Simultaneous optimization of composite structures considering mechanical performance and manufacturing cost

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Abstract

A multi-objective optimization methodology is proposed which simultaneously considers the mechanical performance and the manufacturing cost from the early stage of design of composite laminated plates. Resin transfer molding process is chosen as the manufacturing process for its wide acceptance among industries. Interrelations between the structural parameters and the process parameters are identified. With proper assumptions, the multi-objective problem is formulated into a problem with a single objective function. As design variables, the stacking sequence of layers is investigated which minimizes the maximum displacement and the mold filling time. Injection gate location is also considered in order to minimize the mold filling time for a given structure geometry, material properties and loading condition. The genetic algorithm is adopted as the optimization scheme. The results from the sample problems illustrate usefulness of the developed methodology.

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1. Introduction

Composite materials have been successfully replacing the conventional materials in many structural applications. Major virtues of composite materials include higher specific strength and stiffness, better corrosion and wear resistance among many other things. In the past, performance and weight savings have historically been the key drivers behind the adoption of composites for the aircraft structures. However, as the competition among aerospace industries is becoming ever steep, composite structures are required to match the cost level of their metal counterparts [1,2]. On the other hand, reinforced plastics are estimated to make up 10% of the weight of modern automobiles and this share is gradually increasing. Light weight at reduced cost continues to be the top of the list of challenges facing automotive engineers [3].

Due to its cost effectiveness, resin transfer molding (RTM) process has become attractive as an alternative fabrication technique replacing conventional process methods such as autoclave molding [4,5]. In some aerospace applications, RTM has been demonstrated to be able to make the reduction in manufacturing cost up to 60% [6].

In order to enhance the mechanical performance of final parts, tailoring fiber preform architecture, i.e. to decide fiber volume fraction and fiber orientation angle, is crucial. The fiber preform architecture also affects the fill time during the mold filling stage during RTM process and hence is a key factor to productivity. Generally, many structural parameters are strongly coupled with process parameters in the design and manufacture of composite structures, and both groups of parameters affect each other [7]. In fact, many design variables can be classified as structural variables as well as process variables at the same time. In the conventional design and manufacturing routine, it is a common practice for the designers to optimize the process configuration only after the structural design is decided. This procedure, however, may require excessively high manufacturing cost or labor even if it may lead to the best structural performance. Once the designer determines the structural
configuration, the process cannot be optimized any further since some of the variables for the processing are already evaluated during the structural optimization. For example, it is acknowledged that up to 80% of the manufacturing cost of a structure is fixed once the preliminary configuration has been finalized by structural design [2]. Therefore, process optimization is applied only for the remaining variables and hence the room for cost saving may become limited. This dilemma calls for an optimization method which simultaneously considers structural performance and manufacturing cost. In some cases, the benefits of this method may be offset by the inevitable loss in structural performance. Nevertheless, by offering significantly reduced manufacturing costs with tolerable loss in the mechanical performance, this method can be regarded as an attractive alternative in line with the recent design trend which emphasizes the reduction of manufacturing cost.

In this study, an optimization methodology is suggested to consider the structural and the process criteria at the same time. First, mathematical models for structural and process analyses are introduced and the interrelations between the parameters are investigated. Optimization procedures are proposed using the genetic algorithm. A sample problem is solved and the corresponding results are presented. Validity of the simultaneous optimization methodology is verified by comparing the current results with those by the conventional separate optimization procedure.

2. Problem statement

In this study, composite plate with uniform thickness is selected as the design object and RTM process is chosen as the manufacturing process (Fig. 1). It is assumed that the unidirectional fiber mats are laid up to construct the fiber preform and the fiber volume fraction is uniform throughout the composite plate. Structural design objective is to minimize the maximum displacement under the given loading and supporting conditions. Minimization of the mold filling time is taken as the process objective. In order to optimize the design and process objectives simultaneously, the stacking sequence of layers and the injection gate locations are considered as design variables.

3. Mathematical models for the analysis

To establish the optimization procedure, models for structural analysis and mold filling analysis are introduced. Structural analysis is performed with the finite element method. For the mold filling analysis, the semi-analytic model as well as the finite element method is employed.

