

Cure rate tailoring of thick composites via temperature controlled vascular pathways

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Cure gradients in thick composite parts can lead to significant manufacturing defects. These gradients often arise due to temperature differentials across the part due to differentials in external heat penetration. Through the use of heated vasculature, embedded within the part, the internal temperature distribution can be manipulated to obtain a more even heat distribution. As a result, differences in cure rate across the part can be minimised thereby improving part quality. An optimisation framework that determines both the position and time-dependent temperature of the vascular pathways is outlined for prismatic sections. The internal temperature, heat transfer, and degree of cure fields are determined using finite element analysis. The results obtained demonstrate a significant improvement in the cure homogeneity across the part when compared to typical curing processes without the use of additional vascular heating.

I. Introduction

WITHIN the aerospace industry the use of composite materials has increased due to the rising demands from structural components. As a result there is increasing pressure for manufacturers of composite components to produce larger parts at a faster rate in greater numbers whilst reducing cost. Achieving these goals brings with it susceptibility to manufacturing defects, including those caused by uneven curing and exothermic heat within thick sections. Herein, we investigate the effect of manipulating the internal temperature of a part in order to achieve improved cure quality. This is achieved through the use of embedded heated vasculature.

Composite parts are typically manufactured using pre-impregnated plies that are processed using an autoclave cure cycle - where pressure and temperature is applied to the part. Manufacturing defects, such as warpage, porosity and residual stresses are caused, in part, by gradients in temperature and associated variation in the cure profile across the component.¹ Thick composite parts are particularly susceptible to the effects of temperature gradients as the external heating of the autoclave does not reach all internal points simultaneously. In addition, the heat of reaction, produced by the exothermic curing of the resin, often fails to dissipate within a thick structure elevating the internal temperature significantly.

The typical cure cycle is modified to reduce the impact of temperature variation and several papers have investigated the optimal autoclave curing process.^{2,3} This often comes with an associated increase in cure time and manufacturing cost. As such, even with proven improvements in cure cycle there is significant scope to optimise the cure profile of components, particularly for thick parts and complex geometries.

We propose that through the introduction of a secondary temperature control mechanism, using a vascular network embedded in the component, cure quality can be significantly improved. However, the approach is not limited to autoclave manufacture. With an appropriate vascular network it may be possible to provide the primary heating mechanism internally, utilising the exothermic reaction to our advantage. This could provide an alternative manufacturing technique by which the finished quality of larger and more complex systems could be improved.

Vascular networks have been successfully employed to control the temperature within manufactured components.⁴⁻⁷ Biological systems often provide inspiration for such networks, having evolved complex networks of vasculature to perform a variety of multi-functional tasks, of which thermal regulation is one

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such example.^{8,9} A recent optimisation study of the vascular topology in carbon fibre reinforced polymer (CFRP) blades in gas turbines, demonstrated significant potential to control temperature to aid cooling.¹⁰ Despite the success of vasculature for thermal management of composites in use, there is a lack of literature relating to how these same thermal control mechanism can be exploited during the cure cycle. Such control is of specific interest for manufacturers of larger composite structures, such as turbine blades, where control of cure at the root section compared to the wing tip is critical. A preliminary investigation into the capacity of the vascular networks to mitigate temperature overshoot caused by exothermic reactions demonstrated some success.¹¹ In particular their experimental analysis, a nylon vasculature system connected to a hot water bath using a peristaltic pump, provides an indication of how the proposed vascular system could be implemented in practice. Indeed, there are a number of successful studies on the inclusion of vascular networks within composite structures demonstrating they are feasible to manufacture without compromising structural integrity excessively.^{8,12,13}

The primary aim of this study is to demonstrate how the vascular temperature can be tuned to complement a typical autoclave heating cycle. The vascular pathways allow both the inclusion of extra heat flux to be transmitted to internal sections, minimising cure gradients, and extracting heat, by holding the vasculature at a lower temperature, where there is excessive heat generation from curing of the matrix. This behaviour is investigated for prismatic sections using a Finite Element Analysis (FEA) in ABAQUS FEA using an additional Fortran subroutine (HETVAL) to calculate heat generation and track the degree of cure.¹⁴ This is achieved via a state-dependent variable within the material property assignment. Both the position and the temperature profile of the vasculature is optimised using a gradient based approach. Although gradient based methods do not guarantee global optimality in non-convex problems the significant analysis cost associated with alternative meta-heuristic approaches justifies their usage. As is discussed in more detail in section III this gradient based approach comes with some limitations.

The vascular networks included for curing purposes could additionally be used to provide multi-functionality as a manufactured component. We believe that there is scope to develop multiple use vascular networks, considering behaviour from cure, to in-use multi-functionality and possible self healing mechanisms, however this is beyond the scope of the current preliminary investigation. Ultimately, this research should be seen as the initial stages of developing a *multi*-multi-functional material.

We proceed in the following manner. We begin by providing an outline of the modelling approach used to describe heat flow and cure properties of the part including details of the FEA. The second section presents a general optimisation framework that is adapted for each of the results presented. We follow this general approach with examples of cure homogeneity tailoring for the following scenarios: The temperature profile of a single fixed vasculature in a rectangular section; the optimal position and temperature of a single vasculature in both rectangular and tapered sections; multiple vasculatures, held at fixed locations within a tapered section, possessing a common vascular temperature profile for both autoclave and Out-Of-Autoclave (OOA) boundary profiles; and the optimal position and temperature of multiple vasculatures within a tapered section.

II. Heat and cure profile model development

The time, t , dependent heat profile of the part, subject to internal heat generation, can be described by the differential equation,

$$\frac{\partial u}{\partial t} = \frac{k}{c_p \rho} \nabla^2 u + \frac{q(t)}{c_p \rho}, \quad (1)$$

where u is the heat distribution, k is the thermal conductivity, ρ the mass density c_p the specific heat capacity and q internal heat generation associated with the curing of the composite. We assume that the behaviour is sufficiently well described by an isotropic material. For two-dimensional prismatic sections, equation (1) can readily be solved using the FEA, this has been described in detail and is not repeated here (e.g. Reddy and Gartling (2010)).¹⁵

The degree of cure, α , can be determined for typical polymeric resins via the following temperature T cure rate equation,¹⁶

$$\frac{d\alpha}{dt} = C_1 e^{(-E_1/RT)} + C_2 e^{(-E_2/RT)} \alpha^m (1 - \alpha)^n, \quad (2)$$

where $C_{1,2}$, $E_{1,2}$, m , and n are the cure kinetics parameters, as determined by the material properties, and R is the gas constant. The cure rate, described by equation 2, can often be extended to include additional cure parameters, but the current description is sufficient to capture the behaviour of a typical polymeric resin. The rate of internal heat generation due to the exothermic reaction of cure is related

to the rate of cure and given by,

$$\frac{dq}{dt} = \Delta q \rho \frac{d\alpha}{dt}, \quad (3)$$

where Δq is the total energy released from curing a unit volume of material. The time dependent internal heat profile $q(t)$ and the cure profile $\alpha(t)$ can be found using Euler's method.

