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# Optimal Design of Lightweight Seat Extension Equipment Using Topology Optimization and Design of Experiment

**Yu Jun Song**
*BS. Scholar,*
*Department of Mechanical Engineering, Graduate School*
*Kongju National University (KNU)*
*Namakkal District, Tamil Nadu, India.*

**Euy Sik Jeon**
*Professor,*
*Department of Mechanical Engineering, Graduate School*
*Kongju National University (KNU)*
*Namakkal District, Tamil Nadu, India.*

**Abstract**

In this study, a lightweight seat extension was designed as a convenience device for vehicles. We present a solution that easily optimizes a topology optimization model of a complex profile in a short time by changing the material of the seat extension support from metal to plastic, and by applying a topology optimization design and a design-of-experiment method. During topology optimization design, an optimal lightweight design of the seat extension was performed (DOE) after deriving the basic shape by applying constraints and by a design-of-experiment method after setting the design parameters. The study was validated by comparing it with a finite element analysis as well as the actual model.

**Keywords:** Optimization, Topology, Design of experiment, DOE, Polymer plastic

## INTRODUCTION

Recently, as the demand for driver convenience has increased, many convenience devices for vehicles have been developed, thus increasing the weight of the vehicle. As the number of convenience devices increases yearly, the weight of the car has increased by 10%, the fuel consumption has increased by 7%, and carbon dioxide emissions, which cause environmental damage, are increasing exponentially. Owing to these problems, much research has recently been carried out on the weight reduction of vehicles. In particular, the application of plastic materials of high strength and low weight compared with metal materials is of great interest in the research to reduce the weight of automobiles. Min-Young Lyu[(1)] emphasized the necessity of alternative applications of plastic materials for lightweight vehicles. That study also indicated the significance of the research on applying plastic materials for the realization of lightweight vehicles.

Plastic materials have a relatively low strength compared to metal materials, and therefore structures need to be designed differently from existing metal parts when lightweight materials are substituted. In recent research studies[(4–7)], CAE-based structural optimization techniques were widely used in the design of lightweight materials for parts. Among these, optimal topology design was introduced in many previous studies because it can easily obtain the results for layouts different from existing models, and can eliminate unnecessary portions that experience no stress from a specific load, thereby enabling lightweight design. Yang Dai[(2)] changed the material applied to a hull to laminate, and performed topology optimization for lightweight design, thus verifying the effect of topology optimization through material change.

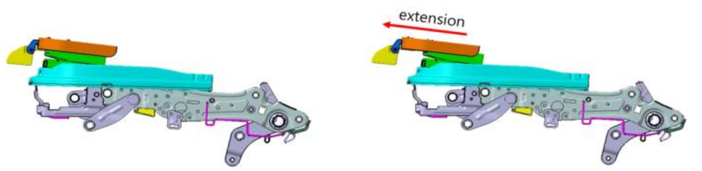
However, the result obtained by performing optimal topology design may be difficult to manufacture owing to its complex shape. In order to convert such a complicated shape into something that can be easily manufactured, a significant amount of design time is required in post-processing. Such problems can be solved by introducing a design-of-experiment method (DOE). M. Hatami[(3)] used the DOE method to perform optimization, setting the partial shape of a variable turbocharger using several parameters, and verified the effect.

In this study, a lightweight design for a seat extension—one of the convenience devices in a vehicle—was performed by applying a plastic material. HyperWorks CAE software performed the topology optimization, and the design-of-experiment method was used to optimize the structure after defining the design variables based on the derived shape. The validity of this study was verified by comparing it with a finite element analysis as well as the actual model.

## LIGHTWEIGHT OPTIMAL DESIGN FOR SEAT EXTENSION

### Definition of seat extension

A vehicle seat is formed to a certain size and cannot be adjusted, so the driver feels discomfort owing to the incompatibility between the seat and his or her body size. For example, the seat may not be able to sufficiently support the thighs of a driver with long legs, thus increasing driver fatigue during a long route. A seat extension device developed to overcome this inconvenience is added to the seat so that a driver with long legs can extend the front part of the seat to a fixed distance in order to reduce the fatigue on the driver's legs. The operating structure of the device is shown in Fig. 1.




