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Lightweight Optimization of Joint Type Seatback including Plastic Materials

Yeong Jo Ju[1] and Euy Sik Jeon[2]

[1]*Professor, Daeil industrial company. Ltd, Kongju National University (KNU), Korea.*

[2]*Department of Mechanical Engineering, Graduate School, Korea.*

Abstract

This paper proposes a method of lightweight strength optimization by adopting topology optimization and design-of-experiment (DOE) for joint-type seatback frame (deformation) to which typical metal materials are applied. The proposed method can use three materials according to the density ratio after optimizing the topology of the joint-type seatback frame of metal materials that satisfy FMVSS 207. In addition, the proposed method was verified to reduce weight and deformation by 14% and 32%, respectively, compared to those of the joint-type seatback frame to which typical metal materials are applied. Furthermore, each material thickness and application ratio of multiple materials was optimized using DOE, and the result showed a reduction of weight and deformation by 23% and 51%, respectively.

Keywords: Lightweight, Optimal design, Joint type, Seat back, Plastic, Material, D.O.E

INTRODUCTION

Owing to the recent development in the automotive industry, automobiles are becoming more advanced and customers are demanding improved automobiles in terms of comfort and convenience.(1) Seats in the convenience modules of automobile closely relate to passengers; in addition to supporting the passenger's body, a number of convenience modules are mounted in the seats.(2) However, these convenience modules have a bad influence on fuel efficiency.

Currently, power seats applied to automobiles are mounted with a supporter, an extension, positioning, and an adjuster. Although these convenience modules provide convenience and comfort to passengers, they are also the main factors that increase the seat weight. Several studies have proposed methods to develop lightweight seat frames while mounting convenience modules on seats.

The lightweight seat frames should not only reduce weight but also have strength to satisfy the law test. Cho(2) and Kim(3) applied high strength steel (HSS) with a higher strength than typical steel to compare the strength of seat recliner and frame according to thickness. Kim(4) verified lightweight and improved durability through the optimization of aluminum seat frames. In addition, Kim(5) verified that high-strength plastic seat frames can be lightweight while maintaining a steel strength. Furthermore, Jung(6) optimized HSS seat-cushion structures according to HSS thickness by using a design-of-experiment (DOE). Kim(7) applied glass-fiber-containing composite materials and verified lightweight possibility of reinforced seat frames.

Previous studies concerning lightweight optimization of seat structures by using lightweight materials have mainly employed a single material. In the present study, the light weight optimization was conducted by applying multiple materials rather than a single lightweight material. More specifically, a method of applying multiple materials, including plastic, was proposed through topology optimization of lightweight and strength improvement of joint-type seatback frames to which typical metal materials are applied. First, a joint-type seatback frame was designed using a typical seatback frame and was verified to satisfy the FMVSS 207 load condition. Then, a method is proposed to determine the application area of plastic, steel, and HSS materials according to the density ratio obtained from the topology optimization of joint-type seatback frame satisfying law test. In addition, it was verified that even if multiple materials containing plastic, with a weak strength according to material thickness, were applied to the seatback by using DOE, the seat satisfied law test and achieved lightweight.

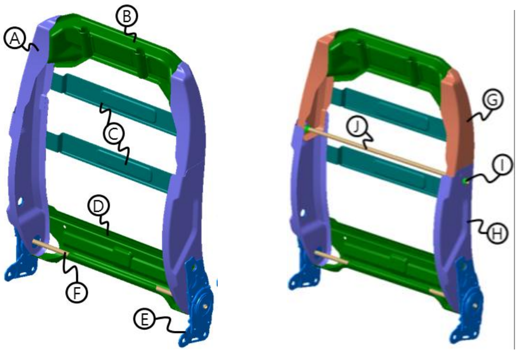
FINITE-ELEMENT ANALYSIS OF SEATBACK FRAME

Joint-type seatback frame design

Generally, an automotive seatback consists of a mechanism that performs front or rear rotation around the recliner. As a seatback is an integral part of the seat, it has a drawback that it cannot support a passenger’s back completely. To overcome this drawback of a seatback, a joint-type seatback was developed that supports a passenger’s back completely by rotating it upper part; this allows smooth adjustment according to various passenger postures. Furthermore, it can reduce passenger tiredness and provide comfort even after a long driving time.