Referring to a representative section, figure 1, the external boundary temperature, $\Omega(t)$ is typically dictated by the autoclave's cure cycle. Each of the vascular pathways, v_i , possess the same associated internal boundary, $\Gamma(t)$, that can manipulated to affect differing internal heat profiles. A common vascular temperature distribution is selected to minimise the number of design variables, however this could be extended in future to allow consideration of independent vascular temperature profiles. The initial internal temperature of the body is assumed to match that of the autoclave cycle at the beginning of cure, i.e. the part begins the cure cycle at room temperature.

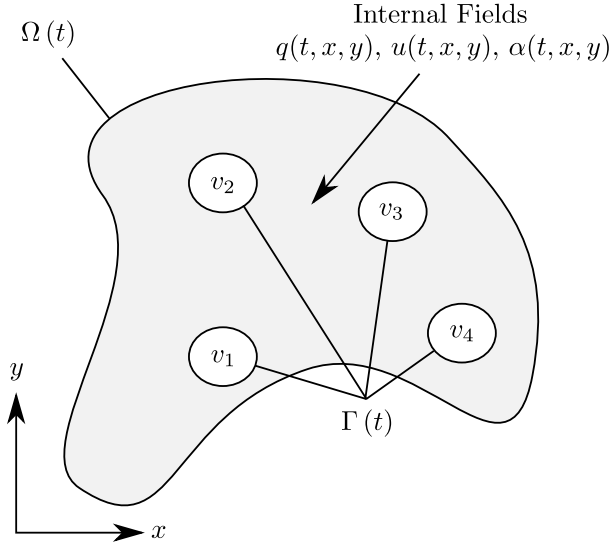


Figure 1: Example of a general two dimensional section with external, $\Omega(t)$, and internal $\Gamma(t)$ boundary conditions for each vasculature position, v_i , together with calculated internal fields $q(t, x, y)$, $u(t, x, y)$, and $\alpha(t, x, y)$.

Following the approach of Wisnom and Li (2002) ABAQUS FEA can be utilised to calculate the cure behaviour using a suitable user sub-routine.¹⁷ An example of a typical prismatic section in a partially cured state is shown in figure 2. The relatively coarse mesh utilised provides sufficient resolution to capture the cure behaviour over the cross section. The results have been compared to those with a finer mesh and there is no significant variation.

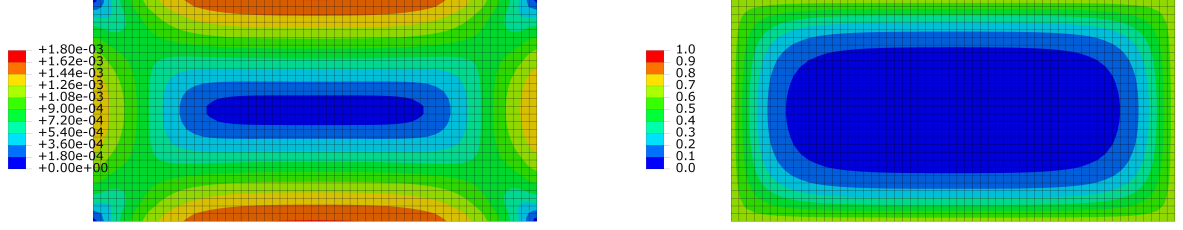
Increasing the number of elements introduces a significant analysis time penalty due to post-processing of the ABAQUS FEA results database ('.odb' files) using Python scripts.^a In future investigations we hope to split the '.odb' file and use a C++ post-processor to alleviate some of these constraints. We now proceed to outline the optimisation framework.

III. Optimisation framework

The objective of the optimisation process is to determine the optimised position v_i and temperature distribution $\Gamma(t)$ of the vasculature, see figure 1, subject to a heated external boundary temperature condition, $\Omega(t)$. The external boundary representing a basic cure cycle, may be described by a piecewise linear function, see table 1. Since the part is totally cured in this time, we make a restriction that any system possessing a vascular network must not exceed this cure time. This restriction is necessary as the epoxy continues to cure at all non-zero temperatures, and the optimiser may seek to obtain a very low temperature cure, with a long cure cycle if not appropriately constrained. By fixing the external boundary condition it is possible to investigate the effect of the vasculature. To obtain further optimised designs, the boundary temperature profile could be optimised in conjunction with the internal one.

Similarly the vascular temperature distribution may be described by a piecewise linear function. We constrain this function so as to allow vasculature temperatures between room and a nominal maximum

^aWe would like to acknowledge the abapy module¹⁸ that provided assistance in developing our own post-processing scripts for ABAQUS FEA.



(a) Typical internal heat flux profile observed.

(b) Typical internal cure profile observed.

Figure 2: Example of a thick rectangular section observed mid-cure showing uneven heat flux and cure distribution leading to possible manufacturing defects.

autoclave temperature, $\Gamma(t) \in [295, 455]$ K. The piecewise linear temperature is specified at regular intervals, γ_i , throughout the cure cycle, where the initial temperature is, $\Gamma(0) = 295$ K.

The analysis assumes that the heat flux required to maintain the demanded temperature can be achieved by the vasculature and that any cooling along the vasculature's depth is negligible. The investigated prismatic section are therefore assumed to be representative of a typical internal cross section. The cross section of a vasculature is defined by circle of radius, r , where its position is specified by the centre points coordinates. These locating points may be positioned arbitrarily within the cross-section provided the vasculature does not cross the sections boundary or cause an intersection with another vasculature. While a more general topology based approach is also possible, the current method is sufficient to demonstrate behaviour without introducing additional modelling complexity.

