Available online at www.sciencedirect.com
SCIENCE @ DIRECT®
Composite Structures 71 (2005) 16–25
COMPOSITE STRUCTURES
www.elsevier.com/locate/compstruct

Optimal design of filament wound type 3 tanks under internal pressure using a modified genetic algorithm

Cheol-Ung Kim [a,1], Chang-Sun Hong [b,2], Chun-Gon Kim [b,*], Jung-Yub Kim [c,3]

[a] *Vehicle Development & Analysis Team, Advanced Technology Center, Research & Development Division for Hyundai Motor Company & Kia Motors Corporation, 772-1 Jangduk-dong, Whasung-Si, Gyunggi-Do 445-706, Republic of Korea*
[b] *Department of Mechanical Engineering, Division of Aerospace Engineering, Korea Advanced Institute of Science and Technology, 373-1 Guseong-dong, Yuseong-gu, Daejeon 305-701, Republic of Korea*
[c] *School of Mechanical and Aerospace Engineering, Sejong University, 98 Kunja-Dong, Kwangjin-Gu, Seoul 143-747, Republic of Korea*

Available online 11 November 2004

Abstract

This research aims to perform the optimal design of filament wound type 3 tanks under internal pressure. So far, most designs have not been optimized to account for the requirements of filament wound structures, and no design method exists for general filament wound structures under internal pressure, satisfying given design requirements. In this research, a new design algorithm which had been proposed in our previous research was utilized. The optimal design algorithm includes the semi-geodesic path algorithm, progressive failure analysis and genetic algorithms. In addition, a modified sub-string genetic operator that improves the genetic algorithm was newly suggested and verified through a basic design. Finally, the optimal design algorithm was applied to a representative filament wound type 3 tank—high pressure hydrogen storage tank.

Keywords: Filament winding; Type 3 tank; ABAQUS; Genetic algorithm

1. Introduction

Composites consist of two or more materials and, macroscopically, have an anisotropic mechanical characteristic according to the combination and array of materials. In particular, a fiber-reinforced composite material is composed of the fiber that receives the primary load and the matrix that plays a role of the load's transmission and maintains the shape. It has higher specific strength and stiffness than conventional materials such as metal and plastic. Therefore, if it is applied to the designs of several structures, a high structural efficiency is expected.

In the filament winding process, which is a popular technique for producing generally axisymmetric composite structures, a fiber bundle is placed on a rotating and removable mandrel. Examples of axisymmetric filament wound structures under internal pressure include fuel tanks, oxidizer tanks, motor cases and pipes. By the way, the trajectory of the fiber path and the corresponding fiber angles cannot be chosen arbitrarily because of the stability requirement. Therefore, most of the design and manufacturing of filament wound structures have been based on manufacturing experience and experiments. Thus, most designs have not been optimized to account for the requirements of filament wound structures, and no design method exists for general

* Corresponding author. Tel.: +82 42 869 3719; fax: +82 42 869 3710.
E-mail address: cgkim@kaist.ac.kr (C.-G. Kim).
[1] Tel.: +82 31 368 2892; fax: +82 31 368 5818.
[2] Tel.: +82 42 869 3719; fax: +82 42 869 3710.
[3] Tel.: +82 2 3408 3774; fax: +82 2 3408 3333.

0263-8223/$ - see front matter
doi:10.1016/j.compstruct.2004.09.006

filament wound structures under internal pressure, satisfying given design requirements.

The final objective of this research is to perform the optimal design of filament wound type 3 tanks.

Several studies have been reported on the optimal design of simple structures such as a cylinder [1–3]. However, the optimal design of filament wound structures with a complex geometry, such as a composite pressure vessel, has seldom been reported. Furthermore, most of the recent studies used simple analytic methods or experiential design procedures [4–9]. As a result, no design method which satisfies given design requirements and which uses sophisticated finite element analysis and well-organized optimal design algorithms has been established for general filament wound structures under internal pressure.

The reason for the absence of such a design method can be conceived of the following two problems. First, no algorithm has been formulated to calculate the non-geodesic winding path while considering several mandrel shapes and various parameters of the winding process. Second, it is very difficult to solve the low design efficiency that occurs when finite element analysis and optimal design algorithms are used simultaneously. Recent studies have therefore used simple analytic methods such as the classical laminated theory, or experiential design procedures such as a parametric study.

In our recent research [10], to solve the first problem, the semi-geodesic path algorithm had been suggested. And, to solve the second problem, finite element analysis and algorithms that optimize design efficiency had been studied. Finally, an optimal design procedure of axisymmetric filament wound structures had been established with a semi-geodesic path algorithm, progressive failure analysis and a genetic algorithm.

In this paper, we also used the suggested design procedure. In addition, a modified sub-string genetic operator that improves the genetic algorithm was newly suggested and verified through a basic design. The optimal design algorithm was applied to a representative filament wound type 3 tank—high pressure hydrogen storage tank.