(a) Collapsed state (b) Extended state

**Figure 1**. The Operating state of the seat extension

The seat extension device includes an upper panel that protrudes forward to support the driver's thigh, a support for the driver's weight (including an internal module that actually makes the seat extension protrude), and a cushion panel combined with the support that functions as a conventional seat. Among these three components, the support applied to the existing product is a complicated structure because it must include the internal module, which is made of metal and accounts for 30% of the weight of the seat extension device. In this study, the complex-shape support was designed to be a simple–shape support, and the material was changed from metal to plastic to achieve the optimal topology design and a lightweight design of the seat extension.

**Optimal topology design of the seat extension support**

Optimal topology design began in 1960 with Rozvany's(8) layout optimization design, and many studies on optimal topology design have been conducted since then. In particular, the density method proposed by Mlejnek(9) is used in many studies even today, as it has the advantage of being capable of roughly deriving an optimized outline of a structure even if the shape of the initial structure is not clearly defined. In this study, the existing support consisting of the two parts shown in Fig. 2 was assumed as a single part, with its shape modified into a rectangular parallelepiped. Then, topology optimization was performed using the density method to derive the initial shape.

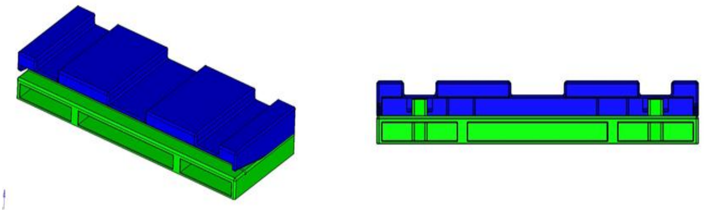


**Figure 2.** Shape of seat extension support of existing model

Since the objective of the topology optimization is to minimize the weight of the seat extension support, the objective function is defined as the minimum volume fraction ($V_{fmin}$), and the design variable is set as the volume fraction ($V_{fExt}$). The constraints are the displacement ($\delta_z$) in the Z-axis direction and the von Mises stress ($\sigma_{von}$) on the support, as shown in the following equation (1). This prevents the performance of the support optimized by topology optimization from being lower than that of the conventional seat extension.

Design Variable : $Vf_{Ext}$

Object function : $V_{Opt} / V_{Ext} = Vf_{min}$ (1)

Constraints : $\delta_z \leq 0.02$

$\sigma_{von} \leq 25$

* $Vf_{Ext}$ : Volume fraction of the design domain
* $V_{Opt}$ : optimized volume
* $V_{Ext}$ : Volume of the design domain
* $Vf_{min}$ : minimum volume fraction
* $\delta_z$ : displacement in the z-axis
* $\sigma_{von}$ : von Mises stress

The displacement ($\delta_z$) in the Z-axis direction is constrained based on a maximum displacement of 0.02 mm generated from the existing seat extension support. The von Mises stress ($\sigma_{von}$) was set to 15 MPa, which is four times smaller than the average yield strength of 60 MPa of plastic, considering the safety factor. Based on the above design area, topology optimization was performed by applying the fixation and loading conditions of the existing support to the simplified rectangular parallelepiped structure, as shown in Figure 3.

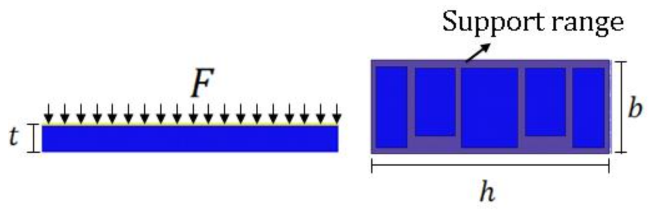



**Figure 3.** Fixation and load condition of structure

B is the longitudinal length of the structure, h is the transverse length of the structure, t is the height of the structure, F is the force, and 980 N was assigned as a distributed force as the strength test standard for the seat extension. The detailed dimensions and properties of the studied structure undergoing topology optimization are listed in Table 1.

**Table 1.** Dimensions and physical properties of structures

| Description | Value | Symbol | Value |
|---|---|---|---|
| Density [kg/mm$^3$] | 1.12E-06 | b [mm] | 115 |
| Young's Modulus [GPa] | 6 | h [mm] | 300 |
| Poisson's ratio [mm/mm] | 0.45 | t [mm] | 26 |

A total of 80 analyses were performed until the convergence condition within the limited range was reached, with the progress up to convergence shown in Fig. 4. After applying

