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INVESTIGATING CURE SHRINKAGE INDUCED STRESS IN THICK COMPOSITE BEAMS BY VIRTUAL MANUFACTURING

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Summary: *Investigating cure shrinkage-induced stress in thick composite beams by virtual manufacturing is the focus of this study. The research aims to understand the behaviour of thick-walled composite structures, particularly in relation to curing shrinkage-induced damages. The curing process of resin is simulated thermally and mechanically to investigate the residual cure-induced stress. The study utilizes a finite element model in Abaqus, considering material properties, mesh, boundary conditions, and user subroutines. Ten different cure cycles are investigated, showing improvements in reducing internal stresses after curing compared to the manufacturer's cycle of about 20%. However, during curing, the investigated cycles provide marginal improvements. This study demonstrates the potential for optimizing cure cycles to reduce internal stresses in thick-walled applications. It is important to note that the proposed method is not experimentally validated and requires accurate measurements for validation.*

1 INTRODUCTION

Composite materials such as Carbon Fibre Reinforced Polymers (CFRP) are well established in the aerospace sector. While the use of these materials has become more widespread, the applications are generally limited to thin-walled composite structures. However, the use of CFRP for thick-walled structures has made an appearance over the last decade [1]. The research on these types of structures is limited and therefore the behaviour is not fully understood. Moreover, the thickness introduces additional challenges for manufacturing, which has recently been mostly performed using Resin Transfer Moulding (RTM). Through experience, it has been observed that thick composite parts, especially those with complex geometries, can suffer from damages that arise from the manufacturing process. It has been theorized that this occurs due to cure shrinkage-induced stress.

Process-induced effects in composite materials have been studied extensively over the last decades. Multiple PhD researches have been dedicated to predicting distortions [2-6]. In addition, a thorough review of shape distortion models is given by Abouhamzeh [7]. The first models specifically for thick composites were developed when it was found that manufacturing thick parts could be challenging. Sensitivity analyses are frequently used to identify bottlenecks. For instance, Bogetti and Gillespie studied the effect of parameters on the residual stress and concluded residual stresses generally increased with laminate thickness with a strong relation to the temperature development [8]. Later, Grooteman did an inverse analysis to assess the sensitivity of process parameters on the spring-in of L-shape parts [9].

Many of the challenges with thick composite parts are related to the temperature. The curing process creates heat and the low conductivity of the resin results in a heat build-up within the composite. High heat peaks can result in uneven curing of the composite and this might result in high internal stresses. These overshoots were first modelled in thick composites by Hojjati and Hoa [10]. Generally thick composites show one of three curing orders: 1) outside-to-inside curing, 2) inside-to-outside curing, and 3) one-side curing, as illustrated in Figure 1. It is known that outside-to-inside curing results in higher temperatures within the composite, resulting in faster curing and consequently resulting in more cure-induced stresses. It is favourable to have either inside-to-outside curing or one-side curing to reduce cure-induced stresses.

The temperature has a significant effect on the chemical cure shrinkage. Chekanov et al. focussed on cure shrinkage and resulting cohesive defects in epoxy resins [11]. They concluded that these defects are mainly defined by gelation and vitrification processes. In addition, a high influence of temperature was observed. These experimental results were further investigated to show that it is possible to control the cure cycle to decrease shrinkage defects [12].

Numerical cure cycle optimisation for thick-sectioned RTM parts was first performed by Michaud [13-15]. While it was possible to significantly improve the average part quality, validation with experiments showed the limitations of the one-dimensional heat transfer model. Similarly, Guo et al. used a one-dimensional numerical model and found that conventional cure cycles should be modified for thick laminates [16]. Ren et al. showed that a one-dimensional model can give valid predictions for laminates with a high span-to-thickness ratio (e.g., thin laminates) [17]. Limitations of one-dimensional models resulted in the need for accurate three-dimensional models. Park et al. developed such a three-dimensional finite element model and found agreement with one- and two-dimensional models [18]. It was shown by Antonucci et al. that it is crucial to include bagging and tooling in the modelling [19]. Using a three-dimensional model Anandan et al. observed thermal spikes when using the recommended cure cycle [20]. They proposed a modified cure cycle to ensure a more homogeneous temperature distribution.