2. Optimal design algorithm

2.1. Consideration of optimal design methods

In engineering problems, most optimal design methods assume that design variables are continuous. However, many cases exist in which the engineer must consider discrete values of design variables, such as the number of plies, stack sequences and ply orientations of laminated composite structures.

In general, the nonlinear discrete optimal design method falls into three types of methods: the branch and bound method (BBM), the approximation method and ad hoc methods [11].

The BBM was originally developed to overcome problems of convex linear programming but many researchers have applied it to problems of nonlinear programming. The BBM is theoretically correct for convex problems but has the disadvantage of a high computational cost and numerical problems associated with the accuracy of nonlinear programming solutions. Thus, if the number of design variables increases, the computational cost increases exponentially [12]. The BBM is therefore applied mainly to evaluate other design methods or applied in conjunction with an approximation method.

The approximation method solves the nonlinear continuous problem and then uses the BBM on an approximate problem rather than on the original nonlinear problem. This method has the advantage of a relatively low computational cost but the disadvantage being unable to guarantee the global optimal solution. The net effect is that the capability of discrete variable optimization can be provided using approximation methods in a general optimization, but the user must be aware of the limitations.

Ad hoc methods are suitable for specific discrete optimal design problems. A genetic algorithm and the Monte Carlo method (simulated annealing) are representative. In these methods, solutions are found statistically in a random sampling of the design area. They are therefore robust but have a high computational cost. In other words, their design efficiency is relatively low.

In this study, a genetic algorithm [13] was used to optimize filament wound type 3 tanks under internal pressure. A genetic algorithm is a search algorithm based on the mechanics of natural selection and genetics. It simulates natural evolution so that multiple design points evolve to converge to a global optimum. The most useful advantage of the genetic algorithm is that it uses discrete design variables by nature. Using discrete values as design variables is therefore simple in genetic algorithms.

The genetic algorithm comprises three operations: function evaluation, selection and reproduction. The two main classes of the genetic operations are mutation and crossover. The genetic algorithm differs from other optimization methods and search procedures in four ways: it works with a coding of the parameter set, not the parameters themselves; it searches from a population of points, not a single point; it uses an objective function, not derivatives or other auxiliary knowledge; and it uses probabilistic transition rules, not deterministic rules [13].

Consequently, the genetic algorithm is a robust optimal design method.

2.2. Design algorithm

In this study, a new design algorithm which had been proposed in our previous research [10] was utilized in order to perform the optimal design of filament wound type 3 tanks under internal pressure.

The optimal design algorithm includes the semi-geodesic path algorithm, progressive failure analysis and genetic algorithms. Fig. 1 shows a flow chart of the used optimal design algorithm. The genetic algorithm controls the overall design procedure. The semi-geodesic path algorithm is applied to the selection of design points, and the progressive failure analysis is applied to the calculation of the fitness.

The Windows-based program for this algorithm was developed with the C++ language and used. Called IDOTCOM_FW, this software application was programmed to enable all the design processes to feed the results back to each other.

2.3. Basic design—type 3 symmetric tank

For verification, the optimal design algorithm was applied to a symmetric pressure tank of type 3, with a load-sharing metallic liner. This basic design is the case which was mentioned in our recent paper [10]. Therefore, in this section, the overall procedure is summarized briefly.

The configuration of the type 3 tank is shown in Fig. 2. The half shape of the tank is the same as the forward part of the ASTEB. The material of the composite is T800/Epoxy (Table 1), and the liner is the aluminum alloy 7075-T6 (Table 2).

The basic design conditions are as follows:

1. The maximum operating inner pressure is 13.79 MPa (2000 psi).
2. The yield of the liner is prohibited.
3. The safety factor of the composite is 3.0.