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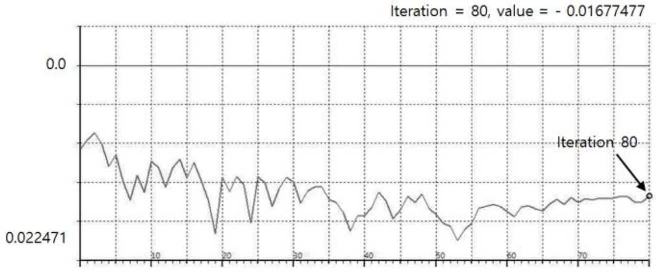
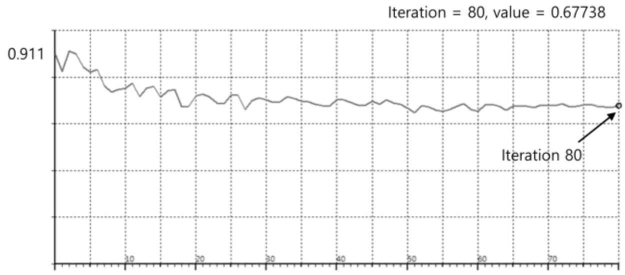
the set conditions using the Hyper-Works CAE software, the optimal topology design was carried out, as shown in Fig. 5.




(a) Convergence graph for displacement

(b)




(c) Convergence graph for volume fraction

**Figure 4.** Convergence result graph

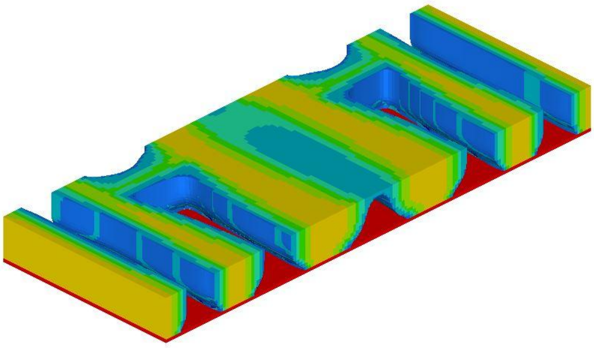
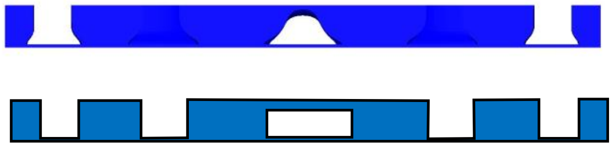


**Figure 5.** Results of topology optimization of structures

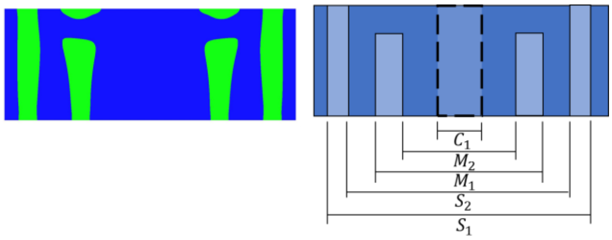
The topology optimization showed that the displacement was about 0.017 mm, the volume was reduced by 32%, and the von Mises stress in the optimized shape was 13 MPa. This confirmed that the optimal topology design yielded a shape that satisfied the constraints.

**Design-of-experiment method (DOE)**

The design-of-experiment method, a statistical analysis method that tests several factors in one experiment and determines the effects of the changes in these factors, is being introduced in mechanical engineering(10) because it can derive the optimum result at a relatively simple opportunity cost. In this study, the shape of the support structure derived from the topology optimization was modified to allow for easy machining considering the formability within the allowable range, and the parameters for the modified shape were set. The lightweight optimized shape of the support to be applied to the seat extension was finally proposed through the design-of-experiment method. The modified shape for the support structure is shown in Fig. 6.



(a) Front view of derived support structure




(b) Top view of derived support structure

**Figure 6.** Modified support structure

Design parameters were set from the modified shape considering the symmetrical shape of the support, and the design-of-experiment method was then performed. The defined design parameters are listed in Table 2.

**Table 2.** Explanation of symbols for variables

| Symbol | Value | Explanation |
|---|---|---|
| $S_1$ | $-5 \leq S_1 \leq +5$ [mm] | Side edges thickness 1 |
| $S_2$ | $-5 \leq S_2 \leq +5$ [mm] | Side edges thickness 2 |
| $M_1$ | $-5 \leq M_1 \leq +5$ [mm] | Mid edges thickness 1 |
| $M_2$ | $-5 \leq M_2 \leq +5$ [mm] | Mid edges thickness 2 |
| $C_1$ | $-5 \leq C_1 \leq +5$ [mm] | Center Hole area |

The parameters defined above are advantageous for reducing the number of calculations as the gap and position between the protrusions of the support are considered simultaneously, thereby increasing the efficiency of the calculation.