3.1. Structural analysis model

Elastic moduli of the composites can be derived from the moduli of the fiber and the matrix by Halpin-Tsai equations [8].

\[
E_1 = E_f V_f + E_m V_m
\]

\[
v_{12} = v_f V_f + v_m V_m
\]

\[
\frac{M_c}{M_m} = 1 + \frac{\xi V_f}{1 - \eta V_f} \quad \text{and} \quad \eta = \frac{(M_f/M_m) - 1}{(M_f/M_m) + \xi}
\]

where \(E, G, v\) are the elastic modulus, the shear modulus and the Poisson’s ratio, respectively. \(M\) represents either \(E_2, G_{12},\) or \(v_{23}\). Subscripts c, f and m denote composite, fiber and matrix, respectively. \(V_f\) is the fiber volume fraction. \(\xi = 2\) for calculation for \(E_2\) and 1 for calculation for \(G_{12}\).

Displacement under the given loading and supporting conditions is calculated by a finite element program, FEAD-LASP [9]. FEAD-LASP uses a mesh system of 16 serendip elements, each with 16 nodes. To estimate the maximum displacement, the displacement of each node is obtained by calculating the square norm of the displacements in the x, y and z directions and the maximum value is selected among them.

\[
d = \text{MaxNode}\left(\sqrt{d_x^2 + d_y^2 + d_z^2}\right)
\]

3.2. Mold filling analysis model

The resin flow in the RTM process can be regarded as the flow through porous media, following Darcy’s law. Darcy’s law relates the fluid flow to the pressure gradient, using the fluid viscosity and the permeability of the porous medium [10].

\[
\bar{v} = -\frac{K}{\mu} \nabla P
\]

where \(\bar{v}\) is the superficial velocity (velocity observed on a macroscopic scale) and \(\mu\) is the fluid viscosity. \(\nabla P\) and \(K\)
denote the pressure gradient and the permeability tensor of the porous medium, respectively.

Permeability can be related to the fiber volume fraction \( V_f \) by Kozeny–Carman equation [11,12].

\[
K_{ij} = \frac{1}{k_0} \frac{R_i^2}{4} \frac{(1 - V_f)^3}{V_f^2} \quad \text{(6)}
\]

where \( k_0 \) is the Kozeny constant and \( R_i \) is the radius of fiber.

The components of the permeability tensor can be related to the principal permeabilities \( K_{xx} \) and \( K_{yy} \) by

\[
\begin{pmatrix}
K_{x'x'} & K_{x'y'} \\
K_{y'x'} & K_{y'y'}
\end{pmatrix} = \begin{pmatrix}
K_{xx} \cos^2 \theta + K_{yy} \sin^2 \theta & (K_{xx} + K_{yy}) \sin \theta \cos \theta \\
(-(K_{xx} + K_{yy}) \sin \theta \cos \theta) & K_{xx} \sin^2 \theta + K_{yy} \cos^2 \theta
\end{pmatrix}
\]

where \( x'-y' \) is the coordinate system in which the permeability tensor is evaluated, and \( \theta \) is the angle between the \( x'-y' \) coordinate and the principal direction \( x-y \).

Preform consists of a number of layers of unidirectional fiber mats stacked in different orientations. The gapwise averaged permeability components \( K_{ij} \) for a preform of \( n \) layers with different thicknesses and permeability is given by [14]

\[
\bar{K}_{ij} = \frac{1}{H} \sum_{l=0}^{n} h_l K_{ij}^l \quad \text{(8)}
\]

where \( h_l \) and \( K_{ij}^l \) are the thickness and the permeability of the \( l \)th layer and \( H \) is the total thickness of the preform. This model neglects through-thickness flow effect since it was derived from saturated flow analysis in which the through-thickness flow is not expected.

Once the permeabilities are known, the pressure distribution can be obtained by solving the following equation [15]:

\[
\nabla \cdot \left( \frac{K}{\mu} \nabla P \right) = 0 \quad \text{(9)}
\]

\( P_{\text{inlet}} = P_0 \) at the injection gate, \( \frac{\partial P}{\partial n} |_{\text{wall}} = 0 \) at the mold wall, \( P_{\text{front}} = 0 \) on the flow front region.

