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Aircraft Seat Design Indicators for Eliminating Economy Class Syndrome

Kohei Ogi[1], Atsuhiko Senba[1]

[1]Meijo University

Corresponding author's Email: 223431002@ccmailg.meijo-u.ac.jp

Author Note: Kohei Ogi is a graduate student in Department of Vehicle and Mechanical Engineering, Meijo University. Atsuhiko Senba is Associate Professor in Department of Vehicle and Mechanical Engineering, Meijo University.

Abstract: One of the serious risks for the passengers in the airplane cabin is the so-called *economy class syndrome* (ECS). It is caused by the combination of "deep vein thrombosis," in which a blood clot forms in a vein of the lower extremity due to poor blood flow caused by prolonged seating, and "pulmonary thromboembolism," in which a blood clot forms in a vein and flows into a pulmonary artery, causing an embolus in the pulmonary artery. Its main cause is thought to be a compression of the popliteal and femoral veins, which are deep veins in the lower extremities, due to the narrow seating environment over a long period. In past studies, experimental investigations have shown that a pressure reduction on the buttocks and thighs is desirable. Experiments have focused on the cushion materials used in aircraft seats. However, they have not been conducted on subjects with the physique of patients diagnosed with ECS or with a similar physique to them because it is often difficult to find such subjects. This study aims to develop a human body model based on the physique of a patient who suffered from ECS to conduct seating simulations using non-linear finite element analyses. Then, we aim to quantitatively identify the causes of ECS and to create a design index for an ideal shape and stiffness of a seat cushion based on the numerical simulations. In the numerical analyses, we verify the seat cushion model and the human body model created by structural analysis software with experimental data. It is important that two human body models: one of a patient diagnosed with ECS (elderly, female, obese body type) and the other of a normal person (male) are analyzed to drive the design index for an ideal seat.

Keywords: Aircraft, Seat, Simulation, Comfort, Design

1. Introduction

The demand for airplanes is expected to increase in the coming 20 years by about 2.2 times, with an average annual growth rate of 4.0% over that period when global air passenger demand (the total number of miles flown by each paying passenger per passenger kilometer) is converted (Japan Aircraft Development Corporation, 2020).

As demand for air travel grows globally and in Japan, many problems remain for aircraft. These include "noise problems caused by engines" (CAB, 2014), "Improved comfort in the cabin environment" (MLIT, 2004), and "improved convenience of flight operations" (MLIT, 2004). Among these various issues, "*economy class syndrome* (ECS)", which greatly affects the body of passengers in the cabin, is one of the important issues that must be resolved as a priority in the future (Landgraf H. et. al., 1994).

ECS is caused by deep vein thrombosis (DVT), which causes blood clots to form in the lower leg veins as a result of prolonged sitting and can be complicated by pulmonary thromboembolism, which causes blood clots to travel to the pulmonary arteries and embolize them. The main likely cause of this case is compression of the popliteal and femoral veins, the deep veins of the lower limbs, due to the prolonged, narrow seating environment (Hidenori Koyama et. al., 2005),

In previous studies, experimental studies have found that pressure reduction in the back of the knee and buttocks is desirable (Dangal, S. et. al., 2020), (Dai Inagaki et. al., 2000). Experiments have been carried out with a particular focus on materials for aircraft seats. However, it has not been possible to carry out experiments on people with or near the physique of patients diagnosed with ECS. The objective of this research is to create a human body model to conduct a seating simulation using finite element analysis software (ANSYS Workbench Mechanical Products 2020 R2). Based on the results, the cause of the economy class syndrome is quantitively identified to discuss design indicators for future ideal seat cushions.

2. Materials and Methods

2.1 Examination of the validity of the seat

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In this study, two experiments are first conducted to extract the mechanical properties of the seat cushion. The first is to obtain the stress-strain data on two types of materials used for a seat cushion. Second, in order to compare the results with the analysis results, the seat cushion is made experimentally and experiments are conducted using a compression testing machine. After that, verification is performed using analysis software under the same conditions as the second experiment.

