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COMPOSITES THEORY AND PRACTICE

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AN ENGINEERING APPROACH TO MODELLING PROCESS-INDUCED DEFORMATIONS OF DOUBLE-CURVED COMPOSITE ELEMENTS

Since deformations induced in composite elements during curing are a problem well-known to engineers that design composite structures, compensating for them is one of the most interesting issues in the field of composite manufacturing. The present work proposes a simple method that allows one to predict process-induced deformations. Development of the method starts with determining and measuring in experiments the factors that contribute to the deformations. These factors are then used in the FEM model to calculate the deformations of a double-curved composite element. The calculated deformations are verified by comparison to the measured deformations of an equivalent sample element. The comparison shows that the model used in the present work enables one to predict 80% of process-induced deformations of a composite double-curved element. Although the accuracy of the prediction is not excellent, the method enables estimation of the deformations and may be used as a base for significant improvement of composite element dimensional accuracy. Taking into account that the computational model used in the method is simple and may be implemented in commonly used FEM software, it appears to be a useful tool for any engineer dealing with composite elements design.

Keywords: deformations, carbon/epoxy composite, finite element method

MODELOWANIE DEFORMACJI POWSTAJĄCYCH W CZASIE WYTWARZANIA ELEMENTÓW KOMPOZYTOWYCH O NIEROZWIJALNEJ GEOMETRII - PODEJŚCIE INŻYNIERSKIE

Ze względu na to, że deformacje powstające w czasie procesu wytwarzania elementów kompozytowych są istotnym problemem dla inżynierów projektujących struktury kompozytowe, kompensacja tych deformacji jest zagadnieniem cieszącym się dużym zainteresowaniem. W niniejszej pracy zaproponowana został prosta metoda, która pozwala przewidywać deformacje powstające w czasie procesu wytwarzania. Pierwszym jej etapem było wyszczególnienie i zbadanie eksperymentalne czynników, które powodują powstawanie deformacji. Następnie czynniki te zostały uwzględnione w modelu MES w celu obliczenia deformacji kompozytowego wyrobu o nierozwijalnej geometrii. Na końcu obliczone deformacje zostały zweryfikowane przez porównanie ze zmierzonymi deformacjami elementu, dla którego wykonane zostały obliczenia. Porównanie to wykazało, że dzięki zaproponowanej metodzie można przewidzieć 80% deformacji kompozytowego elementu o podwójnej krzywiźnie. Chociaż dokładność metody nie jest idealna, pozwala ona na oszacowanie deformacji, które może stanowić podstawę do znacznego poprawienia dokładności wymiarowej wyrobów kompozytowych. Jeżeli zostanie wzięte pod uwagę to, że użyty model obliczeniowy jest bardzo prosty i może być zaimplementowany za pomocą powszechnie używanego oprogramowania MES, przedstawiona metoda okazuje się być użytecznym narzędziem dla inżynierów zajmujących się projektowaniem struktur kompozytowych.

Słowa kluczowe: deformacje, kompozyt węglowo-epoksydowy, metoda elementów skończonych

INTRODUCTION

Process-induced deformations are a serious obstacle to the successful design of high-performance composite elements used in aviation. The complicated curing process of such elements results in differences between the desired and real geometry of a manufactured part. These differences are a source of problems with assembling the structure and deterioration of the structure properties caused by the introduction of assembly stress, increase in mass or violation of shape tolerances. The ability to predict process-induced deformations before element manufacturing allows one to compensate for deformations in the design stage and avoid the abovementioned problems. Therefore, the modelling of deformations has been in the scope of engineers' interest for the last three decades. However, although there has been extensive work done on the modelling of process-induced deformations, the majority of the proposed models allows one to predict solely the deformations of structures that can be modelled by two-dimensional analysis. These models are useful in the case of modelling single-curved composite elements such as a wing spar. Predicting the deformations of double-curved elements is still a challenge for the designer due to the lack of works dedicated to modelling the deformations of such elements. The present work aims to solve this problem by proposing a simple model that predicts the deformations of double-curved composite elements.