Velocity distribution can be estimated from the pressure distribution using Darcy’s law (Eq. (5)).

During the RTM mold filling process, the computation domain changes continuously with time. In the current investigation, this moving boundary problem is handled by the control volume method along with the volume of fluid concept [16]. To solve the governing equation, the control volume finite element method is applied [17]. A numerical mesh system with 153 nodes and 256 triangular elements is used.

In the optimization procedure, many function evaluations may be required in seeking the optimal value. For mold filling time evaluation, numerical method such as the finite element method can provide rather accurate results. Even though numerical method comes handy for complex mold geometry and yields precise results, the computational cost may become prohibitively high to be used for optimization purpose. In this case, a simple semi-analytic model developed by Boccard et al. can be used [18]. This model had been developed to determine the fill time of the mold containing thin flat preforms with isotropic permeabilities. In this method, the time required to fill the mold can be calculated by treating the resin flow inside the mold as partly radial and partly channel-like flows. The mold is completely filled when the resin front reaches the vent which is the farthest from the injection gate. The maximum distance is denoted by \( r_{\text{max}} \). For the radial flow, the time required for the resin to travel the distance \( r_{\text{max}} \) is

\[
t_{\text{fill}}^R = M \left( \frac{r_{\text{max}}}{R_0} \right)^2 \left[ 2 \ln \left( \frac{r_{\text{max}}}{R_0} \right) + \left( \frac{R_0}{r_{\text{max}}} \right)^2 - 1 \right] \quad \text{(10)}
\]

\[
M = \frac{\mu (1 - V_f) R_0^2}{4 K_{\text{iso}} P_0} \quad \text{(11)}
\]

where \( R_0 \) is radius of the inlet port, \( K_{\text{iso}} \) is permeability of isotropic preform and \( P_0 \) is injection pressure. For the channel-like flow, time for the resin front to travel the distance \( r_{\text{max}} \) is

\[
t_{\text{fill}}^C = 2M \left[ \left( \frac{r_{\text{max}}}{R_0} \right)^2 - 1 \right]^2 \quad \text{(12)}
\]

Actual flow is taken to be a combination of the radial and the channel-like flows.

\[
t_{\text{fill}} = x t_{\text{fill}}^R + (1 - x) t_{\text{fill}}^C \quad \text{(13)}
\]

where \( x \) is a constant determined by the ratio between the channel-like flow and the radial flow [18]. If there are several injection gates, the preform can be divided into subdomains and the maximum distance \( r_{\text{max}} \) is determined for each subdomain. The parameter \( x \) and the fill time \( t_{\text{fill}} \) are calculated for each subdomain. The maximum value of \( t_{\text{fill}} \) among the subdomains is the fill time. This semi-analytic model for two-dimensional preforms

![Fig. 2. Coordinate transformation of permeability between isotropic and anisotropic preform.](image-url)
with isotropic permeability can be applied to the preforms with anisotropic permeability through the coordinate transformation (Fig. 2). First, principal permeabilities $K_{xx}$, $K_{yy}$ are obtained from the permeabilities $K_{xx}$, $K_{yy}$, $K_{xy}$ in the global coordinates with Eq. (7). Isotropic permeability $K_{iso}$ can be obtained from principal permeabilities as [19]

$$K_{iso} = \sqrt{K_{xx} \times K_{yy}}$$

(14)

Then $x$ and $y$ coordinates are rotated in the principal directions and $x$ and $y$ coordinates can be extended or contracted as [19]

$$X = x \times \frac{K_{iso}}{K_{11}}$$

(15-1)

$$Y = y \times \frac{K_{iso}}{K_{22}}$$

(15-2)

Finally, coordinates $x$ and $y$ are rotated from the principal coordinate system back to the global coordinate system. This model provides a computational efficiency for the mold filling time estimation and hence is used for injection gate location optimization in this study. Once the optimal injection gate location for a given stacking sequence of layers is decided with this model, more accurate mold filling time can be obtained by the numerical simulation.

