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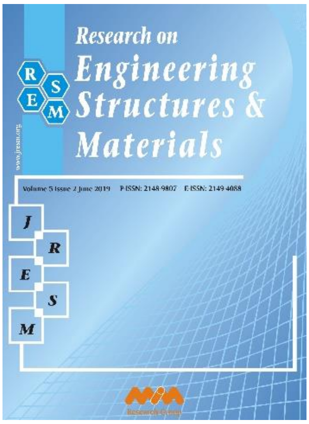

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Research Article

Optimal design of the type III hydrogen storage tank for different carbon/epoxy materials by modified differential evolution method

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Abstract

In this study, the main objective is to minimize the failure index of a cylindrical laminated composite hydrogen storage tank under internal pressure. The first step is to obtain the distribution of stress components based on Classical Laminated Plate Theory (CLPT). The second is to evaluate the burst pressure of the tank according to three different first ply failure criteria and then to compare the results with the experimental and numerical ones from literature. In the final part of the study, the best possible combination of winding angles, stacking sequences and thicknesses of laminates satisfying minimum possible stress concentration will be obtained for different Carbon/Epoxy materials by Differential Evolution Method. The stress components and, the burst pressures reached according to Hashin-Rotem, Maximum Stress, and Tsai-Wu first-ply failure criteria, have been complied with experimental and numerical results in the literature for Type III pressure vessels. Manufacturable Type-III tank designs have been proposed satisfying the 35 MPa burst pressure for different Carbon/Epoxy materials.

1. Introduction

The world's energy requirement is largely derived from fossil resources. Today, an important part of it is fulfill with the use of sources such as nuclear, solar, wind, geothermal, biomass, glacier energies as alternatives to fossil resources. It should also be noted that the use of fossil fuels is subject to restrictions depending on environmental legislation mandates. For this reason, the use of alternative energy sources is increasing in importance and it can be said that the most important alternative energy source of the 21st century is hydrogen energy technology with high energy efficiency in low volumes [1]. Hydrogen energy technology is used in various fields such as gas plants, power plants, aviation, chemical and automotive industries. However, the most restrictive factor in the use of these energy technologies is the storage of hydrogen gas [2]. The design of composite tanks to store hydrogen gas in both high volumes and high pressures has been intensively studied in recent years [3]. For this purpose, the use of low volume and lightweight components is the most important design parameter especially in automotive

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and aerospace industrial applications, hence, pressure vessels used in this area are required to have the prescribed characteristics [4].

Many researchers are investigating the design and optimization of lightweight composite pressure vessels, recently. In the literature, the design and optimization studies of the strength of composite hydrogen storage tanks have focused on laminate stacking sequence. It should be noted that the strengths of these vessels are directly related to the volumes of the fibers[5, 6]. The literature is examined, it can be seen that many studies have been made on the analysis of composite hydrogen storage tanks. For example, in Messager et al. [7], an analytical model has been built on the stacking sequence of the composite cylinders and optimization studies with Genetic Algorithm (GA) have been carried out. It has been shown that the optimization results are compatible with the experimental ones. However, they have not studied optimal design works for complex filamentary structures. Parnas and Katirci [8] obtained optimum winding angles in the production of composite pressure vessels using the Classical Laminated Plate and the Tsai-Wu failure theories. They found that the optimum fiber orientation angles were 52.1° and 54.1° according to the material type. Tabakov [9] performed a stochastic optimization study using GA to calculate the three-dimensional stress-strain in the cylindrical part of the composite pressure vessel. Exact elasticity solutions have been solved by considering the closed ends of the cylindrical shell into account. Richard and Perreux [10] have studied the problems of internal pressure single-sided composite pipe optimization. They investigated the behavior of e-glass, carbon and kevlar fiber supported composites and determined three angles 53.2°, 54.3° and 54.9°as optimum ones. Lin et al. [11] have performed optimization of the angles and thickness of composite plates using GA and Simplified Conjugate Gradient algorithms. They obtained similar results with both algorithms and determined composite layer thickness and winding angle as 1.6 mm and 36.54 °(at 489.941 MPa), respectively. Han and Chang [12] performed a failure analysis of a Type-III pressure vessels according to Hashin failure criterion and investigated stress distribution and damage conditions. They have carried out both experimental and numerical studies using carbon epoxy and have achieved coherent results. The overall structure was safe under the service conditions. Park et al. [13] studied the crack behavior in a type III high-pressure hydrogen vessel using a ply modeling method and the extended finite element method. The weak point of the composite layers has been observed in the transverse direction at the helical winding angle of 35°. In the boundary of the cylinder and dome, 35° winding angle may be important to design safety hydrogen pressure vessel.

