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Lightweight Optimization of Infant Pop-up Seat Frame Using DMTO in Static Condition

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DMTO 기법을 활용한 정적 하중환경의 유아용 팝업시트 프레임의 경량화

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ABSTRACT

This paper proposes a solution to the problems of manufacturing cost and processability by applying discrete material and thickness optimization (DMTO) and minimizing the use of high-strength, lightweight materials in the optimization process. A simple infant pop-up seat model was selected as the application target, and the weight reduction effect and variation in strength according to the optimization results were observed. In this study, a simplified finite element model of an infant pop-up seat frame was first constructed. The model was used to perform a static structural analysis to verify the weight and strength of each part. The D-optimal design of the experimental method was then used to observe the influence of each part on the weight and strength. This process was applied using discrete thickness optimization (DTO) (which applies high-strength, lightweight materials and optimizes only the thickness) and DMTO (which considers both the material and thickness). The DTO and DMTO results were compared to verify the design method that determines the major parts and simultaneously considers the material and thickness. Accordingly, in this study, an optimal lightweight design that satisfied the strength standards of the seat frame was derived. Furthermore, discretization parameters were used to minimize the application of high-strength, lightweight materials.

Keywords : Lightweight(경량화), HSS(고장력강), DTO(이산 두께 최적화), DMTO(이산 재료 두께 최적화), Optimization(최적화)

1. Introduction

Reducing automobile weight is a major field of interest in academia and the industry. The techniques for reducing the weight of automobile parts may consider the alteration of the material, thickness, and shape. Moreover, many targets of application can be considered ranging from the BIW frame to small parts.[1,2] Two main techniques for part weight

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reduction have been studied: a layout design method using a phase optimization technique and thickness optimization method using high-strength and lightweight materials.[3-6] However, it is hard to reflect impractical design results for manufacturing of mass production. Further, it is hard to apply high-strength and lightweight materials to many parts owing to issues with profitability, economic feasibility, and productivity. The weight reduction techniques are also limited by strength regulations such as the Federal Motor Vehicle Safety Standards(FMVSS). To address these problems, material and thickness parameters must be derived within a manufacturable range. The design methods to minimize the proportion of high-strength and lightweight materials, such as HSS, AHSS are required.

Discrete material and thickness optimization (DMTO) can be proposed as a method for applying optimization results directly to the design using discretization parameters. DMTO can be applied to the optimization of complex structures with stacked shapes. The advantage of DMTO is that it omits the postprocessing procedure for deriving manufacturable thickness and material.[7-9] If the assembled product comprises a single material, discrete thickness optimization (DTO) can be considered.[10] DTO can be applied to optimize the thickness through design parameters with discrete values considering the manufacturable range of each part. However, there is a problem wherein the material cannot be changed. This paper proposed an optimization method that applies DMTO to a simplified model of an infant pop-up seat frame in the rear seat of an RV vehicle. To achieve this, finite element modeling was conducted considering the design specifications of the existing seat frame. Moreover, a structural analysis was performed considering the bending and torsional loads. The parameters for weight reduction were configured as three levels of materials and thickness. The parameters were then separated by ID number and discretized considering the effect on strength.

D-optimal design of experiments (DOE) was used to observe the effect of each parameter on the weight and strength. Furthermore, a response surface analysis was conducted to derive the design specifications of the optimized parts.[11,12] In addition, DTO was performed in a similar manner to verify whether there were large differences in weight and strength from the DMTO results.

2. Pre-process

2.1 Material Properties

The materials considered in this paper were as follows: steel for machine structures (SM45C), high-tensile steel (SPFC 980), and ultra-high-strength steel (SPBH 1470). Table 1 lists the mechanical properties of each material.

Fig. 1 shows the standard tensile testing device of the ASTM E8-E8M standard.[13] The ASTM E8-E8M tensile test was performed at least three times for each material. The stress - strain curve is shown Fig. 2 with reference to the median values.