In reality, the permitted position of the vasculatures would be more discrete in nature, owing to the laminar construction. As we are concerned with thick composites the difference between the discrete and continuous system is small and the advantage of a continuous optimisation variable make this assumption appropriate.

With the variables suitably defined the objective function can be defined. Since we seek to minimise the cure gradient over the representative cross section we can utilise the variation from the mean cure over the cross sectional area as a function of time,

$$\text{obj} := \frac{1}{t_c} \int_0^{t_c} \left(\int_A |\alpha(t) - \bar{\alpha}(t)| dA \right) dt, \quad (4)$$

where $\bar{\alpha}(t)$ is the mean cure over the cross section, and t_c is the time at which cure is nominally complete in the entire section - noting that t_c need not correspond to the maximum permitted cure period. Such a definition avoids an optimal strategy that cures the part very rapidly to exploit the fact that once fully cured there can be no cure gradients. This objective function is based on the continuous, in both time and space, cure $\alpha(t, x, y)$. Using FEA we obtain a discrete solution that approximates this function therefore we use an appropriate weighted summation.

It is important to note that the proposed objective function does not take into account any reduction in the structural performance of the system. The inclusion of vascular channels reduces the structural integrity of the part and their positioning within the system may lead to reduction in performance.¹⁹ While we acknowledge the significance of operational structural performance we have not accounted for this in our objective function or constraints so as to isolate the impact on curing aspects. In future works a suitable failure analysis could be included as an additional constraint in the optimisation process. The trade off between improved manufactured quality and reduction in performance could then be demonstrated. Furthermore, using the vasculatures for *multi*-multi-functional purposes could also mitigate structural performance losses.

The optimisation can thus be summarised as,

$$\min_x \text{obj}(x) \text{ such that } \begin{cases} 0 \leq x \leq 1 \\ c(x) \leq 0 \end{cases}, \quad (5)$$

where, $x = [v_1, v_2, \dots, v_m, \gamma_1, \gamma_2, \dots, \gamma_n]$, contains the design variables and $c(x)$, represents a non-linear constraint testing for intersection of the vasculatures. The upper and lower bound range $x \in [0, 1]$ is transformed into the appropriate physical rectangular and trapezoidal positions or temperature range, for

example,

$$T(\gamma_i) = T_l + \gamma_i(T_u - T_l), \quad (6)$$

with T_l and T_u the lower and upper permissible temperatures i.e. 295 K and 455 K. The optimisation procedure can be implemented using a gradient based algorithm via “*fmincon*” in MATLAB.²⁰ As the optimisation algorithm does not always respect the non-linear constraint at all iterations a penalty cost function is instead returned,

$$\text{penalty obj} := \exp\left(\max_x(c(x))\right) \cdot 2C_N, \quad (7)$$

where C_N is the nominal cost of the objective function for the initial feasible design. Such a penalty function is chosen to minimise the impact of discrete changes in the objective function.

As the feasibility of the optimisation is restricted by the computational cost we have selected a gradient based optimisation. Gradient based optimisation techniques are limited by their deterministic nature and so converge to local optima in non-convex problems. For the relatively simple geometries considered in this example we note that the algorithm has reasonable success, particularly for obtaining optimised temperature fields. However, when determining the optimised position for multiple vasculi local minima can cause convergence to sub-optimal designs. This, in part, is due to smoothness lost in the objective function from the introduction of a penalty function in order to satisfy the non-linear intersection constraints.

Meta-heuristic approaches may provide an alternative optimisation mechanism, particularly when considering more complex geometries. However, the increased number of function evaluations may impact the feasibility of such approaches, particularly as the number of design variables increases. Such an approach was beyond the scope of this study but is a relatively straightforward extension. We now discuss the optimisation, and reliability of results, for various representative systems.

IV. Optimisation results

In this section we present the results of a series of optimisation processes. We increase the complexity, and therefore the number of design variables at each stage of the process. The external temperature profiles utilised in the optimisation process are, given in table 1. These are based around a ramp rate of approximately 2-3 K per minute for the autoclave and 1 K for the OOA. While more complex cure and dwell cycles are often recommended, these profiles are sufficiently representative of temperatures experienced within the autoclave and OOA manufacturing processes. We acknowledge that the differences between in and OOA cure cycles are, in reality, more complex than simply changing the external boundary, for example pressure issues for thermal transfer. However, changing the boundary temperature gives some insight into the thermal manipulation requirements for longer cure cycles.

In our study, we consider both a rectangular and a tapered section geometry 2a that provide insight into the curing behaviour. We note that the vasculi diameter of 10mm, was selected based on a potential manufacturing methods using pultruded hollow rods. While these methods have been considered, the diameter selection is taken as a nominal value at this stage. As a secondary consideration a larger vascular diameter aids meshing of the part for ABAQUS FEA.

We now present a series of results: The temperature profile of a single fixed vasculi in a rectangular section; the optimal position and temperature of a single vasculi in both rectangular and tapered sections; multiple vasculi, held at fixed locations within a tapered section, possessing a common vascular temperature profile for both autoclave and OOA boundary profiles; and the optimal position and temperature of multiple vasculi within a tapered section.

Table 1: External Boundary Temperature Profiles.

(a) Autoclave cure cycle.		(b) Out of autoclave cure cycle.	
Time (s)	Temperature (K)	Time (s)	Temperature (K)
0	295	0	295
4200	455	4500	355
7200	455	36000	355

Table 2: System geometry and material properties.

(a) Geometries considered.			
Dimension, mm		Rectangular	Tapered
L_x		200	200
L_y		100	100
ΔL_y		0	50
r		5	5

(b) System material properties.			
Representative epoxy (fibre volume fraction 69%)			
k	4.64e-4 W mm-1 K-1	ρ	2.135e-06 kg mm-3
c_p	1.0e+3 J kg-1	C_1	4.3e+5 min-1
E_1	6.0e4 J mol-1 K-1	C_2	6.3e+7 min-1
E_2	6.0e4 J mol-1 K-1	m	1.358
n	1.718		

A. Single heated vascule located at a fixed position

In order to evaluate how the vascule responds to the external autoclave heating cycle (table 1a) we considered the behaviour of a single vascule located in the lower left quadrant of a rectangular section (table 2a), as indicated in figure 3. Comparing the example cure profile with no additional vascular heating, figure 3a with the optimised solution 3b, we can observe that the additional heating provided by the vascule enables a more even cure. Note that in the no heating example the vascular temperature is not held constant, it is free to vary such that it matches the surrounding internal temperature. It is clear from this comparison that the vascule provides a mechanism through which heat can be delivered to the centre of the section more effectively.

