

Investigation of product quality monitoring in the compression molding process of carbon fibre reinforced composite laminates

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ABSTRACT

In the realm of compression molding of Carbon Fibre Reinforced Composite (CFRC) laminates, pivotal technological challenges related to product quality monitoring are addressed in this study, a multi-source information fusion method based on monitoring feedback is proposed. The study begins with the design of a control system, alongside the establishment of its software and hardware architecture, all of which are rooted in the production line's composition, its processes, and the overarching manufacturing workflow. This paves the way for the refinement and optimization of reliability assessment methods, specifically tailored for monitoring factors and characteristics with functionalization at their core. Then, a higher-order shear deformation theory (HSDT) is proposed based on Iso-Geometric Analysis (IGA), and the static bending, free vibration, and buckling behaviours of CFRC laminates are scrutinized. The narrative culminates under the influence of fluctuating temperature conditions, where the proposed methodology's performance and precision are rigorously validated through an extensive suite of numerical examples. A comparative analysis with theoretical results gleaned from existing literatures yields a harmonious consistency, underscoring the robustness of the approach. The research results of this paper provide theoretical support for the quality analysis of carbon fiber reinforced composite molding process.

Keywords: Compression molding; Carbon Fibre Reinforced Composite (CFRC) laminates; Multi-source information fusion; Higher-Order Shear Deformation Theory (HSDT); Product quality monitoring.

1. INTRODUCTION

Dubbed as the “king of new materials in the 21st century,” carbon fibre has shown broad application prospects in the field of composite materials. CFRC materials, noted for their high specific strength, high specific modulus, fatigue resistance, excellent damage tolerance, and versatile designability [1–3] are deemed ideal materials for achieving lightweight objectives. Lightweighting is a crucial developmental trajectory across various industrial sectors, promising substantial reductions in energy consumption, alleviation of environmental pollution, enhancement of economic benefits, and bolstering competitiveness. Consequently, an exponential growth in demand for the rapid, cost-effective manufacturing and application of CFRC materials has been observed across industries [4].

Compression molding technology, characterized by its low cost, high production efficiency, and excellent mechanical stability and product repeatability, dominates in the manufacturing of CFRC material components [5]. The compression molding manufacturing technique of CFRC laminates, renowned for its reliable performance and straightforward process, has found widespread application in aerospace, automotive, and other industries. However, challenges persist in the form of complex procedures, prolonged mold replacement cycles, and the occurrence of defects such as voids and resin-rich areas, leading to inconsistent product quality. The causative factors for these issues are numerous and intricate, necessitating the implementation of quality monitoring during the compression molding process of CFRC materials to enhance product quality.

In light of these challenges, substantial theoretical analysis and experimental research have been conducted both domestically and internationally, yielding a wealth of findings. These studies provide a theoretical foundation and practical references for further improvement of the compression molding manufacturing process of CFRC materials [6, 7]. Research conducted by NEZAMI *et al.* [8] has indicated that the use of caul plates during the hot press forming process of composite materials can effectively prevent fibre wrinkling defects. Comparisons were made between different layup angles and the usage of edge constraints on the quality of hot-pressed braided composite materials, revealing that interlaminar forces are the principal factors affecting hot press quality. HALLANDER *et al.* [9] focused on the hot press forming of unidirectional prepreg tapes in concave grooves, identifying wrinkles as the primary defect in the hot press forming process. The friction coefficient and layup angle were found to be significant factors influencing wrinkle defects, with increased pressure noted to reduce these defects. DAI *et al.* [10] utilized the orthogonal experimental method to prepare CF/PEEK composite laminates, analyzing the effects of molding pressure, molding temperature, and cooling time on laminate properties. Molding temperature was identified as the most crucial factor affecting the transverse tensile strength of the composite material, while molding pressure was deemed to have a minor impact. BOISSE *et al.* [11], HOSSEINI *et al.* [12], and others compared the effects of tensile, bending stiffness, and in-plane shear behaviour during the hot press forming of braided composite materials on wrinkle defects, concluding that in-plane shear is the main cause of wrinkles. Hongfu LI *et al.* [13] independently developed a unidirectional carbon fibre reinforced nylon-6 composite material with a width of 60mm and applied rapid hot press forming technology to mold it into a composite rectangular box. Their findings underscored the significant impact of pre-consolidation on molding quality.

Building upon these existing studies, this paper focuses on the control system scheme for the compression molding of CFRP laminates, taking into consideration the changes in material properties, temperature, strain displacement relationships, and potential energy during the molding process [14–16]. In conjunction with NURBS basis functions, a method based on IGA and HSDT is proposed, aiming to design a multi-source information fusion method based on visual information and monitoring feedback, to realize the whole life cycle quality inspection and process optimization of molded products [17, 18]. Through intelligent flexible control, the automation level of the molding production line is improved to ensure the stability and consistency of the products in the molding process. The research results of this paper not only enrich the technical path of product quality detection in the molding process of carbon fiber reinforced composites, but also provide theoretical support for the quality analysis of molding process. It is of great significance to promote the application of carbon fiber composite molding technology in aerospace and automotive fields.

2. DESIGN OF THE MOLDING CONTROL SYSTEM FOR CFRP LAMINATES

A profound understanding of the CFRP laminated plate molding process [19, 20] constitutes the foundational premise for the design of the control system. Based on this process, the layout of the production line is devised. Subsequently, the hardware and software systems for molding control are designed. To achieve online monitoring of CFRP laminated plates, the design of the molding monitoring system is undertaken.

