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Lightweight Corrugated Plate for Cargo box by using DOE and Topology Optimization

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Abstract

A lightweight design method is proposed for the cargo box base structure applied to small transfer devices. The conceptual shape was derived by topology optimization of an existing cargo box base structure, to which a corrugated plate was applied and cross-sectional shape parameters were set. The cross-sectional shape was optimized through regression equation using the design of experiments. The optimized model was validated by comparison with an existing model through finite element analysis.

Keywords: Cargo box, Corrugated plate, Topology, DOE, Lightweight

INTRODUCTION

With the recent growth in the food tech delivery and small cargo transportation markets, methods are needed to load a larger cargo box onto small transfer devices such as motorcycles. These small transfer devices need increased power or lightweight cargo boxes to compensate for the loading weight. To reduce weight, corrugated plates with a higher stiffness than ordinary plates are used in long structures that require high rigidity relative to the weight, such as floors and vertical partitions for aircraft, vehicles, and ships. Corrugated plates have flexibility in the corrugation direction and high rigidity in the perpendicular direction when corrugation is applied in one direction[1]. Peng et al. performed bending analysis to increase the flexural rigidity of various corrugated plates through the mesh-free method. Xia et al. analyzed the flexural rigidity characteristics of various corrugated plates by performing theoretical bending analysis on waveform, triangular, and trapezoidal corrugated plates[2,3]. Many computer-aided engineering (CAE)-based structural optimization techniques have recently been introduced for lightweight design[4–7]. Among them, topology optimization offers advantages in that the outputs of other layouts than the existing shape can easily be obtained and a lightweight design can be realized by removing unnecessary parts where no stress is generated by a specific load. Rathbun optimized the strength of a panel by applying the topology technique to a metal sandwich panel core that was subjected to bending[8]. Thus, topology optimization design can produce complex shapes that are difficult to process, and much design time may be required for post-processing to change a complex shape into one that is easy to process. This problem can be solved with the design of experiments (DOE). Hatami performed optimization by setting a partial shape of a variable turbocharger with several parameters using DOE and verified the effects[9]. Hence, methods for analyzing the shape and flexural strength of corrugated plate structures and making them lightweight need to be researched.

In this study, an optimal lightweight design for a cargo box base structure was derived by applying topology and size optimization. Based on the selected shape, the structure was optimized for the design parameters through DOE. This analysis method was validated through a comparison between the existing cargo box base structure and optimized corrugated plate using finite element analysis.

TOPOLOGY OPTIMIZATION DESIGN OF CARGO BOX BASE STRUCTURE

Cargo box structure

Small transfer devices need a lightweight cargo box because the output of the power unit changes severely depending on the loading weight. The existing model consists of a cover, a baseplate, an external frame, and brackets, as shown in Fig. 1. A cargo box base structure consisting of a cargo box base frame, a baseplate, and brackets was selected as the lightweight design target. Table 1 shows the components of the cargo box.

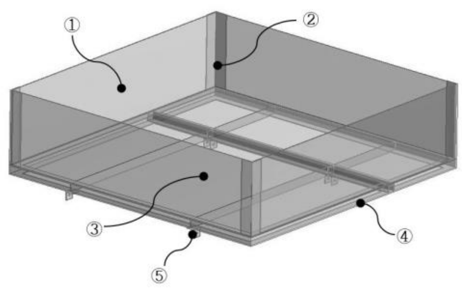


Figure 1: Structure of cargo box

Table 1: Part name of cargo box components

No	Name
1	Cover plate
2	Outer frame
3	Bed plate
4	Lower frame
5	Bracket

Topology optimization

There are two approaches to topology optimization: the homogenization method, which uses the modulus of rigidity of orthotropic materials; and the density method, which uses the modulus of rigidity of isotropic materials. The latter is mainly used for large structures because it is easier to calculate. Directly applying topology optimization to the cargo box base structure is difficult because it is made of a thin plate compared to its size. Therefore, the existing baseplate and base structure in Fig. 2, which consist of two parts, were assumed to be one part and simplified into a rectangular parallelepiped structure for topology optimization. Then, topology optimization was carried out by using the density method to derive the initial shape.