The optimised temperature profile can be observed in figure 4a. It is interesting to note that the optimised solution does not initiate maximal heating at all times. As can be seen, the temperature profile initially increases in-line with the cure cycle, however a plateau, that may account for delays in heat transfer to the inner regions of the part is observed.

The result of the improved cure can be visualised by inspecting the normalised variance as a function of normalised time, figure 4b. The variance normalisation is taken with respect to the maximum observed value and the time normalised by the maximum permissible cure length (7200 s). The objective function can be visualised as minimising the area underneath these curves, scaled by the actual cure time t_c . It can be seen that The improvement in cure variance over the cycle, from the unheated to optimised vascular system represents a change of approximately 11%.

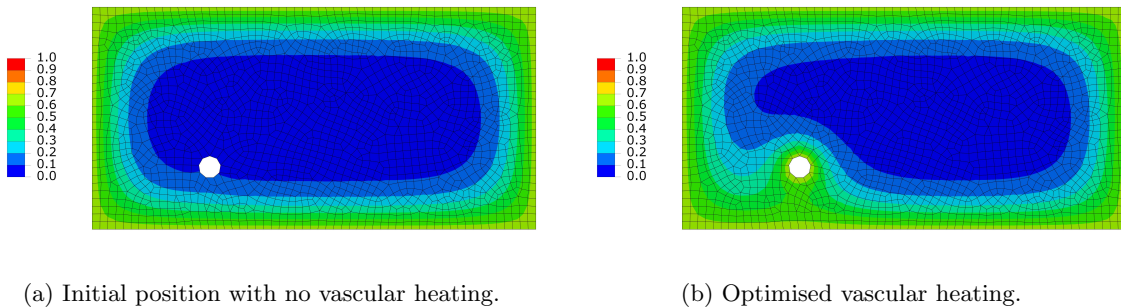
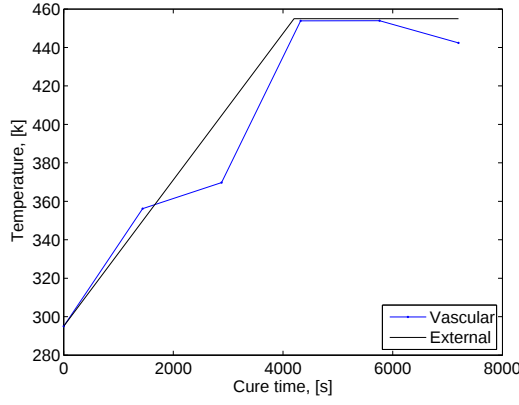
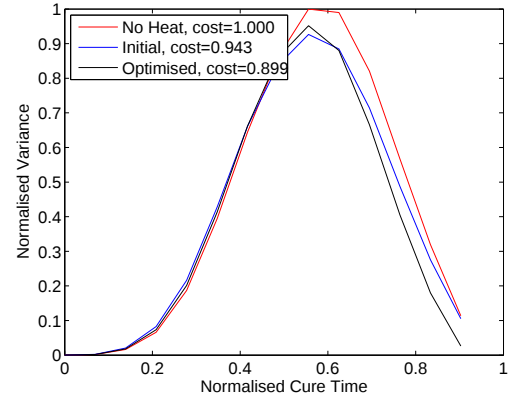


Figure 3: Examples of state of cure for rectangular section, with fixed vascule position, at mid-cycle for initial and optimised designs.



(a) Temperature profile of the autoclave and optimised vasculature.



(b) Normalised variance in cure during cycle - unheated, initial and optimised profiles. .

Figure 4: Results of the temperature optimisation for a single vasculature.

B. Moving vascular position and variable temperature profile

Having demonstrated a significant reduction in the cure variance by tailoring the internal vascular temperature we now consider designs where the vascular position is not fixed. We first consider a rectangular section, figure 5. By comparing the mid-cycle of the cure profile for the non-heated, initial, and optimised vascular positions, it can be seen that by moving the vasculature to the centre of the part cure variance is decreased. Unlike the off-centre vasculature, figure 4a, the temperature profile for the central vasculature, figure 6a, has a more distinct plateau. This behaviour likely reflects the ability to avoid overheating in the central region due to exothermic heat build up by maintaining a lower surrounding temperature.

A second profile with a tapered section geometry, table 2a, was also considered where a similar optimised result is observed. In this instance the vascular position reflected the tapered geometry. Results of the mid-cycle cure profile can be seen in figure 7. In this scenario the initial position for the vasculature was selected to be the mid-point of the feasible domain. The temperature profile observed in the tapered section, figure 8a, does not have the same pronounced plateau. This suggests that the vasculature is reacting to the region of reduced depth, that cures more rapidly, and the vasculature tries to match this cure profile in the deeper region. Despite the differences in temperature profiles the two scenarios offer a significant reduction in cure variance of around 28% and 27%.

C. Multiple vasculatures

Significant improvements in the cure quality can be achieved through the use of a single optimised vasculature. However, the effective control of the cure cycle can be extended through the inclusion of a series of vascular channels. In this scenario six vasculatures were distributed along the centre line of the tapered section in a fixed position.

Comparing the optimised solution, figure 9b with the non-heated vascular system, figure 9a, a significant increase in the homogeneity of the cure profile is observed. The temperature profile of the vasculatures, figure 10a, matches the initial stages of the autoclave cycle but the temperature is reduced in order to prevent excessive heat build up in the centre of the part. A significant improvement is seen in the normalised variance, figure 10b, and reflects a reduction of approximately 65%. This is a significant result demonstrating the potential of this approach to thermal management during cure.

A second analysis, utilising the OOA, cure cycle was analysed for the same geometry. The lower temperature and extended cure cycle presents the possibility of increased optimisation tailoring. Although the unheated cure profile is relatively homogeneous, figure 11a, it can still be improved significantly through vascular optimisation, figure 11c, with a reduction in cure variance of 72% observed, figure 12b. Sub-optimal vascular temperatures can be detrimental and this is illustrated by a significant increase in the variance observed in the initial vascular heating configuration, figure 11b. The optimised temperature profile of the vasculatures, figure 12a, can be observed to react to external boundary temperature. While the exact physical cause of the oscillating profile has not been established it is possible that the vasculatures are acting to mitigate exothermic build up. We now seek to optimise vascular behaviour further, by allowing movement of the vasculature's position within the part.