Table 1 Mechanical Properties of Materials

Symbols	Units	Steel	HSS	AHSS
Level	-	1	2	3
E	MPa	210,000	210,000	210,000
v	-	0.35	0.35	0.35
σ_y	MPa	518	767	1253
ϵ_y	-	0.0025	0.0037	0.006
σ_{UTS}	MPa	587	1120.9	1714.4

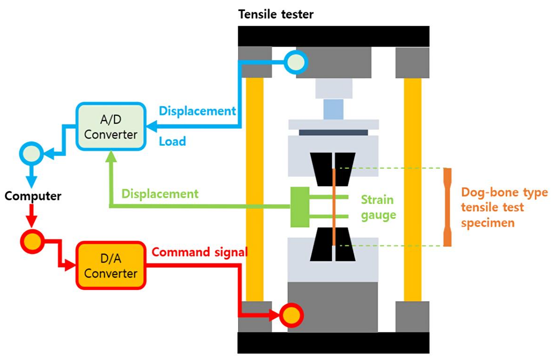


Fig. 1 Schematic diagram of tensile test

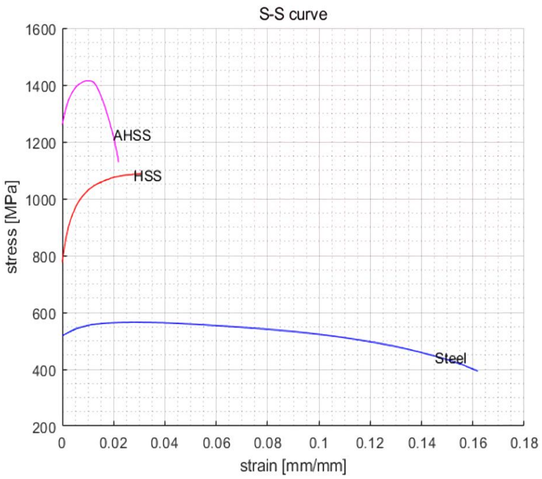


Fig. 2 Stress-strain curve data for Steel, HSS, and AHSS materials

2.2 Finite Element Modeling

A simplified model of the cushion part of the rear seats of the RV vehicle was used for the structural analysis, as shown in Fig. 3,4. Table 2 lists the part components considering the use environment of the seat frame. Part 20 is a rigid body model of the pelvis section of a Hybrid Ⅲ 10-year-old child test dummy[14], which is used to apply load to the seat cushion. Parts 1~7 are detailed parts that comprise the infant pop-up seat. Part 30 is a seat cushion model with an embedded pop-up seat, and Part 40 is a leg part that supports the seat cushion. These parts were set as rigid bodies.

The research paper is concerned with Part 10. Part 10 has a multi-joint mechanism that enables it to be stored and pulled out for convenience. This results in a lower strength than that of static fixed seats. In addition, approximately 30% of the total weight was from the seat cushion (Part 30). It can be considered that the research subject requires low weight while satisfying the FMVSS standards. All the parts were modeled with a square 2D shell. The average size of the elements was set to 5 mm. The seat frame model has 33,828 elements.