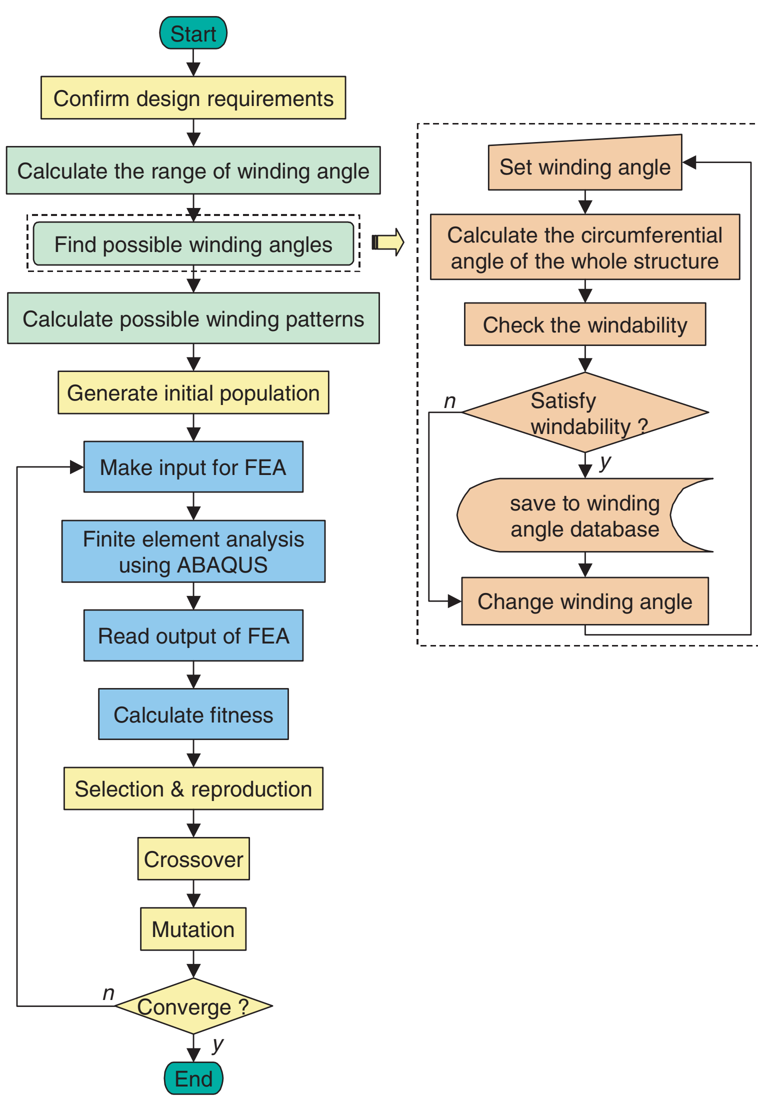

Fig. 1. Optimal design procedure for axi-symmetric filament wound structures.

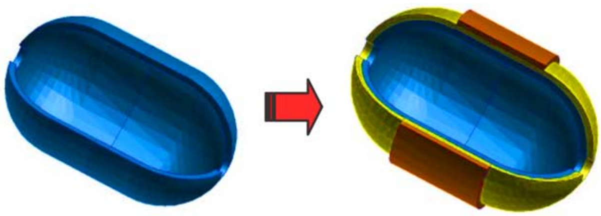

Fig. 2. Configuration of a general type 3 tank.

Table 1
Material properties of T800/Epoxy

	Value
E_1	161.3 GPa
E_2, E_3	8.820 GPa
G_{12}, G_{13}	5.331 GPa
G_{23}	2.744 GPa
ν_{12}, ν_{13}	0.33
ν_{23}	0.45
X_t	2300 MPa
Y_t	30 MPa
Density	1.58×10^{-6} kg/mm^3

Table 2
Material properties of aluminum alloy 7075-T6

	Value
E	72.0 GPa
ν	0.29
σ_{yield}	500.0 MPa
Density	2.8×10^{-6} kg/mm^3

4. The weight reduction is the most important goal of this design.

The objective function is defined as follows:

$$f = \begin{cases} \dfrac{W_{\max}}{W} + 0.1 \times \dfrac{\sigma_{f,\text{design}}}{\sigma_{\text{fiber}}} + 0.1 \times \dfrac{\sigma_{\text{yield}}}{\sigma_{\text{liner}}}, & \sigma_{\text{liner}} \leqslant \sigma_{\text{yield}} \& \sigma_{\text{fiber}} \leqslant \sigma_{f,\text{design}} \\ \dfrac{\sigma_{f,\text{design}}}{\sigma_{\text{fiber}}} + 0.1 \times \dfrac{\sigma_{\text{yield}}}{\sigma_{\text{liner}}}, & \sigma_{\text{liner}} \leqslant \sigma_{\text{yield}} \& \sigma_{f,\text{design}} \\ \dfrac{\sigma_{\text{yield}}}{\sigma_{\text{liner}}}, & \sigma_{\text{liner}} > \sigma_{\text{yield}} \end{cases} \quad (1)$$

where $W_{\max}$ is the possible maximum weight, W the weight of the design point, $\sigma_{f,\text{design}}$ the fiber directional strength with consideration of the safety factor, σ_{fiber} the maximum fiber directional stress of the design point, σ_{yield} the yield strength of the liner, and σ_{liner} the maximum von Mises stress of the liner of the design point.

When the stress terms satisfied the maximum criteria, the weight of the tank, the maximum fiber directional stress of the composite and the maximum stress of the liner were normalized and summed. The relative importance of weight was assumed to be ten times greater than that of stresses. The maximum weight was set to 6.88 kgf, assuming the most conservative case within the design area.

Because the goal of this application was to verify the used algorithm and program, the following four design variables were set for the optimal design: the number of helical layers, the number of hoop layers, the winding angle of the cylinder part, and the thickness of the liner. Each variable was divided into several discrete values for application to the genetic algorithm, and feasible winding angles were calculated using the semi-geodesic path algorithm. The design variables and the genetic algorithm variables are summarized in Tables 3 and 4.