A joint-type seatback frame comprises a connection structure using various mechanisms to connect the side frame to the main frame. The separated connection structure plays a role in connecting a side frame and rotating the upper seatback part by using a four-bar link structure, guide slot structure, or hinge structure. To drive the connection structure, additional modules, such as motors, are needed. However, the addition of modules increases the weight of the joint-type seatback. Moreover, the separated seatback frame causes reduction in strength. Thus, it is necessary to devise a method that not only makes the seatback frame lightweight but also increases strength.

In this regard, a joint-type seatback frame with a hinge structure, from among various connection structures, was designed for both lightweight and strength improvement of the frame. Fig. 1(a) shows the typical seatback frame structure, which is a typical seatback frame, and Fig. 1(b) shows the joint-type seatback frame structure with a separated side frame. In the joint-type seatback frame, the side frame is separated into upper and lower parts, and a connection structure, except for the additional module, is replaced with a hinge bush and hinge shaft for lightweight and strength improvement in the side frame. The side frame is a sheet type and is “U”-shaped. Table 1 lists the names of the parts in the typical and joint-type seatback frames.



(a) Typical-type (b) Joint-type

Figure 1: Seat back frame type

Table 1: Part name of the seat back frame

Symbol	Name	Symbol	Name
A	Side frame	F	Recliner shaft
B	Upper frame	G	Upper Side frame
C	Middle frame	H	Lower Side frame
D	Lower frame	I	Joint bush
E	Recliner	J	Joint shaft

A finite element analysis (FEA) was conducted on the typical and joint-type seatback frames to compare the lightweight and strength of the joint-type seatback frame with a hinge structure.

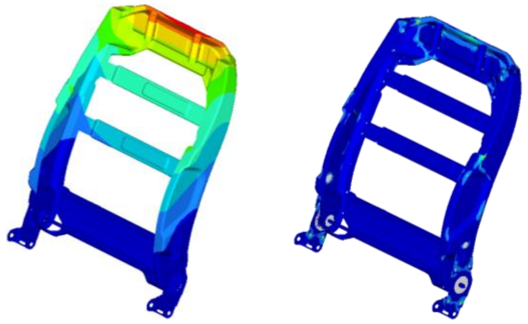
Finite element analysis

An FEA was conducted on the typical and joint-type seatback frames by using Hyper-Works: a CAE software application. As the frames in the two models were sheet types, a two-dimensional (2D) shell element was used to create the models. The typical and joint-type seatback models consist of 104,526 and 110,020 2D shell elements, respectively. The element type was set as Hexa and its size was set as 2 mm^2. The connecting condition of the two seatback frames was set to a rigid condition in the contact region between frames. For the joint-type seatback model, the connecting region of the hinge bush and hinge shaft was set to a rigid region. Furthermore, the thicknesses of the seatback frame and recliner were set at 0.8 and 2.0 mm, respectively. For the joint-type seatback model, the thickness of the shaft was set at 0.2 mm. Moreover, SPCC, which is a steel material generally used in seatback frames, was applied as the material to both models. To apply multiple materials to the joint-type seatback model later, a plastic and HSS with strengths respectively weaker and higher than that of SPCC were selected as the main materials, as presented in Table 2.

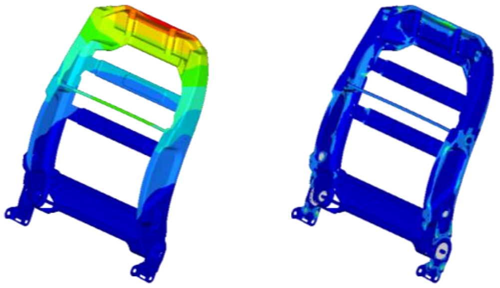
Table 2: Material data

Material	Yield Stress [MPa]	Youngs Modulus [GPa]	Poissons Ratio	Density [kg/mm^3]	Description
CFRP	-	60	0.08	$1.48*10^{6}$	Plastic
SPCC	208.9	210	0.3	$7.86*10^{6}$	Steel
SPFC 780	490	314	0.3	$7.86*10^{6}$	HSS

The FEA on the SPCC applied typical and joint-type seatback frame models applied the FMVSS 207 rear moment test, which is a law static test for automotive seats. The FMVSS refers to a law regulation in North America that protects passengers from various collisions; this must be satisfied by all automobiles.(8) The boundary condition for analysis was set to a completely fixed recliner assuming that the recliner was fixed to the seat cushion. A force of 755 Nm was horizontally applied to the upper part of the seatback frame by considering the seat reference point according to the FMVSS 207 rear moment test.