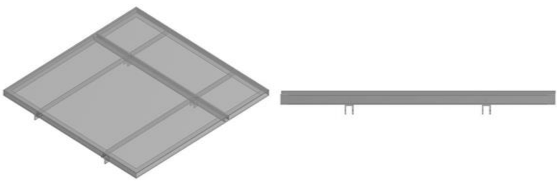


Figure 2: simplified model of cargo box

Because the goal of topology optimization is to derive the shape of the cargo box base structure and minimize its weight, the objective function was defined by the minimum volume fraction (Vf_{min}), and the design parameter was set as the volume fraction (Vf_{Ext}). For the limiting condition, to prevent the base structure—which had been subjected to topology optimization with regard to weight—from becoming lower than the existing base structure, the deflection along the z-axis (δ_z) and von mises stress (σ_{von}) applied to the base structure were defined as follows:

Design Variable : Vf_{Ext}

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

Constraints : $\delta_z \leq \delta_i$

$\sigma_{von} \leq \sigma_j$

where, * Vf_{Ext} : Volume fraction of the design range

* V_{Opt} : Optimized volume

* V_{Ext} : Volume of the design range

* Vf_{min} : Minimum volume fraction

* δ_z : Displacement in the z-axis

* σ_{von} : Von mises stress

The limiting condition for the displacement along the z-axis was applied based on the maximum displacement of the existing cargo box base structure. The limiting condition for the von mises stress (σ_{von}) was set by considering the safety factor at the mean yield strength of the structural steel material. For this simplified rectangular parallelepiped structure based on the above design area, the fixing and loading conditions of the existing cargo box base structure were assigned for topology optimization as shown in Fig. 3.

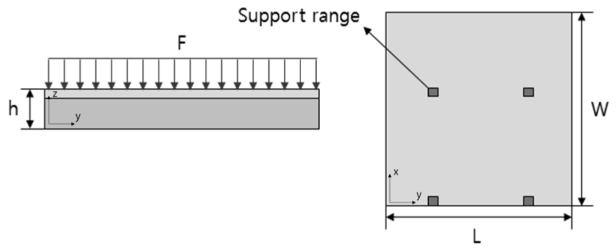


Figure 3: Fixation and load condition of structure

Here, W is the vertical length of the structure, L is the horizontal length of the structure, h is the height of the structure, and F is the force. The maximum loading standard based on the Motor Vehicle Management Act was assigned as the distributed force. Table 2 lists the properties of the structure subjected to topology optimization, and Table 3 lists the settings of the mesh type, size, etc.

Table 2: Material of Corrugated plate

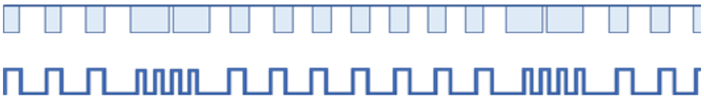
Material	Yield stress [MPa]	Ultimate stress [MPa]	Young's modulus [MPa]	Poisson's ratio	Density [kg/mm^3]
Structural steel	250	460	200.000	0.3	7.85 × 10^{-6}

Table 3: Finite element model input condition

Mesh type	Mesh size	Element
Hexahedron	10 mm	Psolid

After topology optimization was applied with the set conditions using Hyper-Works CAE software, the trend shown in Fig. 4(a) was derived. The shape of the structure was changed to one that is easy to process considering the formability within the allowable range, as shown in Fig. 4(b).

(a) Front view of Topological optimization result



(b) Front view of modified corrugated plate geometry

Figure 4: Modified corrugated plate geometry

To apply the topology optimization results to the press work piece, the bending technique—which is a press processing method—was applied to the entire cargo box base structure excluding the bottom brackets. Thus, a trapezoidal corrugated plate was derived. Fig. 5 shows the 3D model of the corrugated plate that was redesigned based on the topology optimization results.

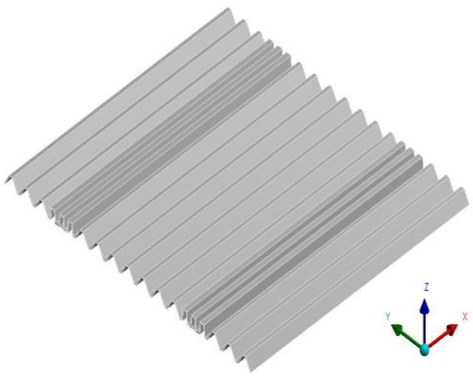
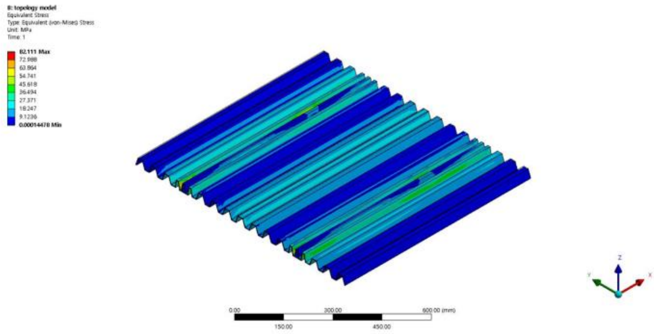