The initial seed value for the genetic algorithm was generated randomly, and ten optimal designs were performed. Table 5 shows the design results. Seven kinds of results were drawn. This outcome shows that the structural behavior of the composite pressure vessel is more nonlinear than that of general basic structures.

Of all the results, the case that best satisfies the given design requirements is a pressure tank with 2 helical layers, 9 hoop layers, a winding angle of 33.5° and a liner of 1.9 mm. As a result, the weight of the optimal case is 4.44 kgf.

3. Modified genetic algorithm

3.1. Improvement of the genetic algorithm

The convergence speed and a reliability of the genetic algorithm are dependent on a characteristic of the problem and methods of the genetic operator. Among several genetic operators, attention is generally limited to basic crossover and mutation operators because of their direct relation to the evolution of a generation.

The crossover operator is the main genetic operator. It operates on two chromosomes and generates offspring by combining features of both chromosomes. In general, crossovers are classified into three kinds: a one-point crossover, a two-point crossover, and a uniform

Table 3
Design variables of the symmetric type 3 tank

	Min	Max	Bits
No. of helical layers	2	5	2
No. of hoop layers	1	16	4
Thickness of liner (mm)	1.0	2.5	4
	Feasible angles		
Winding angle (°)	12.0, 13.0, 14.0, 15.5, 16.5, 17.0, 18.0, 21.0, 21.5, 22.5, 23.5, 24.0, 24.5, 25.0, 25.5, 27.5, 28.0, 28.5, 29.5, 30.5, 31.5, 32.5, 33.0, 33.5, 34.0, 34.5		

Table 4
Genetic algorithm variables for the symmetric type 3 tank

G.A. variable	Value
Population size	100
Probability of crossover	0.7
Probability of mutation	0.1
Tourney size	10
Maximum generation	100
Converge criterion 1 (no. of same fitness)	10
Converge criterion 2 (% error of average value)	0.1

crossover. Fig. 3 shows the operating outline of each method. The one-point crossover combines two chromosomes by choosing a random cut-point. The two-point crossover combines two chromosomes by choosing two random cut-points. The uniform crossover combines chromosomes by choosing more than three random cut-points.

The mutation operator is applied to a single chromosome only. For a binary algorithm, it just randomly changes bits from zeros to ones or vice versa with a certain probability, as shown in Fig. 4.

In general, if the probabilities of the crossover and mutation are relatively low, the problem of a population getting trapped in a local optimum can occur. In a contrary case, the convergence of the solution can be delayed. Selecting and applying suitable genetic operators is therefore important in an optimal design that uses a genetic algorithm.

Composite structures have several discrete design variables such as the number of plies, the stack sequences and the ply orientations. In addition, because the structural behavior is extraordinarily nonlinear, several modifications to the genetic algorithm have been performed and suggested [14–16].

In this paper, a new genetic operator is suggested. It is suitable for the optimal design of axisymmetric filament wound structures and can raise the design efficiency.

Axisymmetric filament wound structures under internal pressure have several design variables such as the mandrel shape, the thickness of the liner, the number of helical layers, the number of hoop layers, the winding angle, the thickness of the skirt, and the winding angle of the skirt. These design variables can be divided into two groups: in the first group, the structural behavior is linear and can be estimated; in the second group, the structural behavior is nonlinear and cannot be estimated. In this study, the first group was named 'variable group 1' and the second group was named 'variable group 2'. After the design variables have been divided into the two groups, the genetic operators are applied individually to each group with different operating probabilities. This process is based on Nagendra's 'sub-string crossover method' (Fig. 5) [16]. Fig. 6 shows the detailed processes of 'the modified sub-string genetic operator' suggested in this paper.

In a crossover process, the location between variable group 1 and variable group 2 is set to a default cut-point for the crossover. New random cut-points are then individually generated with different probabilities within each group. Thus, any type of crossover can occur: from a one-point crossover to a three-point uniform crossover.

Table 5
Design results of the symmetric type 3 tank

Case	No. of helical layers	No. of hoop layers	Winding angle (°)	Thickness of liner (mm)	Weight (kgf)	Fitness
1	2	9	33.5	1.9	4.44	1.751
2	3	10	34.5	1.7	4.47	1.746
3	2	9	31.5	1.9	4.45	1.747
4	3	10	28.0	1.7	4.50	1.733
5	2	10	33.0	1.9	4.51	1.729
6	2	9	33.5	1.9	4.44	1.751
7	2	9	33.5	1.9	4.44	1.751
8	3	10	33.0	1.7	4.48	1.742
9	3	9	34.0	1.8	4.58	1.711
10	2	9	31.5	1.9	4.45	1.747