2.1. Molding procedures of CFRP

In the design of the production line for CFRP laminates, it is imperative to exert precise control over the logic, sequence, and states of various processing and handling units under the principles of reliability, economy, and rationality [21]. Time allocation between procedures must be judiciously arranged to ensure orderly and coordinated operation, thereby enhancing production efficiency. Furthermore, real-time online monitoring of the manufacturing process through the monitoring interface is conducted to preemptively alert against potential hazards or critical conditions. Features such as fault alarms and emergency stops are integrated to guarantee safe and reliable operation of the production line. The sequence of the production process is illustrated in Figure 1.

Corresponding to the production sequence diagram of Figure 1, the intelligent production line of carbon fiber molding is established, as shown in Figure 2. The intelligent production line is equipped with a refrigerated cabinet, a cutting machine, a handling robot system, a constant temperature ply room, a quenching and heating equipment, a molding mold, a conveying cooling system and an automatic control system, which realizes the automation and flexibility control of each link.

The intelligent production line uses carbon fiber reinforced prepreg as raw material to process aircraft wing ribs, automobile shell and other products. The processing flow of the intelligent production line is as follows: after the cutting machine uncoils and cuts the prepreg sheet, the robot grabs the material from the cutting machine to the constant temperature room. After manually loading the product layer into the mold core, the supporting six-axis robot puts the product with the mold core into the press for heating and forming twice.

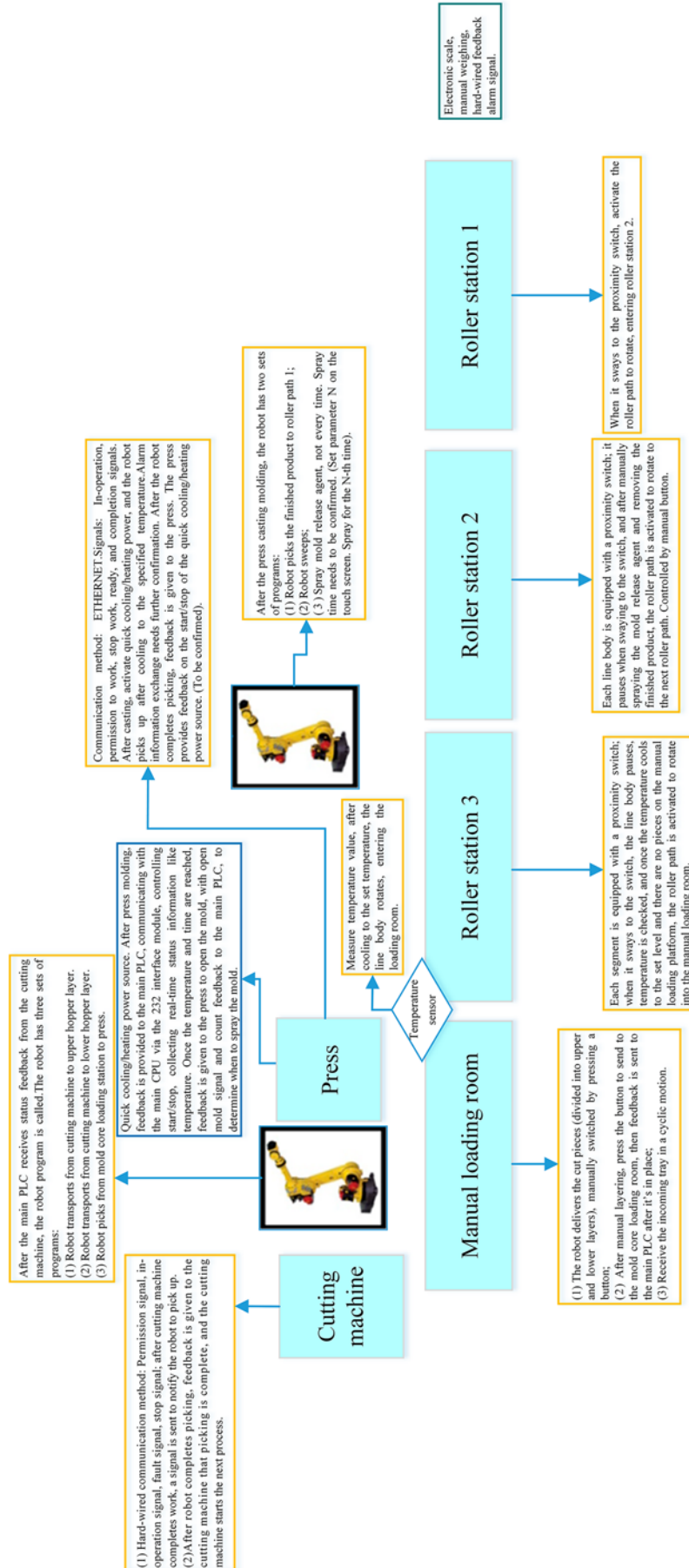


Figure 1: Workflow of the production line.

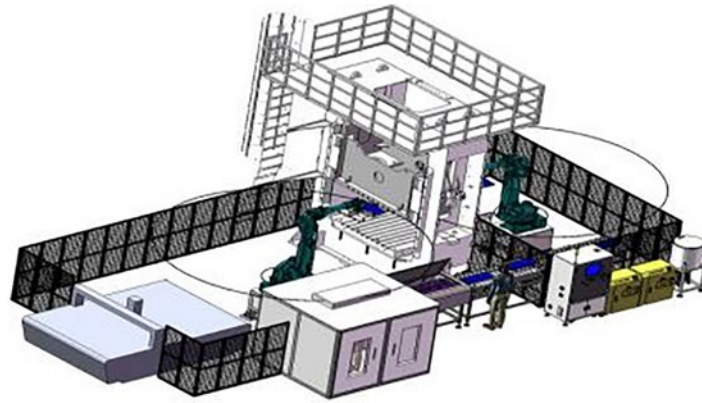


Figure 2: Carbon fiber molding intelligent production line.

