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Composite locomotive frontend analysis and optimization using genetic algorithm

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Abstract. This paper addresses the structural design of the front end of Siemens ER24 locomotive body. The steel structure of the frontend is replaced with composite. Optimization of the composite lay-up is performed using Genetic Algorithms. Initially an optimized single design for the entire structure is presented. Then a more refined optimum is developed by considering the separate optimization of 7 separate regions of the structure. Significant savings in the weight of the structure are achieved.

Keywords: composite frontend; optimization; genetic algorithm; locomotive; buckling

1. Introduction

The application of composites is increasing in many industrial fields. With high strength to weight ratio, composite materials reduce the weight of structures significantly. More weight reduction is possible by optimization of layup, thickness and alignment (Park *et al*. 2001, Robinson 2000). In heavy structures such as train coaches, application of composites can provide more speed and less energy consumption (Kim *et al*. 2007).Current applications of composites in railway industry in often limited to 3D components of frontend structure and crash elements. The manufacturing process is complex and expensive due to complicated shape and aerodynamic features. The ccomposite frontend of Intercity 125 in the UK is an example of the application of composite in rolling stock manufactured in 1977. Since then, many studies have accomplished. Kim (Robinson 2000) and his colleagues investigated the manufacturing process for a train with composite coaches of sandwich panel structure. Harte *et al*. (2007) studied the parametric optimization of composite walls in light rail vehicles. Zinno *et al.* (2010) proposed a method to design sandwich composite roofs in railway vehicles. Due to many variable parameters, various failure modes in the structure and complicated equations, design and optimization of composite materials is a challenge for designers. Among many optimization algorithms, Genetic Algorithm (GA) has been widely used for composite structures. Park *et al*. (2001) used GA to optimize symmetric composite layers under different boundary condition layers. Walker and Smith (2003) proposed a method to minimize the total mass and deformations in composite reinforced structures with several design parameters. In this study, design and optimization of composite frontend of Siemens ER24PC

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locomotive is investigated by Genetic Algorithm.

2. Modeling and boundary conditions

ER24PC is a modern diesel electric locomotive manufactured by Mapna Locomotive Company (Iran) under license of Siemens (Germany) (Fig. 1). Frontend is an integration structure of six metal sheet welded parts and assembled on the frontend main frame structure via welding joints (Fig. 2). In a composite Frontend, the whole structure is altogether in one piece.