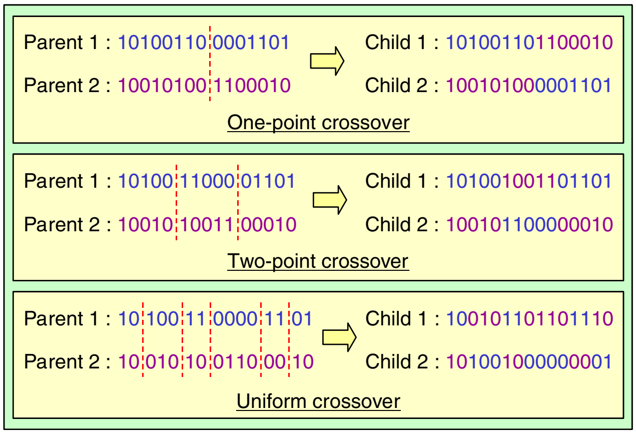

Fig. 3. Classification of crossover methods.

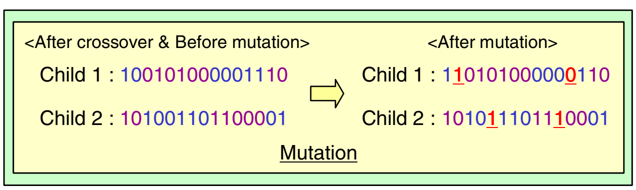

Fig. 4. General procedure of mutation.

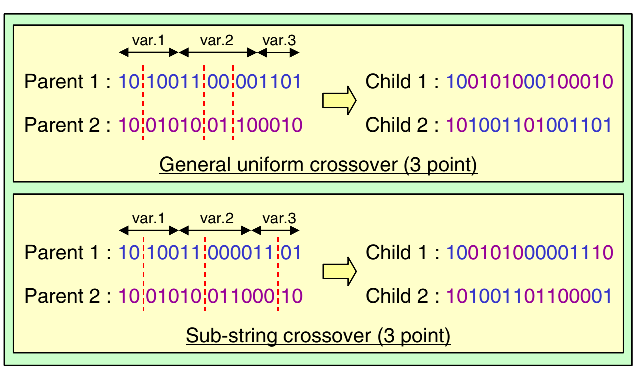

Fig. 5. Comparison between uniform crossover and sub-string crossover.

The mutation process is similar to the crossover process. That is, different probabilities of mutation are applied separately to each group.

By using this operator, the solution can be prevented from getting trapped in the local optimal point. Simultaneously, the convergence of the solution can be accelerated.

3.2. Verification of modified genetic algorithm

To verify the modified genetic algorithm, the basic design of Section 2.3 was again performed using the suggested method. The result was compared with the previous one.

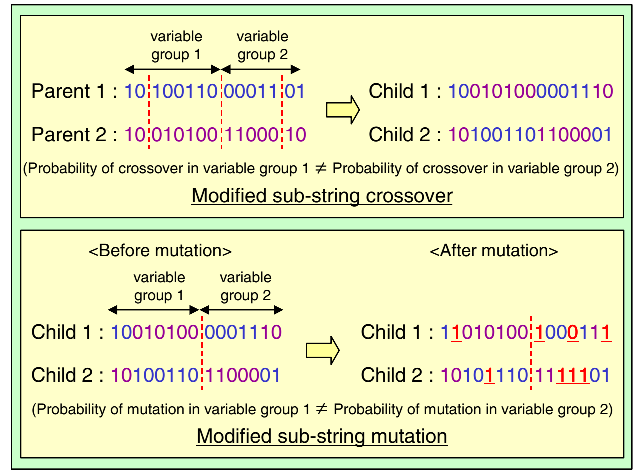

Fig. 6. Modified sub-string genetic operator.

The basic design requirements, the objective function and the design variables were same as in the previous case. Variable group 1 included the number of helical layers and the number of hoop layers. Variable group 2 included the winding angle of the cylinder part and the thickness of the liner.

For the type 3 symmetric pressure tank, Table 6 shows the variables of the modified genetic algorithm. The initial seed value for the genetic algorithm was also generated randomly, and ten optimal designs were performed. Table 7 shows the results of the second of the tank. Seven kinds of results were drawn, and the number of kinds is the same as in the previous results. However, in a comparison with the previous results, the average fitness of the results increased from 1.741 to 1.747.

The new process with the modified sub-string genetic operator was verified through a basic design. Moreover, the new method was confirmed to be more efficient in the optimal design of axisymmetric filament wound structures.