Many studies have been also carried out on optimization of composite laminates. Nikbakta et al. [14] have achieved a review study on optimization problems of structures to improve mechanical or thermal behavior of the composites such as buckling resistance, stiffness and strength along with reducing weight, cost and stress under various types of loadings. Roque and Martins [15] carried out a study on staking sequences for maximization of the natural frequency of symmetric and asymmetric laminates by using Differential Evolution (DE). Chakraborty and Dutta [16] have studied the optimization of the weights of 3-component laminated composites with GA, which is a random search method. Jing et al. [17] investigated the composite critical buckling using with multi-criteria objective function. Similarly, Irisarri et al. [18] studied multi-objective stacking sequence optimization for composite plates. They concluded that non-traditional ply orientations may lead to better designs than classical ones. Zu et al. [19] found the best non-geodesic trajectory with GA for circular toroidal vessels. Francesco et al. [20] have worked with GA to study composite pressure vessels overwrapping a metallic liner (type III COPV) under internal pressure. They have reached the conclusion that the optimal design is first-ply or last-ply failure design objective. However, the authors did not focus on optimum stacking sequence, which is the main motivation and contribution of the current study.

In the present study, the main purpose is to see effect of the different carbon/epoxy material type on optimum stacking sequences design of Type III pressure vessel. The first step is to gain the distribution of stress components based on Classical Laminated Plate Theory (CLPT). The second step is to determine the burst pressure of the Type III pressure vessel by using Tsai-Wu failure criterion and then to compare the result with analytical, experimental and numerical ones from literature. In the final part of the study, for different carbon/epoxy materials, the best possible combination of winding, stacking sequences and thicknesses of laminates satisfying minimum possible stress concentration have been obtained by Modified Differential Evolution (MDE) stochastic optimization method.

2. Stress Analysis of the Tank

Cylindrical part of the Type III tank is composed of isotropic metallic liner and orthotropic composite layers. The laminated composite pressure vessel having radius of "R" is subjected to the internal pressure "p". The force resultants, calculated via considerations of static equilibrium can be expressed as follow [21]:

$$N_x = \frac{1}{2}pR \qquad N_y = pR \qquad N_{xy} = 0 \tag{1}$$

For Type III pressure vessel, strain for the composite and metallic liner is assumed to be the same and also only membrane effects are considered. The stress in metallic liner and composite is related to the stiffness of each material and in the Type III analysis, the stiffness of the metallic liner and composite layer are considered together within the calculation of [A] extensional stiffness matrix.

$$A_{ij} = \sum_{k=1}^{n}[(\bar{Q}_{ij})]_k\,(h_k - h_{k-1}) + [Q_L]\,t_L \tag{2}$$

where, h_k is the distance from the middle plane to the bottom surface of the k_{th} layer, $(\bar{Q}_{ij})_k$ transformed reduced stiffness of the k_{th} layer. Q_L is stifness matrix of the metallic liner and t_L is the thickness of the liner.

By using matrix [A], the strains occurred by the loading in the cylinder, can be calculated as follow [22]:

$$\begin{bmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \end{bmatrix} = [A]^{-1} \begin{bmatrix} pR/2 \\ pR \\ 0 \end{bmatrix} \tag{3}$$

After the obtaining strains for laminates, and using stress-strain relationships, stress at the liner and each lamina can be written as [22]:

$$\begin{bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{bmatrix} = [Q_L] \begin{bmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \end{bmatrix} \tag{4}$$

$$\begin{bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{bmatrix} = [\bar{Q}]^{(k)} \begin{bmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \end{bmatrix} \tag{5}$$

2.1 Failure Analysis

Failure is inability of the structure against to the applied loads. The main reasons of failure can be listed as follows: (i) insufficient of the design procedure, (ii) wrong material choice, (iii) inadequate production facilities and (iv) diversity of service conditions. Many researchers have proposed the formulations for failure predictions of isotropic and anisotropic materials [23-25]. The number of the approaches and important progress clearly demonstrated that there is not any criterion universally accepted by designers as enough under various load conditions. In the present study, three failure criteria chosen from interactive, partial interactive and non-interactive failure approaches have been used for composite material design. Maximum Shear Strain Energy (Von- Mises) theory has been used for isotropic liner.