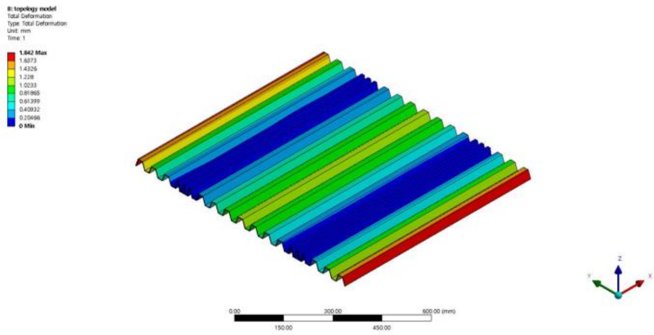
Figure 5 Redesigned 3D model of corrugated plate using topology optimization results

Finite element analysis of corrugated plate

To compare and verify the corrugated plate for the redesigned cargo box base structure via topology optimization, a structural analysis was carried out using the commercial program ANSYS. The same conditions shown in Fig. 3 were used for the loading conditions and constraints. Fig. 6 shows the resulting values of the displacement and stress for the trapezoid corrugated plate derived by topology optimization. Table 4 compares the displacement and stress between the existing model and corrugated plate derived through topology optimization.



(a) Stress analysis of optimization model



(b) Displacement analysis of optimization model

Figure. 6: Topological optimization results of structures

Table 4: Simulation results

Solution	Results	
	Existing model	Topology model
Displacement [mm]	1.847	1.842
Stress [MPa]	80.794	82.111
Mass [kg]	25.579	22.362

SIZE OPTIMIZATION

Setting design parameters

For optimization of the trapezoid corrugated plate, the design parameters were set as shown in Fig. 7. For the design variables, the corrugation angles (θ_a and θ_b) and thickness of the corrugated plate (t) were selected based on the height h and horizontal length L of the structure, which were fixed values. The size optimization was performed at three levels. Table 5 lists the levels of each parameter.

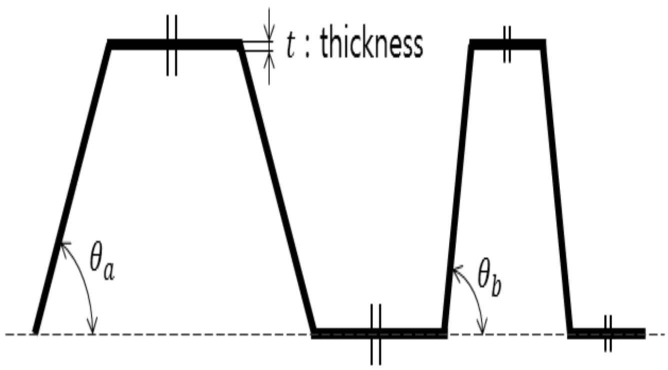


Figure.7: Design variables

Table 5: Level and design variables

Level	θ_a [º]	θ_b [º]	t [mm]
1	50	80	1.8
2	60	85	2.0
3	70	90	2.2

Design of Experiments (DOE)

With the general full factorial design (GFFD), experiments can only be performed at two levels of each parameter. Therefore, curved changes in the performance index depending on the changed level of the parameter cannot be detected. To address this drawback and estimate the curved surface with a small number of experiments, a computerized test was performed using the central composite design (CCD), as given in Table 6. DOE was performed by using the statistical program Minitab 17 based on the data obtained from the test.

