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Investigation of weight reduction of automotive body structures with the use of sandwich materials

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Abstract

The use of sandwich materials in automobile body panels is investigated in this study. In the first part, floor, luggage, firewall and rear wheel panels of a car body-in-white are replaced with panels made of sandwich materials in order to reduce the weight. Final sandwich material configurations are obtained through a trial and error based optimization approach where weights of the panels are minimized while keeping bending stiffness performances of the panels same. In the second part, the use of sandwich materials in laminated steel form as light weight alternatives to free layer surface damping treatments attached to floor panels is investigated. Free layer damping treatments are applied to body panels to decrease primarily the structure-borne noise inside the cabin. This effect is achieved by increasing structural damping in the panel structures. It has been demonstrated that, same level of vibration damping increase in a floor panel can be achieved using a sandwich material in laminated steel form with a lesser amount of weight addition to the original sheet metal floor panel compared to a free layer surface damping treatment.

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Keywords: sandwich materials; viscoelastic materials; performance & safety of alternative material; light weight body; fuel econo

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1. Introduction

The purpose of this study is to investigate the use of sandwich structures for weight reduction in automobile body panels. Main motivation to replace sheet metal body panels with panels made from sandwich materials is to decrease mass of the car body thus contribute to improve motor emissions (due to reduced power needs thus smaller size motors when body weight is reduced). The objective of decreasing body panel weights is possible to achieve because body panels with sandwich structures can potentionally show the same static and vibrational performance with less weight. In this study, the sandwich material configurations that will help us to achieve the target of decreasing mass of body panels are investigated using finite element based simulations for static and vibrational behaviour.

One of the purposes of the use of sandwich structures in car body structures is to decrease the bending and torsional stiffness of body by replacing some body panels with sandwich structures. With the sandwich assembly, the structure gains high flexural rigidity thus a high stiffness-to-weight ratio and also a high bending strength-to--weight ratio. This will enable a reduction in weight of the car body with a static performance kept same as the sheet metal based design of the body panels.

According to Jones (2001) and Nashif et al. (1985), one of the other advantages of sandwich materials is that the vibration damping of a body panel can be increased with the use of a special configuration of sandwich materials called laminated sheet metal panels which is composed of two metal sheet panels joined with a very thin viscoelastic material core with high material damping. This configuration can replace the currently used solution for introducing vibration damping to body panels (especially floor and ceiling panels) which a thick layer of viscoelastic material is bonded on sheet metal body panels (also called free layer damping treatment) as mentioned in the study of Rao (2003). In order to achieve the same damping for body panels, current free layer damping treatment approach requires larger mass addition compared to the overall mass increase if the sheet metal panels were replaced by high damping laminated metal panels.

This study is composed of several chapters. In the second chapter, general information about sandwich structures are reviewed and presented. In the third chapter, static bending analyses are performed and an optimization process is developed in order to obtain the minimum weighted polymeric foam cored sandwich panel which has the same bending stiffness as the steel panel. The last chapter contains development of an optimization process for obtaining the panel with surface damping treatments which has the same average modal damping ratio as laminated steel panel. It is proven that, the weight of floor panels can be decreased by replacing the panels with damping treatments with laminated steel panels which has the less weight.

The car body panels used in this study are floor panel, rear wheel panels, firewall panel and luggage panel. All of these panels are investigated for their static behaviour and only floor panel is investigated for vibrational behaviour.

2. Background

Sandwich structures are composed of a weak (low elasticity modulus) and light-weight core material sandwiched between two strong (high elasticity modulus) and heavy face materials. Due to their high bending stiffness-to-weight ratio, sandwich structures results in lower lateral deformations, higher buckling resistance and higher natural frequencies than do sheet metals. Therefore, at the same loading and boundary conditions, sandwich structure of similar static, strength and buckling performance can be obtained with lower overall weight.

According to Zenkert (1997) and Vinson (1999), sandwich materials use the simple fact that increasing the flexural rigidity of a plate or beam structure can be achieved by placing the material away from the neutral axis as much as possible. By smart distribution of a material in the cross-section of the structure increased flexural rigidity can be achieved with minimal change in weight of the structure. The concept is the same thing that makes I-beams advantageous. In sandwich structures the web of an I-beam is usually replaced by light weight and low rigidity structural core material (made of metal or nonmetal foam, corrugated or honeycomb pattern) while at the outer rigid structural material parts (sheet metals or composite plates) are utilized.

With the use of sandwich panels with thin viscoelastic core, the vibrational characteristics can be improved without adding much weight. This allows the reduction or elimination of vibration damping materials used on the automobile body panels.