The ranges of density, elastic modulus, and Poisson's ratio were set after considering parameters mentioned in Table 2 and the various physical properties of plastic. The design-of-experiment method used in this study is a Latin Hypercube, which allows for efficient placement of experiments in the presence of a large number of parameters. In addition, this method can achieve a main effect with fewer experiments when there is no need to consider interactions in the design of static structures. A total of 45 replicate experiments were performed. Table 3 lists the experimental results

**Table 3.** Different cases proposed by DOE

| No | C1 | M2 | … | S2 | S1 | PP.E |
|---|---|---|---|---|---|---|
| *1* | -0.71 | 0.49 | … | -0.98 | 0.43 | 6477 |
| *2* | -0.95 | -0.45 | … | 0.55 | 0.48 | 5837 |
| *3* | -0.45 | -0.88 | … | -0.88 | 0.85 | 5898 |
| *4* | -0.79 | -0.54 | … | -0.81 | 0.53 | 5609 |
| *5* | 0.82 | 0.74 | … | 0.84 | -0.45 | 5636 |
| *6* | -0.73 | 0.06 | … | 0.69 | -0.98 | 5753 |
| *7* | 0.31 | 0.52 | … | -0.55 | -0.51 | 6178 |
| *8* | -0.06 | 0.86 | … | 0.31 | -0.11 | 6451 |
| *9* | -0.10 | -0.74 | … | 0.12 | -0.64 | 5788 |
| *10* | 0.85 | -0.80 | … | 0.75 | 0.26 | 6213 |
| *11* | 0.61 | 0.13 | … | 0.28 | -0.71 | 5504 |
| *12* | 0.67 | 0.39 | … | -0.66 | 0.09 | 5689 |
| ... | … | … | … | … | … | … |
| *45* | 0.43 | -0.93 | … | -0.09 | 0.6 | 6484 |

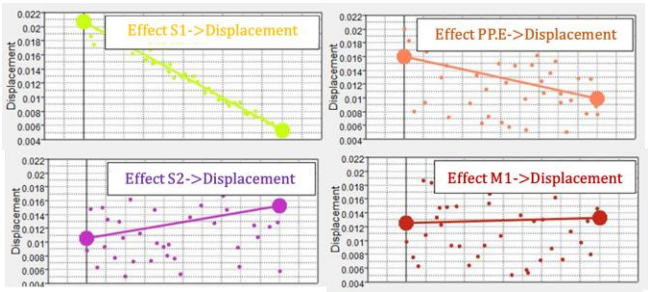



**Figure 7.** Sensitivity analysis results

The sensitivity of each parameter to the result is analyzed using the derived results. The sensitivity of each parameter to the Z-axis displacement was confirmed to be related to S1, S2, and Young's modulus (PP.E). The volume fraction was confirmed to have a high sensitivity to the property. The precision of the design-of-experiment method was then confirmed by regression analysis. The derivation of the regression equation for the volume fraction was excluded because the regression equation is highly dependent on the property of the volume fraction, making the result value obvious. Thus, only the regression equation for the displacement was presented. The regression equation derived for displacement has an accuracy of 97.63% using the following equation (2). The residual graph that confirms the fit of the regression equation is shown in Fig. 8.

$$\text{Disp}(Z) = 0.01060 - 0.007897S_1 + 0.000091S_2 + 0.00511PP.Nu \quad (2)$$

