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A novel process-linked assembly failure model for adhesively bonded composite structures

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ABSTRACT

The globally growing market for polymer composites and their increasing use within aircraft structures has necessitated reliable bonding of composite laminates to prevent structural failure. However, knowledge behind the interaction between curing process parameters and the failure of polymer composite bonded joints is not keeping pace with the market. A novel nonlinear correlation analysis has been employed and applied to experimental data, to attentively quantify the effect of curing parameters on the failure of bonded composite assemblies. The materials (adherends and adhesive) and the bonding processes were selected from those used in assembly of composite aircraft structures.

1. Introduction

The inevitable process-linked structural performance in adhesively bonded polymer composite structures necessitates an urgent need for reliable, controllable and measurable bonding in composite joint assembly and manufacturing. This need is intensified by the fact that no method of measuring properties prior to installation exist to account for variabilities caused by process control during adhesive bonding, and no non-destructive inspection is available to ensure bond integrity [1,2]. Due to such process-linked performance, certified procedures may not produce reliable bonded assemblies with adequate levels of continuing airworthiness for aircraft structures.

Integrated structural adhesive bonds often present significant technical challenges due to the mismatch in mechanical properties between the bonded members (adherends). Correct bonding and integration require knowledge-based methodology, including structural performance modelling (e.g. see Ref. [3]), that quantifies the effects of each bonding process parameter on the structural response. Existing models for predicting the response of composites have been developed with no or little contribution of such process-linked properties [3]. Those models assume that the curing process has fully been accomplished, or slight effects from incomplete curing. This paper addresses this missing gap and explains the interaction between the curing process in a thermoset polymer bond and its achieved mechanical properties.

A nonlinear correlation analysis approach is used to obtain the level of interaction between the main process parameters and the composite bonded joint's mechanical response. This is a novel employment of this approach that accounts for the process parameters in a simple and straightforward manner based on experimental data. Bond deficiencies are mimicked in single-lap composite bonded joints. Curing process parameters are altered, and their effect on the joints failure is obtained. Finally, the correlation method is applied to quantify the effect of each parameter on the response of the joint. The model is recommended to designers and researchers in academia and industry for understanding and quantification of the effect of process-induced deficiencies in composite assemblies.

2. Nonlinear correlation analysis

Considering a system with multiple inputs and outputs, the Error Reduction Ratio (ERR)-Causality approach [4,5] is a correlation method used to measure the effects of each input parameter on outputs in an interactive system, particularly when the interaction is nonlinear. The effects are quantified in a range from 0% to 100%, the larger the ERR, the higher the dependence between selected input and output. The ERR-Causality approach is underpinned by the nonlinear auto-regressive moving average model with exogenous inputs (NARMAX), detailed in Ref. [4], suitable for a complex system with an unknown inner structure (herein a curing bond). Compared with machine learning methods, one advantage of the NARMAX model is transparency, meaning that it can be written down and therefore easily understood. ERR-Causality has successfully been applied to brain signal analysis, climate change and non-destructive testing [6,7]. However, its

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application to composite structure manufacturing is novel. This research has focused on understanding and quantification of the interaction between major curing parameters and their resulting bond failure in a critical composite bonded assembly (e.g. aircraft). The process-linked failure is a multi-parameter nonlinear problem. The purpose of the ERR model developed in Refs. [4,5] is to reveal any hidden nonlinear interaction. Traditional methods, such as coherence and cross-spectrum, usually assume that the system is linear and stationary, and hence cannot sufficiently reveal and characterise hidden information in a complex system that is nonlinear and dynamic. Moreover, in cases with limited number of tests, applying a statistical analysis cannot be suggested. The ERR is more appropriate and easier-to-implement for laboratory scale tests than the statistical models.

In the ERR model formerly developed in Ref. [5], the composite bonded joint is taken as the system. Curing duration and heating rate in curing bond are taken as the system inputs, and failure load, displacement and strain energy are taken as the system outputs (energy is calculated from 0.5 × load × displacement as the load–displacement curves were linear in our experiments). These inputs are controlled in the experiments. Alternative inputs could have been selected e.g. surface treatment and contamination. However, these inputs are constant in all tests to allow the effects of the curing parameters to be interrogated only. The bond area was degraded in some joints to account for contamination.

