DESIGN OPTIMIZATION OF CFRP RECTANGULAR BOX SUBJECTED TO ARBITRARY LOADINGS

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Abstract

Carbon fiber reinforced plastics (CFRP) has been said to have great potential in weight reduction of structures because of its high specific stiffness and strength. However, this is true only in the case of tensile strength and flexural rigidity of plates as same as other light metals.

In this study, the best weight lightening direction of a rectangular box made of hollow beams and panels subjected to arbitrary external loads is discussed by using Finite Element Analysis. The materials used are steel, isotropic and anisotropic CFRP. Based on the results, a design optimization including multi material solution is discussed on the purpose of affordable realization of light-weight structures such as mass production automobile.

1. Introduction

Vehicle weight reduction has been considered as one of the most important solutions to improve fuel economy and reduce harmful emissions[1]. It is believed that multi-material selection can be the solution for the vehicle body weight reduction. Flexural rigidity and torsional rigidity are the major consideration during vehicle design. In the past several years, various lightweight automotive bodies have been developed using high strength steels [2,3], aluminum alloys[4,5] and different composite materials[6]. Among the composite materials, Carbon fiber reinforced plastics (CFRP) has been said to have great potential in weight reduction of structures because of its high specific stiffness and strength[7]. However, most work done in lightweight materials car body design has been limited to single loading condition.

The objective of this study is to find the lightest rectangular box structure subjected to arbitrary static loadings using multi-material solution and thickness optimization. The rectangular box made of hollow beams and panels is similar to the vehicle structure, the materials used in this research are steel, and CFRP, including UD(Uni-directional)material, CTT(Chopped carbon fiber tape reinforced thermoplastics) and UT-CTT(Ultra-chopped carbon fiber tape reinforced thermoplastics).

2. Finite element analysis

As Fig.1 shows, the rectangular box is made up of hollow beams and panels, including floor panel, top panel, front panel, rear panel, left panel and right panel. The dimensions of the box are 2900mm×1400mm×1500mm(Length×Width×Height). The outer cross-section size of hollow beam is 100mm×100mm.

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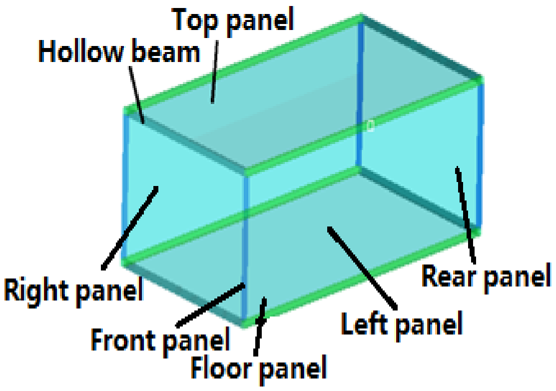

Figure 1. Three-dimension model of rectangular box

2.1. Theoretical calculation

2.1.1. Flexural rigidity calculation

Flexural rigidity EI can be calculated by the following equation:

$$EI = \frac{F}{Z_{\max}} \tag{1}$$

EI : Flexural rigidity（N/mm）
F : Concentrate force (N)
$Z_{\max}$: The maximum flexure deflection(mm).

2.1.2. Torsional rigidity calculation

Torsional rigidity GJ can be calculated by the following equation:

$$GJ = \frac{TL}{\theta} = \frac{TL}{\arctan\left(\frac{|U1| + |U2|}{D}\right) * \frac{180}{\pi}} \tag{2}$$

GJ : Torsional rigidity (N·mm/rad)
T : Torsion force (N)
L : Wheelbase (mm)
θ : Torsion angle (deg)
$|U1|$: The abs value of left measure point deflection (mm)
$|U2|$: The abs value of right measure point deflection (mm)
D : Distance between left measure point and right measure point (mm).

2.2. Finite element model

In this study, finite element models shown were established by using Altair HYPERMESH, the hollow beams and panels are modeled as shell element, the thickness of hollow beams and panels are 2mm and 1mm, respectively. The material properties can be found in Table 1.