Relationships between the stress components and Von-Mises, Tsai-Wu, Hashin-Rotem and Maximum Stress failure theories can be defined as in below:

Maximum shear strain energy (Von-Mises):

σ_{yield} is the yield stress in simple tension, the theory considers the principle stresses $\sigma_1 \geq \sigma_2 \geq \sigma_3$ and point out that failure when the following equality is valid [26].

$$(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2 = 2\sigma_{yield}^2 \tag{6}$$

Tsai-Wu Tensor failure criterion:

According to the theory assumption, failure occurs when the following expression is valid

$$F_1\sigma_1 + F_2\sigma_2 + F_{11}\sigma_1^2 + F_{22}\sigma_2^2 + F_{66}\tau_{12}^2 + 2\,F_{12}\sigma_1\sigma_2 = 1 \tag{7}$$

where, F_{12} can be determined with only a biaxial tension test. For calculating the value of F_{12} an empirical expression is suggested as [27]

$$F_1 = \frac{1}{(\sigma_1^T)_{ult}} + \frac{1}{(\sigma_1^C)_{ult}} \quad , \quad F_{11} = -\frac{1}{(\sigma_1^T)_{ult}(\sigma_1^C)_{ult}} \tag{8}$$

$$F_2 = \frac{1}{(\sigma_2^T)_{ult}} + \frac{1}{(\sigma_2^C)_{ult}} \quad , \quad F_{22} = -\frac{1}{(\sigma_2^T)_{ult}(\sigma_2^C)_{ult}} \tag{9}$$

$$F_{12} = -\frac{1}{2}\sqrt{F_{11}F_{22}} \quad , \quad F_{66} = \frac{1}{{(\tau_{12}^F)_{ult}}^2} \tag{10}$$

Maximum Stress criterion:

The maximum stress first ply failure criterion based on the assumption that failure is occurred if the σ_1, σ_{12} and τ_{12} reach the corresponding ultimate strength parameters of materials. There are three possible modes of failure comparing the stress components of the ply with tensile, compression and shear ultimate values.[27]

$$\sigma_1 \leq (\sigma_1^T)_{ult} \;, \sigma_2 \leq (\sigma_2^T)_{ult} \qquad \text{if} \qquad \sigma_1 > 0,\ \sigma_2 > 0 \tag{11}$$

$$|\sigma_1| \leq (\sigma_1^C)_{ult} \;, |\sigma_2| \leq (\sigma_2^C)_{ult} \qquad \text{if} \qquad \sigma_1 < 0,\ \sigma_2 < 0 \tag{12}$$

$$|\tau_{12}| \leq (\tau_{12})_{ult} \tag{13}$$

Hashin - Rotem criterion:

This criterion involves two failure mechanisms which to be fiber failure and matrix failure, distinguishing between tension and compression [28].

$$\text{Fiber failure in tension } (\sigma_1 > 0);\ \sigma_1 = (\sigma_1^T)_{ult} \tag{14}$$

$$\text{Fiber failure in compression: } (\sigma_1 < 0);\ -\sigma_1 = (\sigma_1^C)_{ult} \tag{15}$$

$$\text{Matrix failure in tension: } (\sigma_2 > 0); \left(\frac{\sigma_1}{(\sigma_2^T)_{ult}}\right)^2 + \left(\frac{\tau_{12}}{(\tau_{12})_{ult}}\right)^2 = 1 \tag{16}$$

$$\text{Matrix failure in tension: } (\sigma_2 < 0); \left(\frac{\sigma_2}{(\sigma_2^C)_{ult}}\right)^2 + \left(\frac{\tau_{12}}{(\tau_{12})_{ult}}\right)^2 = 1 \tag{17}$$