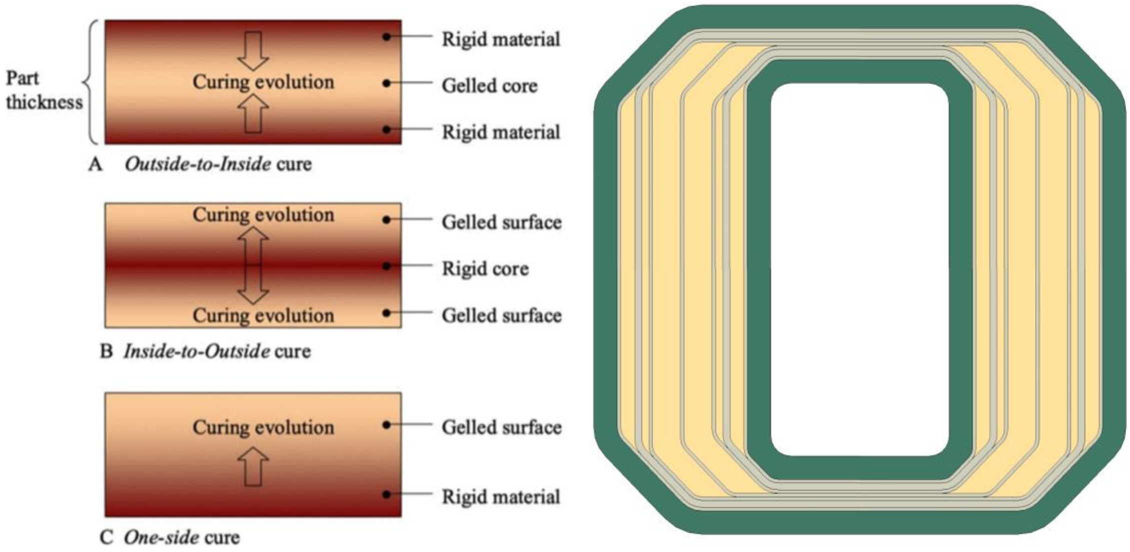

Figure 1: Graphical representation of the three different cure possibilities in thick composites [left] [24], Schematic of the cross section of the modelled brace structure [right].

Most research on process-induced defects in thick composite parts focuses on relatively simple geometries. Thick composites are more and more used for complex shaped parts. In these parts, aspects such as varying geometry can introduce or amplify process-induced defects. Therefore, this paper aims to investigate the cure shrinkage phenomenon in complex shaped parts. The curing process of resin is simulated thermally and mechanically to investigate the residual cure-induced stress. The aim is to create a modelling methodology that will allow for future optimization of the cure temperature cycle that is used to reduce cure-induced stress and prevent cure-induced damages. These resin-curing effects are most significant for complex structures. Therefore, a thick composite brace manufactured using RTM is evaluated in this paper. A cross-section of this brace is modelled in the finite element software Abaqus and is illustrated in Figure 1. This model uses a validated subroutine that calculates the state of the cure and the generated heat over time [21].

In Section 2 the used materials and overview of the modelling strategy is given. An AS4/8552 material is used because of the extensive material data available in literature [22, 4, 23]. Using this model the cure-cycle has been investigated of which the results are shown and discussed in Section 3. The main conclusions of this work are presented in Section 4.

2 MATERIALS AND METHODS

This section presents the methods and materials employed for the Finite Element Analysis (FEA) conducted in this study. The model utilized a 2D representative cross-section of a brace-like structure. The first subsection provides an in-depth description of the geometry. Subsequent sections encompass the mesh utilized, material properties, boundary conditions, user subroutines, and the investigated cure cycles.

2.1 Geometry

The chosen geometry approximates a brace-like structure commonly employed in the aerospace industry. The brace comprises of multiple layers of carbon composite material. Figure 2 visually illustrates this configuration, where the grey regions correspond to braided layers and the yellow regions correspond to unidirectional layers. For the sake of simplicity, both layer types are assumed to possess identical material properties. This assumption is made based on the minimal variation observed between the material properties of unidirectional and braided layers.

2.2 Mesh

The employed mesh, depicted in Figure 3, comprises a total of 127 linear triangular elements of type DC2D3 and 8920 linear quadrilateral elements of type DC2D4. These elements possess approximate global dimensions of 0.4 mm, providing a rough representation of the structure.

2.3 Material Properties

The material properties utilized for the aluminum and composite regions are presented in Table 1. In the case of the composite material, certain properties are dependent on the state of cure. The relationships between these properties and the cure state are provided in Figure 4, Figure 5, and Figure 6. It should be noted that the modeling of the cure mechanics involves additional material parameters, such as the coefficient of thermal expansion, which are described in detail in Section 2.5.

	Density [kg/m^3]	**Young's modulus [GPa]**	**Poisson's ratio [-]**	**Coefficient of thermal expansion [-]**
Aluminium	2072	70	0.3	$24*10^{-6}$
Carbon composite	1579.7	See Figure 4	See Figure 5	See section 2.5

Table 1: The used material properties in the model.