### 4. Optimization procedure

Several types of problems are studied. The number of injection gates considered is either one or two while the number of layers is either seven or eight. Layer angles are given from a set of preassigned values. For a two-angle set, 0°, and 90° are used; for a four-angle set, 0, 45°, 90°, and −45° are used.

Two design objectives, namely the minimum displacement (maximum stiffness) and the minimum mold filling time are considered. It is assumed here that the stiffness of the final product is influenced by the stacking sequence of layers and the mold filling time depends on the stacking sequence of layers as well as the location of resin injection gates. Therefore, as the design variables, the stacking sequence of layers and the locations of resin injection gates are selected. It is noted that the permeability of fiber preform changes for different stacking sequence of layers. As a consequence, once the stacking sequence of layers is given, the optimal gate location for that specific stacking sequence can be decided.

#### 4.1. Simultaneous optimization

As previously explained, it is a common practice in composites design to optimize the process configuration only after deciding structural configuration. Here, this conventional optimization methodology is referred to as the separate optimization. On the other hand, an optimization methodology that takes into account the manufacturing process at early stage of design is called the simultaneous optimization.

When the separate optimization procedure is adopted, the stacking sequence of layers is optimized in order to maximize the stiffness or to minimize the displacement of the structure. Then, for the obtained layer angle configuration and the given geometry of the structure, the optimal gate location is decided in order to minimize the mold filling time. However, the simultaneous optimization methodology needs a different approach in order to consider the stiffness criterion and the mold filling time criterion at the same time from the early stage of the design.

Two design objectives, i.e. enhancement of mechanical performances and reduction of mold filling time, are formulated into a single-objective function as follows. To maximize stiffness, the maximum displacement of the structure under the loading condition (see Eq. (4)) should be reduced. Minimization of mold filling time is considered as a process criterion. In the present study, the penalty function formulation is adopted instead of weighted sum formulation [20]. The objective function is formulated as

$$f(x_i) = \frac{1}{d} \left(1 + \Gamma \frac{t_c}{t} \right)$$

(16)

where $x_i$ is the design vector, $d$ is the maximum displacement and $t$ is the mold filling time. $\Gamma$ is the penalty parameter and $t_c$ is critical mold filling time which serves as a scaling parameter for mold filling time. Note that the minimization problem is converted into a maximization problem for convenience. The penalty parameter $\Gamma$ represents how much emphasis would be placed on the mold filling time criterion. $\Gamma$ is set to unity for simultaneous optimization and zero for separate optimization. The critical mold filling time should be specified by the designer.

In order to maximize the objective function, two design variables, i.e. the stacking sequence of layers and the injection gate location, need to be optimized. In the case of one injection gate, the optimal gate location can be decided regardless of the stacking sequence of layers for the rectangular mold geometry used in this study. For the rectangular mold, the optimal injection gate location that minimizes the maximum distance from the injection port to the vent $r_{max}$ is always coincides with the geometric center of the structure. However, when multiple injection ports are used, the optimal gate locations are coupled with stacking sequence of layers as well as mold geometry, since the optimal injection gate locations that minimize the maximum distance $r_{max}$ vary with the anisotropic permeability.
In the case of one gate injection, the optimal injection gate location is independent of stacking sequence of layers for a given mold geometry if the permeability of the fiber preform and the thickness of the mold are uniform. Hence, an optimal gate location to minimize the mold filling time can be decided first with a semi-analytic model for the mold filling time estimation outlined in the previous section. Then, the optimal stacking sequence of the layers is decided to minimize the maximum displacement of the structure under the given loading and supporting conditions and to minimize the mold filling time.

In the case of two gate injection, the optimal gate location is affected by the stacking sequence of the layers as well as by the mold geometry. For this reason, the optimal gate location and the stacking sequence of layers to enhance the mechanical performance of the structure and to minimize the mold filling time should be decided at the same time. For a given stacking sequence of layers, the permeability of fiber preform is estimated (Eqs. (7) and (8)). Then, all the candidates for injection gate location, which are actually the nodes used in the finite element mesh, are tested and the best one is selected as an optimal injection gate location. As was stated previously, the semi-analytic model for mold filling time estimation (Eqs. (10)–(13)) is employed to determine the optimal gate location for each stacking sequence of layers. Optimal injection gate locations are illustrated in Fig. 3 for different stacking sequences of layers. Since the injection gate location can be uniquely decided for a given stacking sequence, only the stacking sequence of layers is explicitly treated as the design variable. This procedure is summarized in Fig. 4.