Table 6
Modified genetic algorithm variables for the symmetric type 3 tank

G.A. variable	Value
Population size	100
Probability of crossover in variable group 1	0.7
Probability of crossover in variable group 2	0.8
Probability of mutation in variable group 1	0.1
Probability of mutation in variable group 2	0.2
Tourney size	10
Maximum generation	100
Converge criterion 1 (no. of same fitness)	10
Converge criterion 2 (% error of average value)	0.1

Table 7
Second design results of the symmetric type 3 tank

Case	No. of helical layers	No. of hoop layers	Winding angle (°)	Thickness of liner (mm)	Weight (kgf)	Fitness
1	2	9	33.5	1.9	4.44	1.751
2	3	10	33.0	1.7	4.48	1.742
3	2	9	33.5	1.9	4.44	1.751
4	3	10	34.0	1.7	4.48	1.743
5	2	9	33.0	1.9	4.45	1.747
6	3	10	34.5	1.7	4.47	1.746
7	2	9	31.5	1.9	4.45	1.747
8	2	9	32.5	1.9	4.45	1.747
9	2	9	33.5	1.9	4.44	1.751
10	2	9	33.0	1.9	4.45	1.747

4. Application—high pressure hydrogen storage tank

4.1. Introduction of the design

The design model is the hydrogen tank of Fig. 7. Structural stability and airtightness are both important in the design of composite pressure tanks that preserve high pressure gas such as hydrogen. This type of tanks is therefore generally made as type 3 tanks with a load-sharing metallic liner. Thus, the overall design procedure is similar to that described in Section 3.2.

Type 3 tanks are designed in two ways: with and without permitting a liner yield. Although the liner cannot sustain an additional load after a yield, it does not fail because of a plastic deformation. Therefore, both types of designs are possible. When a liner yield is prohibited, as in the case of paragraph 3.2, the structural efficiency is low in spite of high stability. However, if a liner yield is permitted, even though the tank's weight is effectively reduced, the tank is weakened by an unpredictable load such as an impact.

Recently, a new method in which several steps are pressurized, as shown in Fig. 8, has been applied to the manufacture of type 3 tanks [17]. Through this method, it is possible to fabricate a type 3 tank which prohibits a liner yield and which has a high structural efficiency.

Fig. 9 shows the stress–strain graphs of the composite and the liner, under the pressurization of five steps. The pressure of the first step was 1.575 times larger than the service pressure; this pressure is known as auto-frettage pressure. At the auto-frettage pressure, although the liner deforms in the plastic region, the composite deforms in the elastic region. The pressure of the second step was zero. At this step, although the liner could not return to the original shape because of the plastic deformation at the first step, the reaction of the composite was vice versa. Hence, a tensile stress occurred in the composite and a compressive stress was existent in the

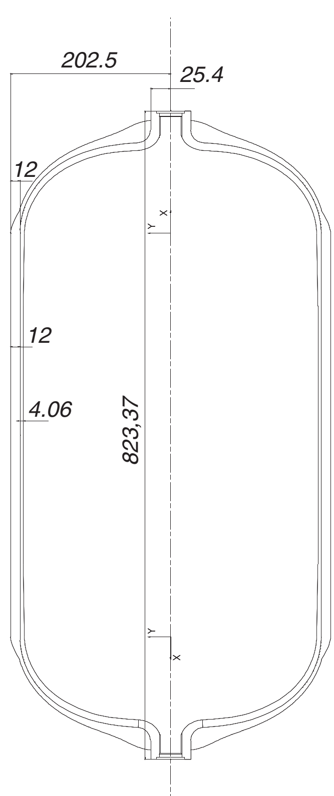

Fig. 7. Original shape of the hydrogen tank.

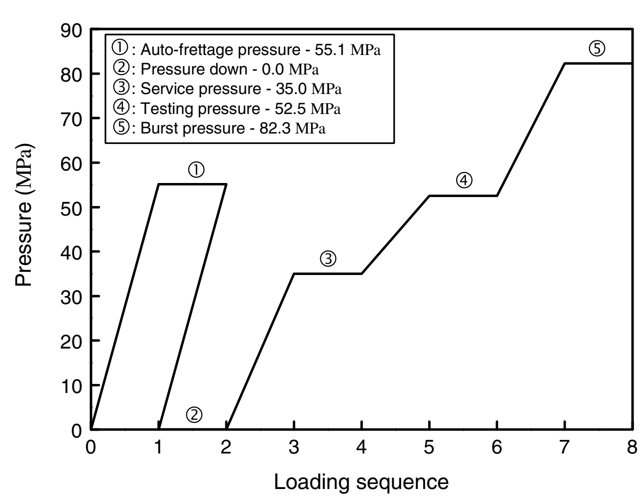

Fig. 8. Pressure history of the hydrogen tank.