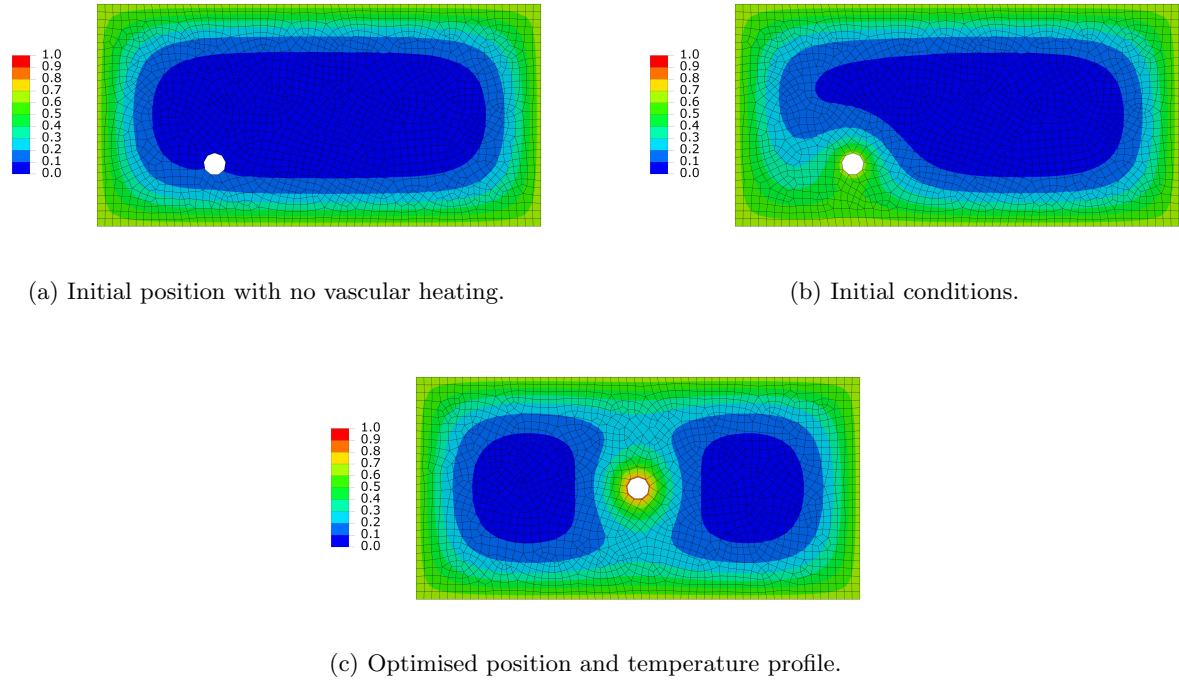


Figure 5: Examples of the state of cure for rectangular section at mid-cycle for no-vascular heating, initial conditions, and optimised designs.

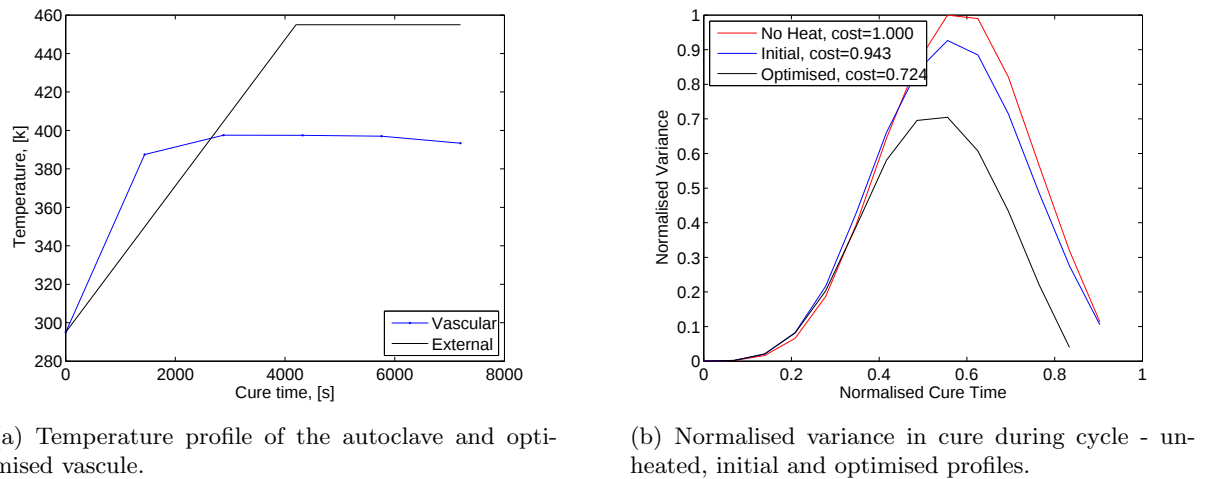


Figure 6: Results of the optimisation for a single vasculature's position and temperature in a rectangular section.