### 4.2. Genetic algorithm

The genetic algorithm is adopted as the optimization scheme [21]. The stacking sequence of the layers is taken as the design variable. In this study, two kinds of pre-assigned angle sets are considered, namely the two-angle set \{0, 90\} and the four-angle set \{0, 45, 90, –45\}.

The stacking sequence of layers is encoded as a string filled with natural numbers. For the two-angle set, 0° corresponds to 0 and 90° to 1. Thus a stacking sequence of six layers [0 90 0 90 0 90] was encoded as [0 1 0 0 1 0]. Similarly is the four-angle set 0°, 45°, 90°, –45° correspond to 0, 1, 2, 3, respectively. For example, a stacking sequence of layers [0 90 45 –45 90 0] is encoded as [0 2 1 3 2 0].

When the fitter members are selected into a mating pool, the selection pressure is obtained by assigning each member a selection probability equal to \(f_i / \sum^n_{i=1} f_i\), where \(f_i\) is the fitness of each individual and \(n_i\) is the total population size. One site crossover is used for the crossover process.

\[
\begin{align*}
\text{Parent 1} & = 01100010 & (17-1) \\
\text{Parent 2} & = 11011110 & (17-2) \\
\text{Child 1} & = 01100110 & (17-3) \\
\text{Child 2} & = 11011010 & (17-4)
\end{align*}
\]

The process of mutation is to change a natural number in the string at a randomly chosen location on a string. Mutation probability is taken to be inversely proportional to the population size [22]. The best individual of the population is preserved for the next generation without crossover or mutation during the evolution. This elitism strategy prevents the loss of the best individual in the population and improves the efficiency of the genetic search [23].
5. Illustrative example and results

Sample problems are solved to illustrate the effectiveness of the proposed scheme. The loading and supporting conditions and the geometry of the structure are shown in Fig. 5. As can be seen in the figure, a rectangular composite laminated plate (400\(\times\)200 mm\(^2\)) is supported along one side by clamping into the wall. Two different types of loading conditions are considered. In the loading condition A (Fig. 5(a)), linearly distributed load is applied at the edge of the plate opposite to the clamped side. The loading condition B designates one point load applied on the corner of the plate as illustrated in Fig. 5(b). Constituent materials are epoxy resin and unidirectional stitched glass fiber mat. The material properties are provided in Tables 1 and 2. The fiber volume fraction is 0.45 and the thickness of one layer is 1 mm.

The parameters for genetic search are defined as

- Population size: \(n_c = 30\)
- Probability of crossover: \(p_c = 0.9\)
- Probability of mutation: \(p_m = 1/n_c = 0.033\)

A total of 32 cases are considered depending on the loading condition, gate number, layer number, angle-set and optimization method as specified in Table 3. It is noted that the optimization method can be specified according to the penalty parameter \(\Gamma\). The conventional separate optimization methodology corresponds to \(\Gamma = 0\), while the simultaneous optimization procedure is \(\Gamma = 1\).

Optimal stacking sequence of layers and injection gate locations obtained by simultaneous optimization are listed in Tables 4–11 and compared with the results by separate optimization. Corresponding results are

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**Table 1**

<table>
<thead>
<tr>
<th>Properties of glass fiber mat</th>
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<tbody>
<tr>
<td>Density, (\rho_f)</td>
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<tr>
<td>Tensile modulus, (E_f)</td>
</tr>
<tr>
<td>Kozeny constant, (k_{11})</td>
</tr>
<tr>
<td>Shear modulus, (G_f)</td>
</tr>
<tr>
<td>Kozeny constant, (k_{22})</td>
</tr>
<tr>
<td>Poisson’s ratio, (\nu_f)</td>
</tr>
<tr>
<td>Fiber radius, (R_f)</td>
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</tbody>
</table>