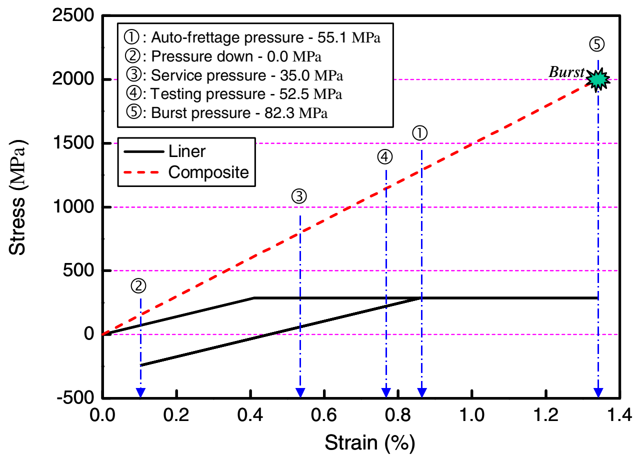

Fig. 9. Comparison of stress–strain curves between composite and liner.

liner. The pressure of the third step was a service pressure. Because the liner starts deformation from a compressive state, both the liner and the composite deform in the elastic region at this step. The pressure of the fourth step was 1.5 times larger than the service pressure. This pressure is for a water-pressurizing test. At this step, all parts of the tank showed elastic deformations. The pressure of the fifth step was the bursting pressure of the tank. This pressure was determined by a given safety factor.

In this design method, deciding suitable design variables is the most difficult and important factor.

In this paper, a design that prohibits a liner yield at the service pressure was performed. The basic model for the optimal design is a type 3 tank that has the following design variables: 3 helical layers, 9 hoop layers, a winding angle of 7.66° for the cylinder part, and a liner thickness of 4.06 mm. This basic model was developed as a hydrogen tank for a car.

The basic design conditions are as follows:

1. The material of the composite is T700/Epoxy, with a fiber volume fraction of 65.0% and a ply thickness of 0.8 mm (Table 8). The liner is the aluminum alloy 6061-T6.
2. Maximum operating inner pressure is 35.0 MPa.
3. The design is based on the results of the original design.
4. The weight reduction is the most important goal of this design.
5. Although the basic model has a liner of various thicknesses, the liner thickness of the design model is constant.

The objective function is the same as Eq. (1).

The possible maximum weight was set to 27.18 kgf, the fiber directional design strength was set to 878.2 MPa and the design strength of the liner was set to 123.2 MPa on the basis of the analysis of the existing model.

The design variables and the classification of variable groups were same as in previous cases. The applied design variables and genetic algorithm variables are summarized in Tables 9 and 10.

Table 8
Material properties of T700/Epoxy (Hydrogen tank)

	Value
E_1	149.12 GPa
E_2, E_3	10.558 GPa
G_{12}, G_{13}	4.138 GPa
G_{23}	3.311 GPa
ν_{12}, ν_{13}	0.253
ν_{23}	0.421
X_t	2408 MPa
Y_t	37 MPa
Density	1.608×10^{-6} kg/mm^3

4.2. Design results

The initial seed value for the genetic algorithm was generated randomly, and ten optimal designs were performed. Table 11 shows the design results of the hydrogen tank. Six kinds of results were drawn.

Of all the results, the case that best satisfies the given design requirements is the hydrogen tank with 4 helical layers, 11 hoop layers, a winding angle of 20.5° and a

Table 9
Design variables of the hydrogen tank

	Min	Max	Bits
No. of helical layers	2	5	2
No. of hoop layers	1	16	4
Thickness of liner (mm)	0.9	4.0	5
	Feasible angles		
Winding angle (°)	6.5, 7.5, 8.0, 8.5, 9.0, 11.0, 12.0, 13.0, 13.5, 15.0, 16.0, 17.0, 17.5, 18.5, 19.0, 19.5, 20.0, 20.5, 21.5, 22.0		

Table 10
Modified genetic algorithm variables for the hydrogen tank

G.A. variable	Value
Population size	100
Probability of crossover in variable group 1	0.65
Probability of crossover in variable group 2	0.75
Probability of mutation in variable group 1	0.05
Probability of mutation in variable group 2	0.15
Tourney size	10
Maximum generation	100
Converge criterion 1 (no. of same fitness)	10
Converge criterion 2 (% error of average value)	0.1

Table 11
Design results of the hydrogen tank

Case	No. of helical layers	No. of hoop layers	Winding angle (°)	Thickness of liner (mm)	Weight (kgf)	Fitness
1	4	11	20.0	1.8	26.26	1.261
2	4	12	21.5	1.7	26.81	1.235
3	4	11	20.5	1.7	25.99	1.269
4	4	11	20.5	1.7	25.99	1.269
5	4	11	17.5	2.0	26.84	1.244
6	4	11	18.5	1.8	26.30	1.260
7	4	12	21.5	1.7	26.81	1.235
8	4	11	15.0	1.9	26.63	1.247
9	4	11	20.5	1.7	25.99	1.269
10	4	11	15.0	1.9	26.63	1.247

liner thickness of 1.7 mm. As a result, the weight of the optimal case is 25.99 kgf.

The overall design results, including the optimal case, differ significantly from the original design. Number of helical and hoop layers increased, the liner became thinner, and the winding angle increased. Thus, the original model was verified as a tank that focused on the use of metal.

