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Two-stage design process of a frame-panel land vehicle structure employing topology and cross section optimization

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Abstract

A new structural design technology has been recently developed to build a new type of land vehicle in military use. While thick panels are only employed in conventional land vehicle structures, solid frames combined with relatively thin composite panels are employed for the new type of vehicle. The structural integrity of the new vehicle structure type is mainly guaranteed by the solid frames while composite panels are used to protect passengers and equipments of the vehicle. To design such a frame-panel structure, frame design needs to be done first. In this paper, a two-stage design process is proposed employing topology and cross section optimization methods. Overall frame arrangement of the new vehicle structure is obtained by the topology optimization in the first design stage and the detailed dimensions of the frames are obtained by the cross section optimization in the second design stage.

Keywords: Land vehicle; Frame-panel structure; Topology optimization; Cross section optimization; Two-stage design process

1. Introduction

The land vehicles in military use have been developed for a long time to enhance the military battle power. High performances of an armored vehicle such as reliable structural integrity, safe protection capability and high speed maneuver are required for the design of an armored vehicle. Conventional ground vehicles are usually constructed by welding several thick panels to protect passengers and devices from external attacks. Such panel welding structures could achieve safe protection capability as well as reliable structural integrity through the simple structural design process. However, thick panels which are required to achieve the design purposes of protection and structural integrity often result in heavy weight of the vehicle. Thus, the heavy weight inevitably results in low speed maneuver and tremendous fuel expenditure. One of the most important current issues in land vehicle design is to increase the maneuvering capability of the land vehicle. To increase the maneuvering capability, a new structural design technology employing frame-panel structure has been introduced recently. Solid frames are employed for the structural integrity while thin panels are employed for the protection of passengers and devices. Fig. 1 shows a frame-panel structure

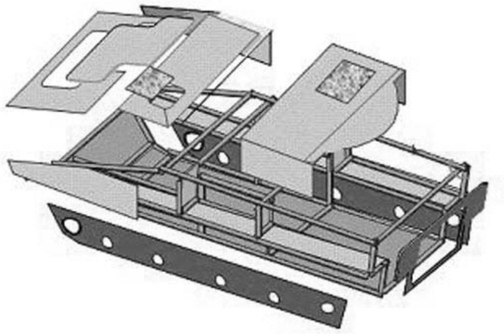

Fig. 1. A land vehicle employing a frame-panel structure.

armored vehicle. Since relatively thin and light panels are employed for the structure, the total weight of the vehicle can be reduced significantly. Although the panels are thin and light, they consist of multi-layers [1-3] which can protect the passengers and the devices of the vehicle effectively. Design of this vehicle type is much more efficient since structural integrity can be achieved by the solid frames while protection can be achieved by the composite panels. Also the maintenance of the structures is much easier than that of the conventional welded panel structures.

As discussed in the above paragraph, the structural integrity can be achieved by the solid frames. In this paper, a two-stage design process of the solid vehicle frame is proposed: the arrangement of solid frames is determined by using a topology

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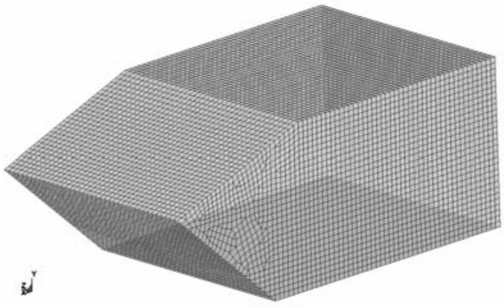


Fig. 2. Finite element model of the land vehicle employing shell elements for the topology optimization.

optimization method [4-6] in the first stage while the sizes of the solid frames are determined by a cross section optimization method in the second stage. For the topology optimization method, several loading conditions are employed. The finite element model of the land vehicle employing shell elements is shown in Fig. 2. The topology optimization is carried out by using a commercial FE code [7]. The final solid frame arrangement is determined by considering physical constraint conditions such as wheel and door attachments. However, the solid frame cross section size is not determined in this stage. Therefore, optimal size of the frame cross section should be determined in the second stage through another optimization using the same FE code.

The purpose of this paper is to propose and show the effectiveness of a two-stage design process by which the structural design of a land vehicle system could be done efficiently. For the efficiency of the two-stage design process, shell elements were only employed for the topology optimization stage in which multiple loading conditions were considered and design variables were divided into four groups to enhance the efficiency of the serial cross section optimization. Using the two-stage design process, the main frame structural design of a land vehicle in military use could be done successfully.