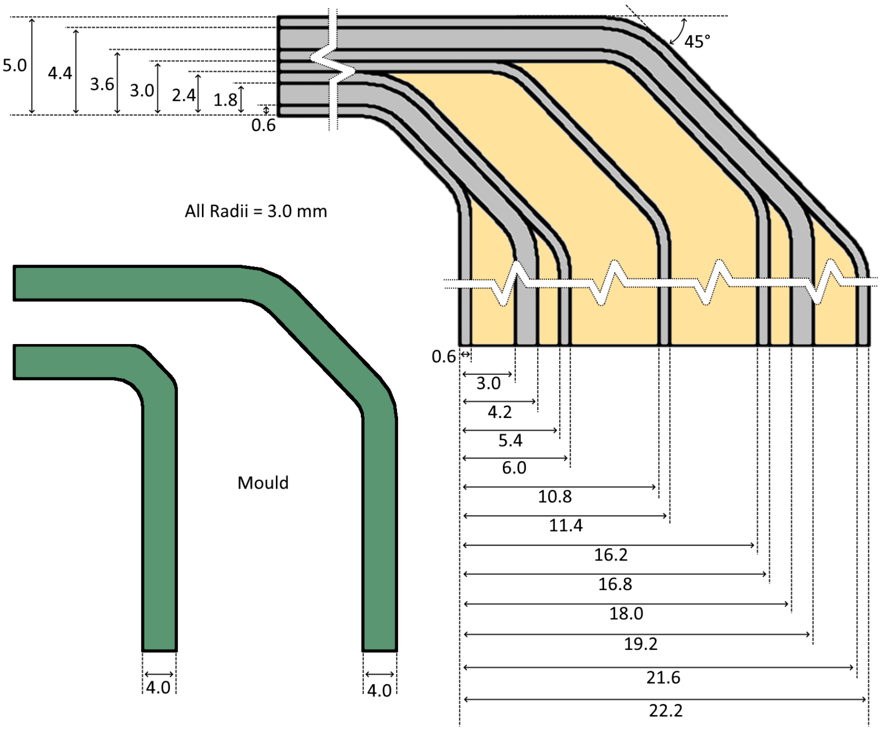

Figure 2: Dimensions of the model. All measurements given in mm. The heartlines represent break line views.

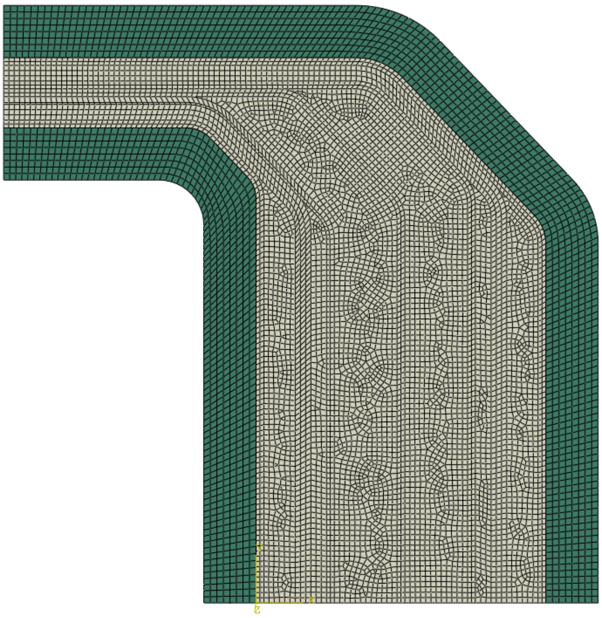

Figure 3: The mesh of the model.

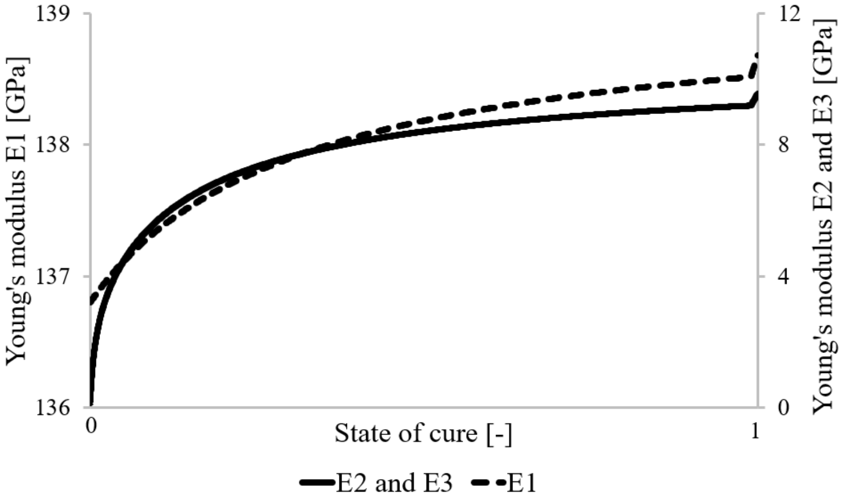

Figure 4: Graph of the Young's modulus of the carbon composite material as a function of the state of cure.