Fig. 1 ER24PC diesel electric locomotive

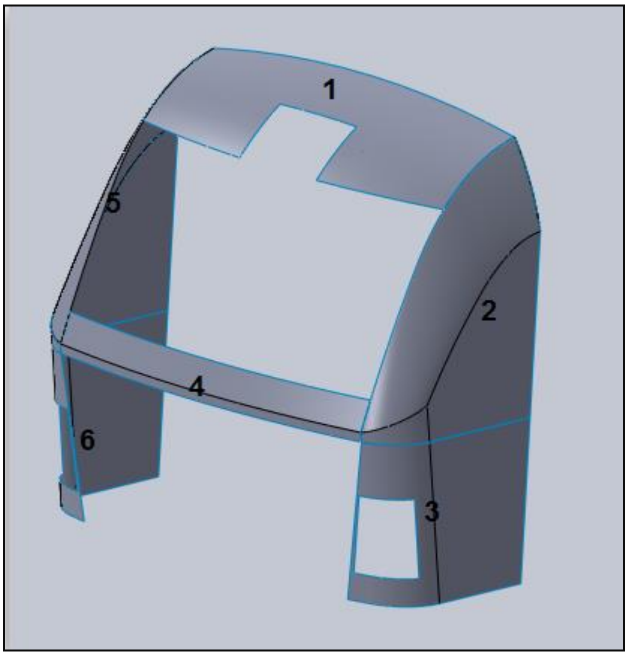

Fig. 2 3D-Model of frontend structure

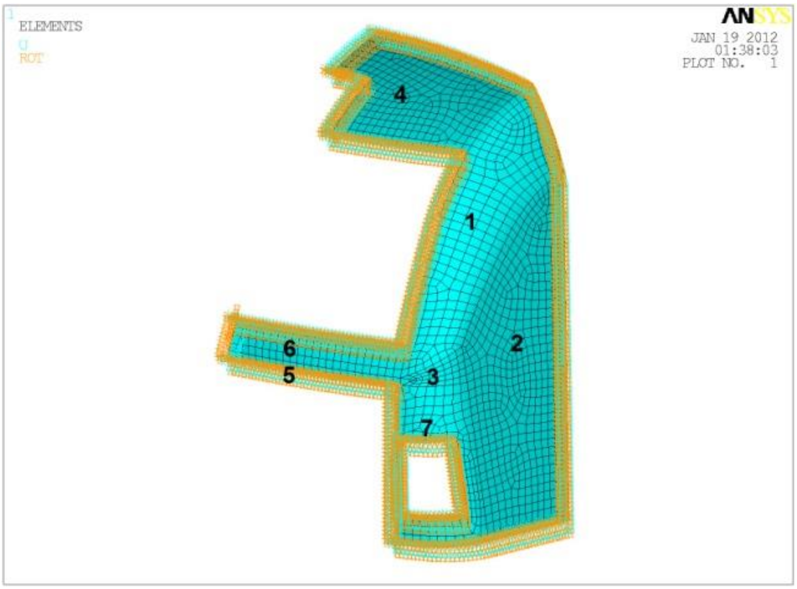

Fig. 3 Boundary conditions on frontend half-structure

Table 1 Engineering factors of Glass-Epoxy

E_1(*GPa*)	E_2(*GPa*)	υ_{12}	υ_{23}	G_{12}(*GPa*)	G_{23}(*GPa*)
50	15.2	0.254	0.428	4.7	3.28

Table 2 The strength of Glass-Epoxy

X_t (*MPa*)	X_c (*MPa*)	Y_t (*MPa*)	Y_c (*MPa*)	S(*MPa*)
1000	600	30	120	70

Due to its complicated shape, the frontend is modeled in SolidWorks commercial software and imported to ANSYS for finite element (FEM) analysis. Since the model is symmetrical with respect to vertical axis, the structure is modeled in half to reduce analysis time. Boundary conditions are considered fixed in joint points of frontend to the main frame. If one specific pattern of layup is considered for the whole structure, the layup must withstand the exerted load on critical areas. Such a design results in too high safety factors in areas with lower loadings than critical parts. Consequently, the cost of production and the amount of material to be used is increased. To optimize the structure with the purpose of weight (mass) reduction, it should be divided into different parts. For each part a suitable layup based on its loading condition should be considered. For this purpose, the frontend structure is divided into seven parts. The finite element model of this structure is shown in Fig. 3. The layup of seven surfaces are considered independently and the weight of each surface is set as objective function separately from its fracture and deflection strengths. To extract the amount of forces in loading the frontend structure, EN12663 norm (BS EN-12663 2010) is used. Based on this norm, a 300 kN force is exerted on the frontend face. In order to investigate the loading more precisely, the resulting pressure of 50 kPa on the surface of the frontend is considered instead of 300 kN force. Engineering factors and glass-epoxy properties are shown in Table 1 and Table 2.

3. Finite element analysis and genetic algorithm

ANSYS is used for numerical analysis and it is linked to MATLAB for optimizing calculations. In some cases where there is not a unique answer, such as multi-purposed optimizations, GA is useful to determine the simultaneous results. GA provides different potential outputs. The selection of the final results is based on the user's view. GA is a method of optimization inspired from natural phenomena and evolution processes in nature. GA frequently changes the population of single solutions of a problem known as evolution. In each step of the evolution, two members of the population are chosen as parents and their children are considered to be the next generation. In this way, the population is evolved into an optimized solution. GA uses 3 sets of rules for production of the next generation:

- *Selection Rule*: By this rule, the persons used for production of the next generation are selected.
- *Crossover Rule*: This rule combines two parents and produces the children of the next generation.
- *Mutation Rule*: This rule produces new populations by creating random changes on parents.

In the GA code programmed for this study, uniform crossover and uniform mutation methods are applied which are applicable for real variables. In Uniform Crossover method a random string of digits "0" and "1" with the chromosome length is created. Then identical cells of three chromosomes are considered. The existence of "1" in each random string means no change. If the random number in the string is "0", the cells of two chromosomes are exchanged. However if the random number in the string is "1", in Uniform Mutation method means no change and if the random number in the sting is "0" a random number between the high and low range is replaced.