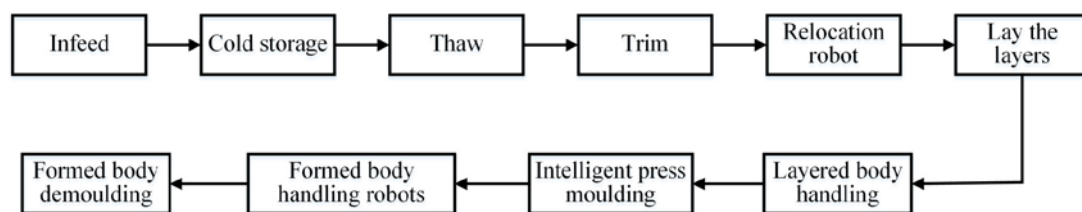


Figure 3: Composite material production line production process diagram.

After forming, another robot takes out the formed product with the mold core from the other side of the press and places it on the conveyor line. The product is manually taken away, and the empty mold core is transported + cooled and automatically sent to the constant temperature room for waiting. After the product is manually loaded, the action is repeated.

The main process of trial production and production of composite materials by integrated whole line equipment is shown in Figure 3.

2.2. Design of control hardware system for molding process of CFRP laminates

The control system of the intelligent production line for molding CFRP laminates comprises the upper computer control system, the lower computer control system, and the communication network. Industrial computers and configuration software make up the upper computer control system, which communicates with the lower computer PLC to automate oversight of the entire production line, ensuring stable and reliable operation. The lower computer utilizes universal PLCs and their peripheral devices to control production and monitor the status of processing and handling units. Issues such as mold release success in the mold changing units and the interfacing between processing units are addressed. Closed-loop control of the production process is realized through CC-Link, enhancing processing effects and energy efficiency. The production line operates in two modes: “automatic control” and “manual control”. Under normal circumstances, automatic control is the primary mode, with manual control having the highest priority to facilitate equipment debugging and promptly shut down equipment in the event of malfunction or issues with automatic control. Communication between each substation PLC and the main PLC is conducted using the TCP/IP protocol, ensuring the orderly operation of all units within the production line.

2.3. Design of control software system for molding process of CFRP laminates

The intelligent production system for CFRP laminates consists of multiple processing and handling units, characterizing the control system with a multitude of input and output signals, monitoring feedback, and execution signals. This constitutes a complex flexible manufacturing control system. A comprehensive analysis primarily considers the allocation of input and output variables of processing and handling units to the I/O ports of the main or substation PLCs under the premise of fulfilling production processes and technology. The

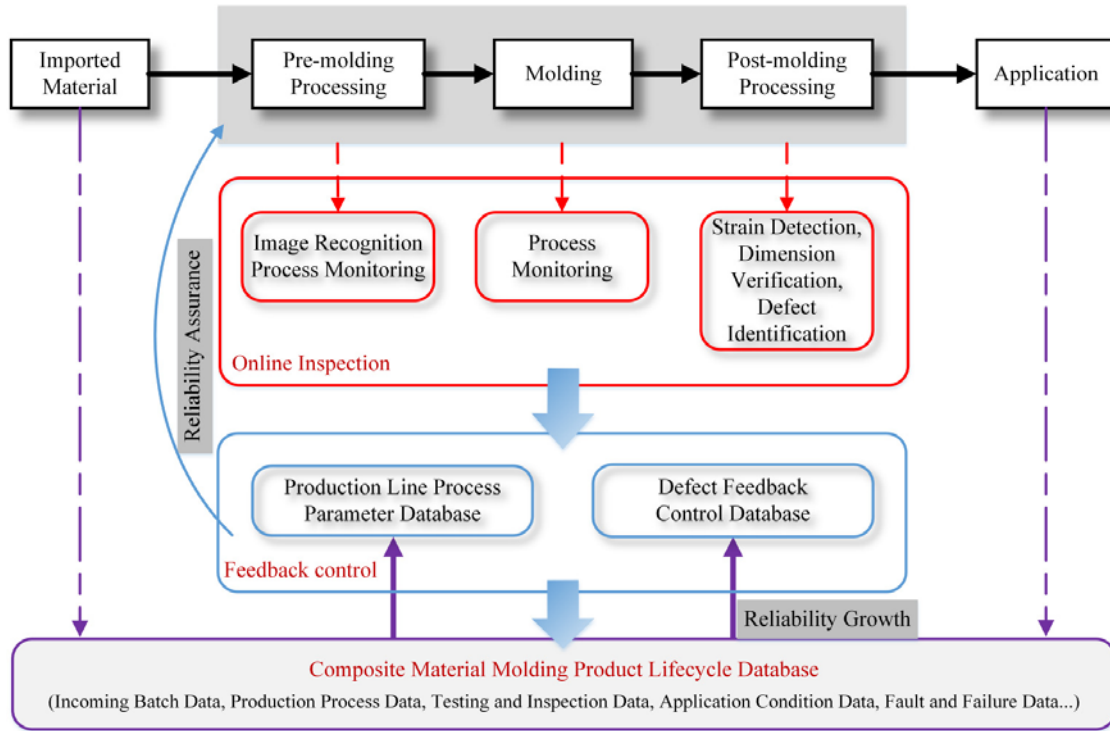


Figure 4: Composition framework of the monitoring system.

definition of the roles of I/O ports is established, and communication between main and substation PLCs is set up accordingly. The PLC programs for the main and substation are modularized based on the operation content, sequence, and production technology of the processing and handling units. Within these modules, the relationships between input and output variables and their respective operations, along with the relevant monitoring and control methods, are determined. Subsequently, a logical integration is performed to complete the program flow design.