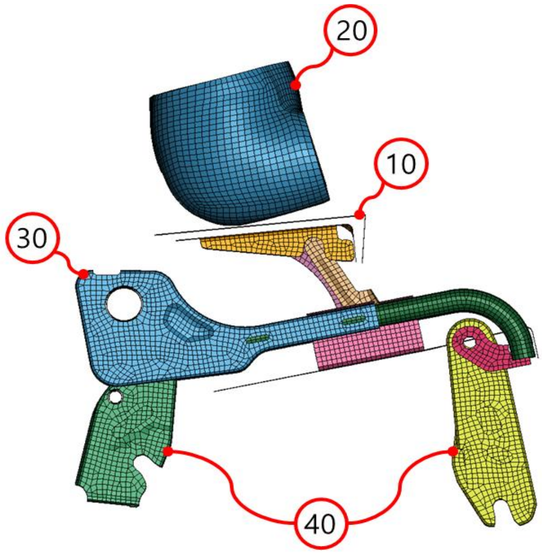


Fig. 3 Finite element model of all seat frame

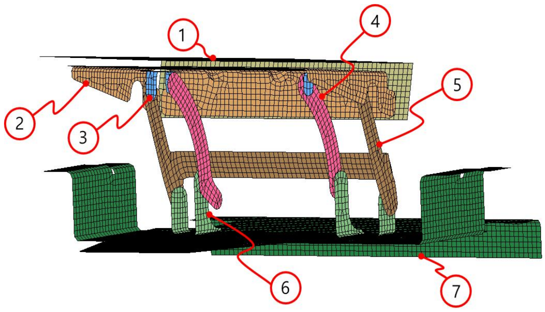


Fig. 4 Finite element model of infant seat frame

Table 2 Configuration of seat frame

Symbol	Part name	Weight (%)
1	Pop-up Cushion	25.6
2	Upper Plate	21.2
3	Upper Bracket	1.4
4	Rear Link	2.0
5	Front Link	4.1
6	Lower Bracket	2.7
7	Base	42.9
10	Infant Pop-up Seat	100
20	Pelvis	-
30	Seat Cushion	-
40	Leg	-

2.3 Boundary Condition

Fig. 5 and Table 3 present the boundary conditions applied to the seat frame. As shown in Fig. 5, a fixed condition was applied to the leg. Furthermore, a bending load (F1) and torsional load (F2) were applied. This paper referred to a previous research, although it does not have a defined standard for each load condition.[15]

3. Structural Analysis of Seat Frame

3.1 Fundamental Analysis

In fundamental analysis, identical thicknesses and materials were applied to all the parts. The materials (steel, HSS, and AHSS) and thicknesses (1.0 t, 1.5 t, and 2.0 t) each consisted of three levels. Hence, nine cases could be considered for the structural analysis according to the materials and thickness. Fig. 6 shows the structural analysis results of these cases. Fig. 6 (a) shows the displacement of the pelvis part under the bending load. The analytical results demonstrate that the impact of the thickness is higher than that of the material. The analytical results applying Material Level 1 (steel) and Thickness Level 2 (1.5 t), which produced average results, were selected as the strength standards for the bending load. Fig. 6 (b) shows the analytical results under torsional load. The analytical results applying Material Level 1 (steel) and Thickness Level 2 (1.5 t), which had produced

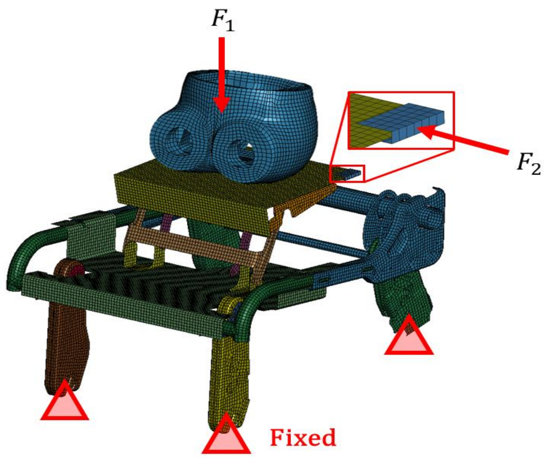
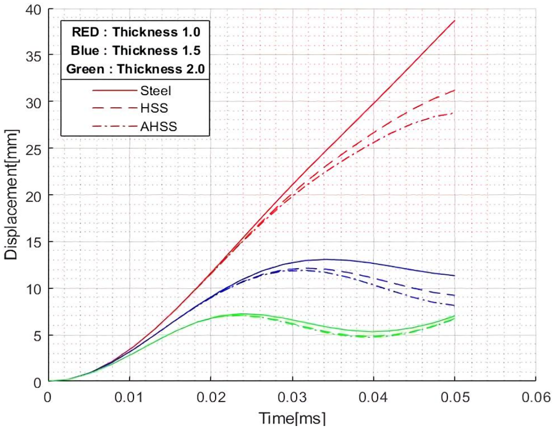