Table 6: Different types proposed by DOE [results]

No	θ_a [º]	θ_b [º]	t [mm]	Disp. [mm]	Stress [MPa]	Mass [kg]
1	70	80	1.8	5.07	86.35	20.19
2	60	90	2.0	2.58	76.21	20.86
3	70	80	2.2	2.86	63.61	23.95
4	60	85	2.0	2.63	79.20	20.44
5	60	85	2.0	2.69	79.20	20.49
6	50	85	2.0	1.59	90.39	19.14
7	60	85	2.2	1.99	70.17	22.65
8	50	90	2.2	1.13	80.30	21.71
9	60	85	2.0	2.69	79.27	20.57
10	70	85	2.0	3.51	65.15	22.10
11	50	80	2.2	1.28	80.57	20.99
12	60	85	2.0	2.69	79.20	20.57
13	60	85	2.0	2.62	79.20	20.37
14	70	90	2.2	2.46	64.99	24.67
15	60	85	1.8	3.62	88.21	18.29
16	70	90	1.8	4.40	81.00	20.31
17	50	80	1.8	2.28	94.14	16.63
18	60	85	2.0	2.69	78.97	20.27
19	60	80	2.0	2.89	78.30	20.14
20	50	90	1.8	2.06	92.06	17.35

Fig. 8 shows the residual graph for verifying the fitness. The results of the analysis of variance for the stress, displacement, and weight of the corrugated plate confirmed their significance because the p-value was smaller than 0.05 except for the design parameter corrugation angle (θ_b) under stress. The R-sq value, which indicates the accuracy of experiment, was 83.85% for stress, 89.53% for displacement, and 98.50% for weight. Thus, the experimental results were confirmed to be good. Eq. (2) represents the regression equation of response according to the results of the analysis of variance.

$$\text{Displacement(mm)} = 7.36 + 0.0997\theta_a - 0.0348\theta_b - 3.8470t$$

$$\text{Stress(MPa)} = 221.60 - 0.7635\theta_a - 0.1680\theta_b - 41.0601 \quad (2)$$

$$\text{Mass(kg)} = -15.01 - 0.1541\theta_a + 0.0607\theta_b + 10.6002t$$

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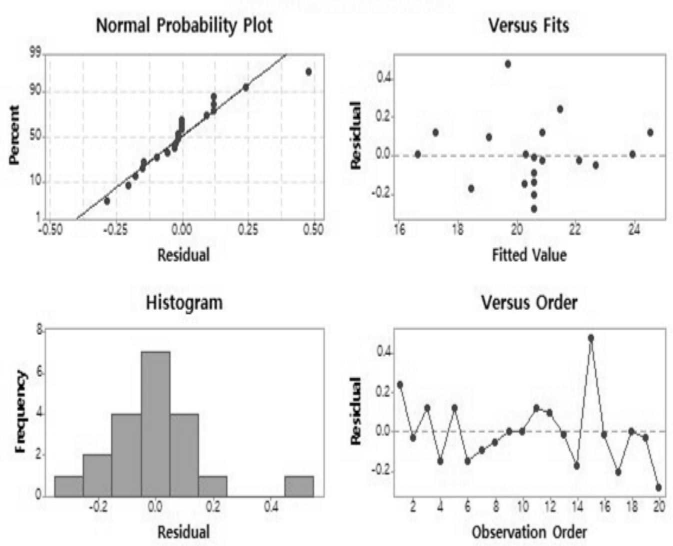


Figure 8: Residual graph of mass

RESULTS OF OPTIMIZATION

The optimization conditions were derived by using the response optimization tool of Minitab. As shown in Fig. 9, the results on the analysis of the main effects for the lightweight design of the corrugated plate revealed that every design parameter influenced the weight. The thickness of the corrugated plate had the largest effect.

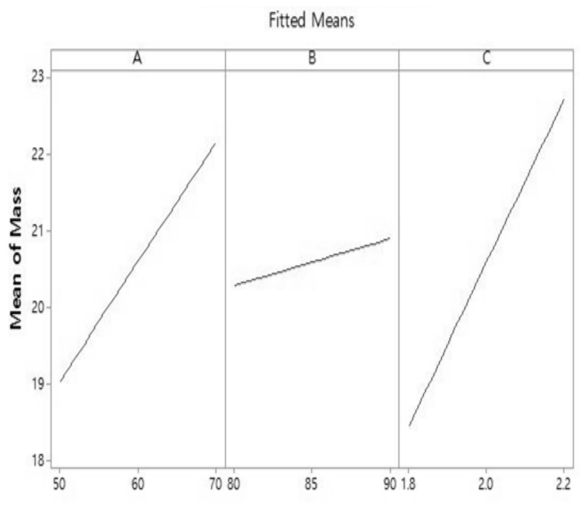


Figure 9: Main Effects Plot for Mass

As shown in Fig. 10, the optimized corrugation angles (θ_a and θ_b) were 50° and 85.6°, respectively, and the optimized thickness (t) was 2.0941mm.