2.4. Design of molding process monitoring system for CFRP laminates

To enhance the quality of the molded components of CFRP and reduce the scrap rate during R&D, prototyping, and production, a reliability assurance system for the CFRP molding product line has been established. This is achieved through the construction of an online monitoring system and online production feedback control system, thereby advancing the molding process. The reliability assurance system includes an online production monitoring system and an online production control system. The primary composition framework of the system is illustrated in Figure 4.

3. THE IGA-BASED ON LOGARITHMIC HSDT

3.1. Material properties

The temperature dependency of material properties is considered by expressing the Young's modulus E_e , Poisson's ratio ν_e , thermal expansion coefficient α , and thermal conductivity K of CFRP using a temperature function $P(T)$, as described by equation (1):

$$P(T) = P_{-1}T^{-1} + P_0T^0 + P_1T + P_2T^2. \quad (1)$$

where, T denotes the environmental temperature, $T = T_0 + \Delta t$; T_0 represents room temperature, generally taken as 293K; ΔT signifies the temperature rise only in the thickness direction, namely the temperature gradient; P_0 , P_{-1} , P_1 , P_2 are the unique constants constituting the material.

The effective material properties of the CFRP laminates are homogenized using the Mori-Tanaka scheme, with the relationship between the effective bulk modulus and shear modulus assumed as:

$$\nu_0 = \frac{\nu_m(5K_m + 4\nu_m)}{3(K_m + 2\nu_m)}. \quad (2)$$

The effective values of material properties such as Young's modulus E_e and Poisson's ratio ν_e are calculated through the following formulas:

$$E_e = \frac{10K_e\nu_e}{4K_e + \nu_e}. \quad (3)$$

$$\nu_e = \frac{3K_e - \nu_e}{2(3K_e + \nu_e)}. \quad (4)$$

3.2. Temperature variation

The temperature change includes the temperature change in the z direction of the thickness and the temperature change on the xy plane. In order to improve the monitoring efficiency, it is assumed that the temperature field is constant on the xy plane, and the temperature gradient only occurs in the thickness direction. The temperature change of the entire plate thickness includes linear temperature rise and nonlinear temperature rise.

For the linear temperature rise process, it can be expressed as:

$$T(z) = T_b + \frac{2z + h}{h} \Delta T. \quad (5)$$

where T_b is the temperature at the bottom of the plate, it is equal to the initial temperature, namely the room temperature T_0 .

As for non-linear temperature rise process, it can be written as:

$$-\frac{d}{dz} \left(K(z) \frac{dT}{dz} \right) = 0. \quad (6)$$

where K is the thermal conductivity of the plate.

It is assumed that the position of the temperature neutral plane is $z = h/2$, the boundary conditions are:

$$\begin{cases} T = T_b & z = -\frac{h}{2} \\ T = T_t & z = \frac{h}{2} \end{cases}. \quad (7)$$

In the case of power-law functionally graded materials, the solution to equation (6) under the boundary conditions of equation (7) can be represented by a polynomial series:

$$T(z) = T_b + \frac{\Delta T}{C} \left[\left(\frac{2z + h}{h} \right) - \frac{K_{tb}}{(g+1)K_b} \left(\frac{2z + h}{h} \right)^{g+1} + \frac{K_{tb}^2}{(2g+1)K_b^2} \left(\frac{2z + h}{h} \right)^{2g+1} - \frac{K_{tb}^3}{(3g+1)K_b^3} \left(\frac{2z + h}{h} \right)^{3g+1} + \frac{K_{tb}^4}{(4g+1)K_b^4} \left(\frac{2z + h}{h} \right)^{4g+1} \right]. \quad (8)$$

At this point,

$$C = 1 - \frac{K_{tb}}{(g+1)K_b} + \frac{K_{tb}^2}{(2g+1)K_b^2} - \frac{K_{tb}^3}{(3g+1)K_b^3} + \frac{K_{tb}^4}{(4g+1)K_b^4}. \quad (9)$$

where $K_{tb} = K_t - K_b$, with K_t and K_b being the thermal conductivities at the top and bottom surfaces of the plate, respectively.

3.3. Strain-displacement relationship

Under the assumptions of small deflection and small rotation, the strain vector ε is represented as:

$$\varepsilon = \left(\varepsilon_{xx} \quad \varepsilon_{yy} \quad \varepsilon_{xy} \quad \varepsilon_{yz} \quad \varepsilon_{xz} \right)^T. \quad (10)$$

Thus, the in-plane strains are expressed as:

$$\begin{pmatrix} \varepsilon_{xx} \\ \varepsilon_{yy} \\ \varepsilon_{xy} \end{pmatrix} = \begin{pmatrix} \varepsilon_{xx}^0 \\ \varepsilon_{yy}^0 \\ \varepsilon_{xy}^0 \end{pmatrix} + z \begin{pmatrix} \kappa_{xx}^0 \\ \kappa_{yy}^0 \\ \kappa_{xy}^0 \end{pmatrix} + f(z) \begin{pmatrix} \kappa_{xx}^1 \\ \kappa_{yy}^1 \\ \kappa_{xy}^1 \end{pmatrix}. \quad (11)$$

$$\begin{pmatrix} \varepsilon_{xx}^0 \\ \varepsilon_{yy}^0 \\ \varepsilon_{xy}^0 \end{pmatrix} = \begin{pmatrix} \partial u / \partial x \\ \partial v / \partial y \\ \partial u / \partial y + \partial v / \partial x \end{pmatrix}. \quad (12)$$

$$\begin{pmatrix} \kappa_{xx}^0 \\ \kappa_{yy}^0 \\ \kappa_{xy}^0 \end{pmatrix} = \begin{pmatrix} -\partial^2 w / \partial x^2 \\ -\partial^2 w / \partial y^2 \\ -2\partial^2 w / \partial x \partial y \end{pmatrix}. \quad (13)$$

$$\begin{pmatrix} \kappa_{xx}^1 \\ \kappa_{yy}^1 \\ \kappa_{xy}^1 \end{pmatrix} = \begin{pmatrix} \partial \theta_x / \partial x \\ \partial \theta_y / \partial y \\ \partial \theta_x / \partial y + \partial \theta_y / \partial x \end{pmatrix}. \quad (14)$$