LITERATURE REVIEW

There have been some works aiming to predict process-induced deformations throughout the last decade. Ersoy et al. used FEM analysis to predict the deformations of a C-sectioned composite element [1]. The analysis employed two-dimensional plane strain elements. The results of the analysis were compared to the deformations of adequate specimens and the correlation appeared to be good. Dong presented in his work [2] an analytical method to predict the deformations of curved composite components and assemblies. This approach was validated against the FE analysis. Arafath et al. used a closed-form analytical model based on the theory of elasticity to analyse process-induced deformations of curved composite parts [3]. The results of the model agree with the FE results. Svanberg and Holmberg in their two works [4, 5] presented an analytical viscoelastic model that accounts for the mechanisms generating deformations in composite elements. This model has also been implemented in FE software as a subroutine. The results of the two-dimensional plane strain analysis of an L-sectioned bracket were compared with the measured shape distortion of a composite element showing good agreement. All the abovementioned works successfully model the deformations of two-dimensional cases. However, the plane strain approach used in them is appropriate only for modelling deformations of single-curved elements of a significant length. Since the shapes of composite elements are generally much more complicated, the plane strain approach is not universal. There have also been some works that employed three-dimensional analysis of the composite parts and structure deformations. Dong conducted an FE analysis of T-stiffener structures [6]. Bapanapalli and Smith presented a study in which a linear three-dimensional FE model was used to model deformations of a U-sectioned composite element [7]. The results of the simulation were compared to measured deformations of composite elements showing satisfactory agreement. Fernlund et al. used a complex technique in which an FE two-dimensional model was used to model the curing process while a three-dimensional model was used to model the deformations of a double-curved composite part [8]. Commercial software COMPRO designed purposefully for modelling process-induced deformations of composite elements was used in this work. The results of the simulation were validated by comparison of the calculated deformations to the measured deformations of a composite element. From the three methods that use the three-dimensional approach to predict composite element deformations, only the last one proved to be able to predict the deformations of general composite structures, whereas the other two - predicted only the deformations of elements that might have been modelled by two-dimensional techniques as well. The model presented in the last work is, however, quite complex and requires the use of commercial software dedicated to the simulation of process-induced deformations that is not as widespread among engineers as commonly used and universal FE software (Ansys, Nastran or Abaqus).

PURPOSE AND OUTLINE

The purpose of the paper is, therefore, the development of an approach that allows one to predict process-induced deformations of composite parts with general single- or double-curved geometry with the use of common FE software, keeping calculations as simple as possible and using as few material properties as possible. Such a simple approach will enable quick improvement of composite structure dimensional accuracy and will be available to every engineer that deals with the design of composite elements.

The work starts with a description of the factors causing the deformations of composite elements that are described in literature. Then experiments aiming to measure the influence of these factors on the deformations are conducted. The factors that are proved to have a significant impact on the deformations are subsequently employed in the FE model in order to predict the deformations of a double-curved composite element. Finally, the calculated deformations are compared to the measured deformations of an equivalent sample element.

MECHANISMS GENERATING DEFORMATIONS

There are several mechanisms that generate deformations of a composite part during the curing process described in literature. The two most significant of them are spring-in (Fig. 1) and tool-part interaction (Fig. 2) [9]. These mechanisms are described below.

Spring-in occurs inevitably in curved composite elements. It is caused by coupling between the anisotropic contraction of a composite and curved geometry. The composite contracts during curing as a result of chemical shrinkage that occurs when the resin polymerizes and cooling of a composite that was cured at an elevated temperature [10]. Since the glass and carbon fibres are much stiffer than the resin, shrinkage of the resin is hindered in directions parallel to the reinforcement. In consequence, the composite part shrinks more through-the-thickness than in-plane. In the case of curved elements, this anisotropic shrinkage causes extension of the inner radius and reduction of the outer. Since the fibres in the circumferential direction of the curved part are not easily distorted, stress arises in the curved part and causes an increase in part curvature after demoulding.