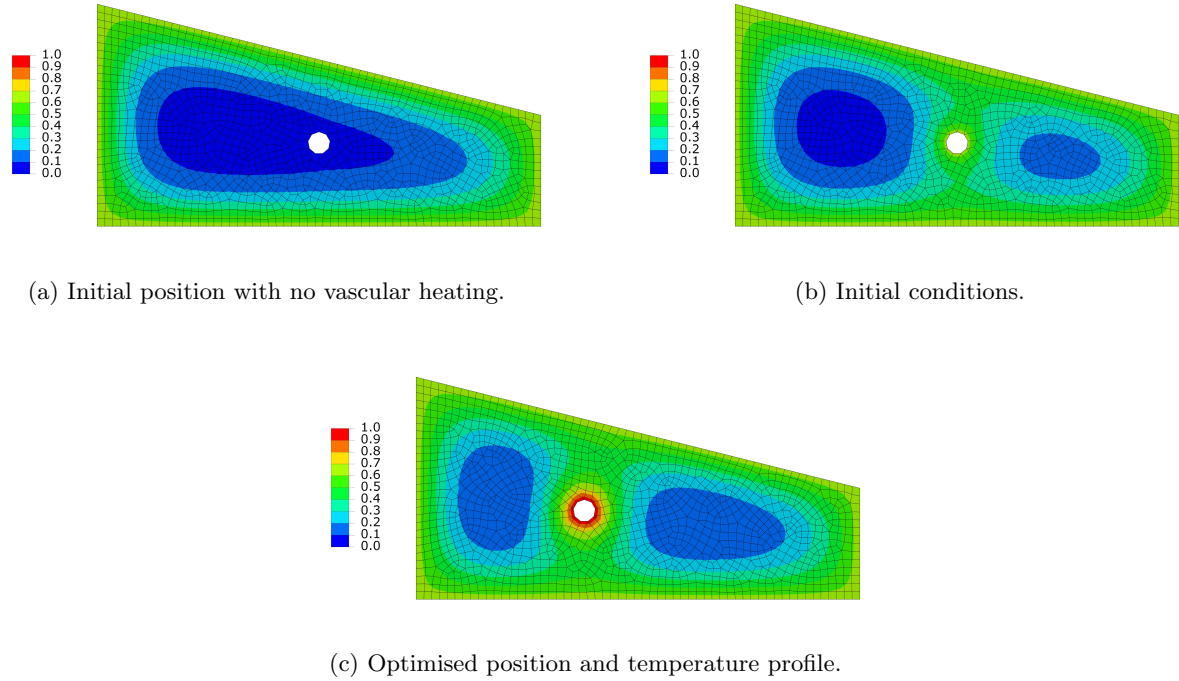


Figure 7: Examples of state of cure for tapered section mid-cycle for unheated, initial, and optimised designs.

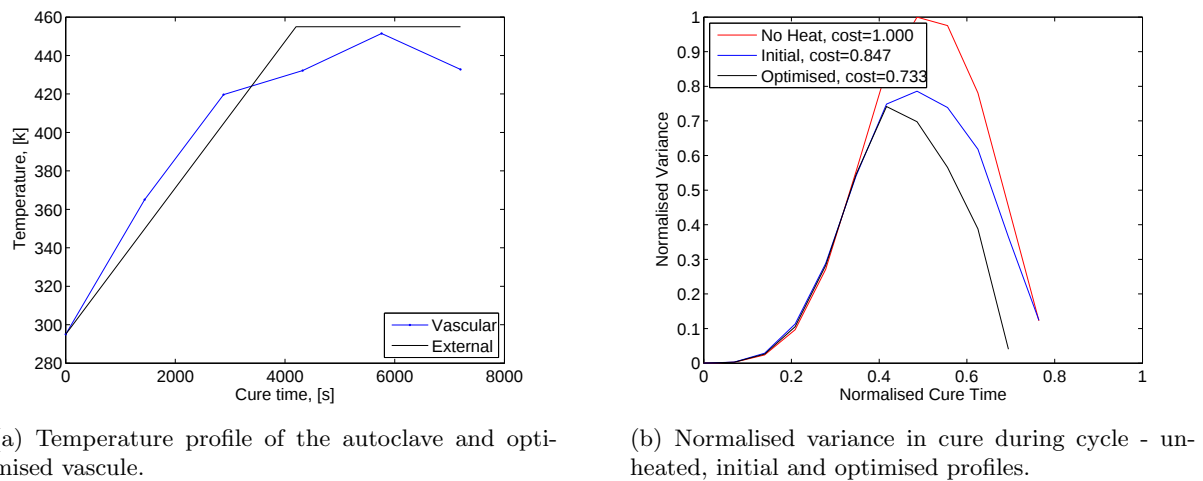


Figure 8: Results of the optimisation for a single vasculature's position and temperature in a tapered section.

In order to provide additional design freedom the autoclave cycle optimisation was extended to introduced variable vascular position. The initial conditions, shown in figure 13b, reflects a regular spacing in the feasible interval for each variable. The results of the optimisation, shown in figure 13c, appear to show convergence to a local optima. These results from this scenario are presented for completeness, however, further ongoing investigation is required before drawing final conclusions regarding these results.

Although the results shown in figure 13 appear to show a sub-optimal design, when inspecting the iterative output of the cost function, there is improvement from the initial conditions as is expected from a gradient based optimiser. There remains scope to investigate if convergence to this solution is driven by the physical characteristics of the system or is a manifestation of local minima in the objective function. It is possible that this behaviour is caused by the non-smooth transition between objective and penalty objective functions. Such a penalty function was required since the gradient based algorithm respects upper and lower bounds for the variables but it does not guarantee the feasibility of the non-linear constraints that govern vascular intersection. Several alternatives exist that may improve the objective function's behaviour that may improve the robustness of the final solution. For example allowing vascular intersection would remove the need for the penalty function. Alternatively, using a vascular distribution function rather than specifying individual vasculature positions would remove the need to test for intersections. These changes are beyond the scope of the current analysis and will be considered in ongoing investigations.

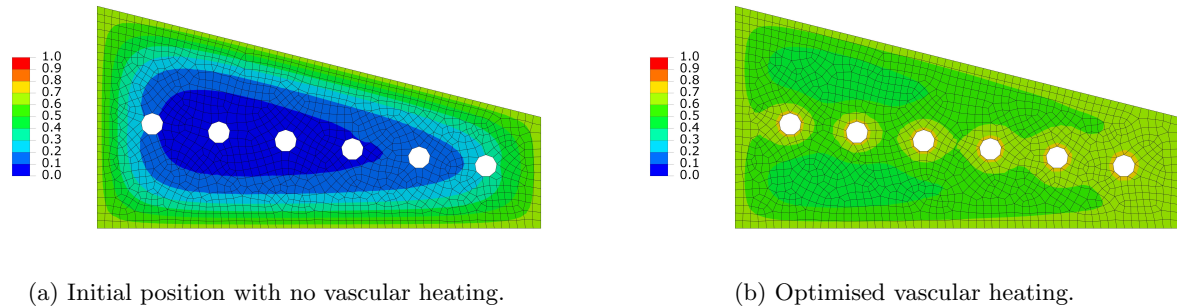


Figure 9: Examples of state of cure for tapered section mid-cycle, autoclave, for unheated and optimised vascular temperature.