The transverse shear strains are shown as:

$$\begin{pmatrix} \varepsilon_{yz} \\ \varepsilon_{xz} \end{pmatrix} = \frac{df(z)}{dz} \begin{pmatrix} \theta_y \\ \theta_x \end{pmatrix}. \quad (15)$$

It can be expressed as:

$$\frac{df(z)}{dz} \left(x, y, z = \pm \frac{h}{2} \right) = 0. \quad (16)$$

Based on equations (11) and (15), the strain vector ε can be represented in the following form, with the 11 components being:

$$\varepsilon = Z \left(\varepsilon_{xx}^0 \ \varepsilon_{yy}^0 \ \varepsilon_{xy}^0 \ \kappa_{xx}^0 \ \kappa_{yy}^0 \ \kappa_{xy}^0 \ \kappa_{xx}^1 \ \kappa_{yy}^1 \ \kappa_{xy}^1 \ \varepsilon_{yz}^s \ \varepsilon_{xz}^s \right)^T. \quad (17)$$

Matrix Z is a function of the thickness coordinate, as shown below:

$$Z = \begin{pmatrix} 1 & 0 & 0 & z & 0 & 0 & f(z) & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & z & 0 & 0 & f(z) & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & z & 0 & 0 & f(z) & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & df(z)/dz & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & df(z)/dz \end{pmatrix}. \quad (18)$$

3.4. Potential energy

The total energy of the CFRP laminates is denoted as:

$$\Pi = U_p - U_T - T_p - U_G - U_F. \quad (19)$$

The strain energy U_p can be expressed as:

$$U_p = \frac{1}{2} \int_{\Omega-h/2}^{h/2} \int_{\Omega} \sigma \varepsilon dz d\Omega. \quad (20)$$

where Ω represents the mid-surface of the plate.

The initial thermal strain energy U_T can be expressed as:

$$U_T = \frac{1}{2} \int_{\Omega-h/2}^{h/2} \int_{\Omega} \sigma^t \tilde{\varepsilon} dz d\Omega. \quad (21)$$

where

$$\tilde{\varepsilon} = \begin{pmatrix} \left(\frac{\partial w}{\partial x} \right)^2 & \left(\frac{\partial w}{\partial y} \right)^2 & \frac{\partial w}{\partial x} \frac{\partial w}{\partial y} & 0 & 0 \end{pmatrix}. \quad (22)$$

The kinetic energy T_p can be expressed as:

$$T_p = \frac{1}{2} \int_{\Omega-h/2}^{h/2} \int_{\Omega} \rho \dot{\bar{U}}^T \dot{\bar{U}} dz d\Omega. \quad (23)$$

where ρ is the material density.

The global displacement vector can be written as:

$$\bar{U} = \Lambda \bar{u}. \quad (24)$$

where

$$\bar{u} = \begin{pmatrix} u & v & w & -\partial w / \partial x & -\partial w / \partial y & 0 & \theta_x & \theta_y & 0 \end{pmatrix}^T. \quad (25)$$

$$\Lambda = \begin{pmatrix} 1 & 0 & 0 & z & 0 & 0 & f(z) & 0 & 0 \\ 0 & 1 & 0 & 0 & z & 0 & 0 & f(z) & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \end{pmatrix}. \quad (26)$$

The geometric strain energy U_G can be expressed as:

$$U_G = \frac{1}{2} \int_{\Omega-h/2}^{h/2} \int \nabla^T w \sigma^0 \nabla w dz d\Omega. \quad (27)$$

σ^0 is the in-plane pre-buckling stress, that is:

$$\sigma^0 = \begin{pmatrix} \sigma_{xx}^0 & \sigma_{xy}^0 \\ \sigma_{xy}^0 & \sigma_{yy}^0 \end{pmatrix}. \quad (28)$$

The work done by the external transverse load U_F can be written as:

$$U_F = \frac{1}{2} \int_{\Omega} w \bar{p} d\Omega. \quad (29)$$

3.5. IGA

3.5.1. NURBS basis functions

In one-dimensional space, the node vector is composed of a non-decreasing array:

$$\Xi = \{\xi_1, \xi_2, \dots, \xi_{n+p+1}\}, \quad \xi_i \leq \xi_{i+1} \quad (30)$$

where Ξ is the basis function, $\xi_i \in R$ is the i -th node in the vector, and $i = 1, 2, \dots, n + p + 1$, p is the order, n is the number of B-spline basis functions. If the nodes are equidistant in the parameter space, it is called uniform, otherwise it is not uniform if the spacing is unequal. The node coordinates can be repeated, and the repeated nodes are called heavy nodes.

The basis function is C_{∞} continuous within the node span and C_{p-m} continuous at the node positions, where m indicates the multiplicity of the node.