Also, in displaying genes and chromosome coding, real numbers are used since there is no need for transforming out of its code state and also to use less hardware memory. In the current algorithm, two indices of maximum generation number and objective function iteration are used. The final generation number is set to 100 and the number of objective functions is 10. It means that if either the objective function shows no changes in 10 generations or the final number of generation reaches to 100, the algorithm is stopped. If the iteration of answers passes a certain number, mutation and interaction methods are applied in order to modify the function of GA. Among various fracture methods used to predict the occurrence of fracture in materials, the interactions between different strains and stresses are not considered in maximum strain and stress methods. In Tsai-Hill index, the difference between compressive and tensile components is not distinguished either. In this study Tsai-Wu index is used because these two problems are solved. This index for plane stress and strain is used as follows (Walker and Smith 2003)

$$\begin{gathered}F_1\sigma_1 + F_2\sigma_2 + F_6\tau_{12} + F_{11}\sigma_1^2 + F_{22}\sigma_2^2 + F_{66}{\tau_{12}}^2 + 2F_{12}\sigma_1\sigma_2 = 1 \\ F_1 = \frac{1}{X_t} + \frac{1}{X_c} \qquad F_2 = \frac{1}{Y_t} + \frac{1}{Y_c} \qquad F_6 = 0 \\ F_{11} = -\frac{1}{X_t X_c} \qquad F_{22} = -\frac{1}{Y_t Y_c} \qquad F_{66} = -\frac{1}{S^2}\end{gathered} \tag{1}$$

In which X_t and X_C are tensile and compressive strengths in longitudinal direction. Y_t and Y_c are tensile and compressive strengths in transverse direction, respectively. Also the shear strength objective function, *S*, (Eq. (2)) is a set of factors of weight sums and maximum deformations. In other words, targets are divided into two parts of weight (*W*) and deflection (δ). In order to make

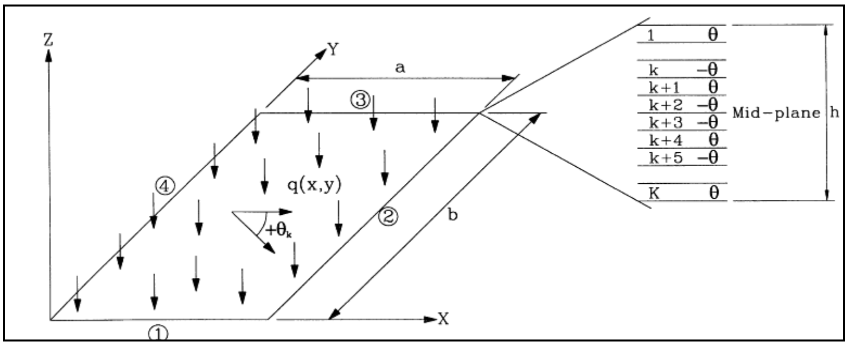

Fig. 4 Rectangular surface and boundary conditions

the objective function dimensionless, weight and deformations are divided to initial weight (W_0) and initial deflection (δ_0) which includes initial layup and thickness of 0.75mm. Variables are the thickness (t) and the angle of alignments of yarns (θ). Both variables are discrete. Mathematical form of the problem is shown in Eq. (3) in which Tsai-Wu index and deflection are considered less than 1 and 1mm respectively (Akbulut and Sonmez 2008, Lin and Lee 2004).

$$\begin{aligned} & p(\theta_j, t_j) = \mu W_i^* + (1-\mu)\delta_i^* && j = 1, n \\ & && 0 \le \mu \le 1 \\ & W_i^* = \Sigma \frac{W_i}{W_0} \qquad \delta_i^* = \Sigma \frac{\delta_i}{\delta_0} && i = 1, m \end{aligned} \tag{2}$$

$$Min \qquad p(\theta_j, t_j)$$

$$\begin{aligned} & t^{\min} \le t_j \le t^{\max} && j = 1, n \\ & \theta^{\min} \le \theta_j \le \theta^{\max} && j = 1, n \\ & Tsai - Wu < 1 && \\ & \delta_i < 1 && \end{aligned} \tag{3}$$

4. Analysis of rectangular surface and validation

Numerical analysis and optimization of a rectangular surface (as shown in Fig. 4) is performed in advance by ANSYS with Shell99 element type of equal width and length of 1m under the pressure loading of 100 kPa with a combination of clamped, free and simple edges.