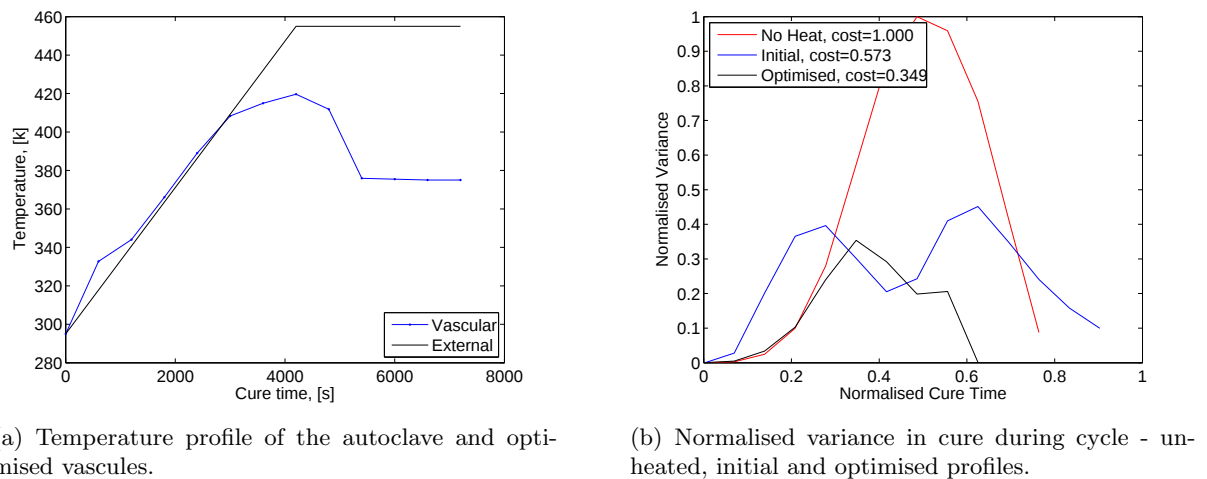


Figure 10: Results of the temperature optimisation for multiple fixed vasculature with autoclave external conditions.

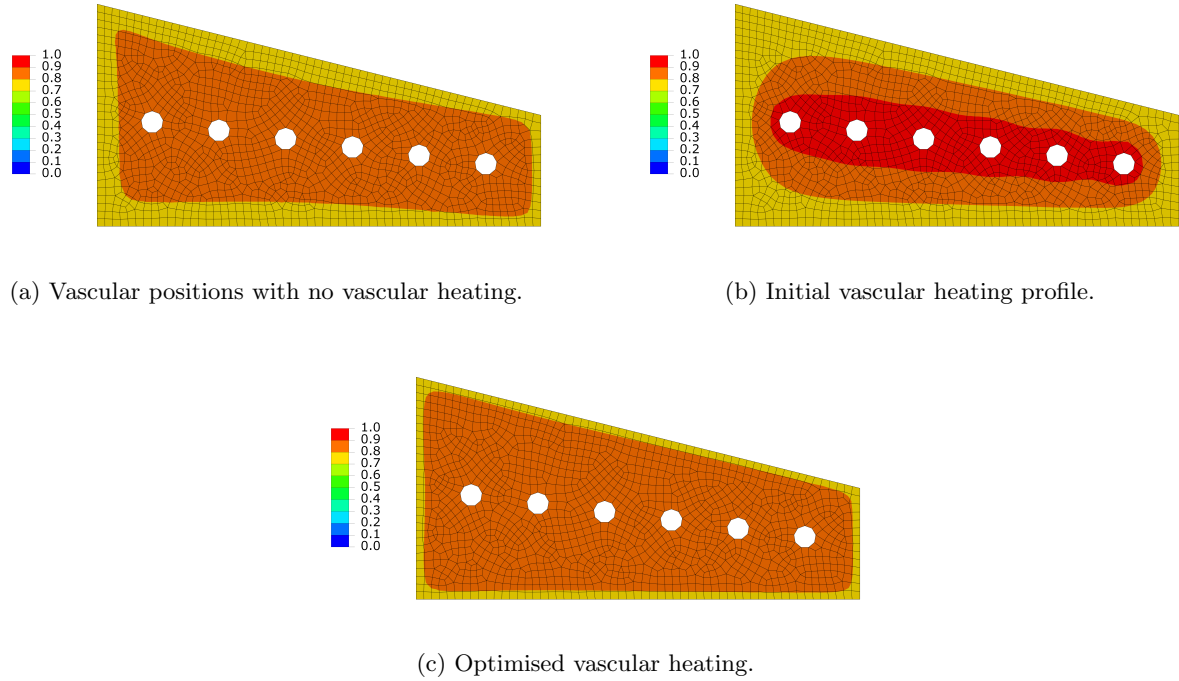


Figure 11: Examples of state of cure for tapered section mid-cycle, OOA, for unheated, initial, and optimised vascular temperature.

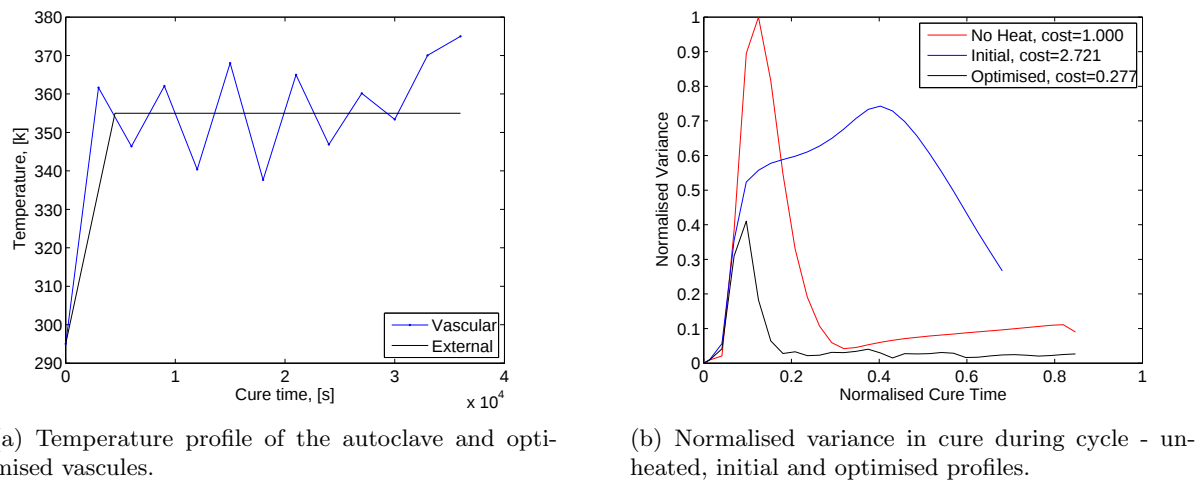


Figure 12: Results of the temperature optimisation for multiple fixed vasculature with OOA external conditions.