3. Optimization Algorithms

Differential Evolution Method

As a stochastic optimization method, Differential Evolution (DE) enables to find alternative solution for composite design. In DE, there are four main stages: initialization, mutation, crossover, and selection. Scaling factor, crossover, and population size are three parameters checked by the algorithm, also. A population of solutions instead of a single solution at each of iteration is considered in Differential Evolution method. DE is effective in attaining global optimum avoiding local minimum of the objective function [29, 30]. However, it is computationally expensive. In the literature, DE has been investigated to design of fiber composite structures from simple rectangular plates to complex geometries [31].

4. Problem Definition

In this study, there are three different Type III Aluminum Carbon/Epoxy pressure vessel problems which have been solved; Problem 1 and 2 are verification cases and Problem 3 is an optimization problem which proposes optimum design satisfying the mentioned burst pressure. In the first step, for verification problems 1 and 2, stress components and failure index values based on Tsai-Wu, Hashin-Rotem and Maximum Stress failure theories only (which is related with burst pressure of the tank) have been calculated and then compared to experimental and Finite Element Analysis results from the literature [32, 33]. In the prediction of burst pressure and stacking optimization problems, it is focused on cylindrical parts of the pressure vessels. In these problems, Type III tanks are considered as composed of composite plies and aluminum liner (see Figure 1).

The second step is design and optimization part: overall procedures for different optimization cases can be summarized as

- Close-end cylindrical section of the Type III tanks have been only considered subjected to high internal pressure " P ".
- It is considered to be constant over the length of the cylinder for inner radius (R) thicknesses of the composite layers (t_c) and aluminum liner (t_{liner}).
- For the Problem 3, three different failure criteria to be interactive, partial-interactive and non-interactive: Tsai-Wu, Hashin-Rotem and Maximum Stress have been used as constraints.
- All optimization cases of composite cylindrical tanks have been assumed to be single objective optimization problem.
- Fiber orientation angles $\theta_1, \theta_2, \theta_3, \ldots, \theta_n$ and number of layers are selected as the design variables.

Problem 1:

In the Problem 1, the stress and failure indexes of Tsai-Wu and Maximum Stress failure criteria have been computed for Type III Aluminum-Carbon/Epoxy composite pressure vessel. Material properties have been taken from ref. [22] (see Tables 1 and 2). The internal radius of the tank is 100 mm and the volume is 10 Liter. The other parameters; ply thickness, liner thickness and applied pressure are 0.42, 3 mm and 164.5 MPa, respectively. For Type III tank, it has been considered that the liner and reinforcing materials are Aluminum T6061 and composite T700 Carbon/Epoxy. The main purpose of this problem is to compare failure indexes obtained by the present study and results by Alcantar [22] for Type III pressure vessel.

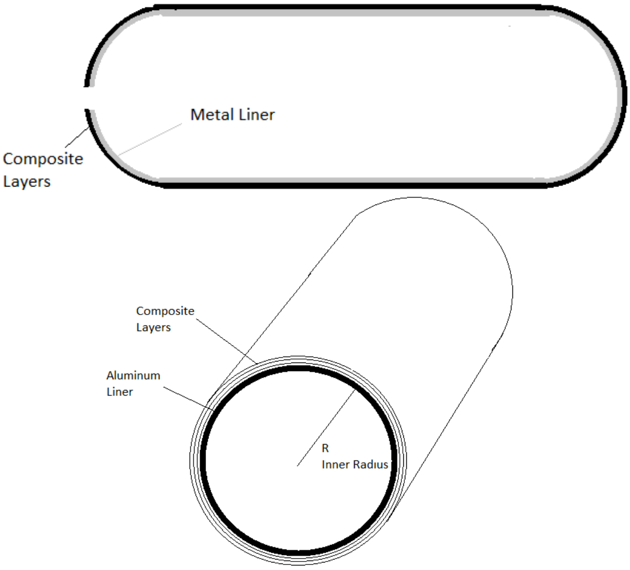

Fig. 1 Configuration of the Type III tank

Table 1 Mechanical properties of T6061 Al and T700 Carbon/Epoxy composite materials [22]

