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Thermal response of frame-like composite structures to analytically assess manufacturing distortion

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ABSTRACT

The proposed approach assesses frame-like composite parts prone to distortion without needing a full-scale finite element simulation. These structures are reduced to a series of constant cross-sections and curvatures. A simplified shape response of each thin-walled composite cross-section during curing is analytically obtained by employing homogenization methods at different geometrical levels. This includes a novel approximation method for the mechanical properties of a T-section including a gusset filler. The model is validated against a currently deployed finite element approach. A good agreement is reached for the thermal response of a gusset and a cross-section, whereas for an extruded frame-like structure, the analytically calculated deformation is about 20% higher than the simulated one. The cause is identified and solutions are proposed. Nevertheless, knowing its limitation, the ease of use together with the high potential for automation makes this altogether a possible method for predicting process-induced deformation in the early design phase.

1. Introduction

Especially in the aerospace industry, composites that are manufactured by the autoclave process need to meet high standards with respect to geometrical design tolerances. There are, however, several drivers within the trinity of material, design and production that can result in a distorted part after manufacturing [1]. The subsequent compensation of this distortion by shimming in the assembly is a costly and time-consuming process. The use of finite element (FE) simulations is a way to predict process-induced deformations (PID) prior to tooling manufacturing. Currently, the (commercially) available simulation tools to analyse distortion require extensive information about the material, design and process [2,3]. Hence, they are mostly applied towards the end of the product development stage. During concurrent engineering however, in which part design and tooling development are parallel operations, these simulations may deliver too late the input to compensate tooling design for part distortion. Thus, a need arises for a simpler modelling approach that adequately assesses possible distortions while relying on limited information. Once identified, the development schedule of affected parts can subsequently be adapted to incorporate suitable countermeasures at a later stage, which need to be derived from a more detailed investigation.

One of the most prominent deformation modes is the so-called spring-in of angular features. It describes the reduction in the enclosed angle Θ of a curved composite laminate, as shown in Fig. 1, which is processed at elevated temperatures. For an angled composite laminate, the spring-in or change in included angle $\Delta\Theta$ can be predicted based on its initial geometry, the temperature change ΔT and the coefficient of thermal expansion in radial (through-thickness) and tangential direction (α_n and α_t, respectively). For thermoset matrices, in which the chemical reaction causes additionally a strain component in radial and tangential directions (ϕ_n and ϕ_t, respectively), the total angle change can be analytically expressed as [4]:

$$\Delta\Theta = \Theta\left\{\left[\frac{(\alpha_t - \alpha_n)\Delta T}{(1 + \alpha_n \Delta T)}\right] + \left[\frac{(\phi_t - \phi_n)}{(1 + \phi_n)}\right]\right\} \tag{1}$$

This approach can be extended towards curved sandwich panels, as shown in [5,6]. Using similar assumptions as for sandwich panels, the spring-in behaviour of a simple curved continuous I-section composite frame was investigated to a limited extent in [7]. As strain anisotropy during curing is among the main drivers for distortion of thicker laminates (≥ 4 mm) [8,9], such an analytical model offers a fast estimation of part distortion tendencies requiring neither detailed design nor manufacturing data. There is unfortunately no engineering approach currently available, which derives the needed orthotropic thermoelastic strain behaviour for arbitrary beam cross-sections.

Furthermore, T-shaped sections are commonly used in aeronautical frame design. The deltoid geometry, which is created by the web's plies

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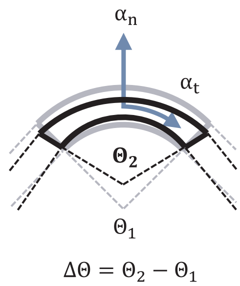


Fig. 1. Spring-in of a curved composite laminate. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

splitting and continuing into the flange, is known as the gusset filler (see Fig. 2(a)). The gusset filler defines the joint's structural integrity and increases the out-of-plane load transfer capability [10]. Former investigations showed that the gusset filler geometry [11] and materials [12,13] have a significant influence on its load bearing capability. There have been numerical studies covering the structural response of such structures under tensile loading [14], even considering defects [15]. Dong showed that the deformation in a FE-analysis of an integral skin-stiffener structure is most sensitive to the fibre volume fraction of the laminate, followed by the radius-thickness ratio and its bonding length [16]. Li et al. established a numerical process simulation model to follow the residual stresses and deformation development during curing of an integral skin stiffener structure [17]. Identifying the thermal strain contribution and the analytical modelling of a gusset filler area was not yet conducted.