The B-spline basis functions are defined by the recursive Cox-de Boor formula, denoted as:

When $p = 0$,

$$N_i^0(\xi) = \begin{cases} 1 & \xi_i \leq \xi < \xi_{i+1} \\ 0 & \text{otherwise} \end{cases}. \quad (31)$$

When $p = 1, 2, 3, \dots$

$$N_i^p(\xi) = \frac{\xi - \xi_i}{\xi_{i+p} - \xi_i} N_i^{p-1}(\xi) + \frac{\xi_{i+p+1} - \xi}{\xi_{i+p+1} - \xi_{i+1}} N_{i+1}^{p-1}(\xi). \quad (32)$$

B-spline basis function has the following properties:

- (1) $\sum_{i=1}^n N_i^p(\xi) = 1$;
- (2) with non-negative, namely $N_i^p(\xi) \geq 0$;
- (3) When 0/0 appears in the formula, 0/0 = 0 is agreed.

The linear combination of B-spline basis functions constitutes a B-spline curve. Given n basis functions N_i^p , $i = 1, 2, 3, \dots, n$, piecewise polynomial B-spline curves are represented as:

$$C(\xi) = \sum_{i=1}^n N_i^p(\xi) B_i \quad (33)$$

Among them, the coefficient B_i of the basis function is called the control point, which is similar to the node coordinates in the finite element.

B-spline curve has the following properties:

- (1) In the absence of repeated nodes or control points, it has $p - 1$ derivative;
- (2) The nodes or control points are repeated k times, and the number of continuous derivatives is reduced by k .

In order to solve the problem that B-spline curves cannot accurately represent shapes such as conic curves, rational B-splines are constructed by introducing weights and denominators on the basis of B-splines. In addition, if the node difference in the node vector is not uniform, it is called non-uniform rational B-spline (NURBS).

For two-dimensional domains (such as plates and shells), NURBS surfaces can be defined by:

$$S(\xi, \eta) = \sum_{i=1}^n \sum_{j=1}^m R_{ij}^{pq}(\xi, \eta) P_{ij} \quad (34)$$

where $R_{ij}^{pq}(\xi, \eta)$ represents the product of univariate NURBS, which is:

$$R_{ij}^{pq}(\xi, \eta) = \frac{N_i^p(\xi) N_j^q(\eta) \omega_{ij}}{\sum_{k=1}^n \sum_{l=1}^m N_k^p(\xi) N_l^q(\eta) \omega_{kl}} \quad (35)$$

In equation (52), the basis functions for the ξ and η directions are denoted by $N_i^p(\xi)$ and $M_j^q(\eta)$ respectively, and ω_{ij} represents the weight coefficient.

3.5.2. Formulations based on NURBS

As a new finite element simulation analysis framework, the core idea of isogeometric analysis (IGA) is to change the basis function in traditional finite element analysis from Lagrange polynomial to NURBS basis function, accurately establish the original model [22, 23], and describe the solution space. Therefore, the displacement field of the FG plate is represented by the NURBS basis function and the displacement field of each control point, as follows:

$$u(\xi, \eta) = \sum_{i=1}^n \sum_{j=1}^m R_{ij}^{pq}(\xi, \eta) u_{ij} \quad (36)$$

$$u_{ij} = \begin{pmatrix} u_{ij} & v_{ij} & w_{ij} & \theta_{xij} & \theta_{yij} \end{pmatrix}^T \quad (37)$$

By substituting equation (36) into the equations (20), (21), (23), (27), and (29), and then transforming them into equation (19), using Hamilton's principle, one can obtain the thermodynamic formulas for static bending analysis, free vibration analysis, and buckling analysis, respectively:

$$(K - K^t)d = F. \quad (38)$$

$$(K - K^t - \omega^2 M)d = 0. \quad (39)$$

$$(K - K^t - \lambda_{cr} K^G)d = 0. \quad (40)$$

where ω represents the angular frequency, d is the displacement field vector of the plate and λ_{cr} is the critical buckling load.

The stiffness matrix K can be written as:

$$K = \int_{\Omega} B_k^T C B_k d\Omega. \quad (41)$$

where

$$B_k = \begin{pmatrix} \partial R_{ij}^{pq} / \partial x & 0 & 0 & 0 & 0 \\ 0 & \partial R_{ij}^{pq} / \partial y & 0 & 0 & 0 \\ \partial R_{ij}^{pq} / \partial y & \partial R_{ij}^{pq} / \partial x & 0 & 0 & 0 \\ 0 & 0 & -\partial^2 R_{ij}^{pq} / \partial x^2 & 0 & 0 \\ 0 & 0 & -\partial^2 R_{ij}^{pq} / \partial y^2 & 0 & 0 \\ 0 & 0 & -2\partial^2 R_{ij}^{pq} / \partial xy & 0 & 0 \\ 0 & 0 & 0 & \partial R_{ij}^{pq} / \partial x & 0 \\ 0 & 0 & 0 & 0 & \partial R_{ij}^{pq} / \partial y \\ 0 & 0 & 0 & \partial R_{ij}^{pq} / \partial y & \partial R_{ij}^{pq} / \partial x \\ 0 & 0 & 0 & 0 & R_{ij}^{pq} \\ 0 & 0 & 0 & R_{ij}^{pq} & 0 \end{pmatrix}. \quad (42)$$

where C is the material constants matrix, given by:

$$C = \begin{pmatrix} A & B & E & 0 \\ B & D & F & 0 \\ E & F & H & 0 \\ 0 & 0 & 0 & A_s \end{pmatrix}. \quad (43)$$

where

$$(A_{ij}, B_{ij}, D_{ij}, E_{ij}, F_{ij}, H_{ij}) = \int_{-h/2}^{h/2} \begin{pmatrix} 1, z, z^2, f(z) \\ zf(z), f^2(z) \end{pmatrix} Q_{ij}(z, T) dz, \quad i, j = 1, 2, 6. \quad (44)$$

$$A_s = \int_{-h/2}^{h/2} \left(\frac{df(z)}{dz} \right)^2 Q_{ij}(z, T) dz, \quad i, j = 4, 5. \quad (45)$$

where Q_{ij} is an elastic constant.