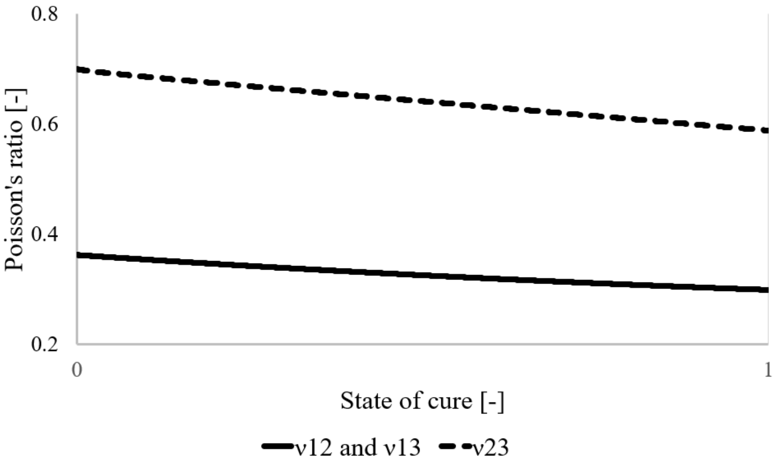

Figure 5: Graph of the Poisson's ratio of the carbon composite material as a function of the state of cure.

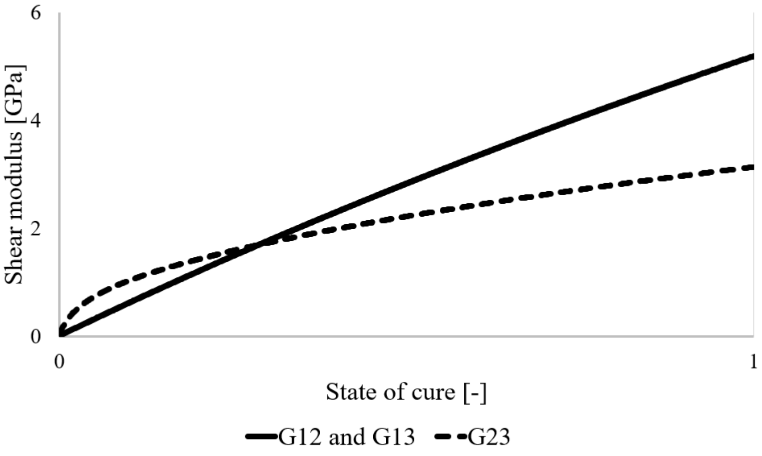

Figure 6: Graph of the shear modulus of the carbon composite material as a function of the state of cure.

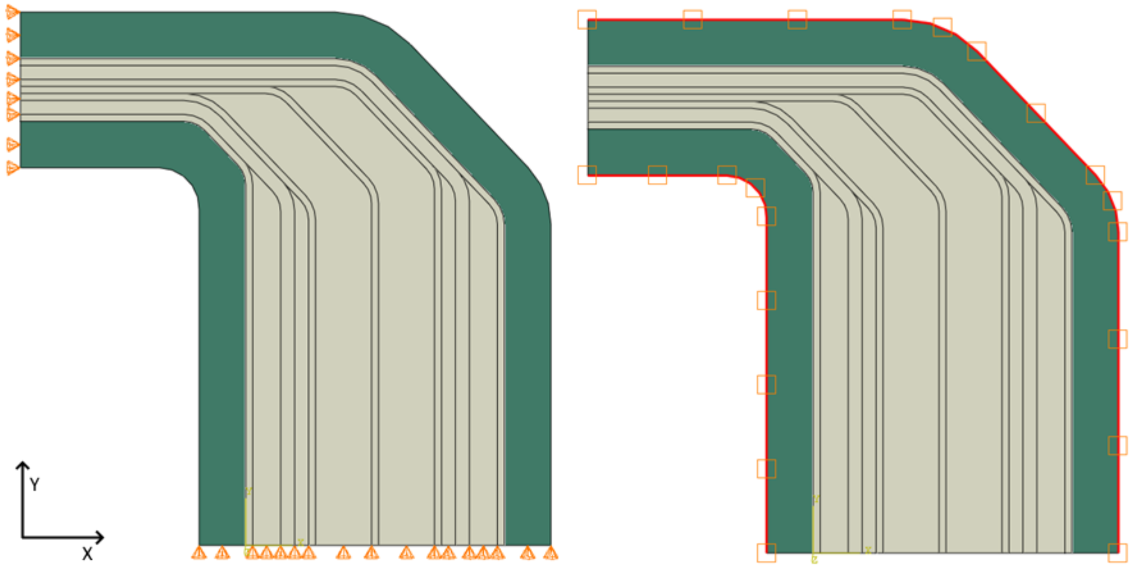

Figure 7: The applied boundary conditions. The mechanical conditions that ensure the symmetry conditions are shown on the left, the thermal boundary conditions are shown on the right.