2.1.1 Experiments of seat materials

In this experiment, the stress-strain relationship of selected materials is calculated with the aim of calculating material data for nonlinear structural analysis of seat surfaces. Two types of materials with different stiffness were examined. The material properties are described below.

The density of Urethane A (manufactured by Yawata Screw Co., Ltd.) is 35 ± 3.0 kg/m^3. The density of Urethane B (manufactured by Inoac Corporation) is 22 kg/m^3. The stiffness of each material is obtained from the compression test.

Using a precision universal testing machine (SHIMADZU, AGS -5 kNX), stress-strain diagrams of the two selected materials are drawn to determine the nonlinear stiffness of each material. The compression surface with the material of the compression testing machine is circular with a diameter of 200 mm. We conducted the compression test for the Urethane A and Urethane B, where each cushion sample was considered the size of the disc to apply compression load from the testing machine. A compression testing machine measures the reaction force (N) and the compressive displacement (mm) of each material. The maximum value of the compressive displacement is determined by considering the thickness of each material and using the displacement that provides enough strain. The compression speed of the compression testing machine is 15 mm/min. The strain is calculated from the compressive displacement (mm) and the initial thickness of two materials (mm).

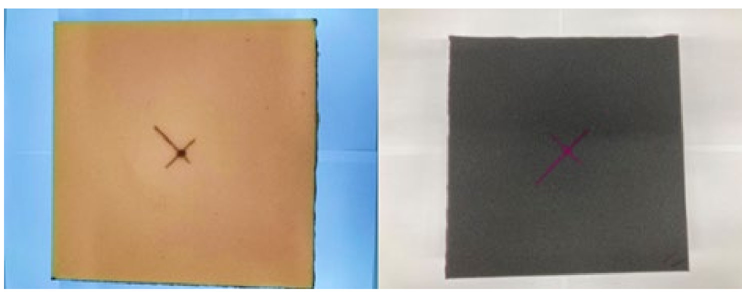


Figure 1. Urethane A (left), Urethane B (right).

2.1.2 Experiments for comparison with analysis result

In this experiment, an experiment is conducted to verify the validity of the seat models generated by the analysis software.

A seating surface consisting of Urethane A and B is prepared and a proper force is loaded using a compression testing machine. The load is applied until the displacement reaches about 30 mm, which results in a compressive strain of 0.6. The test force (N) and stroke (mm) are calculated from the values measured by the compression testing machine. The results of this experiment are used to compare them with the analytical results.

2.1.3 Analysis method

We used the finite element analysis software (ANSYS Workbench Mechanical Products 2020 R2) to analyze the seat surface of the same dimensions as those used in the experiment. The compression surface of the compression testing machine is a metal cylinder, and the analysis considered to be equivalent to the experiment is carried out by applying a load on the upper surface of the metal cylinder from the condition that the metal cylinder is brought into contact with the seat surface. Contact conditions between the metal cylinder and the seat surface employ the bond function of ANSYS. It is noted that, in the simulation, the one side of the back of the seat is completely fixed to ignore the deformation seat metal frame in the simulation. The setting of load conditions substitutes the test force obtained in 2.1.2. In addition, nonlinear structural analysis is performed to analyze the large deformation of cushion materials. That is, both the large deformation option and the nonlinear analysis option in ANSYS are used. Two kinds of non-linear models are used to set the material constant: the first uses the Ogden hyper foam model (second-order); the second uses the Ogden hyper foam model (third-order). The experimental results of material data on 2.1.1 are curve-fitted and analyzed using material constants.

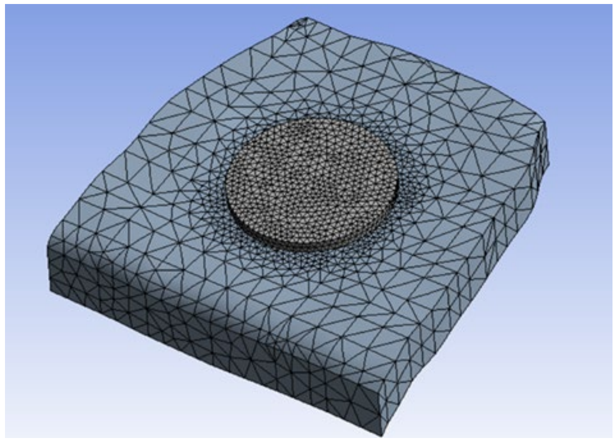


Figure 2. Analytical model of seat surface validation.