**Table 2**

<table>
<thead>
<tr>
<th>Properties of epoxy resin</th>
</tr>
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<tbody>
<tr>
<td>Viscosity, (\mu)</td>
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<tr>
<td>Tensile modulus, (E_m)</td>
</tr>
<tr>
<td>Density, (\rho_m)</td>
</tr>
<tr>
<td>Shear modulus, (G_m)</td>
</tr>
<tr>
<td>Poisson’s ratio, (\nu_m)</td>
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illustrated in Figs. 6–13. In these figures, each design objective shown in the ordinate is non-dimensionalized. Displacement is non-dimensionalized by dividing with the critical displacement specified as 10 mm. Mold filling time is non-dimensionalized in a similar manner using the arbitrarily chosen critical values, i.e. 500 s for one gate injection and 250 s for two gate injection.

When the conventional separate optimization procedure is employed for the loading condition A, optimal stacking sequence of layers for two-angle set is identical

| Table 3 |
| Classification of problems |
| Case index | Loading condition | Number of gates | Number of layers | Angle-set | Penalty parameter, $\Gamma$ |
| As720 | A | 1 (single gate) | 7 | 2 | 0 |
| As721 | | | | | 1 |
| As740 | | | | | 4 |
| As741 | | | | | 1 |
| As820 | | | | | 8 |
| As821 | | | | | 2 |
| As840 | | | | | 4 |
| As841 | | | | | 1 |
| Ad720 | | 2 (double gates) | 7 | 2 | 0 |
| Ad721 | | | | | 1 |
| Ad740 | | | | | 4 |
| Ad741 | | | | | 1 |
| Ad820 | | | | | 8 |
| Ad821 | | | | | 2 |
| Ad840 | | | | | 4 |
| Ad841 | | | | | 1 |
| Bs720 | B | 1 (single gate) | 7 | 2 | 0 |
| Bs721 | | | | | 1 |
| Bs740 | | | | | 4 |
| Bs741 | | | | | 1 |
| Bs820 | | | | | 8 |
| Bs821 | | | | | 2 |
| Bs840 | | | | | 4 |
| Bs841 | | | | | 1 |
| Bd720 | | 2 (double gates) | 7 | 2 | 0 |
| Bd721 | | | | | 1 |
| Bd740 | | | | | 4 |
| Bd741 | | | | | 1 |
| Bd820 | | | | | 8 |
| Bd821 | | | | | 2 |
| Bd840 | | | | | 4 |
| Bd841 | | | | | 1 |

| Table 4 |
| Results of sample problem (loading condition A, one injection gate, seven layers) |
| Case index | Penalty parameter | Angle-set | Gate location $(x, y)$ | Stacking sequence |
| As72e | 0 | 2 | (L/2, H/2) | 90 |
| As72i | 1 | 2 | (L/2, H/2) | 90 90 0 0 0 9 0 9 0 |
| As74e | 0 | 4 | (L/2, H/2) | 90 |
| As74i | 1 | 4 | (L/2, H/2) | 90 90 0 0 0 9 0 9 0 |

| Table 5 |
| Results of sample problem (loading condition A, one injection gate, eight layers) |
| Case index | Penalty parameter | Angle-set | Gate location $(x, y)$ | Stacking sequence |
| As82e | 0 | 2 | (L/2, H/2) | 90 |
| As82i | 1 | 2 | (L/2, H/2) | 90 90 0 0 0 9 0 9 0 |
| As84e | 0 | 4 | (L/2, H/2) | 90 |
| As84i | 1 | 4 | (L/2, H/2) | 90 90 0 0 0 9 0 9 0 |
with that for four-angle set. It is apparent that the optimal stacking sequence to maximize the stiffness is \[90^\circ\] for the given loading condition \(A\), since the structure undergoes the deflection in the direction of \(90^\circ\). In the case of one injection gate, the optimal injection gate is at the center of the mold, i.e. \((x = L/2, y = H/2)\). In the case of two injection gates, the optimal injection gates are located at \((x = L/4, y = H/2)\) and \((x = 3L/4, y = H/2)\) for both the two-angle set and the four-angle set. Here, \(x-y\) coordinate is defined in Fig. 5.