As shown in the figure, this problem has one independent surface for which m=1 and μ=0.5 are considered according to Eq. (2). Deflection constraint of ($\delta_i \le 1$) is neglected. Due to the limitations of manufacturing composite surfaces, the results of this problem including the thickness and yarn angles are applied and chosen. The angles of layers are (60, ±90, ±45, ±30, 0) and the thicknesses of layers are (2.25, 2, 1.75, 1.5, 1.25, 1, 0.75 mm). In order to avoid the effects of bending in the problem, the surfaces are considered symmetrical. The results of boundary conditions (F,S,C,S) and (S,S,S,S) are compared for this problem by a validation method with the results of Walker study (Walker and Smith 2003). In this notation F stands for Fixed, S for Simple and C for

Table 3 Result validation

Boundary Condition	Reference	Weight (kg)	Deformation (m)	Objective Function	Difference (%)
(F,S,C,S)	Walker	21.6	0.053	1.187	-1.6
	Present Work	21.6	0.056	1.206	
(S,S,S,S)	Walker	14.4	0.069	0.839	-7.3
	Present Work	16	0.052	0.901	

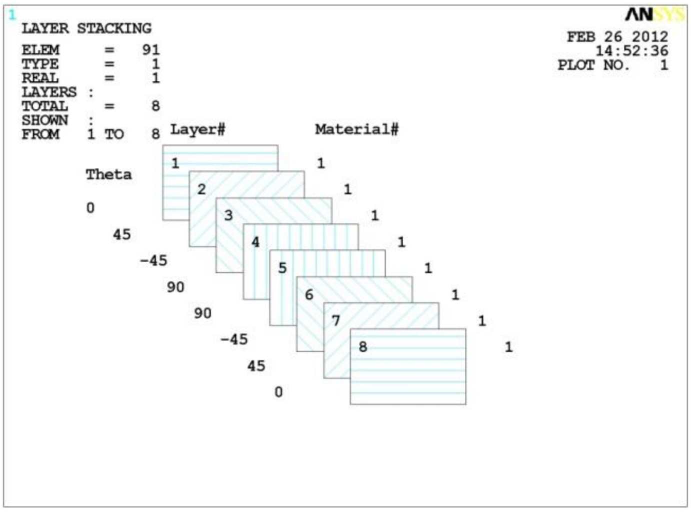

Fig. 5 Layup of (90/-45/45/0)s in initial model of composite structure

Clamped boundary conditions. The comparison of current method with the results of Walker study is shown in Table 3. The results of numerical simulation and optimization of the current method are consistent with the results of Walker for both of the boundary conditions. The difference between results for (S,S,S,S) is -7.3% and -1.6% for (F,S,C,S) boundary conditions respectively.

5. Results of finite element analysis of frontend structure

In order to analyze the composite model, a layup of 8 layers with (90/-45/45/0)s of 1mm thickness for each layer is considered for the whole structure as shown in Fig. 5.

The graphical illustration of Tsai-Wu index for the initial model is shown in Fig. 6. This shows that the index is less than 1 for the whole structure.

Graphical illustration of the deformations for the initial model is shown in Fig. 7. This shows that maximum deflection occurs in part 4 with magnitude of 0.68 mm.

In order to reduce the weight and production cost, optimization of each surface is performed independently yet simultaneously. According to Eq. (2) the number of targets, m, is 7 (m=7) and the number of variables is 56. In addition, the deflection magnitude of less than 1mm and μ=1 are considered to be the constraints. In order to achieve better results, thickness of zero (t=0) is considered for no addition of layers to the thickness. In other words, the number of layers is indirectly considered variable.