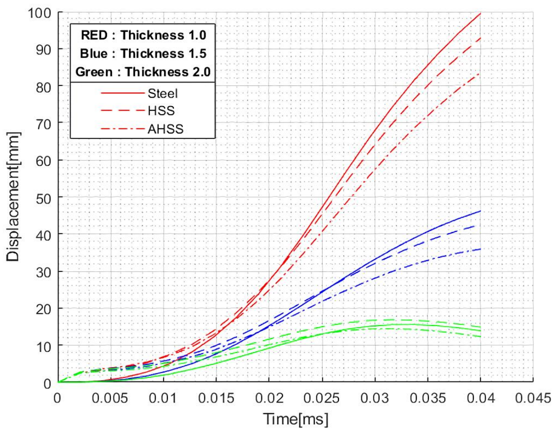
Fig. 5 Finite element model with boundary condition applied; configuration of seat with (F1) bending load applied and (F2) torsional load applied

Table 3 Load condition applied to seat frame

Case	Symbol	Force [N]
1	F_1	1,200
2	F_2	900



(a)



(b)

Fig. 6 Results of basic analysis considering Material Level 3 and Thickness Level 3; fundamental analysis results with (a) bending load applied and (b) torsional load applied

average results in the bending load analysis as well, were selected as the strength standards for the torsional load.

3.2 Discrete Thickness Optimization

The optimal design problem is formulated as follows, and Fig. 7 shows the optimization process. The thickness of each part (x_i) was applied as the DTO parameter, as shown in Equations 1 and 2. AHSS (ID: 3) was applied as the material for all the parts, which is shown in Equation 3. In terms of the discretization parameters of each part, x_i was determined by D-optimal DOE. The mass (m), maximum displacement under bending load (δ_B), and maximum displacement under torsional load (δ_T) were derived from the structural analysis results (Equation 4). Subsequently, a response surface (meta model) was generated for each result through a polynomial.

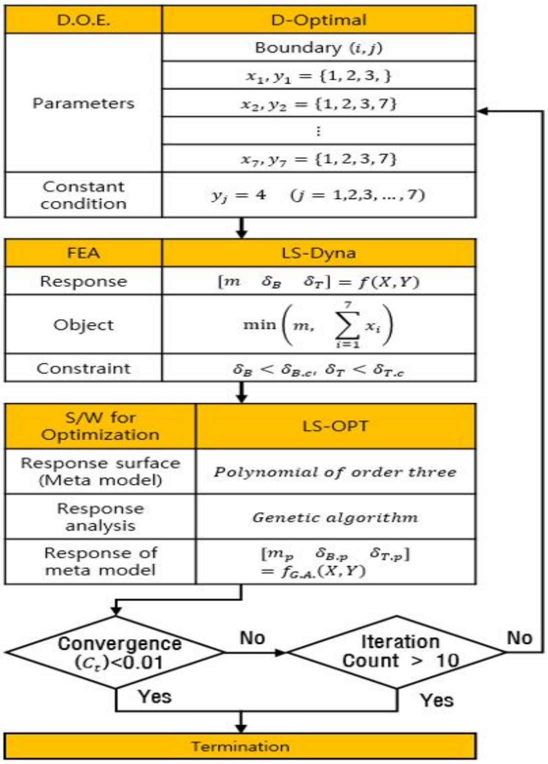


Fig. 7 Discrete thickness optimization procedure

The optimization was conducted using genetic algorithm. As shown in Equation 5, the objective function was set as the minimization of the sum ($\sum_{i=1}^{7} X^i$) of the mass (m) and thickness ID. The constraints for the maximum displacement under bending load and maximum displacement under torsional load were 11.57 mm and 41.82 mm, respectively.