Consider the results for one injection gate and seven layers presented in Table 4 and Fig. 6. The stacking sequences are tabulated in Tables 6-11.
Fig. 6. Results of sample problem for one injection gate and seven layers under loading condition A (Fig. 5(a)). Displacement and mold filling time are non-dimensionalized by dividing their critical value, \( d_c = 10 \text{ mm}, t_c = 500 \text{ s} \), respectively.

Fig. 7. Results of sample problem for one injection gate and eight layers under loading condition A (Fig. 5(a)). Displacement and mold filling time are non-dimensionalized by dividing their critical value, \( d_c = 10 \text{ mm}, t_c = 500 \text{ s} \), respectively.

Fig. 8. Results of sample problem for two injection gates and seven layers under loading condition A (Fig. 5(a)). Displacement and mold filling time are non-dimensionalized by dividing their critical value, \( d_c = 10 \text{ mm}, t_c = 250 \text{ s} \), respectively.

Fig. 9. Results of sample problem for two injection gates and eight layers under loading condition A (Fig. 5(a)). Displacement and mold filling time are non-dimensionalized by dividing their critical value, \( d_c = 10 \text{ mm}, t_c = 250 \text{ s} \), respectively.
Fig. 10. Results of sample problem for one injection gate and seven layers under loading condition B (Fig. 5(b)). Displacement and mold filling time are non-dimensionalized by dividing their critical value, $d_c = 10$ mm, $t_c = 500$ s, respectively.

Fig. 12. Results of sample problem for two injection gate and seven layers under loading condition B (Fig. 5(b)). Displacement and mold filling time are non-dimensionalized by dividing their critical value, $d_c = 10$ mm, $t_c = 250$ s, respectively.

Fig. 11. Results of sample problem for one injection gate and eight layers under loading condition B (Fig. 5(b)). Displacement and mold filling time are non-dimensionalized by dividing their critical value, $d_c = 10$ mm, $t_c = 500$ s, respectively.

Fig. 13. Results of sample problem for two injection gate and eight layers under loading condition B (Fig. 5(b)). Displacement and mold filling time are non-dimensionalized by dividing their critical value, $d_c = 10$ mm, $t_c = 250$ s, respectively.
sequence of layers obtained by the conventional separate optimization procedure leads to an excessively long mold filling time. However, when the simultaneous optimization methodology is adopted, the layers with 0° orientation angle replace the inner layers which have lesser influence on the bending stiffness than the outer layers to achieve a better permeability for the less mold filling time. Hence mold filling time is reduced by a factor of 10 with only marginal sacrifice of the stiffness. We can see the similar results in the case of eight layers presented in Table 5 and Fig. 7.

For two injection gates, an excessively long mold filling time is inevitable even though the injection gate locations are optimized for the given stacking sequence of layers obtained by the conventional separate optimization procedure. However, as shown in Figs. 8 and 9, the mold filling time can be greatly saved with a slight loss in the mechanical performance through the simultaneous optimization methodology.

For the loading condition B, the advantage of simultaneous optimization over conventional separate optimization procedure can be verified again (Figs. 10–13). It can be seen that the optimal injection gate locations change according to the optimal stacking sequence of layers. In general, the results with four-angle set show a better performance than those with two-angle set because of larger design space.

6. Conclusions

In the present study, a methodology to simultaneously optimize the structural and process parameters for designing and manufacturing composite plate by RTM is presented. The stacking sequence of layers and the location of injection gates are optimized to minimize the maximum displacement and the mold filling time for the specified geometry with uniform thickness, material properties and applied loading condition. While the conventional separate optimization procedure often leads to an excessively high manufacturing cost, the simultaneous optimization methodology can avoid high manufacturing cost with a slight loss in the mechanical performance. In the case of the multi-objective optimization problem, it is noted that the designer should decide how much emphasis will be placed on each objective by modulating the penalty parameter \( \Gamma \), in the objective function defined in Eq. (16).

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