2. Determination of frame arrangement

2.1 Initial shape of a vehicle structure and the loading conditions

Fig. 2 shows the initial FE shell model employed for the topology optimization. The length, width and height of the vehicle are 3200mm, 1800mm and 1300mm [8], respectively and shell thickness is 38.1mm. Material of the vehicle is AL7039 and total mass of the structure is 2208 kg. Material properties of AL7039 are given in Table 1. With the initial FE shell model shown in Fig. 2 and a set of loading conditions, a topology optimization was carried out. The given loading conditions consist of driving load, drop load, twist load, and inertial load. For driving load condition, a dynamic analysis of an armored vehicle was carried out and the maximum constraint forces obtained from the dynamic analysis are applied to the vehicle wheels. All the loading conditions which are used for the topology optimization are summarized in Table 2.

Table 1. Properties of the shell model.

Material	Thickness [mm]	Density [kg/m^3]	E [GPa]	S_Y [MPa]
AL7039	38.1	2850	71.7	330

Table 2. Loading conditions for topology optimization.

Type of loads	Loading condition	Boundary condition	Remarks
Driving load	Results from dynamic analysis	Inertia relief	6 Cases
Drop load	15G (up and down)	6 wheel fix	1 Case
Twisting load	8000G (up)	3 wheel fix 1 wheel loading	4 Cases
Inertial load	8G (front and rear) 5G (left and right)	6 wheel fix	3 Cases

※ G denotes the acceleration of the gravity.

Considering all the loading conditions simultaneously, a topology optimization was carried out. For the optimization, it was requested that 30% of the total mass of the initial model should be reduced. The connected regions of frames and wheels were constrained to be remained during the topology optimization process.

2.2 Topology optimization results

The topology optimization was carried out using a commercial FE code ANSYS and the initial solid frame arrangement shape was obtained based on the topology optimization result shown in Fig. 3. The red regions indicate dense mass distribution while the blue regions indicate sparse mass distribution. Along the dense mass distribution regions, solid frames are located. Fig. 4 shows the initial frame arrangement obtained from the topology optimization and Fig. 5 shows the comparison of the topology optimization results and the initial frame arrangement. In most of the cases, the frame arrangement was determined by the topology optimization results. In some occasions, however, frame arrangements were determined by other reasons such as manufacturing convenience.

Considering the manufacturing convenience such as the connectivity of panels, final vehicle frame arrangement was determined as shown in Fig. 6. The frames consist of four types. Each of the types has the same shape and dimension. Even if the total mass can be reduced with more types of frames, it will increase the manufacturing cost in return.

3. Determination of frame cross section size

3.1 Initial cross section shape and size

The vehicle frame arrangement shape obtained by the topology optimization does not provide the detailed size of the frame cross section. In this section, a gradient based opti-

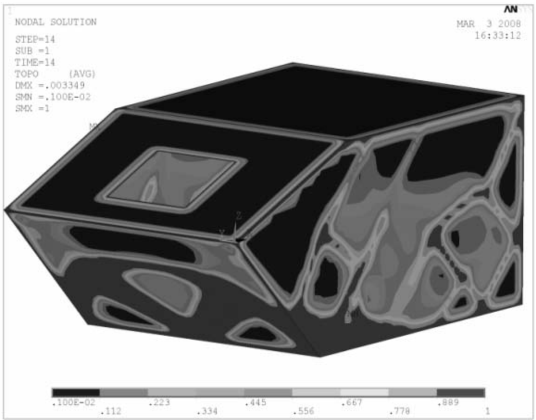


Fig. 3. Topology optimization result.