2.1. ERR-Causality method

The orthogonal least squares algorithm has been used in the proposed method. This is a popular algorithm used for nonlinear systems. It searches through all possible candidate model terms to select the most effective ones. These are then used to build the model expression [5]. The significance of each selected model term is measured by the ERR index which indicates how much of the change in the system response (output), in percentage, can be accounted for by including the relevant model terms containing inputs. Consider a function with a linear form of terms:

$$y(k) = \sum_{i=0}^{N} \theta_i p_i(k), k = 1, 2, \ldots, M \quad (1)$$

where $y(k)$ is the system output (mechanical response herein) to regress upon. $p_i(k)$ are regressor terms constructed by input variables $\{u_i\}$. θ_i is the vector of unknown coefficients of regressions to be estimated, M denotes the number of data points in the data set, and N denotes the number of terms in the model that is yet to be determined. Eq. (1) can be written as

$$Y = P\Theta \quad (2)$$

where

$$Y = \begin{bmatrix} y(1) \\ y(2) \\ \vdots \\ y(M) \end{bmatrix}, P = \begin{bmatrix} P^T(1) \\ P^T(2) \\ \vdots \\ P^T(M) \end{bmatrix}, \Theta = \begin{bmatrix} \theta(1) \\ \theta(2) \\ \vdots \\ \theta(M) \end{bmatrix} \quad (3)$$

and $P^T(k) = (p_1(k), p_2(k), \ldots, p_N(k))$. Matrix P is decomposed as $P = W \times A$ where

$$W = \begin{bmatrix} w_1(1) & w_2(1) & \ldots & w_N(1) \\ w_1(2) & w_2(2) & \ldots & w_N(2) \\ \vdots & \ddots & \ddots & \vdots \\ w_1(M) & w_2(M) & \ldots & w_N(M) \end{bmatrix}, \quad (4)$$

and $A = \{a_{ij}\}$ is an upper triangular matrix with unity diagonal elements. Therefore, Eq. (2) is re-written as

$$Y = WG \quad (5)$$

where $G = A\Theta = [g_1 \quad g_2 \quad \ldots \quad g_N]^T$. Eq. (5) is now ready to represent the relation between Y and G. We then estimate the effect of each model term to the system output (Y). Values are initially set at $a_{ij} = 0$ for $i \neq j$ (A then becomes an identity matrix), as such $w_1(k) = p_1(k)$. g_1 is calculated from

$$g_1 = \frac{\sum_{k=1}^{M} w_1(k) y(k)}{\sum_{k=1}^{M} w_1{}^2(k)} \quad (6)$$

For $j = 2, 3, \ldots, M$ set $a_{jj} = 1$, thus

$$a_{ij} = \frac{\sum_{k=1}^{M} w_i(k) p_j(k)}{\sum_{k=1}^{M} w_i{}^2(k)} \quad (7)$$

where $i = 1, 2, \ldots, j - 1$. The algorithm then calculates

$$w_j(k) = p_j(k) - \sum_{i=1}^{j-1} a_{ij} w_i(k) \quad (8)$$

and

$$g_1 = \frac{\sum_{k=1}^{M} w_j(k) y(k)}{\sum_{k=1}^{M} w_j{}^2(k)} \quad (9)$$

The ERR values for each term p_i is finally defined as

$$ERR_i = \frac{g_1^2 \sum_{k=1}^{M} w_i{}^2(k)}{\sum_{k=1}^{M} y^2(k)} \quad (10)$$

The larger the ERR, the higher dependence between the $\{p_i\}$ terms and the output, Y, an index to indicate the importance of each term (constructed by the process parameters as inputs) for the output, the mechanical response.

3. Composite joints: assembly, materials and processing

Composite single-lap bonded joints are the most common, economic and easily repeatable joints used to measure the performance of adhesively bonded structures. It is the weakest joint configuration as a result of loading eccentricities causing adherend bending which produces high stress concentrations in the through–thickness direction, and resulting in peeling stress driven failure. This configuration therefore provides conservative failure prediction for composite bonded assemblies compared to other joints. For instance, the reduction in strength for double-lap joints (using ASTM-D3528) would be less than that for the single-lap joints in the presence of the examined bond deficiencies here.

3.1. Bonded assembly and materials

A 2 mm-thickness carbon fibre-reinforced composite laminate was manufactured from aerospace grade unidirectional Hexply® M21/T800S pre-preg using manual laying-up and autoclave curing. The laminate stacking sequence was $[0^\circ\ 90^\circ\ 45^\circ\ -45^\circ]_S$. These were cut to joint lap adherend dimensions (details in Fig. 1 with the dashed line representing the defected bonds).

Joints were bonded as advised by ASTM D5868 [8] using Cytec FM® 94 modified epoxy adhesive film. This aerospace qualified adhesive, which can produce high temperature and good moisture resistant bonds, was applied to the 25 mm × 25 mm overlap region of the adherends. The nominal thickness of the bond was 0.25 mm which is smaller than that in the Standard (0.76 mm). Six categories of single-lap joints with and without bond defects

Table 1
Bond categories in single-lap joints (pressure = 0.28 MPa).

Category	Deficiency method	Label	Cure condition
Standard bond	None	SB	120 °C, 2 °C/min
Weak bond	Bond centre pre-cure	WP	120 °C, 2 °C/min
Weak bond	Rapid heating	WR	120 °C, 4 °C/min
Weak bond	75% reduced cure time	WT	120 °C, 2 °C/min
Kissing bond	Single-side PTFE bond	KS	120 °C, 2 °C/min
Kissing bond	Double-side PTFE bond	KD	120 °C, 2 °C/min