These are shown in Equations 6 and 7. The error between the predicted value from the response surface and the analytical result for the predicted value was determined. The iterative analysis was terminated when the convergence value was 0.01 or less.

Parameters

$$X^7 = x_1, x_2, x_3, x_4, x_5, x_6, x_7 \tag{1}$$

$$Y^7 = y_1, y_2, y_3, y_4, y_5, y_6, y_7 \tag{2}$$

Constant condition

$$y_j = 3(j = 1, 2, 3, \dots, 7) \tag{3}$$

Response

$$[m,\ \delta_B,\ \delta_T] = f(X,\ Y) \tag{4}$$

Minimize objective function

$$\min(m,\ \sum_{i=1}^{7} X^i) \tag{5}$$

Constraints

$$\delta_B < \delta_{B,C} \tag{6}$$

$$\delta_T < \delta_{T,C} \tag{7}$$

where

X^i : Thickness ID of each part (i=7)

Y^i : Material ID of each part (i=7)

$\sum_{i=1}^{7} X^i$: Sum of thickness IDs of each part

m : Weight of infant-seat frame

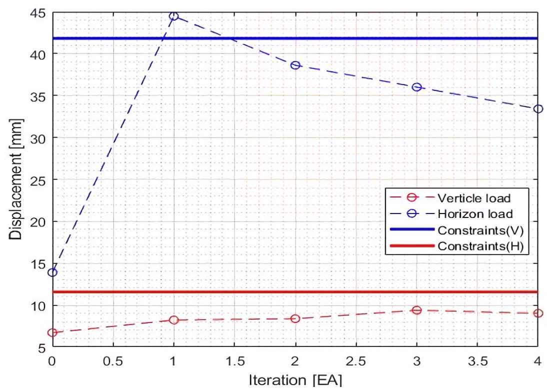
δ_B : Maximum displacement under bending load

$\delta_{B,C}$: Constraint of maximum displacement for bending load

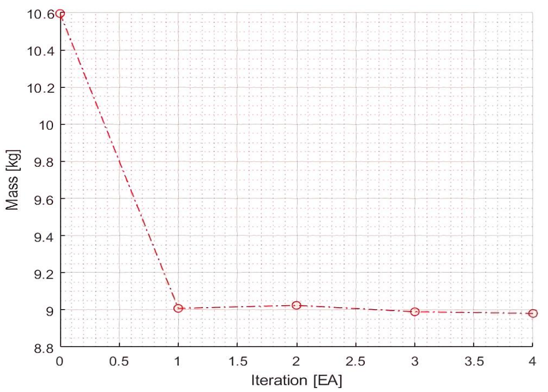
δ_T : Maximum displacement under torsional load

$\delta_{T,C}$: Constraint of maximum displacement under torsional load

Fig. 8 (a) shows the variation in the maximum displacement per iteration, and Fig. 8 (b) shows the variation in weight per iteration. In the fourth iteration, when the optimization was completed, a weight of 8.98 kg was derived. The weight reduction effect was approximately 15.2%. However, considering



(a)



(b)

Fig. 8 DTO optimization results; variation in (a) maximum displacement and (b) seat frame mass through DTO optimization

profitability, economic feasibility, and productivity, it is difficult to apply high-strength and lightweight materials to all the parts.