Fig. 10 shows a comparative graph of fiber directional stress for the original model and the design model. As shown in the graph, the stress of the design model is relatively low. The weight decreased by 4.4%, and the maximum fiber directional stress decreased by 18.1%. Based on the performance factor of Eq. (2), the design was improved by 23.5%. Consequently, the optimal design was efficient and successful. Eq. (2) is expressed as follows:

$$\text{Performance factor} = \frac{P \times V}{W} \tag{2}$$

where P is the burst pressure, V the volume, and W the weight.

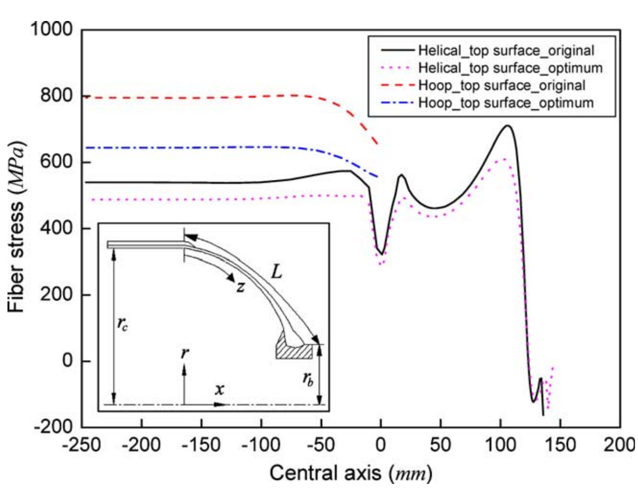

Fig. 10. Fiber directional stresses of the hydrogen tank.

5. Conclusion

In this research, the optimal design of filament wound type 3 tanks under internal pressure was performed. A new design algorithm which had been proposed in our previous research was utilized. The optimal design algorithm includes the semi-geodesic path algorithm, progressive failure analysis and genetic algorithms. In addition, a modified sub-string genetic operator that improves the genetic algorithm was newly suggested and verified through a basic design. Finally, the optimal design algorithm was applied to a representative filament wound type 3 tank—high pressure hydrogen storage tank. The design was improved by 23.5% based on the performance factor. Consequently, the optimal design was efficient and successful.

References

[1] Jaunky N, Knight Jr NF, Ambur DR. Optimal design of general stiffened composite circular cylinders for global buckling with strength constraints. Compos Struct 1998;41:243–52.
[2] Richard F, Perreux D. A reliability method for optimization of $[+\theta/-\theta]n$ fiber reinforced composite pipes. Reliab Eng Syst Saf 2000;68:53–9.
[3] Messager T, Pyrz M, Gineste B, Chauchot P. Optimal laminations of thin underwater composite cylindrical vessels. Compos Struct 2002;58:529–37.
[4] Azzam BS, Muhammad MAA, Mokhtar MOA, Kolkailah FA. A finite element presentation of an optimum design for the filament-wound composite pressure vessels. In: 40th International SAMPE Symposium, 8–11 May 1995, p. 867–80.
[5] Azzam BS, Muhammad MAA, Mokhtar MOA, Kolkailah FA. A theoretical and design analysis of the filament-wound composite pressure vessels. Sci Eng Compos Mater 1995;4(2):73–87.
[6] Krikanov AA. Composite pressure vessels with higher stiffness. Compos Struct 2000;48:119–27.
[7] Tabakov PY. Multi-dimensional design optimization of laminated structures using an improved genetic algorithm. Compos Struct 2001;54:349–54.
[8] Parnas L, Katirci N. Design of fiber-reinforced composite pressure vessels under various loading conditions. Compos Struct 2002;58:83–95.
[9] Kim CU, Park JS, Hong CS, Kim CG. Design of filament wound composite pressure tanks using finite element analyses. In:

American Society for Composites 17th Annual Technical Conference Proceeding CD, 21–23 October 2002.

[10] Kim CU, Kang JH, Hong CS, Kim CG. Optimal design of filament wound structures under internal pressure based on the semi-geodesic path algorithm. Compos Struct, in press.

[11] Thanedar PB, Vanderplaats GN. Survey of discrete variable optimization for structural design. J Struct Eng 1995;121(2): 301–5.

[12] Ringertz UT. On methods for discrete structural optimization. Eng Optim 1988;13:47–64.

[13] Goldberg DE. Genetic algorithm in search, optimization, and machine learning. Addison-Wesley Publishing Company; 1989.

[14] Conceicao Antonio CA. A multilevel genetic algorithm for optimization of geometrically nonlinear stiffened composite structures. Struct Multidisciplinary Optim 2002;24:372–86.

[15] Liu B, Haftka RT, Akgun MA, Todoroki A. Permutation genetic algorithm for stacking sequence design of composite laminates. Comput Meth Appl Mech Eng 2000;186:357–72.

[16] Nagendra S, Jestin D, Gurdal Z, Haftka RT, Watson LT. Improved genetic algorithm for the design of stiffened composite panels. Comput Struct 1996;58(3):543–55.

[17] Proposal for A New Draft Regulation, European Integrated Hydrogen Project, 2001.