(a)Displacement and stresses of typical type



(b)Displacement and Stresses of joint type

Figure 2: Finite element analysis results of seatback frame with SPCC

Table 3 presents the FVMSS 207 law test results of the two SPCC applied models, with maximum deformations of 22.65 and 23.59 mm occurring at the upper seatback, and maximum stresses of 1873 and 1540 MPa, respective ely, occurring at the upper seatback, side frame, and recliner parts. The maximum deformation in the joint-type seatback model (Fig. 2(b)) was increased by 9.13%, while the maximum stress was decreased by 14.9% compared to those of the typical seatback model (Fig. 2(a)). This result indicates that deformation increases because of the separated seatback side frame, while stress reduces because the loads are separated.

Table-3. Analysis results of seatback frame with SPCC

Type	Material	Displacement [mm]	Stresses [Mpa]	Mass [kg]
Typical	SPCC	21.61	1811	3.368
Joint		23.59	1540	3.713

TOPOLOGY OPTIMIZATION OF JOINT-TYPE SEAT BACK FRAME

Topology optimization

Topology optimization is regarded as one of the structure optimization problems; it assumes holes inside the structure to enable designs that simultaneously satisfy lightweight and high strength by determining the shape, such as the number of holes, hole location, and connection between sections, without violating the design conditions(9). Thus, topology optimization has been applied to a truss structure design mainly in the structure optimization field because of the above-mentioned merits. In particular, it has been widely used in the transportation machinery industry, such as automobiles, in which CAE-based structure optimization techniques have begun to be applied in recent years(10). Generally, topology optimization can be divided into density and homogenization methods. The density method is similar to the homogenization method conceptually and is relatively easy to apply; thus, it has been widely used(11). In the present study, topology optimization was applied for selecting a multiple-materials application area in the joint-type seatback model. The problem of topology optimization is as follows:

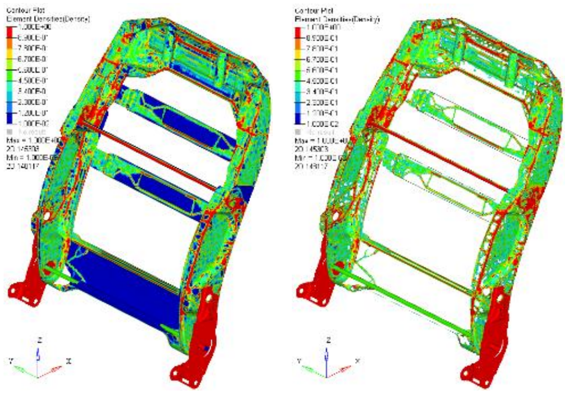
$$\begin{array}{llll} \text{Minimize} & f_1 = \text{Mass fraction of the seatback} & & \\ \text{Subject to} & -0.4 \leq t_i \leq +0.4 & n=1\sim5 & (1) \\ & -0.1 \leq t_i \leq +0.1 & n=6\sim7 & \\ & \sigma_{von} \leq 780\text{MPa} & & \end{array}$$

The objective of topology optimization is to select a multiple-materials application area; thus, it was defined as the minimum mass fraction (Mf_{min}) in the joint-type seatback model according to the static test standard. Table 4 presents the frames to which multiple materials were applied in the joint-type seatback model and the range of each frame. The design range of each frame was set to a limited condition based on the processable thickness of multiple materials, as presented in Table 2. As described in Section 2.2, topology optimization was conducted by applying the FMVSS 207 law test.