3.3 Discrete Material Thickness Optimization

DMTO is a discrete optimization technique that simultaneously considers the thickness and material of each part. The optimal design problem was formulated as follows. The optimization process can be expressed as in Fig. 9 In terms of the discretization

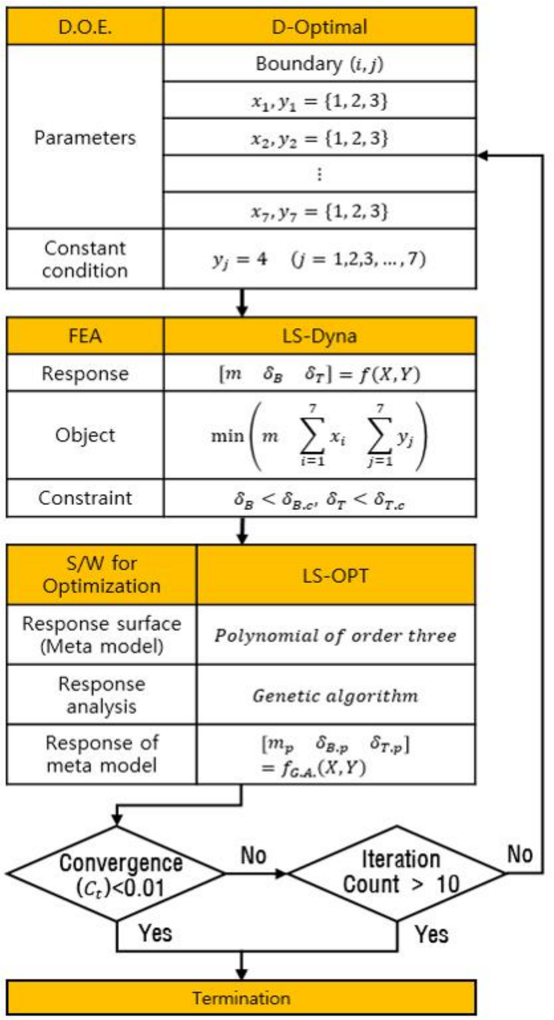
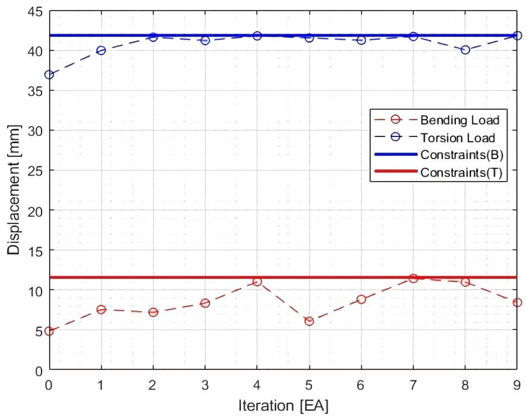


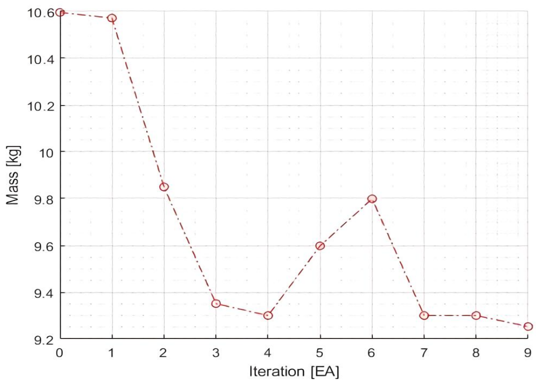
Fig. 9 Discrete Material and thickness optimization procedure

parameters of each part, x_i and y_i were determined by D-optimal DOE, and through the analytical results, mass (m), maximum displacement for bending load (δ_B), and maximum displacement for torsional load (δ_T) were derived. Subsequently, for each result, a response surface (meta model) was generated through a polynomial, and optimization was performed.

The objective function was set as the minimization of the sum ($\sum_{i=1}^{7} X^{i}$, $\sum_{i=1}^{7} Y^{i}$) of mass (m) and thickness ID. The error between the predicted value from the response surface and the analytical result for the



(a)



(b)

Fig. 10 DMTO optimization results. Variation in (a) maximum displacement and (b) seat frame mass through DMTO optimization

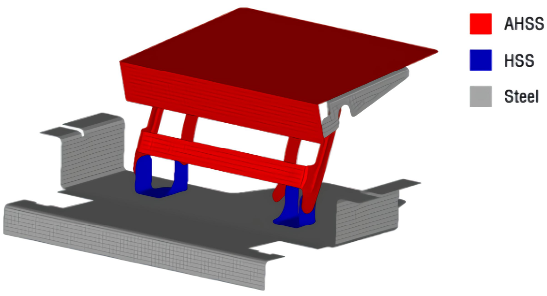


Fig. 11 DMTO optimization results

predicted value was compared, and the iterative analysis was stopped when the convergence value was 0.01 or less.