2.4 Boundary Conditions

The applied boundary conditions are visually depicted in Figure 7. The mechanical boundary conditions are set to enforce symmetry, resulting in the left edge being fixed in the x-direction and the bottom edge being fixed in the y-direction. This arrangement ensures a global fixation of the model. On the other hand, the thermal boundary conditions are applied externally to the mould. These conditions encompass the specified thermal curing cycle.

Between the mould and carbon part, appropriate contact formulations are employed. The normal and tangential behaviour is modelled as hard frictionless contact. Additionally, a gap conductance of 800 J/s m^2 T is incorporated between these two surfaces.

2.5 User Subroutines

The analysis incorporates two user subroutines, which are comprehensively described by Koenis et al. [21], including all their inputs. Figure 8 provides a schematic overview of the analysis, which is composed of two steps: the thermal analysis followed by the mechanical analysis.

During the thermal analysis, the input variable is the cure cycle. The finite element model computes the temperature at each point. At every time increment, the subroutine USDFLD is utilized to calculate the degree of cure and the heat generated at each node. This information, combined with the cure cycle input, is employed to determine the temperatures at the subsequent time increment and so forth. Once the thermal model is solved, nodal temperatures are known at each time step, accounting for the cure mechanics.

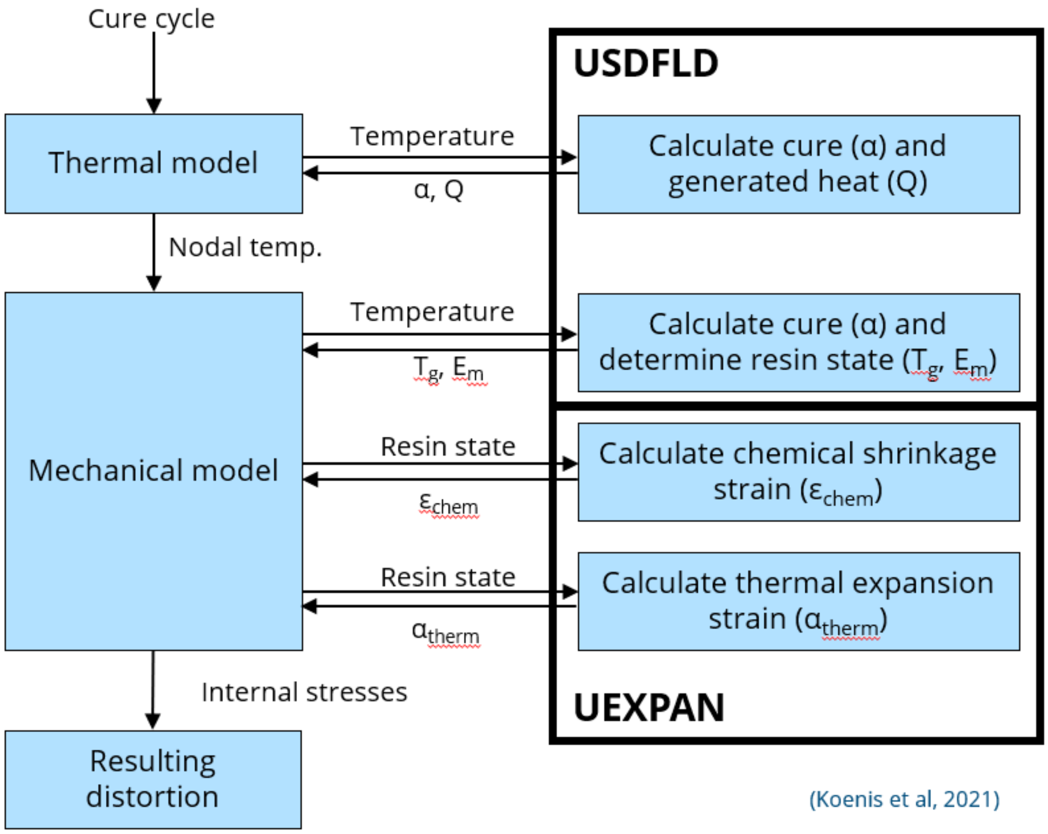

Figure 8: A schematic overview of the analysis with the inputs outputs used subroutines and transferred variables. [21]

The nodal temperatures obtained from the thermal analysis are transferred to the mechanical analysis. In the mechanical model, the USDFLD subroutine is employed to calculate the degree of cure, along with the associated glass transition temperature and Young's modulus. The outputs from the USDFLD subroutine serve as inputs for the UEXPAN subroutine, which calculates the chemical and thermal shrinkage of the composite material.