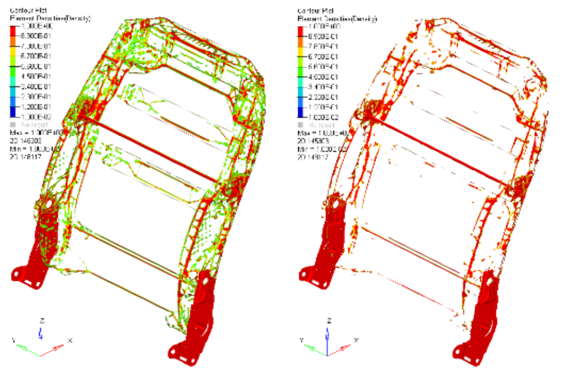
Table 4: Design variable for topology optimization

Symbol	Value	Explanation
t_1	-0.4 ~ +0.4 [mm]	Upper frame thickness
t_2		Middle frame thickness
t_3		Lower frame thickness
t_4		Upper Side frame thickness
t_5		Lower Side frame thickness
t_6	-0.1 ~ +0.1 [mm]	Recliner shaft thickness
t_7		Joint shaft thickness

Fig. 3 shows the derived shape after the performance of topology optimization, with conditions set using Hyper-Work, which is a CAE software application. Fig. 3(a) shows a section in which the density ratio in the joint-type seatback model is in the range of 0.0–1.0. In addition, Figs. 3(b)–(d) show sections whose density ratios are 0.3–1.0, 0.5–1.0, and 0.7–1.0, respectively.



(a) Current value 0 (b) Current value 0.3



(c) Current value 0.5 (d) Current value 0.7

Figure 3: Topological optimization results of structures

The density ratio according to the topology optimization result was derived, as shown in Table 5. An FEM of the joint-type seatback model was conducted by applying multiple materials for lightweight and strength improvement in the joint-type seatback model based on the above results.

Table 5: Density ratio according to topology optimization results

Indicator function	Element(ea)	Ratio(%)
0.0 – 0.1	22468	22.78
0.1 – 0.2	3522	3.57
0.2 - 0.3	6640	6.73
0.3 – 0.4	11313	11.47
0.4 – 0.5	18878	19.14
0.5 – 0.6	12060	12.23
0.6 – 0.7	6691	6.78
0.7 – 0.8	4946	5.01
0.8 – 0.9	3429	3.48
0.9 – 1.0	8695	8.81

Lightweight with multiple materials

Table 6 presents combinations of three materials, that is, plastic, steel, and HSS, according to the density ratios specified in Table 5. The plastic application was set to an area whose indicator function was 0.0–0.3; this is a material area that can be removed at the largest ratio, as shown in Fig. 3(b), because plastic is a weak material. In contrast, steel and HSS were applied to an area whose indicator function was 0.3 or higher, as shown in Figs. 3(c) and (d), to set the combinations by varying the application ratio.

Table 6: Cases according to density ratio with multiple materials

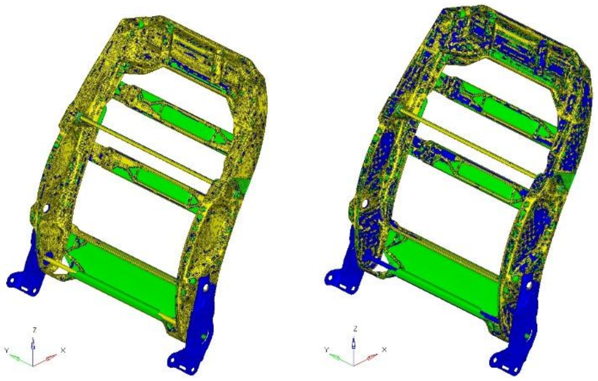
Cases	Plastic ratio (%)	Steel ratio (%)	HSS ratio (%)
Case 1	22.78	40.91	24.09
Case 2	22.78	53.13	36.31
Case 3	22.78	10.30	55.45
Case 4	22.78	10.30	66.92
Case 5	33.08	49.62	17.31
Case 6	33.08	42.83	24.09
Case 7	33.08	30.61	36.31
Case 8	22.78	77.22	0
Case 9	22.78	0	77.22
Case 10	33.08	66.92	0
Case 11	33.08	0	66.92

The FEA result, in which FMVSS 207 law test was applied, as described in Section 2.2, according to the combinations in Table 6, showed that the maximum deformation, maximum stress, and weight/lightweight ratio can be determined according to each combination, as shown in Table 7. The maximum deformation compared to that in the joint-type seatback model (Table 3) was 15.9 mm on average, which decreased by 32%, and the maximum stress was 1,650 MPa on average, which increased by 7%. The weight was 3.16 on average; this decreased by 14%.