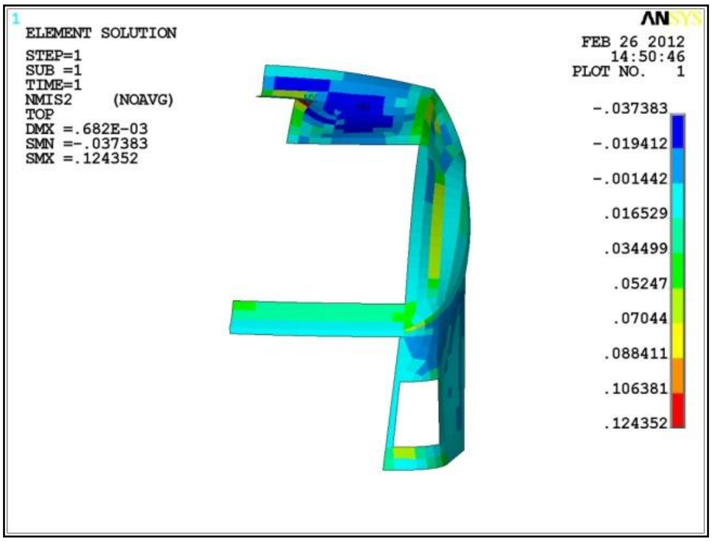

Fig. 6 Tsai-Wu fracture criteria for the steel model

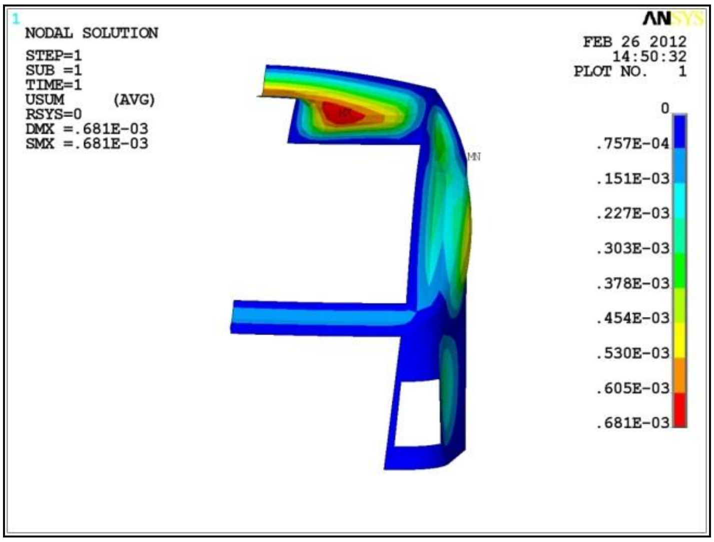

Fig. 7 Deformations of the composite model

The design of composite structures should not be accomplished without neglecting their limitations. Engineers and designers cooperate closely to achieve best manufacturing processes. One important design technique for composites is to consider at least 10% of the layers in principals axes (0,90, +45,-45) in order to provide sufficient strength in these directions and considering layers with 45 angle degrees to increase buckling resistance. For this purpose, the design is considered with 16 layers in which 8 are aligned in principal axes (0,90,+45,-45) with thickness of 0.25 mm. The alignment of other 8 layers is determined by optimization. To simplify the production process, not only the minimum strength in these directions is maintained, but also the 4 beginning and ending layers are similar which simplifies the production process.

Table 4 Optimized angles and thicknesses of the surface

Surface No.	Layer angle and thickness
Surface 1	(30|0|-45|90||0.5|2|0.25|0.25)s
Surface 2	(0|-60||0.75|0.5)s
Surface 3	(90|60|45|1.25|1.25|2)s
Surface 4	(90|0||1|0.75)s
Surface 5	(-30|90|-45|-45||0.5|1|0.5|1.25)s
Surface 6	(0|-60|90||1.25|0.25|0.75)s
Surface 7	(-45|-45|-45|90||0.25|0.25|0.25|0.5)s