3. Use of sandwich materials for reducing the weight of car body-in-white panels considering static stiffness characteristics

The finite element model of FIAT Car body model that Özgen (2001), has used in his study is again used (Figure 2). The floor panel, firewall panel, rear wheel panels and luggage panel of this body model will be redesigned with sandwich materials. These panels are chosen due to their load carrying conditions. Floor panel is chosen as the load-carrying panel and others are the some of the examples for non-load-carrying panels. In this design study, the curvatures and shapes of panels are not changed but its sandwich configurations such as thicknesses and materials of both face and core layers are determined. It is aimed to obtain a minimum weighted sandwich panel for these panels having the same static performance as steel panel. This performance is maximum displacement in the panels observed in the bending stiffness analysis of car body-in-white under test loads. For this purpose, while determining the sandwich material configurations for these panels, the sandwich material parameters that give maximum displacement close to the maximum displacement given by sheet metal panels are determined.

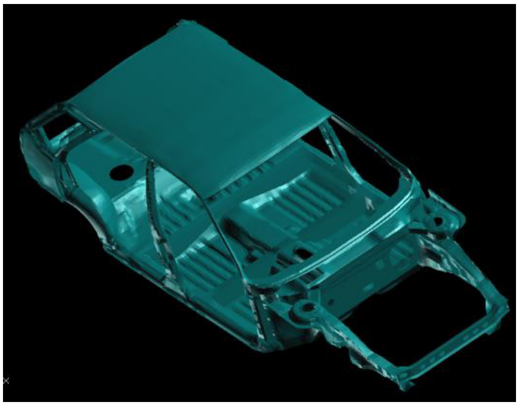

Fig. 1. FIAT car body-in-white CAD model.

Bending stiffness of an automobile body may be determined by applying 6432 N vertical load on mid floor area of the body and clamping the regions where suspension springs are located as seen in Figure 2.

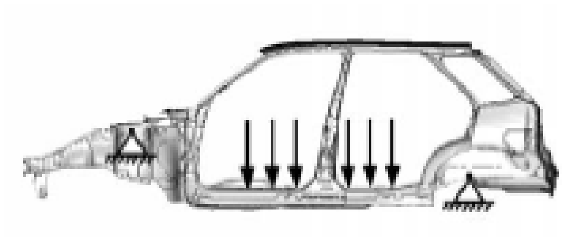

Fig. 2. Load/Boundary conditions of FIAT car model in the study of Özgen (2001).

The design procedure is described in below flowchart in Figure 3.

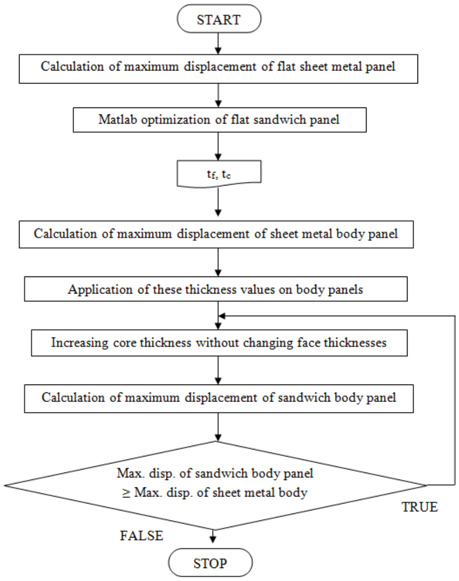

Fig. 3. Flowchart of design procedure.

This optimization study divided into two as with clamped and simply supported boundary conditions. And study for simply supported B.C. is also divided into two by different constraint types. As first constraint type, face thicknesses must be equal and have at least 0.2 mm thickness each and total thickness of sandwich panel must not exceed 10 mm. As the second type, only the thickness limitations are changed in order to see how the optimization results depend on the thickness limitations. For this type, face thicknesses must also be equal and have at least 0.1 mm thickness each and total thickness of sandwich panel must not exceed 20 mm. Flat sandwich panel deformations are calculated using analytical formulas that are shown in the studies of Zenkert (1997), Vinson (1999), Plantema (1996) and Young (2002). Actual floor panel deformations are calculated using a finite element model composed of shell elements.

The luggage, firewall and rear wheel panels are studied with a process that the thickness of face materials are chosen as thinner than the half of original panel thickness and core thicknesses are increased from zero until maximum displacement reaches the value of the one for steel panels. Optimization of every part is handled individually.

The resulting thickness values of this optimization study and weight reduction are shown in Table 1.

Table 1. Design process and results.