Table 7: Analysis results according to combinations

Cases	Displacement [mm]	Stresses [Mpa]	Mass [kg]	Mass ratio(%)
Case 1	15.24	1726	3.256	-12
Case 2	14.67	1603	3.256	-12
Case 3	14.30	1596	3.256	-12
Case 4	14.04	1582	3.256	-12
Case 5	16.58	1808	3.056	-17
Case 6	16.04	1806	3.056	-17
Case 7	15.43	1677	3.056	-17
Case 8	19.40	1533	3.256	-12
Case 9	13.76	1554	3.256	-12
Case 10	20.59	1610	3.056	-17
Case 11	14.78	1655	3.056	-17

As the present study aims for lightweight of the joint-type seatback model, two models were selected as presented in Table 8 among the joint-type seatback models that applied multiple materials, and lightweight optimization was conducted through DOE. Fig. 4(b) shows Case 7 in which the lightweight improved by 17% and the mean and error of the maximum deformation and stress were small. Fig. 4(a) shows Case 4, in which lightweight improved by 12%, and the maximum deformation and stress were small. In Cases 8–11, lightweight and strength improvement were achieved but three materials (plastic, steel, and HSC) were not applied; thus, they were excluded.



(a) Case 4 (b) Case 7

Figure-4. Seatback model according to combinations with multiple materials

Table 8: Analysis and combinations of Fig. 4

Cases	Plastic (%)	Steel (%)	HSS (%)	Disp. [mm]	Str. [Mpa]	Weight [kg]
Case 4	22.78	10.30	66.92	14.04	1582	3.256
Case 7	33.08	30.61	36.31	15.43	1677	3.056

LIGHTWEIGHT OPTIMIZATION OF JOINT TYPE SEATBACK FRAME

Design of experiment

The DOE, which is a statistical analysis method that determines effects according to changes in several factors set in the experiment, has been adopted in the machinery field. DOE has the advantage of deriving optimum results with relatively simple opportunity cost; therefore, it has been widely used in many studies in the mechanical engineering field. In the joint-type seatback model, which was derived by applying multiple materials and DOE, the material thickness was set as a design variable and final lightweight optimization was conducted through DOE. Table 9 presents the thickness range according to each material in the joint-type seatback model, to which multiple materials were applied, as shown in Fig. 4, as a design variable to be applied in the DOE. The setup of the design variable is such that it can achieve more lightweight than the analysis results according to the combinations presented in Table 7 because the maximum deformation, stress, and weight in the joint-type seatback model can be changed according to each material's thickness.

Table 9: Design variable and range for D.O.E

Symbol	Value	Explanation
P_1	$-0.4 \leq P_1 \leq +0.4$ [mm]	Plastic material area thickness
S_1	$-0.4 \leq S_1 \leq +0.4$ [mm]	Steel material area thickness
H_1	$-0.4 \leq H_1 \leq +0.4$ [mm]	HSS material area thickness

The DOE applied in the present study was developed by McKay in 1979 as a Latin-Hypercube sampling. It has the advantage of obtaining main effects with a small number of experiments when interactions are not considered in a static structure design or when the number of factors is large. The number of analyses in the joint-type seatback model used in Case 4 (Fig. 4(a)) and Case 7 (Fig. 4(b)) is 10 times. Table 10 presents the experimental values commonly applied to the two models.

Table 10: Experiment table for D.O.E

No.	**P_1 (mm)**	**S_1 (mm)**	**H_1 (mm)**
No.1	1.14	1.04	1.05
No.2	0.40	0.57	0.50
No.3	0.64	0.47	0.79
No.4	0.65	0.75	0.40
No.5	0.91	0.49	0.83
No.6	0.81	0.70	0.97
No.7	0.50	0.98	0.70
No.8	1.02	1.14	0.58
No.9	1.11	0.88	0.96
No.10	0.80	0.96	1.20

Table 11 presents the results obtained using the experimental values in Table 10. This table shows that the maximum deformation increased by 1.2% compared to the results in Table 7, whereas the maximum stress and weight decreased by 49.4% and 7%, respectively. The optimum values of the design variables P_1, S_1, and H_1 are 0.91, 0.49, and 0.83 mm, respectively.