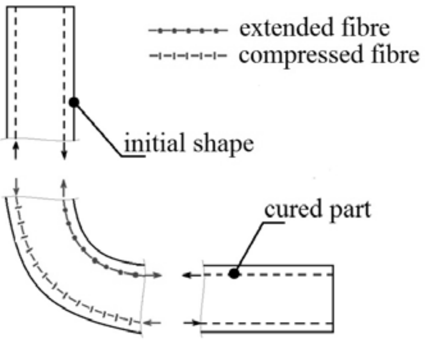

Fig. 1. Spring-in mechanism

Rys. 1. Mechanizm spring-in

Tool-part interaction is a mechanism generating warpage of both flat and curved composite parts. It is caused by interaction between the pressure imposed on the part and elevated temperature during curing [11]. As the composite in the tool is heated to the curing temperature, the tool expands usually more than the composite that has a low coefficient of thermal expansion due to the presence of reinforcement. The autoclave or vacuum bag pressure induces friction that causes stretching of the composite ply adjacent to the tool. If the element vitrifies in such a state, the stress in the ply is released after demoulding causing warpage of the element.

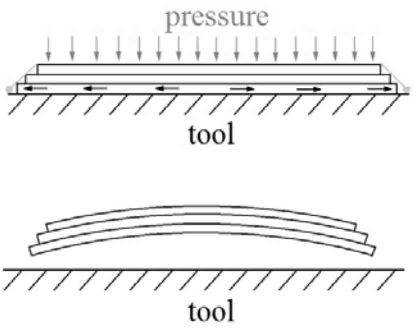

Fig. 2. Tool-part interaction mechanism

Rys. 2. Mechanizm tool-part interaction

SAMPLE ELEMENT

In the present work, the deformations of a double-curved element are predicted (Fig. 3). The element is made of unidirectional carbon/epoxy prepreg MTM-46/GF0103-38%RW. The lay-up of the element is $[90^\circ/0^\circ/90^\circ/90^\circ/90^\circ/0^\circ]_S$. The curing process of the element is performed in a vacuum bag in an oven. The thermal cycle consists of a 2°C/min ramp and 8 h dwell period at 80°C followed by cooling. The element is cured on a convex tool made of a RenShape BM 5055 epoxy board dedicated for prepreg tools. The thermal expansion coefficient of the tool material equals 35÷45 x 10^{-6} 1/°C according to the manufacturer data.

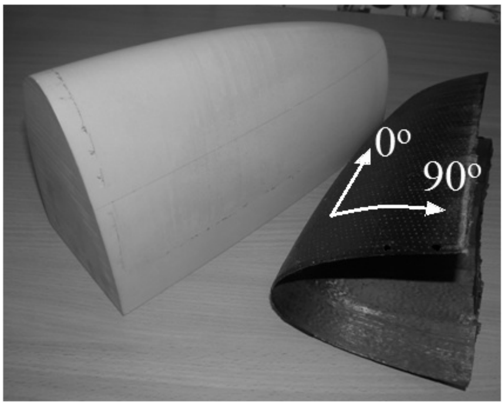

Fig. 3. Sample element with marked reinforcement directions and tool on which it was cured

Rys. 3. Element próbny z zaznaczonymi kierunkami zbrojenia oraz foremnik, na którym został utwardzony

EXPERIMENTAL MEASUREMENTS OF FACTORS CONTRIBUTING TO DEFORMATIONS

Factors that contribute to spring-in - thermal expansion and chemical shrinkage of the composite - were measured experimentally. The thermal expansion coefficient of the cured prepreg in the perpendicular and parallel direction to the reinforcement fibres was measured with a dilatometer according to the ASTM E228-11 standard. Measurement of the prepreg strain induced by chemical shrinkage that takes place during curing has not been standardized yet. Therefore, the strain induced in the prepreg in the present work was measured by a method that is described in detail in another author's work [12]. The method consists in measuring the decreasing thickness of the prepreg sample during curing. The sample is placed in a purposefully designed apparatus in a dynamic mechanical analyzer (DMA) that measures and records the static displacement of the drive shaft that follows the decrease in sample thickness. The curves of the sample thickness strain during curing are shown in Figure 4 [12].