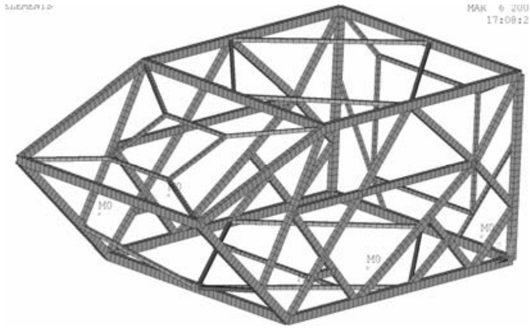
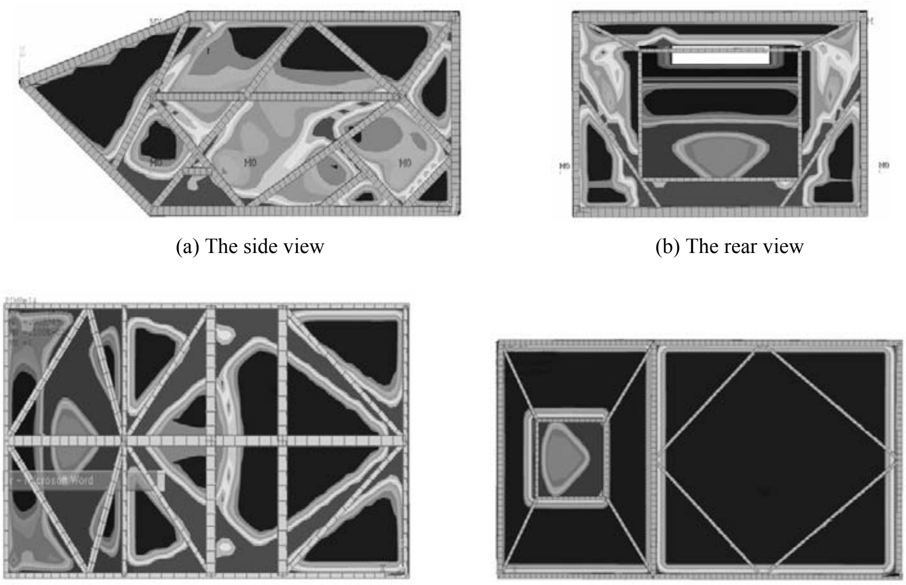


Fig. 4. Initial vehicle frame arrangement shape.



(a) The side view

(b) The rear view

(c) The bottom view

(d) The top view

Fig. 5. Four views of the frame arrangement shape and comparison to the topology optimization result.

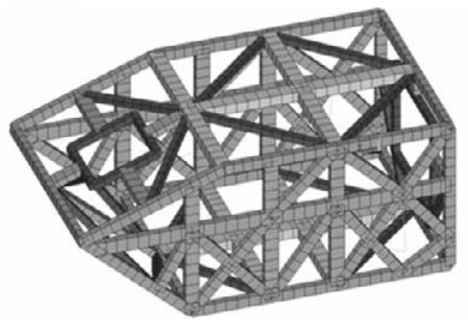
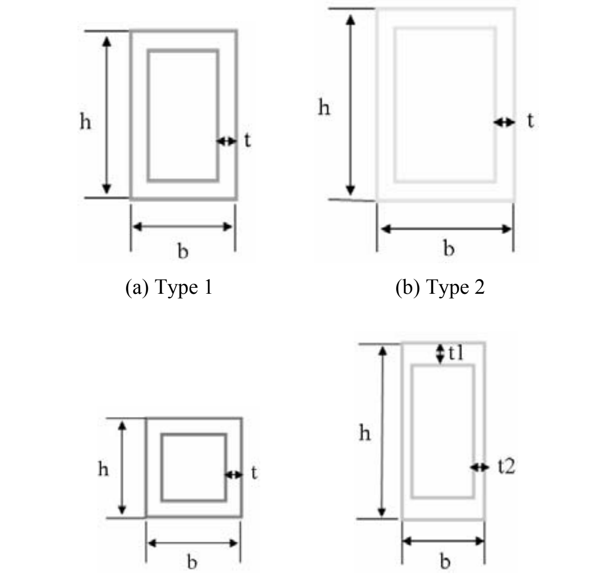


Fig. 6. Final vehicle frame arrangement shape.

mization method in FE code ANSYS is employed to find the size of the frame cross section. A hollow rectangle shape is chosen for the cross section and the size of the cross section is determined by the optimization method. Four types of cross sections are employed for the vehicle frame model. The initial sizes of the four types of cross sections are shown in Fig. 7 and Table 3. Each cross section type has design variables: height (h), breadth (b) and thickness (t). Type 1 represents the main frames which determine the overall shape of the vehicle and the number of the main frames is 19. Type 2, 3 and 4 rep-

Table 3. Initial sizes of the four cross sections.