2.2 Human body model simulation

2.2.1 Human body

One side of the thigh (left side) of the human body model is created with the body shape data in the AIST/HQL database 2003 of the National Institute of Advanced Industrial Science and Technology. Two models are created: one for male; and one for female. Both models are based on the average height and weight of the Japanese. (MHLW,2019) The human body model referred to is upright, but the knee joint is bent at 90 degrees and adjusted to take into account the length below the knee from under the floor.

Table 1. physical information used in human body models.

Sex	Height (mm)	Weight (kg)
Male	1696.0	64.6
Female	1587.0	51.6

The material constants of the human body model are determined by referring to the material constants of the analysis simulation (Xiaoying, Liu et. Al., 2022). The material constants are as follows.

Table 2. Material constants for human body models.

Name	Elasticity modulus (MPa)	Poisson's ratio	Density (kg/m^3)
Soft tissue	0.45	0.48	937

2.2.2 Human body model analysis method

Contact analysis is performed using finite element analysis software. It is assumed that, in the simulation, no sliding or separation between the seat surface and the human leg model. The load applied to the seat cushion is corresponding to the gravitational acceleration of the mass of the human model. Also, since contact analysis is computationally intensive and complex, it is simplified and seated simulation is performed. The seat surface is made of Urethane A and used Ogden hyper foam model (second-order).

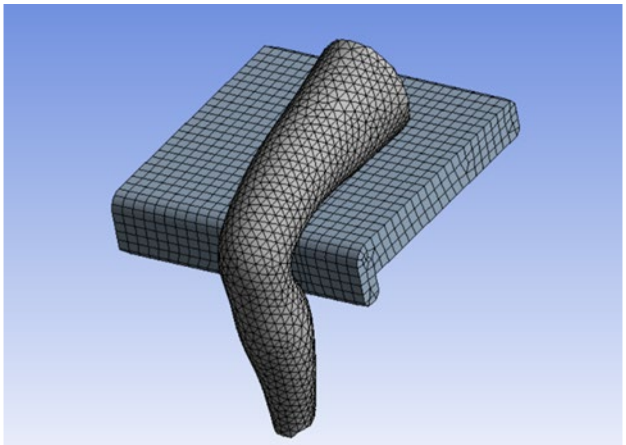


Figure 3. Analytical model for seated simulation.

3. Results and Discussions

3.1 Examination of the validity of the seat

3.1.1 Experiments of seat materials

From experiments 2.1.1, the relationship between stress and strain of Urethane A and Urethane B is as follows (Fig. 4) (Fig. 5).

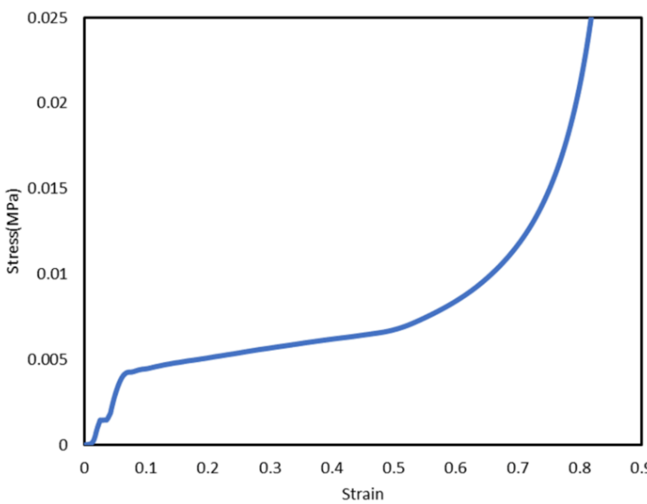


Figure 4. Stress-Strain diagram of Urethane A.