Panel	B.C.	Flat [mm]	Body [mm]	Weight Reduction
Floor	Clamped	t_f: 0.1 t_c: 1.3	t_f: 0.1 t_c: 15.5	72%
	S.S. (Constraint type 1)	t_f: 0.1 t_c: 0.72	t_f: 0.2 t_c: 11	54.4%
	S.S. (Constraint type 2)	t_f: 0.16 t_c: 0.86	t_f: 0.16 t_c: 12.5	61.1%
Luggage			t_f: 0.2 t_c: 10	54.9%
Firewall			t_f: 0.4 t_c: 9	52.4%
Rear Wheel			t_f: 0.2 t_c: 1.5	49%

4. Use of sandwich materials for increased damping of car body-in-white panels

The purpose of this study is to investigate the difference between the amounts of viscoelastic material addition for sandwich material and free layer surface damping treatment applications. The surface damping treatments are applied on the floor panel where the seats are located as seen in Figure 3. The investigation is done using the same viscoelastic material for both of these methods. Since there is no data to design a free layer surface damping treatment thickness, a laminated steel, a special type of sandwich structure, with a specific thickness and materials for face and core layers is chosen. Free layer surface damping treatment with the same material as the core layer of laminated steel is added on steel sheet metal panel with the initial thickness guess of the thickness of laminated steel's core layer. The thickness is incrementally increased until the same damping performance (i.e modal loss factors for panel frequency response functions) as laminated steel configuration is achieved. Then, total weights of both panel with free layer surface damping treatment and laminated steel is compared in order to show that laminated steels may have the same damping performance as panels with free layer surface damping treatments with a less weight addition.

Fig. 4. Photographic image of surface damping treatment applied on the floor panel.

4.1. Verification of optimization method by an application of vibration damping of beams

The optimization process is first applied on beams since theoretical formulas for estimating the loss factor at each mode and frequency response function plots are known. The chosen laminated steel panel has 0.1 mm thick 3M-467 viscoelastic adhesive bonded between two steel sheets with 0.5 mm thickness each. The boundary condition of this beam is selected as simply supported and With an arbitrary selection, a unit harmonic force is applied at +z direction on the quarter of length.

The optimizaton process starts with adding the same viscoelastic material with the same thickness as the core of sandwich structure on the beam as a surface damping treatment. The process continues by increasing the thickness of damping treatment until the loss factor of the structure reaches that of sandwich material for the first few modes except the first (fundamental) one. A thickness is obtained for each modes and the free layer surface damping treatment thickness is accepted to be their average. Loss factors and frequency response functions (FRF) are estimated with MSC.Actran along with theoretical formulas that are shown in the studies of Nashif et al. (1985) and Jones (2001) and have shown a good agreement with each other as seen in Figure 5 and 6. After process is verified, the same process is applied on floor panel of FIAT car model.

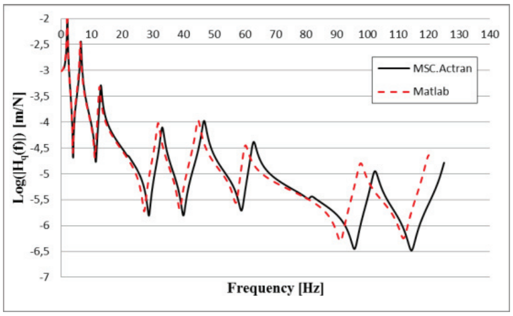

Fig. 5. FRF's of the sandwich beam determined via virtual analysis and theoretical formulas.

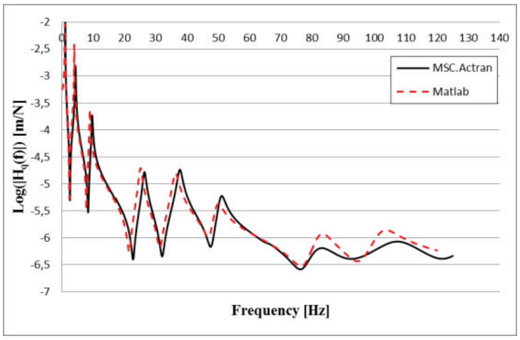

Fig. 6. FRF's of the beam with free layer surface damping treatment determined via virtual analysis and theoretical formulas.

In order to find an optimum free layer surface damping treatment thickness, the initial guess of viscoelastic material (the same material of the core layer of sandwich structure at the same temperature) addition is chosen to be the core layer thickness of the sandwich structure. The modal loss factors of beam with free layer surface damping treatment are increasing with the mode number in an order but in sandwich structure they are not. Therefore, the initial guess of thickness is increased until the average modal loss factor of 2nd, 3rd, 4th, 5th, 6th and 7th modes satisfy the same average loss factor of the sandwich structure. And with these design criteria, free layer surface damping treatment is obtained as 41.5 mm. By this way, the weight is reduced by 85% with using a sandwich structure instead of free layer surface damping treatment The comparison of FRF plots of steel beam, sandwich beam and beam with free layer surface damping treatment is shown in Figure 7.