	E_1(GPa)	E_2(GPa)	G_{12}(GPa)	ν_{12}	ν_{23}	σ_{ult} (MPa)
6061Al	70	70	26.92	0.3	0.3	310
T700 Carbon/Epoxy	181	10.3	5.86	0.28	0.49	-

Table 2 Strength parameters of T700 Carbon/Epoxy composite materials [22]

$\sigma^T_{1_{ult}}$(MPa)	$\sigma^C_{1_{ult}}$(MPa)	$\sigma^T_{2_{ult}}$(MPa)	$\sigma^C_{2_{ult}}$(MPa)	$\tau_{12_{ult}}$(MPa)
2150	2150	298	298	778

Problem 2:

In Problem 2, stress calculation and determination of the burst pressure according to Classical Laminated Plate Theory and Tsai-Wu failure criterion have been done for Aluminum- Carbon Epoxy pressure vessel (Type III). The burst pressure results have been compared with experimental and Finite Element analysis results by Liu et al [32]. The pressure vessel is composed of T6061 Aluminum liner and T700 Carbon/Epoxy composite plies. Mechanical properties and strength parameters of these materials are given in Table 3 and 4, respectively.

Table 3 Mechanical properties of T6061 Al and T700 Carbon/Epoxy composite materials [32]

	E_1(GPa)	E_2(GPa)	G_{12}(GPa)	ν_{12}	ν_{23}	$\boldsymbol{\sigma_{yield}}$ (MPa)
6061Al	70	70	26.92	0.3	0.3	246
T700 Carbon/Epoxy	154.1	10.3	5.17	0.28	0.49	-

Table 4 Strength parameters of T700 Carbon/Epoxy composite materials [32]

$\boldsymbol{\sigma^T_{1ult}}$**(MPa)**	$\boldsymbol{\sigma^C_{1ult}}$**(MPa)**	$\boldsymbol{\sigma^T_{2ult}}$**(MPa)**	$\boldsymbol{\sigma^C_{2ult}}$**(MPa)**	$\boldsymbol{\tau_{12ult}}$**(MPa)**
2500	1250	60	186	85

Geometrical properties for considered Type III pressure vessel have been indicated in Table 5.

Table 5 Geometrical Dimensions of the Type-III Pressure Vessel [32]

Internal Radius (mm)	Stacking Sequences (°)	Liner Thickness (mm)	Thickness of Composite Ply (mm)
44	$[90_2/18.6/ -18.6/ 90_2 /28.9/ -28.9/ 90_2]$	1.8	0.42

Problem 3:

The main aim of the Problem 3 is to see effect of usage different Carbon/Epoxy materials on the design and optimization of the Type III hydrogen storage tanks. The optimization problems have been solved by using Differential Evolution Method. The materials considered in this problem and their properties are listed in Table 6. Thickness of the each lamina (t_{liner}) and radius of the tanks (R) are 1.8 and 200 mm, respectively. In the failure index calculations the strength properties of the materials are taken from references [22], [32] and [34].

The mathematical representation of Problem 3 is defined as

Minimize: $F_{T\,[1]}$ (Tsai-Wu Failure Index at first layer)

Constraints: $\{F_{\text{Tsai-Wu}}, F_{\text{Hashin-Rotem}}, F_{\text{Maximum Stress}}\} \leq 1$,

$\{\theta_1, \theta_2, \theta_3, \ldots\} \in \{0, 15, 30, 45, 60, 75, 90\}$

$P_{burst} > 35$ MPa, Symmetric & Balance stacking sequences:

$[\pm\theta_1/\pm\theta_2/\pm\theta_3/\ldots/\mp\theta_3/\mp\theta_2/\mp\theta_1]$

Table 6 Mechanical properties of the materials

	E_1 (GPa)	E_2 (GPa)	G_{12} (GPa)	ν_{12}	σ_{yield} (MPa)
T6061Al [22]	70	70	26.92	0.3	246
Carbon/Epoxy (T700) [22]	181	10.3	5.86	0.28	-
Carbon/Epoxy (IM6/SC1081) [34]	177	10.8	7.6	0.27	-
Carbon/Epoxy (T700s) [32]	154.1	9.66	5.17	0.25	

4. Results and Discussion

There are three main stages to find the optimum solution. The first step is to enter the material properties and calculate the stiffness matrices. The second part is to give the fiber orientation angles parametrically and arriving at the objective function. The last step is running the optimization algorithms (Differential Evolution) and finding the optimum solution (see Figure 2).