The thermal energy matrix N^t can be written as:

$$N^t = \int_{-h/2}^{h/2} \sigma^t dz = \begin{pmatrix} N_{xx}^t & N_{xy}^t \\ N_{xy}^t & N_{yy}^t \end{pmatrix}. \quad (46)$$

where σ^t is the initial stress matrix caused by temperature rise.

$$\sigma^t = \begin{pmatrix} \sigma_{xx}^t & \sigma_{xy}^t \\ \sigma_{xy}^t & \sigma_{yy}^t \end{pmatrix}. \quad (47)$$

The stiffness matrix induced by the temperature rise K^t can be written as:

$$K^t = \int_{\Omega} B_T^T N^t B_T d\Omega. \quad (48)$$

where

$$B_T = \begin{pmatrix} 0 & 0 & \partial R_{ij}^{pq} / \partial x & 0 & 0 \\ 0 & 0 & \partial R_{ij}^{pq} / \partial y & 0 & 0 \end{pmatrix}. \quad (49)$$

The mass matrix can be represented as:

$$M = \int_{\Omega} B_M^T m B_M d\Omega. \quad (50)$$

where

$$B_M = \begin{pmatrix} R_{ij}^{pq} & 0 & 0 & 0 & 0 \\ 0 & R_{ij}^{pq} & 0 & 0 & 0 \\ 0 & 0 & R_{ij}^{pq} & 0 & 0 \\ 0 & 0 & -\partial R_{ij}^{pq} / \partial x & 0 & 0 \\ 0 & 0 & -\partial R_{ij}^{pq} / \partial y & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & R_{ij}^{pq} & 0 \\ 0 & 0 & 0 & 0 & R_{ij}^{pq} \\ 0 & 0 & 0 & 0 & 0 \end{pmatrix}. \quad (51)$$

$$m = \rho \begin{pmatrix} h & 0 & 0 & 0 & 0 \\ 0 & h & 0 & 0 & 0 \\ 0 & 0 & h & 0 & 0 \\ 0 & 0 & 0 & h^3/12 & 0 \\ 0 & 0 & 0 & 0 & h^3/12 \end{pmatrix}. \quad (52)$$

The geometric matrix caused by the pre-buckling load K^G can be written as:

$$K^G = \int_{\Omega} B_G^T \tau B_G d\Omega. \quad (53)$$

where

$$B_G = \begin{pmatrix} 0 & 0 & \partial R_{ij}^{pq} / \partial x & 0 & 0 \\ 0 & 0 & \partial R_{ij}^{pq} / \partial y & 0 & 0 \end{pmatrix}. \quad (54)$$

$$\tau = \begin{pmatrix} h\sigma^0 & 0 & 0 & 0 & 0 \\ 0 & h\sigma^0 & 0 & 0 & 0 \\ 0 & 0 & h\sigma^0 & 0 & 0 \\ 0 & 0 & 0 & h^3\sigma^0/12 & 0 \\ 0 & 0 & 0 & 0 & h^3\sigma^0/12 \end{pmatrix}. \quad (55)$$

It can be seen from the above formula that the shear correction coefficient is no longer necessary, and the second derivative of the NURBS basis function is included in the formula of the stiffness matrix. Therefore, in the current LHSST model, C1 continuity is a necessary condition. However, compared with the traditional finite element method, it is difficult to construct elements that satisfy C1 continuity. Under the framework of isogeometric analysis (IGA), the NURBS basis functions selected in this paper have Cp-1 continuity, which can well meet the C1 continuity requirements of LHSST. In addition, the IGA method also shows significant advantages in dealing with higher continuity requirements (such as C3 continuity), and the high continuity of NURBS basis functions can well meet the requirements of C3 continuity generalized displacement. This is one of the outstanding advantages of IGA compared to other shear deformation plate theory methods.

4. RESULTS AND DISCUSSION

Based on the IGA of HSDT, the static bending, free vibration, and buckling behaviors of CFRP laminates are studied.

Figure 5 compares the convergence of the first natural frequency of square plates under simply supported boundary conditions.

Figure 6 compares the convergence of the first-order natural frequency of fixed circular plates.

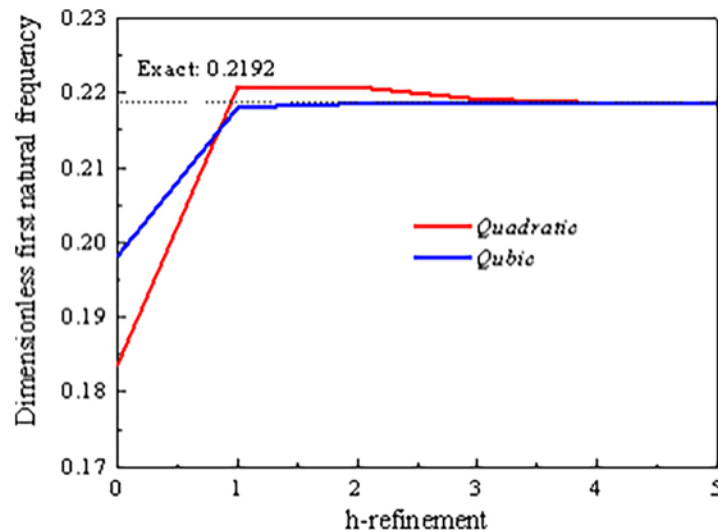


Figure 5: Convergence of the first natural frequency of square plates under simply supported boundary conditions.