Table 11: Analysis results D.O.E

Case 4	**Displacement [mm]**	**Stresses [Mpa]**	**Weight [kg]**	**Weight ratio(%)**
No.1	9.65	427.06	3.89	19
No.2	28.61	1393.15	2.52	-23
No.3	14.75	698.68	3.12	-4
No.4	37.30	1801.48	2.41	-26
No.5	13.63	648.15	3.24	0
No.6	11.06	496.96	3.58	10
No.7	16.62	790.76	3.06	-6
No.8	19.90	984.14	2.95	-9
No.9	10.88	498.24	3.65	12
No.10	8.46	347.93	4.12	27
Case 7	**Displacement [mm]**	**Stresses [Mpa]**	**Weight [kg]**	**Weight ratio(%)**
No.1	10.55	478.47	3.62	19
No.2	31.50	1566.30	2.43	-20
No.3	17.20	947.43	2.72	-11
No.4	36.60	1653.55	2.54	-17
No.5	15.61	848.96	2.83	-7
No.6	12.64	620.51	3.16	3
No.7	17.90	835.70	3.05	0
No.8	19.41	864.29	3.17	4
No.9	11.94	567.64	3.37	10
No.10	9.66	420.71	3.65	19

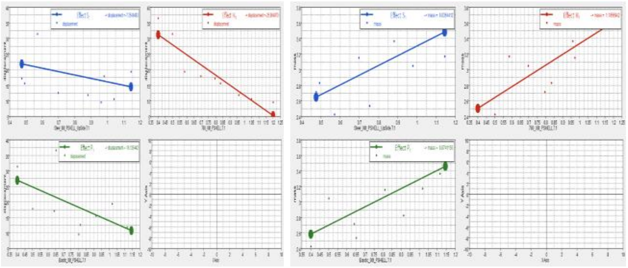
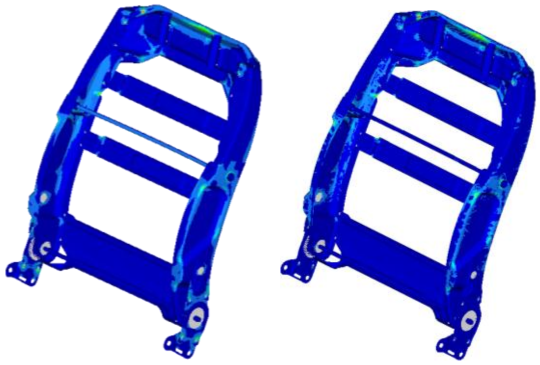


Figure 5: Sensitivity analysis result of deformation and weight for Case 7

The DOE verified that the result of the sensitivity analysis of deformation and weight on the HSS value was high.

Table 12: Result of initial value and optimum value

Type	Material	Disp. [mm]	Stress [Mpa]	Weight [kg]
Typical	SPCC	21.61	1811	3.368
Joint		23.59	1540	3.713
Joint	Plastic 33.08% Steel 30.61% HSS 36.31%	15.61	848.96	2.83



(a) Initial (b) Optimization

Figure 6: Compare initial with optimization

Fig. 6 shows the stress distribution of the joint-type seatback model to which multiple materials were applied to compare the values between SPCC single material and multiple materials. As shown in Table 12, the joint-type seatback model to which the optimized multiple materials were applied decreased the maximum deformation and stress by 51.09% and 44.87% compared with those of the initial seatback model, and the weight was decreased by 23%. As such, the lightweight of the joint-type seatback frame, to which multiple materials were applied, was optimized.

CONCLUSIONS

The present study proposed an optimization method to enable lightweight and strength improvement by applying multiple materials by means of DOE to a joint-type seatback frame, to which typical metals were applied.

The design of the joint-type seatback frame satisfied the load condition specified in the FMVSS 207 law test standard by using a typical typical seatback frame. The present study also proposed a method to determine the application area of plastic, steel, and HSS materials according to the density ratio through the DOE of the joint-type seatback frame, to which metal materials that passed the law test were applied. The optimization result showed that the weight and deformation were decreased by 14% and 32% than those of the joint-type seatback frame to which typical metal materials were applied according to the application area of the multiple materials. In addition, the result verified that the maximum weight and deformation decreased by 23% and 51%, respectively, than those of the seatback frame to which typical metal materials were applied according to the application ratio of multiple materials and material thickness by means of DOE. The above result verifies that when multiple materials are applied to the joint-type seatback frame, both the requirement of lightweight and the FMVSS207 law standard were satisfied.

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