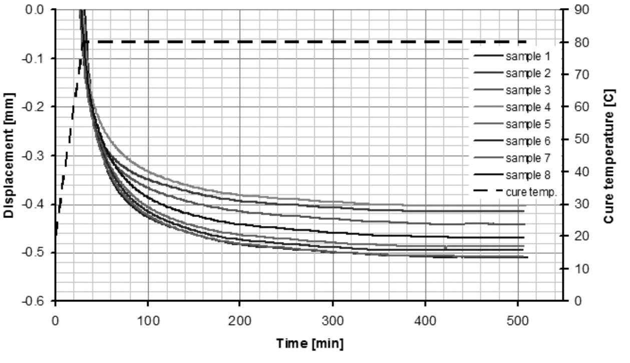

Fig. 4. Result of chemical strain measurement - displacement of DMA drive shaft that represents decrease in composite sample thickness in respect of cure time

Rys. 4. Wyniki pomiaru odkształcenia wywołanego skurczem chemicznym - przemieszczenie czujnika DMA reprezentujące zmniejszanie się grubości próbek kompozytowych przedstawione w zależności od czasu utwardzania

Since the state of the resin in the prepreg sample changes from liquid to solid throughout the cure cycle, not all the measured chemical strains induced by the resin contribute to spring-in arising in the element. The point of gelation is the moment in which the resin reaches sufficient stiffness, so that the strains caused by the volumetric changes of the resin can contribute to the deformations [13]. The point of gelation was determined by the DMA to be after 240 minutes from the beginning of isothermal curing [12]. Therefore, only the chemical strain that took place after this moment was acknowledged to be a factor contributing to spring-in of the composite element (Table 1). The chemical strain was measured only in the direction perpendicular to the fibres (through-the-thickness) because in the fibre direction, this strain is hindered by the fibre stiffness and can be assumed in calculations to be negligible without a loss of accuracy [1].

TABLE 1. **Measured values of factors that contribute to spring-in**

TABELA 1. **Zmierzone wartości czynników powodujących mechanizm spring-in**

Coefficient of thermal expansion α_T	In fibre direction x	3×10^{-6} 1/°C
	Perpendicular to fibres y,z	34×10^{-6} 1/°C
Chemical strain ε_{sc}	In fibre direction x	0
	Perpendicular to fibres y,z	0.007

The influence of tool-part interaction was verified by the following experiment: flat specimens with dimensions 300 x 40 made of 8, 12 and 16 prepreg plies with reinforcement along the specimen were cured on an epoxy board similar to the one used for the sample element tool and in similar conditions as the sample element. After curing the specimens remained flat, which excluded a significant influence of tool-part interaction on the deformations of composite parts cured in the conditions used in this work. A lack of this mechanism may be explained by the fact that the tool-part interaction is observed mainly in autoclave cured composite parts [11]. The pressure in an autoclave is several times higher than in the vacuum bag used to cure elements in the present work and, therefore, the friction between the tool and the adjacent composite ply may be insignificant.

NUMERICAL MODEL

Ansys software was used in order to develop a numerical model that predicts process-induced deformations of the sample element (Fig. 3). As the experimental section has shown, the most significant mechanism that contributes to process-induced deformations is spring-in. Therefore, both factors that cause this mechanism - thermal expansion and chemical shrinkage - have to be taken into account in the numerical model. Due to its negligible influence on deformations in curing conditions used for the experiments presented in this work, tool-part interaction was neglected. Since the only influence of the tool is linear expansion of its dimensions caused by a temperature rise that can be modelled analytically, the tool was not modelled at all. The composite part was modelled with use of solid-shell elements (SOLSH 190) with the possibility of setting the lay-up of composite plies. Only half of the part was modelled with symmetry boundary conditions set in the symmetry plane (Fig. 5).

