in the cabin. After preliminary assessments, it is taken that to reduce the weight of the seat is harder than improving the seat's maximum deflection. Therefore, it has been decided that aluminium will be used as the material for the standing seat's main support structure but the current design needs to be revised and refined to have better trade-off between strength and weight.

To reduce the structure mass and maximum deflection, the dimensions of square-hollow cross-section are modified and the overall main structure's height is reduced. The latter design modification puts the contact force point to the main support structure at a lower point than in the previous design as illustrated in Figure-9. In this case, the original height of the main support structure for the standing seat is reduced from 1700 mm to 1150mm. Moreover, holes are introduced into the structure design, which will help to reduce the mass of the structure. FEA analysis is conducted on this modified design and the obtained results are presented in Figure-10.

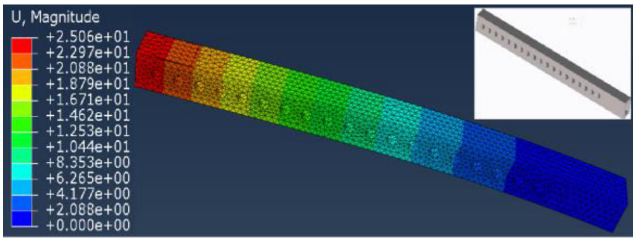


(a) Change in height and introduction of holes

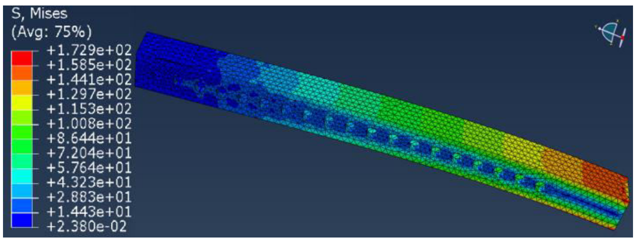


(b) Modified dimensions of the cross-section

Figure-9. Design modifications for the standing seat.



(a) Simulated deflection



(b) Simulated Von Mises Stress

Figure-10. FEA analysis results for the modified design.

It can be seen in Figure-10 that the maximum deflection of the main support structure for the standing passenger seat has tremendously improved by making the

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design changes. The resultant maximum deflection and von mises stress for the modified standing seat structure design are 25 mm and 172.9 MPa, respectively, which satisfy design requirements and also yield strength of aluminium material. Additionally, the estimated mass for this standing seat design is 11.7 kg, which is also less the reference mass of 12 kg. The overall assembly of the proposed standing passenger seat design is analysed using ABAQUS in all required loading directions as specified by the regulation and the result for the standing seat assembly under 9-g forward pull force is depicted in Figure-11. All in all, it is taken that this standing passenger seat design can satisfy the imposed design requirements and able to be used in aircraft standing cabin implementation.

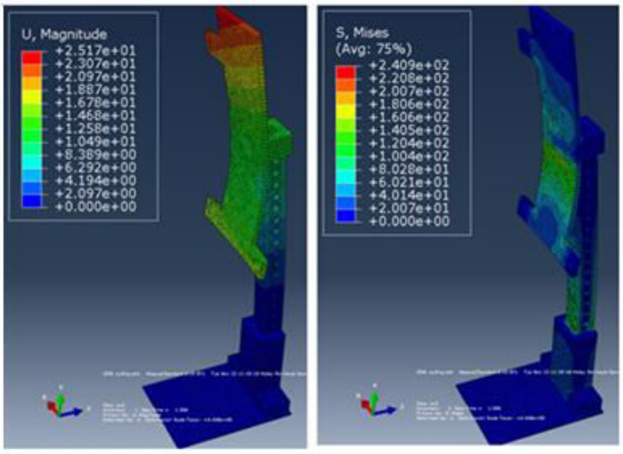

Figure-11. FEA analysis results for the full assembly of the proposed standing passenger seat design.

CONCLUSIONS

The application of a high-density aircraft cabin arrangement by reducing seat pitch with conventional cabin seats seems to have reached its applicability limit. This is implied with the increased issues of passengers' discomfort as available legroom at their seat further diminishes with reduced pitch. One of the revolutionary aircraft cabin design concepts that have been explored and proposed to help remedy and reach acceptable compromise with regards to this situation is the standing passenger cabin concept, which is aimed for short-haul flights. The main stumbling block to future successful implementation of this cabin concept is the approved design of the standing passenger seat, which should provide proper support in terms of safety and comfort to the passengers. In view of this, the work in this paper is conducted to study the adequacy of proposed standing passenger seat design from previous work and refine it for further improvement. Based on the findings, the standing passenger seat has been shown to satisfy the strength requirements that are imposed by the aviation authorities. Furthermore, the design has also been improved for weight reduction. The next future work on this standing passenger seat design is to conduct proper analysis on its ergonomics aspect for passenger comfort and material selection process to possibly further reduce its weight.

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