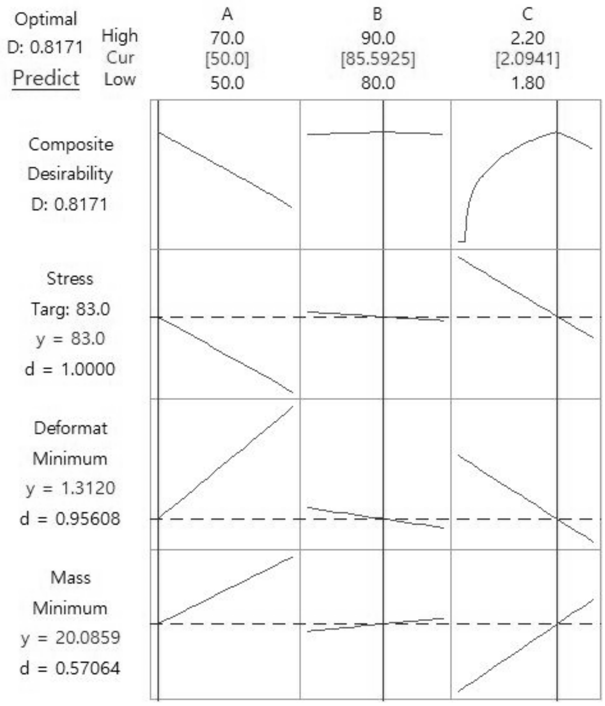
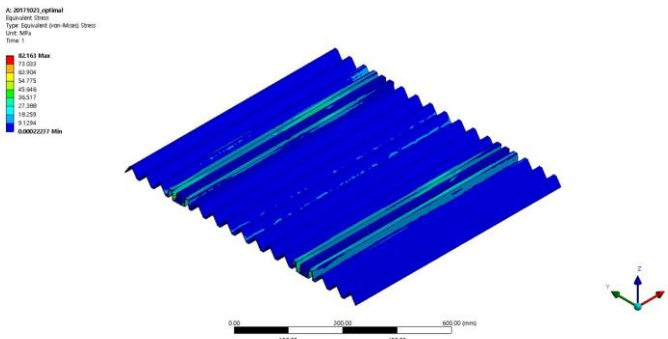
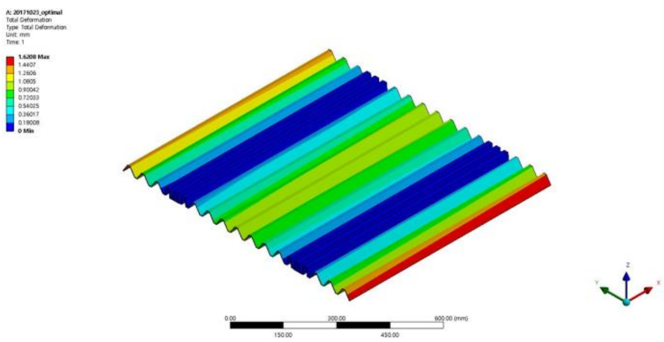


Figure 10: Optimization conditions

Fig. 11 shows the results of the finite element analysis using the final model after size optimization based on the results derived through DOE. Table 7 compares the finite element analysis results of the existing model and size-optimized model.



(a) Stress analysis of optimization model



(b) Displacement analysis of optimization model

Figure 11: Analysis of optimization model

Table 7: Results of the optimization

Solution	Results		
	Existing model	**Topology model**	**Optimum model**
Displacement [mm]	1.84	1.84	1.62
Stress [MPa]	80.79	82.11	82.16
Mass [kg]	25.57	22.36	21.01

The analysis results confirmed that the displacement of the optimized model along the z axis decreased slightly and its weight decreased by 18% compared to the existing model.

CONCLUSION

In this study, topology optimization was used to derive the shape of a corrugated plate for the cargo box base structure of small transfer devices, and an optimal lightweight design model was developed by applying DOE. The proposed solution can perform simple optimization when a specific processing method is required or when the topology optimization model using CAE structural analysis presents a complex shape. The optimization was performed by applying limiting conditions to the corrugated plate, and the finite element analysis results confirmed that the displacement along the z-axis decreased, the stress was within the range of allowable stress, and the weight decreased compared to the existing cargo box base structure.

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