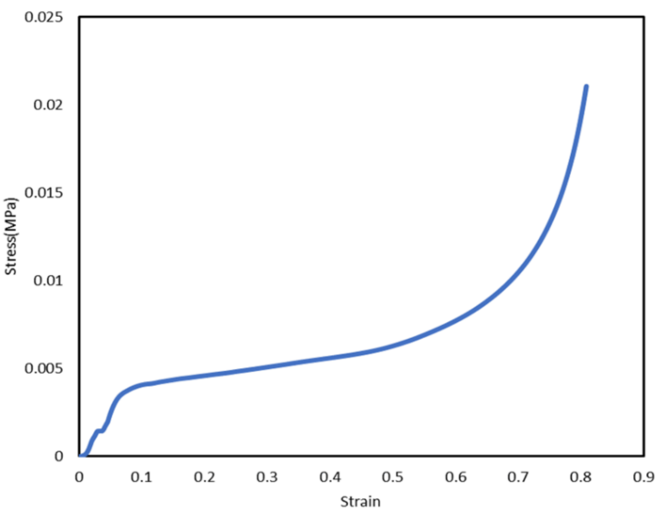


Figure 5. Stress-Strain diagram of Urethane B.

3.1.2 Comparison of experimental and analytical results

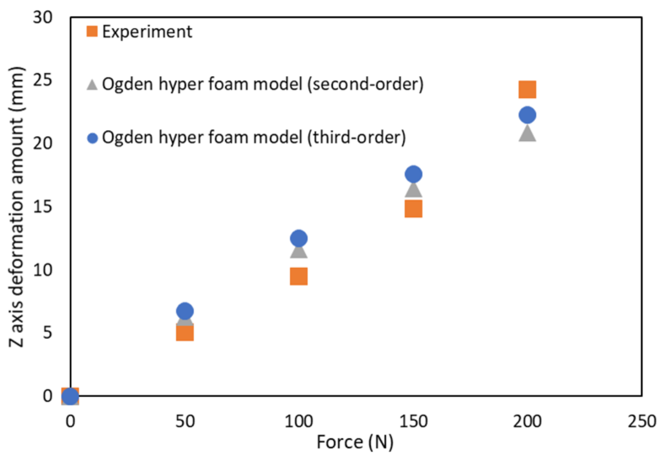


Figure 6. Result of Urethane A.

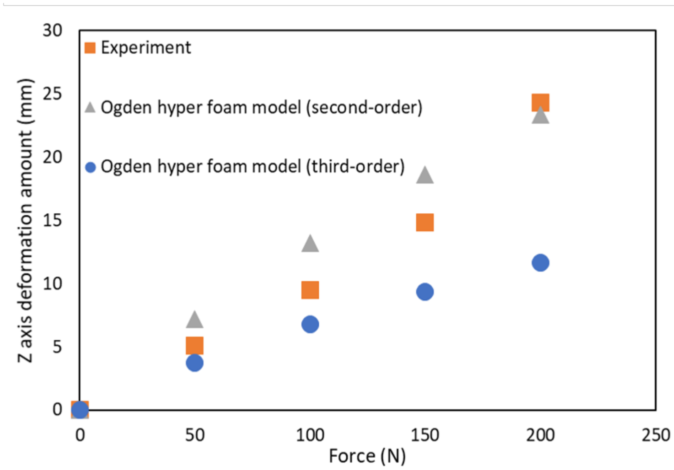


Figure 7. Result of Urethane B.