The goal is to use the established spring-in model (Eq. (1)) to quickly estimate the deformation of a frame-like structure with the available geometrical data of an early part design. To this end, the proposed analytical approach calculates the needed orthotropic thermoelastic strain behaviour for arbitrary frame cross-sections. The contribution of the gusset filler to the expansion behaviour of T-shape cross-sections is formulated for the first time. The approach is then validated at different geometrical levels.

2. Method

2.1. Description of approach

The method approximates frame-like structures by a finite number of sections each having a constant cross-section and curvature. For each section, Eq. (1) approximates the deflection due to the spring-in effect. The part's global deformation, as determined in the global coordinate system (X, Y, Z), is then the sum of changes in single curvature κ of each segment as given in the curve coordinate system. The used "*Frenet-Serret frame*" consists of the tangential vector t(s) following the beam

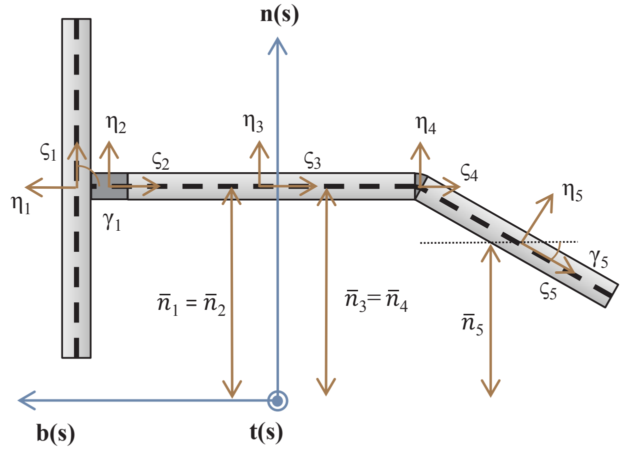


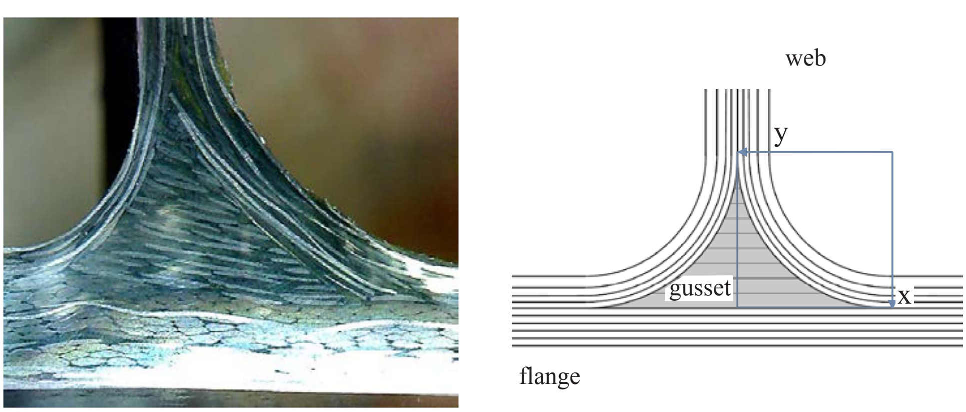
Fig. 3. Cross-section in the curve reference frame system. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

axis curve c(s), the normal direction n(s) pointing towards the curvature centre and the cross product of the two, the binormal vector b(s) [18].

To derive the thermomechanical behaviour of each cross-section analytically, it needs to be first decomposed into smaller units, the so-called single flat laminate walls, as defined in [19]. Once the properties of each wall are known, it can subsequently be homogenized at cross-section level. The i-th wall has its own set of tangent (ς_i) and normal (η_i) axes. Its orientation is given by the angle γ_i between the local (ς, η) and the planar cross-section axes (n, b) together with the distance ($\bar{n}_i$,$\bar{b}_i$) to the cross-section origin (see Fig. 3). The properties of each laminate wall are derived by an established method to homogenize laminae, as described in [20]. Micromechanics are used to determine the lamina's mechanical properties as presented, for example, in [21]. For a t-joint, two walls are connected perpendicularly, i.e. one of the walls connects to the other one at a midpoint, creating the so-called gusset filler area (dark grey area in Fig. 2(b)). Since the local properties vary significantly for this area, a different approach is used for homogenization. To avoid the replication of calculation effort for both the thermal expansion and chemical shrinkage, they are combined to an isotropic "equivalent" value of thermal expansion for the matrix material [22]. If not stated otherwise, the equivalent value covering both expansion behaviours is subsequently used.

The proposed model is based on the following assumptions:

1. For each single composite wall, its layup is assumed to be symmetric and balanced (for every ply with a fibre angle of $+\varphi$, there is an identical ply with an angle of $-\varphi$).



(a) (b)

Fig. 2. Gusset filler area of a t-joint - micro section of a real sample (a) and schematic representation (b). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)