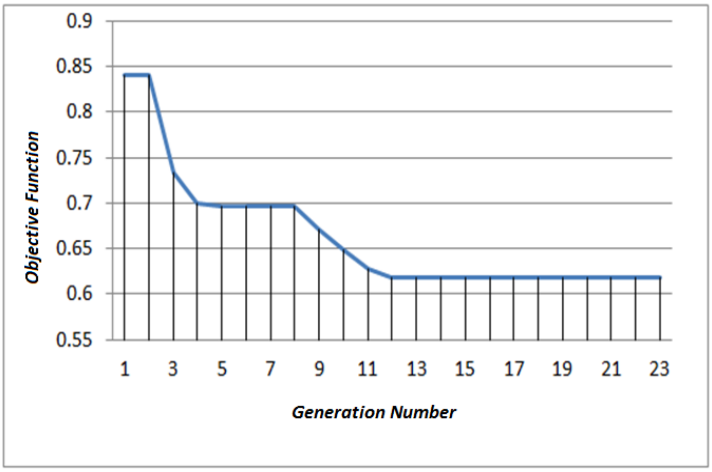

Fig. 8 Objective function vs. the number of generations

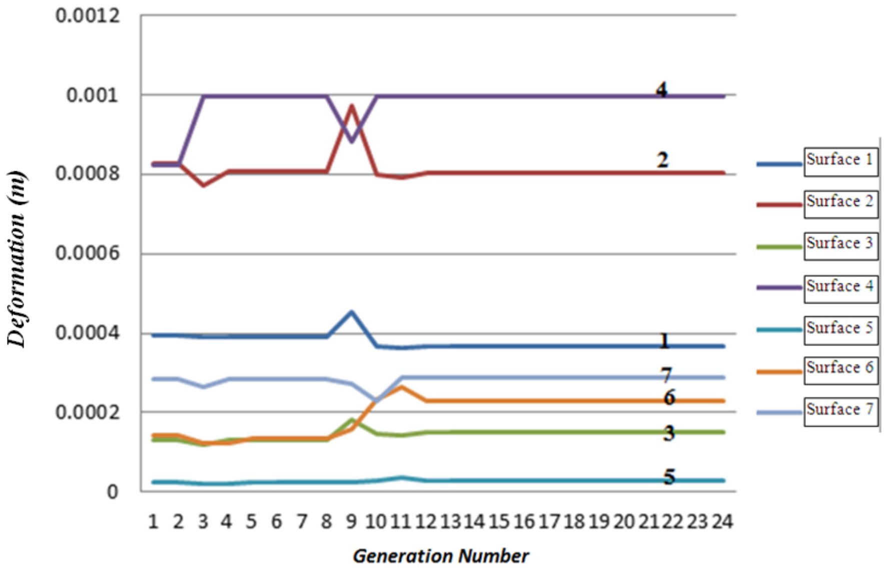

Fig. 9 Deformation vs. the number of generations

Fig. 10 Frontend deformation results for optimized structure

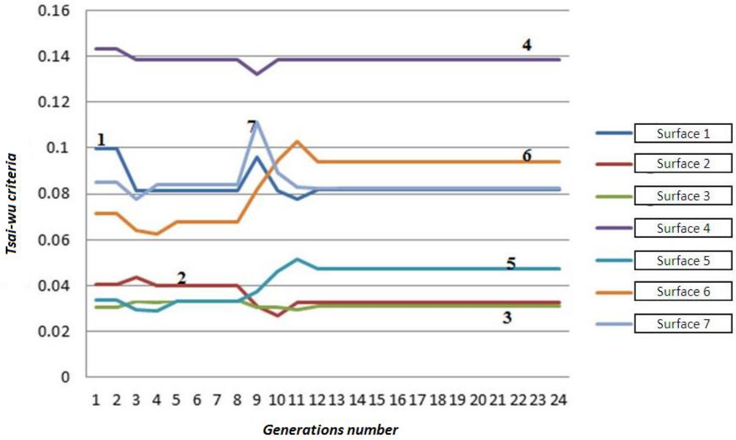

Fig. 11 Tsai-Wu criteria vs. the number of generations

Optimization by GA is performed with a population of 25 people in each generation and optimum results of layer angles and their thicknesses of 8 middle layers is obtained after 24 generations as shown in Table 4.

The trend of convergence to optimum results is apparent in the objective function graph with respect to the number of generations as illustrated in Fig. 8. Considering all variables the number of possible cases is 8^{56}, however the best result is achieved by 436 iterations of the objective function. The graph of variation in deformations for each target with respect to the number of generations is illustrated in Fig. 9. It is shown that the total deflection for all surfaces is less than 1mm. graphical illustration of deformations for the optimized structure is shown in Fig. 10. Maximum deflection in this model is 0.93 mm that occurs in surface 4 with magnitude of less than 1 mm.