These calculated parameters, including the degree of cure, glass transition temperature, Young's modulus, and shrinkage, are then utilized in the Finite Element Analysis (FEA) to compute the internal stresses that may lead to distortion of the composite part. By considering these factors, the FEA enables the evaluation of potential internal stresses and their impact on the structural integrity of the composite component.

2.6 Evaluated Cure Cycles

This research explores ten distinct cure cycles for the RTM process. Figure 9 illustrates these cure cycles. Among them, one cycle adheres to the prescribed manufacturer's specifications. The remaining nine cycles are characterized by a consistent ramping pattern, where the manufacturer's cycle serves as the baseline. However, the slope of the ramp differs for each cycle, resulting in nine additional unique cycles. Once a cycle reaches the maximum temperature of the manufacturer's cycle, it maintains that temperature until all cycles gradually ramp down to ambient temperature at the end of the curing process. It should be noted that these cycles represent an initial attempt at exploring different types of cure cycles and have not been optimized yet.

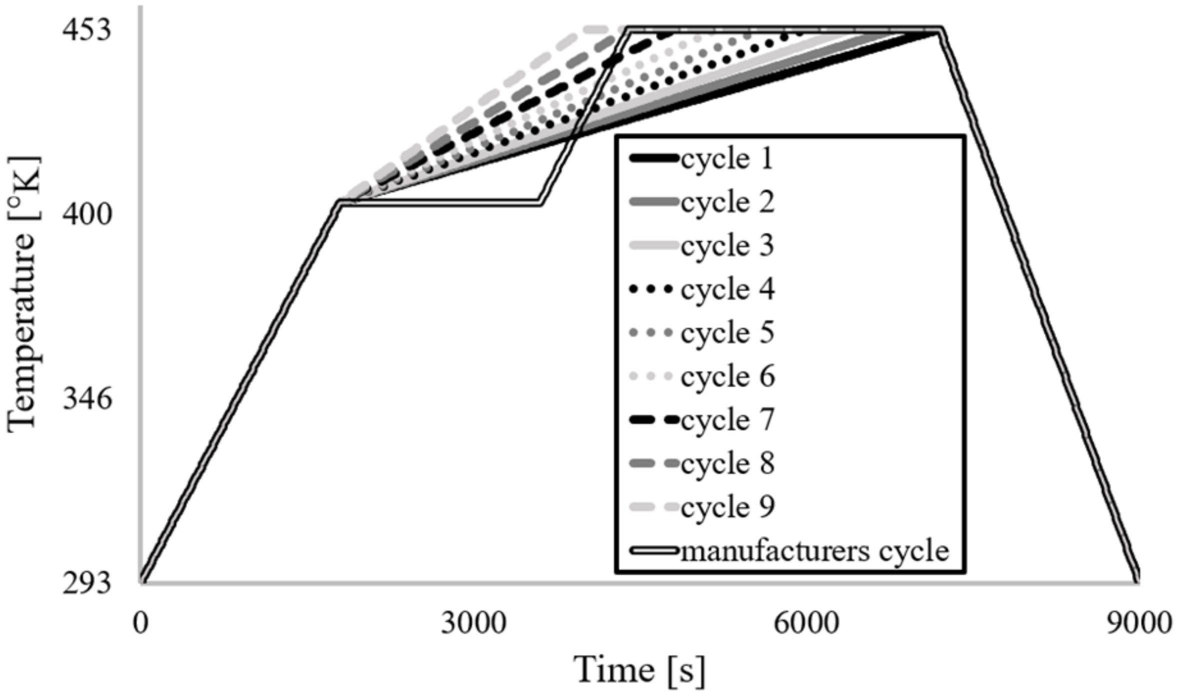

Figure 9: Graph of the ten investigated cure cycles.

3 RESULTS AND DISCUSSION

This section presents the research results obtained from the thermal and mechanical analyses, followed by their corresponding discussions. Since the thermal and mechanical analyses were conducted consecutively, the results will be discussed in a similar manner, allowing for a comprehensive examination of the findings from both analyses.

3.1 Thermal Results

The most prominent difference is observed between the manufacturer's cycle and cycle one. The results of these cycles are depicted in Figure 10 and Figure 11, respectively. Figure 10 illustrates that the manufacturer's cycle generates a high thermal peak, particularly in the middle of the composite part. This outcome is expected since the resin cure produces heat, and the conductive properties of the composite material are relatively low. The temperature in the middle of the composite reaches a level that is 80 °C higher than the temperature specified by the manufacturer's cycle. This leads to rapid local hardening of the resin, which is undesirable. In general, a more controlled and uniform cure is preferable. It is worth noting that the manufacturer's cycle has the potential to initiate a thermal runaway process, characterized by an unstable temperature increase, particularly in thicker carbon composites.