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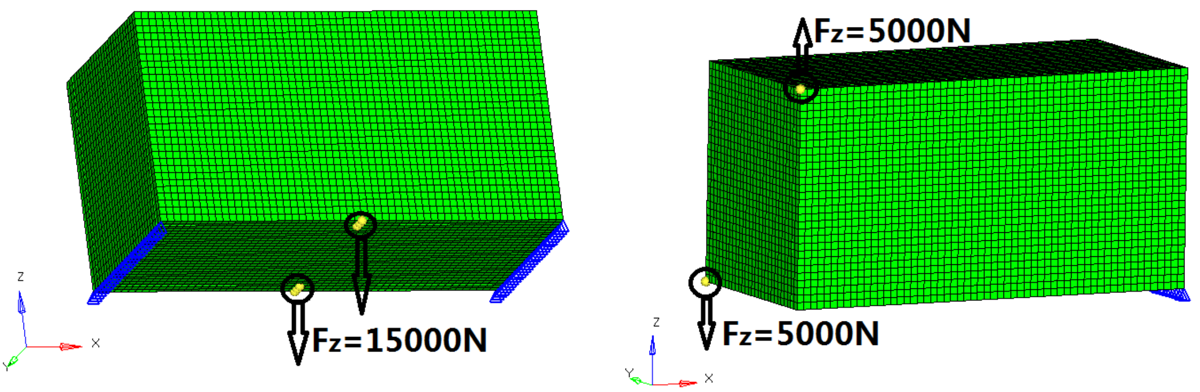
In flexure modeling Fig. 2(a), the concentrate force F_z was loaded at left and right side of the middle part of the rectangular box structure. The boundary condition was to constrain translation in x, y and z-directions at front side and rear side of the rectangular box structure.

In torsion modeling Fig. 2(b), a pair of opposite concentrate forces F_z were loaded at front side of the rectangular box structure. The boundary condition was to constrain the translation in x, y and z-directions at rear side of the structure.

Table 1. Material parameters

Material property		Steel	UD	CTT	UT-CTT
Density (g/cm^3)		7.80	1.30	1.35	1.50
Elastic Modulus (GPa)	E_1	211	101	34	41
	E_2	211	4.5	34	41
Shear Modulus (GPa)	G_{12}	81	1.5	12	16
	G_{13}	81	1.5	1.5	1.0
	G_{23}	81	1.5	1.5	1.0
Poisson ratio	υ_{12}	0.3	0.34	0.33	0.28
Tensile strength (MPa)	σ_{1y}	780	1573	315	528
	σ_{2y}	780	21	315	528
Compression strength (MPa)	σ_{1c}	780	461	240	370
	σ_{2c}	780	70	240	370
Resin matrix		-	PP	PP	PA6
Vf (%)		-	50	50	55

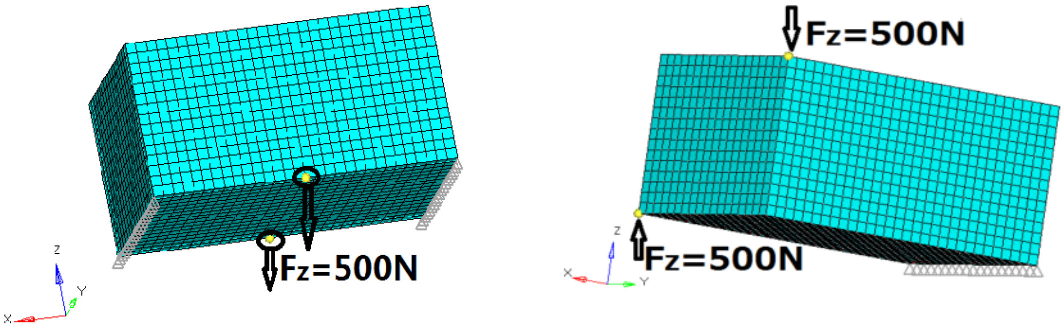


(a) Flexure modeling **(b)** Torsion modeling

Figure 2. Finite element model of rectangular box

2.3. Results

In order to reduce the design variables in the following design optimization, the sensitivity of panels and hollow beams to the flexural and torsional rigidity should be conducted. The finite element modelings of scaled rectangular box shown in Fig.3 were used to study the relationship between components thickness and rigidity for reducing the CPU calculation time.