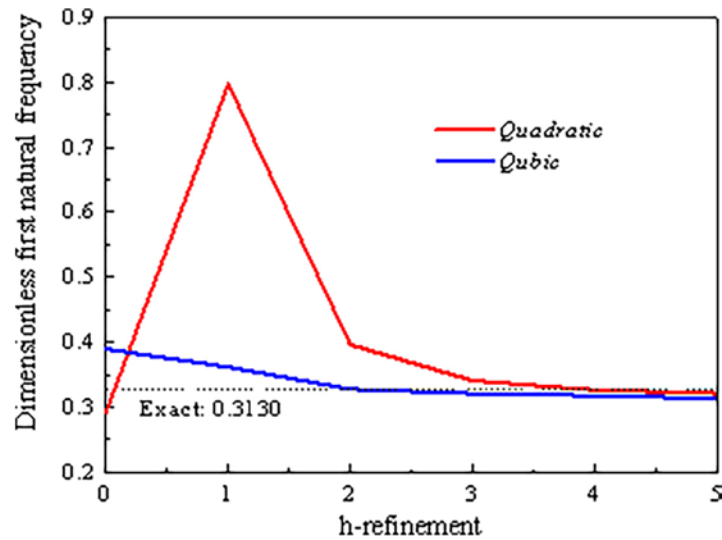


Figure 6: Convergence of the first-order natural frequency of fixed circular plates.

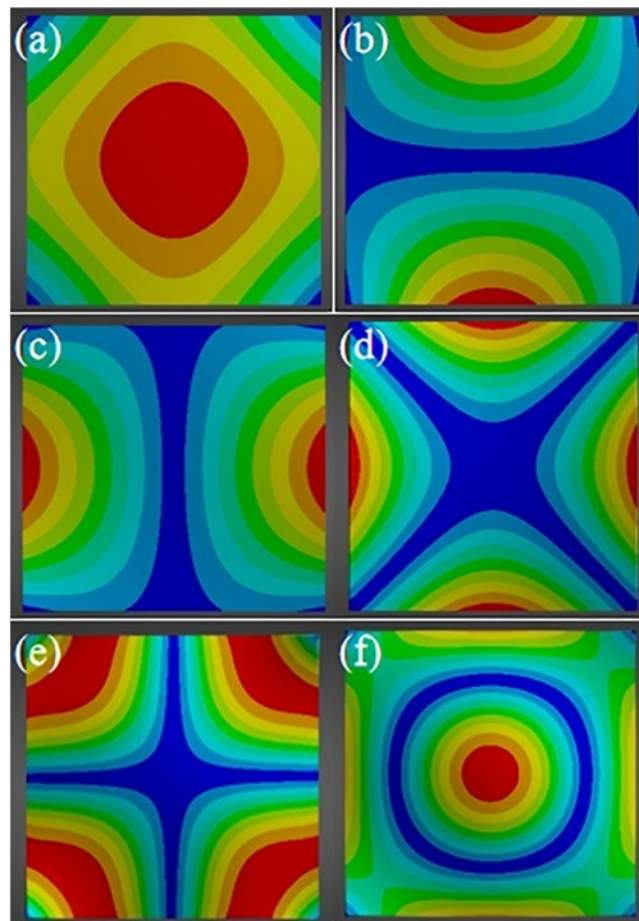


Figure 7: The first six modes of vibration for a square plate at a uniform temperature rise of $\Delta T = 300K$: (a)–(f): Modes 1–6.

Figure 7 shows the first six modes of vibration for a square plate at a uniform temperature rise of $\Delta T = 300K$, and different vibration modes reflect the state changes of the molded products in the temperature field and stress field. By combining with the on-line monitoring system of the molding production line (Figure 4), the temperature curve is monitored and fed back in real time during the molding process, and the pressure, mold temperature and heating time are adjusted in time to optimize the quality of the molded products and reduce the problems of bubbles and poor glue.

The results demonstrate that the new logarithmic HSDT combined with the IGA method is efficient and accurate for the static bending, free vibration, and buckling analysis of CFRP plates, providing theoretical support for the quality analysis of the molding process.

5. CONCLUSIONS

The investigation presented herein has culminated in the development of a quality monitoring and control system, informed by multi-source data, for the molding process of CFRP laminates. This innovative system is designed to enable real-time monitoring and facilitate a closed-loop control mechanism throughout the molding process, thereby significantly enhancing the quality of the end product. The conclusions of this research can be summarized as follows:

- (1) The formulation of a multi-source information fusion technique has been achieved. This approach integrates visual and feedback data to monitor with precision the arrangement of carbon fibres within the mold pre- and post-molding, in addition to detecting deformations and defects in the final product. Consequently, it has been observed that monitoring accuracy is substantially improved.
- (2) The application of IGA, in conjunction with HSDT, has provided novel insights into the static bending, free vibration, and buckling behaviours of CFRP laminates. This research has verified the enhanced precision in simulating the mechanical properties of the composite materials during the molding process, a factor which is instrumental in augmenting the quality of manufacturing.
- (3) Further, this study furnishes theoretical support for refining the molding process of CFRP plates, offering considerable benefits in reducing the frequency of defects and augmenting the performance of the final product. A proposed quality monitoring system, informed by a synergy of multi-source data, has been shown to significantly elevate both the quality of molded CFRP composite products and the efficiency of the molding process when analyzed through the lens of HSDT and integrated with multi-source information fusion monitoring technologies.

Future research will further optimize the visual inspection algorithm in the molding process, improve the quality monitoring accuracy of complex curved surface products, and promote the wide application of carbon fiber composite molding technology in automobile, aerospace and other fields. In addition, the application of deep learning and artificial intelligence technology in molding quality monitoring will be explored to achieve intelligent production line control in the true sense and continuously improve the overall quality and consistency of molding products.

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