Parameters

$$X^{7} = x_1, x_2, x_3, x_4, x_5, x_6, x_7 \tag{8}$$

$$Y^{7} = y_1, y_2, y_3, y_4, y_5, y_6, y_7 \tag{9}$$

Response

$$[m,\ \delta_B,\ \delta_T] = f(X,\ Y) \tag{10}$$

Minimize object function

$$\min(m,\ \sum_{i=1}^{7} X^{i},\ \sum_{i=1}^{7} Y^{i}) \tag{11}$$

Constraints

$$\delta_B < \delta_{B,C} \tag{12}$$

$$\delta_T < \delta_{T,C} \tag{13}$$

where

X^{i} : Thickness ID of each part (i=7)

Y^{i} : Material ID of each part (i=7)

$\sum_{i=1}^{7} X^{i}$: Sum of thickness IDs of each part

$\sum_{i=1}^{7} Y^{i}$: Sum of material IDs of each part

m : Weight of infant-seat frame

δ_B : Maximum displacement under bending load

$\delta_{B,C}$: Constraint of maximum displacement

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under bending load

δ_T : Maximum displacement under torsional load

$\delta_{T,C}$: Constraint of maximum displacement under torsional load

Fig. 10 shows the results of the DMTO optimization. In the ninth iteration, convergence occurred, and optimization ended. This shows that more optimization iterations for DTO were required. The results in Fig. 10 (a) demonstrate that all the constraints were satisfied. Fig. 11 shows the AHSS material was applied to three of the seven parts. They are also the 1, 4, 5 parts in Fig. 4.

4. Results

With regard to the DTO and DMTO results, there was an approximately 79.1% difference in the maximum displacement under bending load (δ_B) and a 94.4% difference in the maximum displacement under torsional load (δ_T). The difference in the maximum displacement under torsional load was not as large.

However, the maximum displacement under bending load was approximately 9 mm smaller in the DTO results. Five fewer iterations were performed for DTO (-44.4%). The weight (m) reduction effect of DTO was approximately 15.2% and that of DMTO was 14.6%. Table 4 presents the quantitative results for DTO and DMTO.

Table 4 Design parameters through each optimization result

Part No.	DTO		DMTO	
	x_i	y_1	x_i	y_1
1	3	3	3	2
2	3	3	3	3
3	3	3	3	3
4	3	3	3	3
5	2	3	3	1
6	2	3	3	1
7	1	3	3	1
$\sum_{i=1}^{7} X^i$	17	-	3	–
$\sum_{i=1}^{7} Y^i$	-	21	-	14
Total Weight[kg]	3		1	

5. Conclusions

This paper proposed a weight reduction method using DMTO for an infant pop-up seat frame. An optimal lightweight design that satisfies the strength standards of the seat frame was performed. Furthermore, discretization parameters were used to minimize the application of high-strength and lightweight materials. In terms of the design parameters, three levels of materials and thickness were applied to seven parts of the infant pop-up seat. The optimization results demonstrated that DTO is efficient when one material is used, whereas DMTO is more effective when economical materials must also be considered. Because DTO and DMTO exhibited similar weight reduction effects, the thickness and material of the parts can be determined efficiently by selecting the technique according to the design environment. This paper considered an infant pop-up seat of only seven parts. If the extended structure like general seat model or assembled modules is applied, DTO and DMTO are likely to exhibit a larger difference in the number of iterations.

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