(a) Flexure modeling **(b)** Torsion modeling

Figure 3. Finite element model of scaled rectangular box

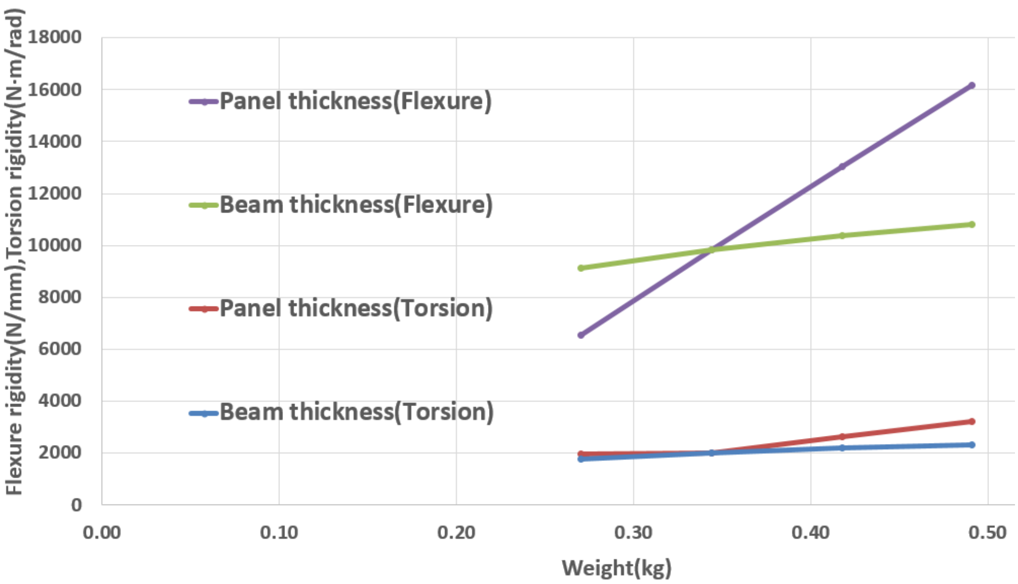


Figure 4. The relationship between components thickness and rigidity

The flexural and torsional rigidity can be calculated by equation (1) and (2). As Fig.4 shows, the flexural and torsional rigidity will increase with thickness increasing. Comparing with the hollow beams, however, the panels play much more important role in flexural and torsional rigidity which means that the panels thickness should be considered as design variables during optimization work.

Additionally, the FEA results of steel rectangular box should be made as the comparison with the results of the optimal structure. From the results of numerical simulation, the flexural and torsional rigidity is 5926 N/mm and 83047000 N·mm/rad, respectively. Correspondingly, the total weight of the structure is 298.7kg. The results will be reference for the following optimization process.

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3. Optimization process

In this study, the material types rather than material properties are introduced as design variables in order to reduce the design variables. Each candidate material type has been assigned an ID number from 1 to m, which can be in any arbitrary order. Define the material used for ith component as a design variable named M_i ($M_i \in \{1, 2, ..., m\}$). If a material type is given to M_i , all the related properties of the material can be identified exactly. Besides, the thickness of hollow beams was set to same with the steel one due to the panels' important role in the flexural and torsional rigidity optimization. Besides, the thickness of front panel and rear panel are same in the real vehicle design process, as well as the thickness of left panel and right panel. Therefore, the thickness of floor panel, top panel, front panel and left panel were considered as design variables during optimization work.

3.1. Flexural and torsional rigidity optimization

The optimization model can be formulated as follows：

Objective function: $Minimum W = W(T_{panel}, M_i), i = 1, 2$

Constraints: $EI\left(T_{panel}, M_i\right) \geq EI(steel)$

$GJ(T_{panel}, M_i) \geq GJ(steel)$

Design variables: $1 \leq T_{floorpanel} \leq 1.5$

$1 \leq T_{toppanel} \leq 1.5$

$1 \leq T_{frontpanel} \leq 1.5$

$1 \leq T_{leftpanel} \leq 1.5$

$M_i \in \{1, 2, 3, 4\}$

W : Total weight (kg)

$T_{floorpanel}$: The thickness of floor panel (mm)

$T_{toppanel}$: The thickness of top panel (mm)

$T_{frontpanel}$: The thickness of front panel (mm)

$T_{leftpanel}$: The thickness of left panel (mm)

M_i : The material used for ith component

3.2. Optimization results

Table 2. The optimization results of flexural and torsional rigidity

	Before optimization		After optimization							
	Rigidity	W (kg)	M_{beam}	M_{panel}	$T_{floorpanel}$ (mm)	$T_{toppanel}$ (mm)	$T_{frontpanel}$ (mm)	$T_{leftpanel}$ (mm)	Rigidity	W (kg)
Flexure case	5926	299	UD	CTT	6.6	1.0	1.0	3.1	5917	106
Torsion case	83047000	299	UT-CTT	CTT	8.5	6.4	8.1	4.9	82690000	211

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The optimization results in Table 2 show that the optimal structure with 64.55% weight reduction can be obtained when the materials of hollow beams and panels are UD and CTT during flexural rigidity optimization, while the weight reduction of 29.43% can be achieved in the torsional rigidity case.

4. Conclusions

A rectangular box, a representative light weight vehicle frame component, which is made of hollow beams and panels subjected to flexural and torsional loadings was optimized by using multi-material solution and thickness optimization. As a result, weight reduction of 64.55% by CFRP can be achieved comparing with steel one considering the flexural rigidity, while weight reduction of 29.43% can be achieved comparing with steel one in the torsional rigidity case.

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