Fig. 12 is the variation of yielding index with respect to the number of generations. It shows

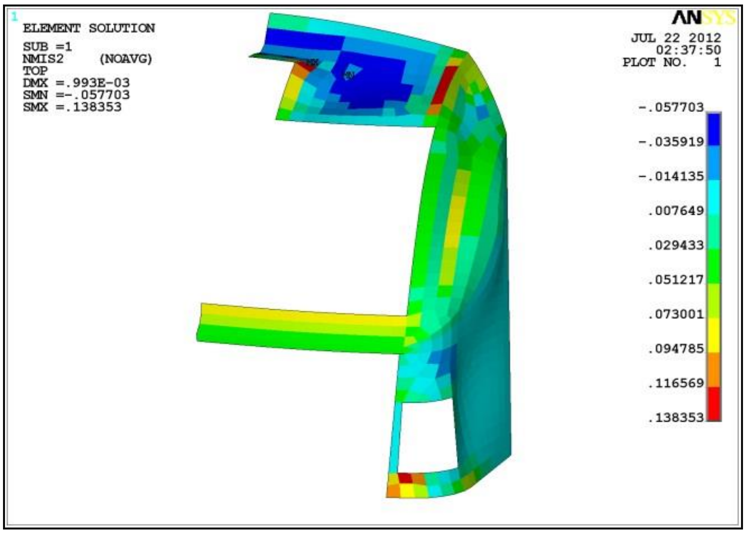

Fig. 12 Tsai-Wu criteria for the optimized composite frontend structure

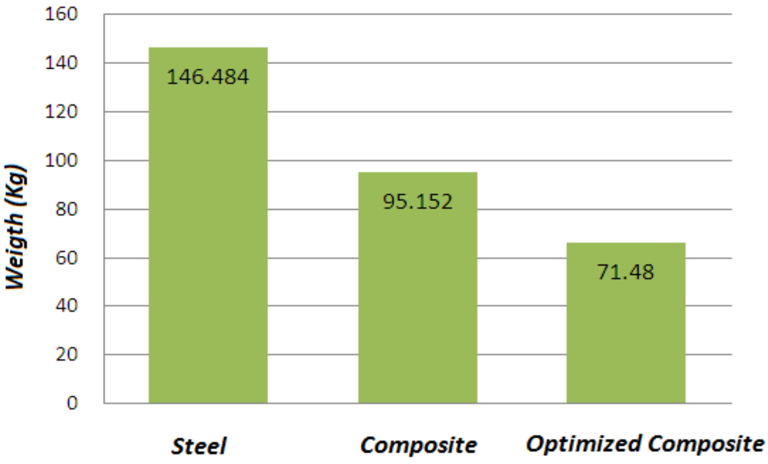

Fig. 13 Comparison diagram of total weight of frontend structure

that for all surfaces Tsai-Wu index is less than 1. Graphical illustration of the optimized structure is shown in Fig. 11 with maximum magnitude of 0.14.

The mass of all surfaces for metal sheet material and composite material is shown in Table 5. Fig. 13 shows the comparison of the total weights in which the optimized structure shows 51.2% reduction in weight than metal sheet structure and 24.8% less weight in comparison to initial composite structure. While the overall weight of the frontend is reduced, there will be additional processing costs associated with having different lay-ups in the 7 different regions compared to one for the initial design. On the other hand, the reduced weight will result in other savings in the design of other components of the vehicle and in the fuel consumption over the life of the vehicle.

Table 5 Total weight comparison (mass) of metal, composite frontend, optimized composite frontend

Mass (kg)	Metal Sheet	Composite Sheet	Optimized Composite Sheet
Surface 1	14.3910	9.3480	9.8400
Surface 2	28.3140	18.3920	10.8900
Surface 3	1.0998	0.7144	1.0340
Surface 4	16.7310	10.8680	7.8650
Surface 5	1.1700	0.7600	0.8500
Surface 6	4.8204	3.1312	2.6780
Surface 7	6.7158	4.3624	2.5830
Total Mass (kg)	146.484	95.1520	71.4800

6. Conclusions

In this study, the design of composite structure for ER24PC locomotive is investigated. Firstly, an initial design is considered and optimized. In deformation control condition, Tsai-Wu criteria will not reach to the critical values. Otherwise, the best result is achieved when Tsai-Wu index just meets its critical value. Deformation and weight vary reversely, i.e., increasing thickness which results in weight increase will improve the resistance of the structure to deformation. As shown in graphs of deflection and weight, the variation of objective function with respect to the number of generation shows that the objective function is significantly decreased in initial generations. In contrast, for higher number of the generations, no dramatic decrease of objective function is observed. In initial generations due to high numbers of genius persons (Optimized answers) the growth of generation numbers decreases. In comparison to metal sheet frontend, Optimized composite frontend provides best results with 51.2% lower weight of the structure, while basic composite structure provides 24.8%.

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