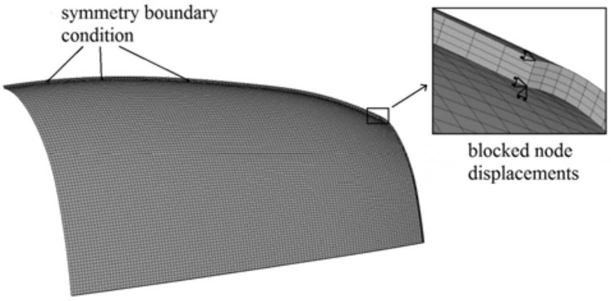

Fig. 5. Numerical model of sample element with applied boundary conditions

Rys. 5. Model numeryczny elementu próbnego z zadanymi warunkami brzegowymi

The linear elastic material model was used. The only modelled cure phase was cooling from curing to ambient temperature. The load set to the model was, therefore, the temperature difference ΔT applied to the elements. Since the composite element was cured at 80°C and room temperature is assumed to be 20°C, the temperature difference $\Delta T = -60$°C. Both thermal contraction and chemical shrinkage were modelled by coefficients of thermal expansion:

1. CTE in fibre direction

$$\alpha_x = \alpha_{Tx} = 3 \times 10^{-6}\ 1/^{\circ}\mathrm{C}$$

2. CTE in direction perpendicular to fibres

$$\alpha_y = \alpha_z = \alpha_{Ty} + \varepsilon_{scy}/(-\Delta T) = 151 \times 10^{-6}\ 1/^{\circ}\mathrm{C}$$

The material properties of a fully cured composite were used in the model. These properties are listed below:

$$E_x = 128290 \text{ MPa}$$

$$E_y = E_z = 7000 \text{ MPa}$$

$$G_{xy} = G_{xz} = 4270 \text{ MPa}$$

$$G_{yz} = 3000 \text{ MPa}$$

$$v_{xy} = v_{xz} = 0.288$$

$$v_{yz} = 0.300$$

The assumptions made in the numerical model presented above, that all contraction takes place when the composite material has constant elastic properties of a fully cured composite, is reasonable in the case of temperature contraction that takes place during cooling after curing. On the other hand, chemical shrinkage takes place during the cure cycle when the material stiffness is lower than that of the cured composite and the composite in resin-dominated directions has viscoelastic, not elastic properties [14]. Therefore, the calculated deformations resulting from chemical shrinkage may be encumbered with an error.

COMPARISON OF NUMERICAL AND EXPERIMENTAL RESULTS

The calculated and measured deformations are presented in Figure 6 as displacement of the inner surface of the composite element in respect of tool geometry. In the case of the calculated results, the displacement of the tool surface caused by elevated temperature during curing was subtracted from the displacement of the element surface in order to take into account the influence of thermal expansion of the tool on the process-induced deformations. Deformations of the sample element were measured by a coordinate measuring machine (CMM).

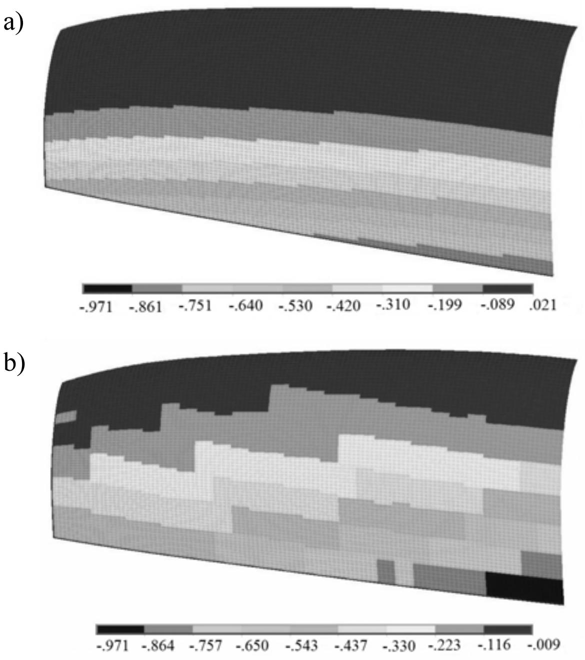

Fig. 6. Displacement [mm] of sample element inner surface in respect of tool surface: calculated (a) and measured (b)

Rys. 6. Przemieszczenie [mm] wewnętrznej powierzchni elementu próbnego względem powierzchni foremnika: obliczone (a) i zmierzone (b)

The difference between the calculated and measured deformations is up to 20% in areas where the deformations are significant. Such a difference is not negligible. However, taking into account the simplicity of the numerical model, such a difference between the calculations and measurements is not surprising.