Type	Height (h) [mm]	Breadth(b) [mm]	Thickness(t) [mm]
1	90.0	60.0	8.0
2	120.0	90.0	5.0
3	60.0	60.0	5.0
4	120.0	60.0	9.0 (t1)
			5.0 (t2)



(a) Type 1 (b) Type 2

(c) Type 3 (d) Type 4

Fig. 7. Four types of frame cross sections.

resent supplementary frames which reinforce the main frames. The numbers of the three types are 6, 14 and 11, respectively. Therefore the total number of vehicle frames is 10 and the number of design variables for each type is 3, 3, 3 and 4, respectively. The reason why Type 4 has 4 design variables is that the bending loads acting on the type in the two thickness directions are clearly different. The other types, however, do not have such clearly different bending loads in two thickness directions. So, to save manufacturing cost, we chose only one thickness parameter for Type 1, 2, and 3.

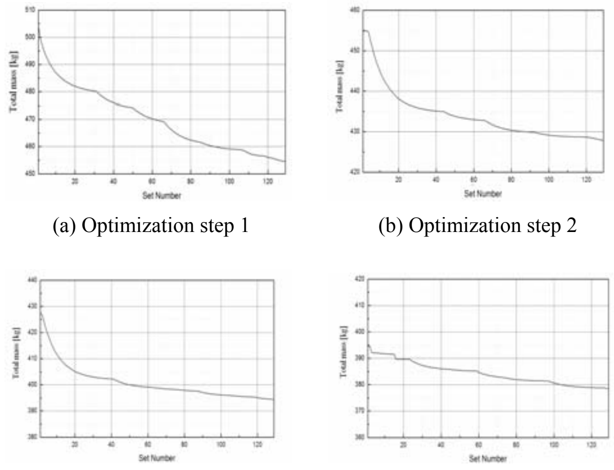
Loading conditions for the optimization are identical to the previous conditions which are used for the topology optimization. Objective function is the total mass of the frame structure and constraint conditions consist of the maximum displacement of 5 mm and the maximum stress of 330 MPa which is the yield stress of AL7039.

3.2 Cross section optimization results

The optimization process consists of four steps to reduce the computation time. In step 1, design variables associated with type 1 cross section are optimized. After finishing step 1, design variables associated with type 2, 3, and 4 cross sections

Table 4. Total frame mass variation through the optimization.

	Total frame mass [kg]	Reduction ratio [%]
Initial value	504.35	0
Step 1	454.58	9.87
Step 2	427.82	15.17
Step 3	394.41	21.80
Step 4	378.54	24.94



(a) Optimization step 1 (b) Optimization step 2

(c) Optimization step 3 (d) Optimization step 4

Fig. 8. Mass variation history during the four-step optimization.

are optimized serially. The initial total frame mass is 504.35kg but after the 4 steps the total mass is finally reduced to 378.54kg. The stepwise mass variation is shown in Table 4 and Fig. 8. Total mass is reduced by 24.9 % compared to initial mass. The optimum values of design variables are also shown in Table 5. Most of the design variables are decreased during the process. Interestingly, however, there exists a design variable which is increased during the optimization process (as shown in Table 5).

4. Conclusions

The frame structure of new type of land vehicle in military use is designed by employing topology and cross section optimization. In the first stage, topology optimization is carried out to obtain the frame arrangement shape. By considering some physical constraints, the final frame arrangement shape is determined based on the topology optimization results. In the next stage, cross section optimization is carried out to determine the detailed sizes of the vehicle frames, which are classified into 4 types. To reduce the computation time, the cross section optimization is carried out serially in four steps. It was found that the total frame mass could be reduced by approximately 25% through the optimization process.

Table 5. Initial and optimal values of design variables.

Type	Design variables	Initial value	Optimum value	Changing ratio
1	h[mm]	90.0	80.4	- 10.7%
	b[mm]	60.0	46.6	- 20.3%
	t[mm]	8.0	5.9	- 26.3%
2	h[mm]	120.0	90.0	- 25.0%
	b[mm]	90.0	117.8	+ 30.9%
	t[mm]	5.0	3.0	- 40.0%
3	h[mm]	60.0	48.0	- 20.0%
	b[mm]	60.0	48.1	- 19.8%
	t[mm]	5.0	3.0	- 40.0%
4	h[mm]	120.0	107.8	- 10.2%
	b[mm]	60.0	49.9	- 16.8%
	t1[mm]	9.0	6.3	- 30.0%
	t2[mm]	5.0	3.0	- 40.0%

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