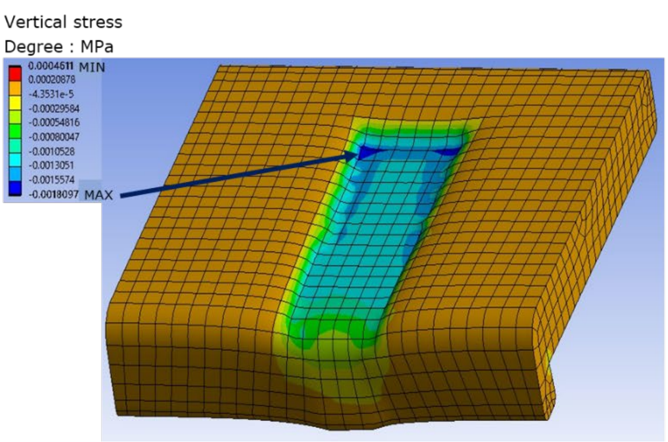
For this analysis, we analyze the load to the seat cushion due to the gravity corresponding to the weighs between 40 kg and 80 kg, which is the largest population. Therefore, the analysis is performed in 50 N increments over a range of 0 N to 250 N compressive load on the seat surface.

Figure 6 is a comparison of the results for Urethane A, where the orange marker is the experimental result, the gray marker is the Ogden hyper foam model (second-order) and the blue marker is the analytical result with the Ogden hyper foam model (third-order). Both the Ogden hyper foam model (second-order) and the Ogden hyper foam model (third-order) show a good agreement with the experimental data. Overall, the Ogden hyper foam model (second-order) is more suitable.

Figure 7 is a comparison of the results for Urethane B. As with Urethane A, the orange marker is the experimental result, the gray marker is the Ogden hyper foam model (second-order) and the blue marker is the analytical result of the Ogden hyper foam model (third-order). The results show the same trend as those of Urethane A, and the Ogden hyper foam model (second-order) is suitable because it takes a close value to the experiment. In the Ogden hyper foam model (third-order), the curve-fitted material constant slightly deviated from the measured data, and the poor accuracy is the cause of the deviation based on the results of the uniaxial test alone. Moreover, the reason for the large discrepancy in the Ogden hyper foam model (third-order) is that the material constants contain negative values.

3.2 Human body model simulation

The results of the male and female human body models are shown as follows. The color map in each figure is the normal stress (MPa) to the Z-axis, and this time the red represents the minimum stress and the blue represents the maximum stress because the Z-axis is up.



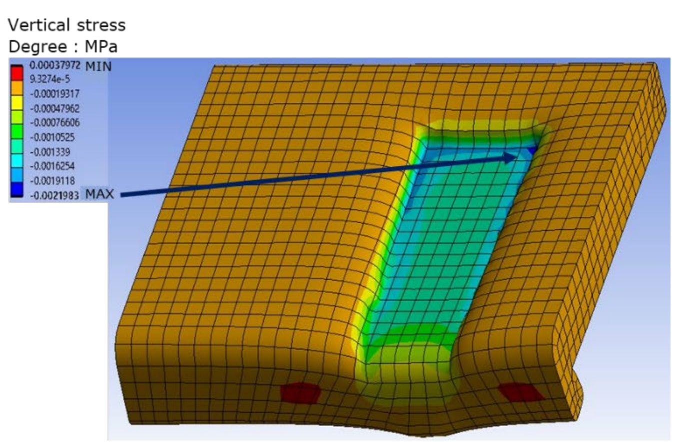


Figure 8. Result of male model.

Figure 9. Result of female model.

Figures 8 and 9 show differences in pressure distribution between male and female, showing that both have higher pressure on the back of the knee, and that the area where the maximum normal stress is applied is larger in the female human model, which is probably affected by the distance between the seating surface and the floor and the knee. Although the number of samples for this comparison of two different bodies is limited, the difference cannot be ignored to evaluate the risk of ECS.

4. Conclusion

To perform nonlinear structural analysis of aircraft seats, the material constants of a nonlinear stress finite element model of seat surface materials are determined by curve fitting to match the strain relationships with experimental data. As a result, the Ogden hyper foam model (second-order) seems to be suitable for both Urethane A and Urethane B.

This time, we compared the stress values for the cushion when male and female seated and found that wider distribution of stress on the back of their knees for female's case, so we can make a temporary assumption that females are more likely to have ECS.

In the analyses of the human body model, only the average height and weight models of male and female Japanese were compared, but in the future, it is necessary to create a wider range of models for different physiques and carry out analysis simulation, and we would like to make efforts to eliminate the ECS.

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