CONCLUSIONS

The numerical model described in the present work allows one to predict approximately 80% of significant deformations induced in a double-curved composite element during the curing process. Generally, this difference is substantial and the numerical results fail to be a base to eliminate deformations. However, if we take into account that the model is very simple and requires the measurement of only two material parameters: thermal expansion and chemical strain, it proves to be a useful tool for rough prediction and compensation of undesired process-induced deformations of composite elements. Since the model predicts 80% of the deformations, its results enable compensation of the same amount of deformations, before the composite part is made, by tool geometry correction. This is a significant improvement gained by little computational and experimental effort.

It should be underlined, however, that the presented numerical model was validated for a composite element cured in a vacuum bag. In the case of elements cured in an autoclave, the tool-part interaction mechanism may not be negligible. In such a case, this mechanism should be taken into account in the numerical model as well.

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REFERENCES

[1] Ersoy N., Garstka T., Potter K., Wisnom M.R., Porter D., Stringer G., Modelling of the spring-in phenomenon in curved parts made of a thermosetting composite, Composites: Part A 2010, 41, 410-418.

[2] Dong C., Modeling the process-induced dimensional variations of general curved composite components and assemblies, Composites: Part A 2009, 40, 1210-1216.

[3] Arafath A., Vaziri R., Poursartip A., Closed-form solution for process-induced stresses and deformation of a composite part cured on a solid tool: Part II - Curved geometries, Composites: Part A 2009, 40, 1545-1557.

[4] Svanberg J.M., Holmberg J.A., Prediction of shape distortions, Part I. FE-implementation of a path dependent constitutive model, Composites: Part A 2004, 35, 711-721.

[5] Svanberg J.M., Holmberg J.A., Prediction of shape distortions Part II. Experimental validation and analysis of boundary conditions, Composites: Part A 2004, 35, 723-734.

[6] Dong C., Process-induced deformation of composite T-stiffener structures, Composite Structures 2010, 92, 1614--1619.

[7] Bapanapalli S.K., Smith L.V., A linear finite element model to predict processing-induced distortion in FRP laminates, Composites: Part A 2005, 36, 1666-1674.

[8] Fernlund G., Osooly A., Poursartip A., Vaziri R., Courdji R., Nelson K., George P., Hendrickson L., Griffith J., Finite

element based prediction of process-induced deformation of autoclaved composite structures using 2D process analysis and 3D structural analysis, Composite Structures 2003, 62, 223-234.

[9] Albert C., Fernlund G., Spring-in and warpage of angled composite laminates, Composites Science and Technology 2002, 62, 1895-1912.

[10] Radford D.W., Rennick T.S., Separating sources of manufacturing distortion in laminated composites, Journal of Reinforced Plastics and Composites 2000, 19, 621-641.

[11] Kaushik V., Raghavan J., Experimental study of tool-part interaction during autoclave processing of thermoset polymer composite structures, Composites: Part A 41 (2010) 1210-1218.

[12] Osmęda A., Measurement of strain induced by chemical shrinkage in thermoset composites, under review in Journal of Composite Materials.

[13] Yu H., Mhaisalkar S.G., Wong E.H., Observations of gelation and vitrification of a thermosetting resin during evolution of polymerization shrinkage, Macromolecular Rapid Communications 2005, 26, 1483-1487.

[14] Kim Y.K., White S.R., Stress relaxation behaviour of 3501-6 epoxy resin during cure, Polymer Engineering and Science 1996, 36, 2852-2862.