Problem 1:

The results of the Problem 1 can be summarized as: (i) the present failure indexes calculations using Tsai-Wu and Maximum Stress theories have been compared with the results achieved by Finite Element Method (see Table 7). It is shown that good agreement between the present and FEM results by Alcantar et al. [22] are obtained. (ii) For Type III pressure vessels, the burst pressure prediction has also been developed by using the stress-strain matrix calculation method given in Alcantar et al. [22].

Table 7 Results of the Tsai-Wu and Maximum Stress failure indexes

Burst Pressure (MPa)	Failure Index			
	Tsai-Wu [22]	Tsai-Wu [Present Study]	Maximum Stress[22]	Maximum Stress [Present Study]
164.5	0.83	0.85	0.90	1.00
105	0.51	0.35	0.56	0.64

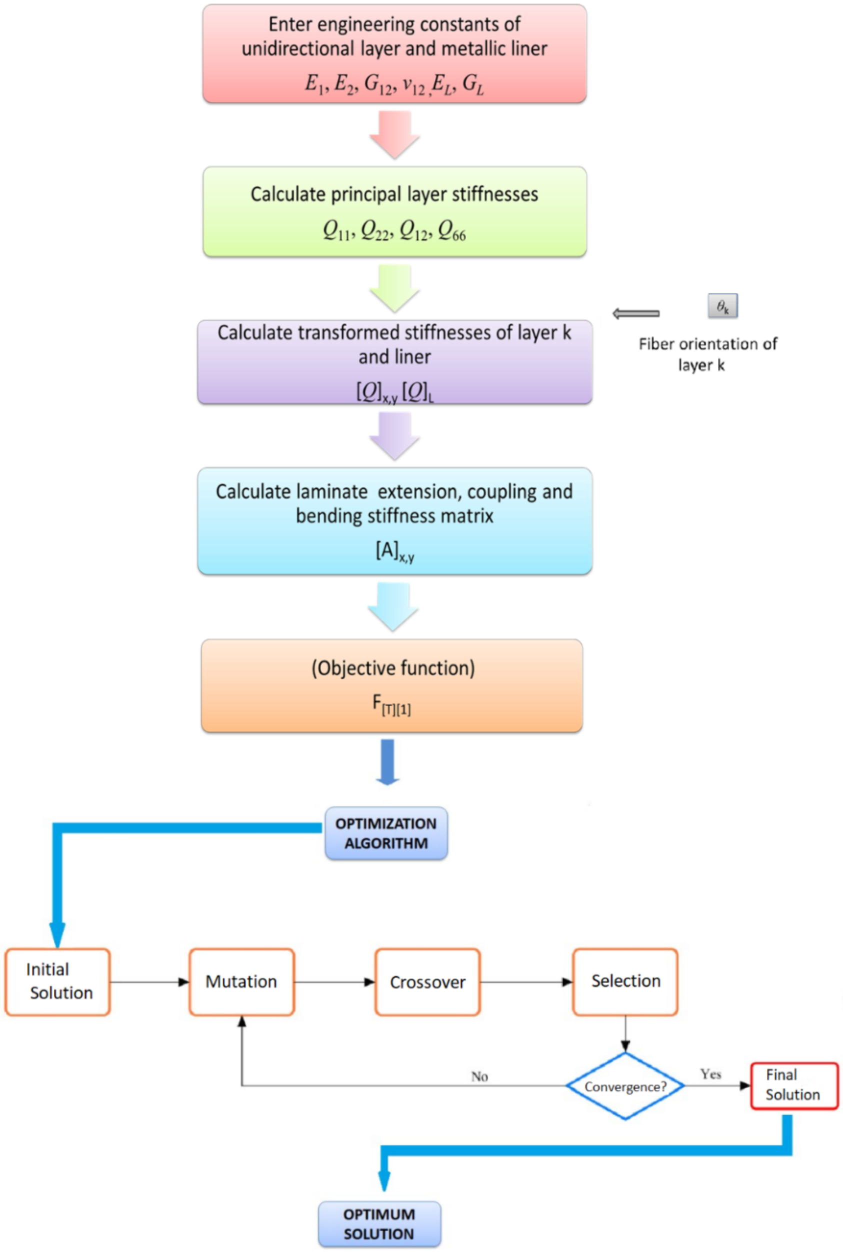

Fig. 2 Optimization process of the Type III Hydrogen Storage Tank

Problem 2:

Table 8 shows comparison results of the calculated burst pressure values that satisfy Tsai-Wu failure criterion constraint with the experimental and Finite Element analysis results. It can be seen that good agreement is reached between the experimental and Tsai-Wu burst pressure values with the error of 15%. Additionally, burst pressure values calculated by using Maximum Stress and Hashin-Rotem failure criterion have predicted with the maximum error of 30 %. It should be noted that the predicted results in the manuscript is based on first ply failure theories. Therefore, progressive failure approach would produce more accurate results.

Table 8 Comparison of the burst pressure for Problem 2

	First Ply Failure				
	Tsai-Wu [Present Study]	Maximum Stress [Present Study]	Hashin-Rotem [Present Study]	Finite Element [15]	Experimental [15]
Burst Pressure (MPa)	90	70	70	99.8	106

It is seen that the predictions made here are based on the first ply failure criteria, however, the progressive failure approach should be used in order to obtain the final ply failure burst pressure. It should also be noted that the use of first ply failure approach provide safer designs during the optimization procedure.

Problem 3:

The optimization problem given above has been solved for different three Carbon/Epoxy materials. After the solution of the optimization problems, three different stacking sequences design of Type III pressure vessel having burst pressure over the 35 MPa have been reached (see Table 9). According the results:

(i) it is seen that obtaining distinct designs having total thickness satisfying over 35 MPa burst pressure are possible.

(ii) All of the designs have symmetric, balanced and integer fiber orientation angles, therefore, it provides easy manufacturable productions.

Table 9 Optimization results of the Problem 3 for different Carbon/ Epoxy composites

Design Cases	Material	Ply Thickness (mm)	Stacking Sequences	Ply No	Total Thickness (mm)
a	Carbon/Epoxy (T700)	0.42	$[90_2/\mp60/\pm45/\mp45/\mp45/\pm45/\pm45]_s$	28	11.76
b	Carbon/Epoxy (T700s)	0.127	$[90_2/\mp30/90_2/\pm60/\pm30/90_4/\pm45/\pm45/\pm60/\mp30/\pm30/90_4/\pm45/\pm30/90_4/\mp45/\mp45]_s$	80	10.16
c	Carbon/Epoxy (IM6/SC1081)	0.127	$[90_2/\pm30/\mp75/\pm60/\pm60/\pm30/\pm45/90_4/\pm30/\pm 60/\pm45/\mp45/\pm30/90_2/\pm30/\mp45/\mp30/90_2/\pm45/$	112	14.224

$\mp 45/\pm 30/90_4/\mp 75/\mp 45/90_2]_s$

The results of the present study can be summarized as;

(i) A manufacturable Type III pressure vessel designs have been proposed for different materials.
(ii) Even for the same materials, different mechanical properties have significantly changed the design. Additionally, small differences on thickness of the ply and mechanical properties have been found to be important for the same material types.

5. Conclusion

In this study, the failure analysis and the optimum designs of composite hydrogen storage tanks have been investigated. The optimizations have been carried out for different Aluminum-Carbon/Epoxy (Type III) materials. The number of plies and fiber orientation angles of the laminated composites are taken as design variables. Single-objective optimization approach has been selected for design and mathematical verification of model problems. The burst pressure calculations for Type III hydrogen storage tanks have been compared with the experimental and Finite Element Method results from the literature. It can be seen that good agreement is reached between them with the maximum error of 10%. Even for the three Carbon/Epoxy materials in close proximity to each other, design and optimization results have crucially changed. It can be concluded that the generalization for optimum stacking sequences of Carbon/ Epoxy materials should be avoided.

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