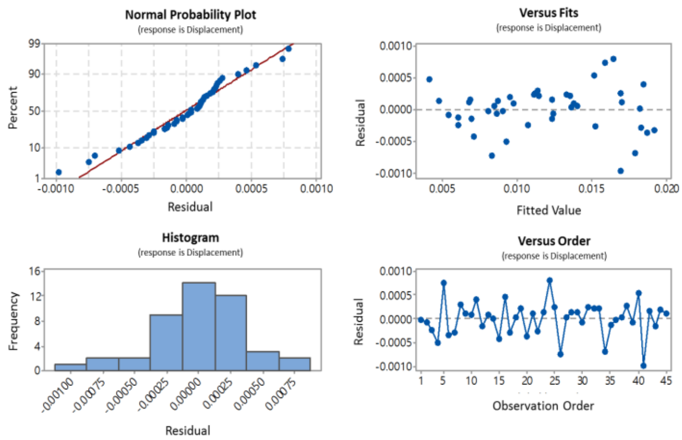
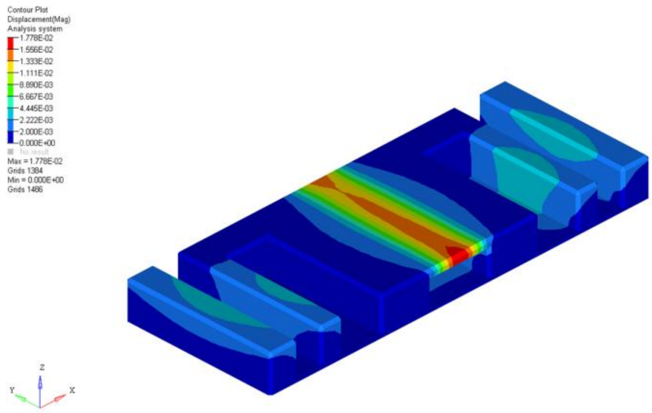
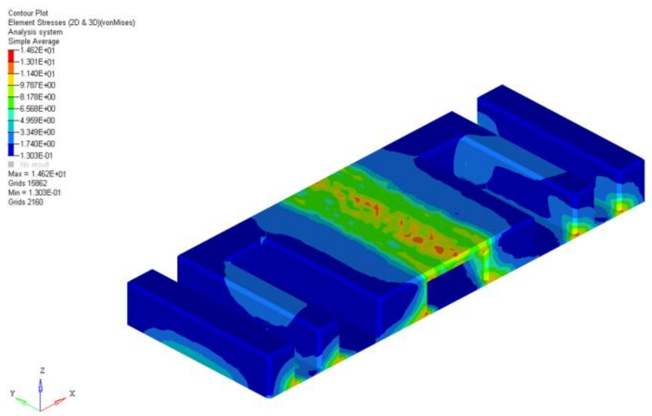



**Figure 8.** Residual graph of displacement

Based on the results obtained through the design-of-experiment method, a lightweight optimized model was created. The finite-element-analysis software Optistruct was used to analyze the results, as shown in Fig. 9. The analysis result showed that the displacement in the Z direction was about 0.17 mm, and the von Mises stress was 14.62 [MPa ]




(a) Displacement analysis of optimization model




(b) Stress analysis of optimization model

**Figure 9.** Analysis results of optimization model

## VERIFICATION THROUGH MODEL

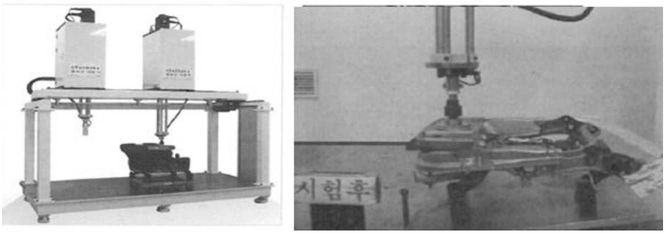



**Figure 10.** Static load tester

In order to verify the effect of the lightweight optimal design performed in this study, an actual model was fabricated and tested. A static load tester was used to measure the displacement of the optimized support by applying a 980N distributed force to the top panel of the seat extension. Table 4 shows a comparison of the Z-axis displacement and weight of the lightweight optimized model, the existing seat extension model, and the finite element analysis model.

**Table 4.** Explanation of symbols for variables

| Symbol | Optimization | FE analysis | Initial |
|---|---|---|---|
| Weight [kg] | 9.70 | 9.27 | 12.50 |
| Displacement [mm] | 0.0186 | 0.0178 | 0.2 |

## CONCLUSION

After changing the existing model made of metal material to a plastic model, we performed the optimal topology design and applied the design-of-experiment method to the derived shape to propose a new lightweight optimal design model. The proposed solution can easily perform optimization if a specific process method is required or if the shape of the optimal topology design model from the CAE structure analysis is complicated. The optimization is performed with the given constraints and conditions. The weight is reduced compared with the weight of the conventional seat extension with a reduced displacement in the Z-axis. A lightweight optimal model satisfying the required strength was presented. The validity of the lightweight optimal design method presented in this study was verified through comparison with the fabricated test model as well as the finite-element-analysis model.

## ACKNOWLEDGEMENTS

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