Among all the evaluated cure cycles, cycle one exhibits a significantly lower thermal peak, as shown in Figure 11. Although there is still a thermal peak that surpasses the mould temperature, it is lower and less steep compared to the peak resulting from the manufacturer's cycle. Moreover, there is no rapid curing observed. According to existing literature, this outcome is beneficial and expected to lead to lower thermal stresses.

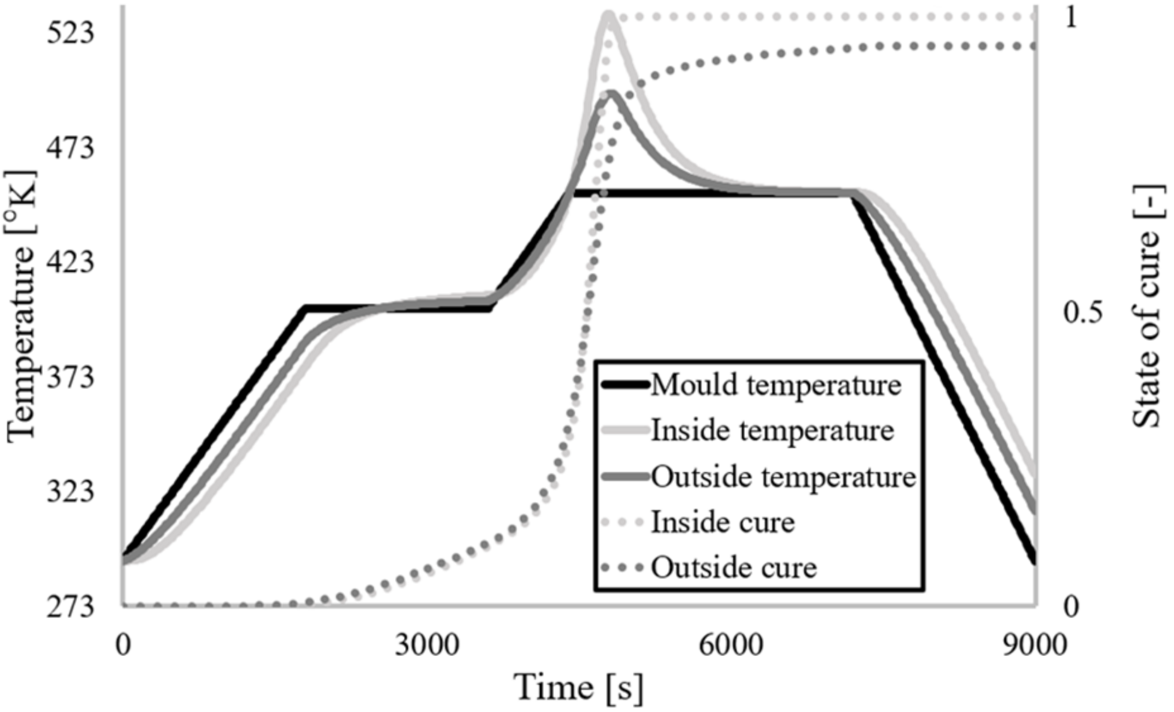

Figure 10: Results of the manufacturers cycle. Shown are the applied cycle [black solid], the outside temperature of the composite part [dark grey solid], the inside temperature of the composite part [light grey solid], the cure on the outside of the composite part [dark grey dotted] and the cure on the inside of the composite part [light grey dotted].