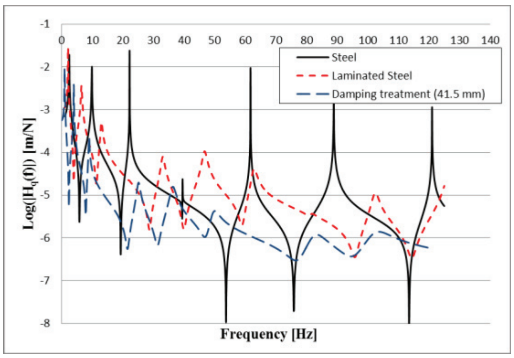

Fig. 7. Comparison of FRF plots of beams.

Table 2. Loss factors of the beams with free layer surface damping treatment determined via MSC.Actran and theoretical formulas.

Method	Modes [Hz]						
	1	2	3	4	5	6	7
Theoretical	0.008	0.015	0.024	0.032	0.039	0.047	0.056
MSC.Actran	0.008	0.016	0.024	0.032	0.039	0.046	0.056

4.2. Vibration damping of floor panel of FIAT Car

For the investigation of vibration damping of floor panel of FIAT Car, the same design procedure and sandwich material configuration are used. The floor panel of FIAT Car is shown in Figure 8.

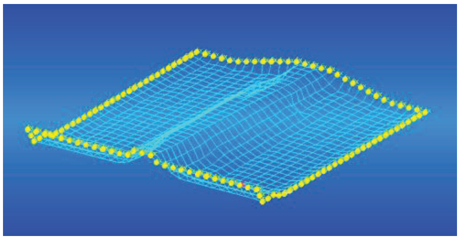

Fig. 8. The floor panel of FIAT Car.

In order to find an optimum free layer surface damping treatment thickness, the initial guess of viscoelastic material addition is again chosen to be the core layer thickness of the sandwich structure. This thickness is is increased until the average modal loss factor of 2nd, 3rd, 4th, 5th and 6th modes satisfies the same average loss factor of the sandwich structure. And with these design criteria, free layer surface damping treatment is obtained as 18 mm. Frequency response functions of the floor panel with sheet metal, sandwich structure and 18 mm free layer surface damping treatment are plotted in Figure 9.

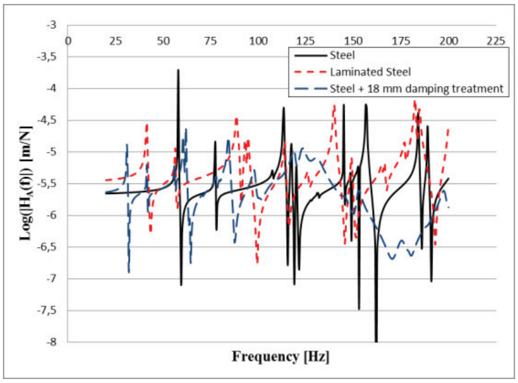

Fig. 9. Comparison of FRF plots of floor panel.

Table 3. Comparison of loss factors of sandwich structure and damping treatments.

Method	Modes [Hz]					
	1	2	3	4	5	6
Sandwich	0.011	0.009	0.010	0.010	0.025	0.039
18 mm damping treatment	0.01	0.0096	0.011	0.0012	0.0255	0.0037

As seen, the same average modal loss factor of first few modes of sandwich structure with a 0.1 mm viscoelastic material addition is obtained by adding the same material on the top of steel panel as free layer surface damping treatment with 18 mm thickness. By this way, the weight is reduced by 68% with using a sandwich structure instead of free layer surface damping treatment.

5. Discussions and conclusions

The static, vibrational and acoustic properties of sandwich structures are investigated within this study. It is seen that, foam cored sandwich structures can show the same bending stiffness performance as the steel sheet metal panel with at least 50% less weight. It is also shown that, instead of damping treatments added on the panels, using sandwich panel with a thin viscoelastic material core can reduce the weight by approximately 60–70% keeping the same damping performance.

Considering these benefits of sandwich structures, they can be very widely used in car body design. The laminated metals with very thin viscoelastic core layers are mostly used for vibration dissipation. Other types as cellular foamed, honeycomb cored and balsa wood cored sandwich panels may be used for reducing weights of the panels under physical loads such as bending, torsion and buckling etc. Using sandwich structures instead of sheet metals the amount of emissions can be decreased because the power needs are reduced by weight reduction.

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