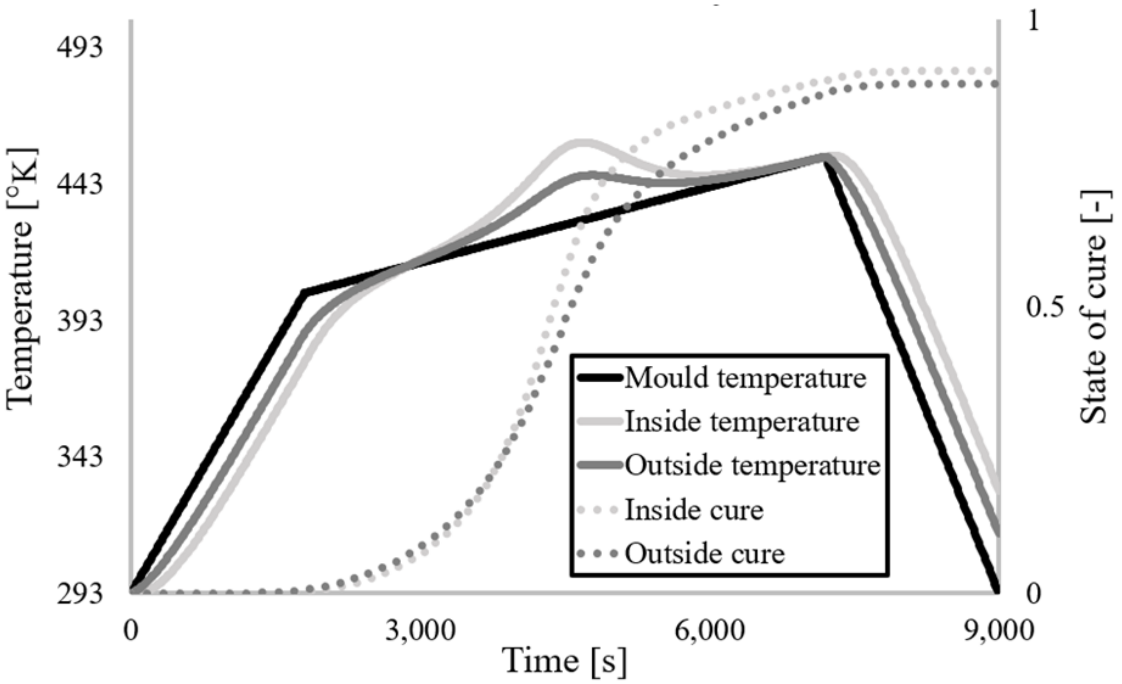

Figure 11: Results of cycle one. Shown are the applied cycle [black solid], the outside temperature of the composite part [dark grey solid], the inside temperature of the composite part [light grey solid], the cure on the outside of the composite part [dark grey dotted] and the cure on the inside of the composite part [light grey dotted].

3.2 Mechanical Results

The mechanical results primarily focus on the internal stresses generated by the resin curing process. The exact location of peak stresses is not emphasized, but rather the timing and magnitude of these peaks are taken into account. The results are presented in Table 2, which is divided into maximum stresses during curing (up to the cooldown ramp) and maximum stresses after curing (following the cooldown ramp). The resulting stresses are normalized with respect to the stresses observed in the manufacturer's cycle to facilitate comparison.

During the curing phase, the investigated cycles show marginal improvements in internal stresses. Some cycles even perform worse than the manufacturer's cycle. The reason for this discrepancy is unclear. It has been hypothesized that the absence of high internal thermal peaks should lead to improved internal stress. However, this effect is not observed when considering stress during the curing phase. It is possible that when the resin is still hot, close to its glass transition temperature, it is unable to regain high levels of stress.

After the complete curing cycle and cooldown, a substantial improvement in maximum stress is observed. All curing cycles outperform the manufacturer's cycle, with some providing up to a 20% reduction in maximum internal stress. This indicates that a customized curing cycle can significantly reduce the combined stresses induced by chemical and thermal shrinkage. Furthermore, it demonstrates that a reduced thermal peak can effectively mitigate the internal stresses caused by resin curing.

It is important to note that the investigated cure cycles are initial attempts and have not been optimized specifically for reducing internal stress. This report highlights the possibility of investigating the impact of cure cycles on internal stresses in thick composites using the proposed analysis. This opens up opportunities for optimizing cure cycles for specific applications and resin systems.

It should be acknowledged that the method proposed in this report has not been validated. Validation is challenging, as accurately measuring the temperature and cure of the resin during the process can be intrusive and affect the measurements themselves.

	Max. stress during curing [%]	Max. stress after curing [%]
Manufacturers cycle	**100**	**100**
Cycle 1	**96.4**	**79.3**
Cycle 2	96.5	79.8
Cycle 3	96.9	80.7
Cycle 4	96.8	82.0
Cycle 5	96.9	83.7
Cycle 6	97.7	85.8
Cycle 7	99.2	88.3
Cycle 8	100.6	90.7
Cycle 9	102.2	92.1

Table 2: The results of the mechanical analysis. Shown are the maximum stresses that occur during the curing and after curing and after cooldown. All stresses are normalized to the stresses that occur when the manufacturers cycle is used for easy comparison.

4 CONCLUSION AND RECOMMENDATIONS

This report demonstrates several important findings and recommendations:

Findings:

1. The proposed FEA method for investigating internal stresses induced by curing is functional and effectively highlights the impact of different cure cycles on these stresses.
2. Selecting an initial optimized cure cycle for thick composites can result in a substantial reduction in internal stresses after curing, indicating the potential for significant improvement.
3. The method is adaptable for various types of resin and fibre systems, provided sufficient material data is available.
4. The developed method serves as a robust foundation for the development of an optimization tool to further minimize internal stresses in thick composites.

Recommendations:

1. Validate the proposed method by comparing it with experimental measurements or other reliable experimental data to assess its accuracy and reliability.

2. Investigate the feasibility of adapting the method to accommodate different types of resin and fibre systems, considering that some material parameters may be challenging to measure or obtain.

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