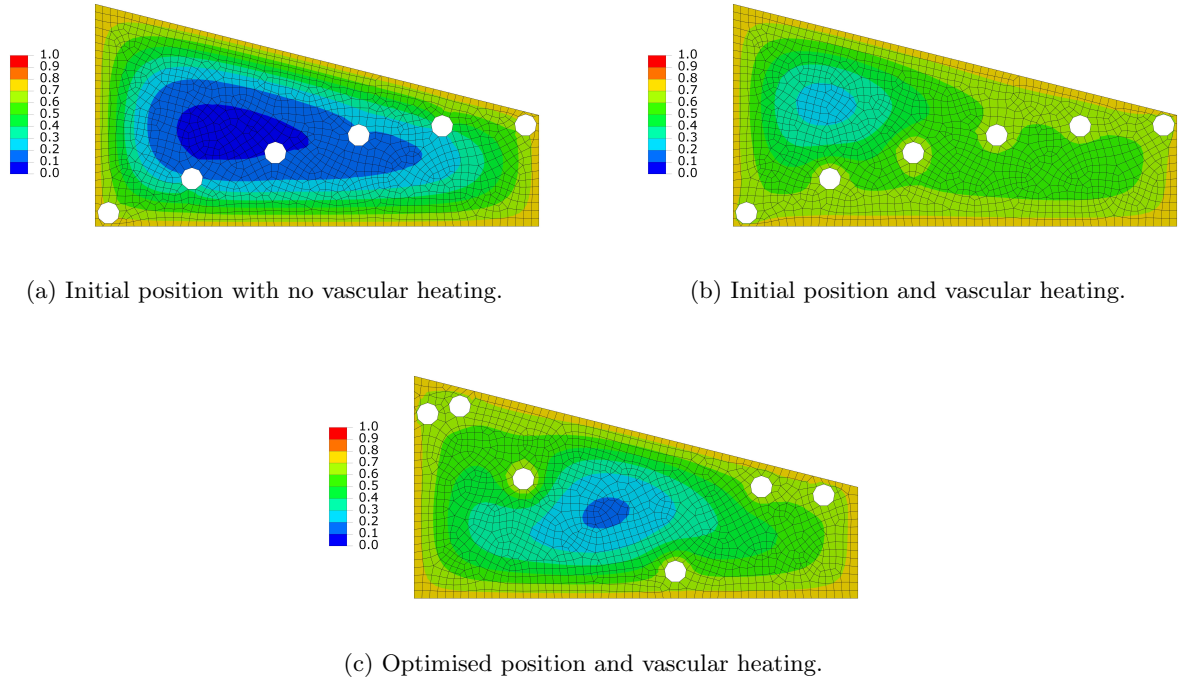


Figure 13: Examples of state of cure for tapered section mid-cycle for unheated, initial vascular position and temperature and optimised designs for autoclave cure cycle.

D. Summary of results

Our analysis shows improvements in the variation of cure for all the observed scenarios, table 3. These improvements indicate the potential of vascular heating control to produce higher quality parts in a variety of manufacturing methods.

We have observed vascular temperature profiles that react to the external heating cycle. This result suggests that further improvements could be realised by optimising both the autoclave cycle and interior vascular network. Our investigation assumed a common vascular temperature, however increasing design freedom to allow independent vascular temperatures could improve the cure quality further. In particular where the thickness varies significantly.

When comparing the normalised variance profiles a trend is observed in our results. The optimised results manifest improvements in variance in the latter stages of cure. One such explanation for this behaviour could be that controlling the exothermic heat build up in the later stages of cure presents the optimal strategy. Alternatively, internal vascular heating may not be sufficient to overcome the dominant effects of the autoclave cycle. Determining the precise cause of this behaviour remains to be established in future investigations.

Finally, it is observed that vascular position plays a key role in determining the effectiveness in controlling cure variation. Our results suggest that as the number of vasculi increases the optimisation process becomes more sensitive to finding local minima. At this stage further investigation is required to determine if the vascular position is capturing some underlying physics or if the gradient based optimisation has found a local minimum. The non-linear constraints and associated non-smooth change from objective to penalty function could be the source of such unexpected behaviour.

V. Concluding remarks

The curing of thick composite parts often results in uneven temperature distributions leading to the development of cure gradients, that results in reduced manufacturing quality leading to lower structural performance. We propose a thermal management mechanism via a system of heated internal vasculi that can be tailored to match the external heat profile and geometry of the part. Herein we have developed a gradient based optimisation procedure able to identify optimised vascular positions and temperature profiles that minimises the variance in cure over a typical cross sectional area. The optimised designs have allowed us to identify that the vascular temperature profile reacts to the external autoclave temperature.

Table 3: Percentage reduction in cure variation for each of the scenarios considered.

Scenario	Improvement
Fixed vasculature rectangular	11%
Moving vasculature rectangular	28%
Moving vasculature tapered	27%
Autoclave multiple fixed vasculatures	65%
OOA multiple fixed vasculatures	72%

Initially heating the internal regions of the system then reducing in temperature to account for the exothermic heat generation and penetration of heat from the boundary. Furthermore, we identified how vascular position can be altered to improve performance further. As the number of vasculatures is increased additional complexities are introduced into the optimisation process. Local minima in the design space, due in part to the non-linear constraint imposed to avoid intersection of vasculatures, limits the capacity of the optimiser to find the optimal solution. Such a phenomena is expected to be more pronounced in non-convex geometric sections and as such the use of meta-heuristic optimisation, or alternative vascular distribution methods, may be more appropriate.

With a series of vasculatures positioned inside a tapered section. We have observed how the temperature profile can be tuned for both autoclave and OOA cure cycles. We observed that the vascular pathways react differently when exposed to differing location, boundary conditions, and section geometries. In fact, the optimised temperature profiles demonstrate how an active internal cure system, that responds to external temperatures could be highly beneficial regardless of vasculature location.

There remains significant scope to extend the investigation particularly for the position optimisation of multiple vasculatures. We propose ongoing investigation to resolve the limitations identified in the optimisation framework, in addition to more rapid analysis by optimising ABAQUS FEA analysis or using an alternative solver. Once these issues have been resolved the analysis can be extended to the three dimensional geometries and determining the required vascular heat flux rates to obtain the optimised internal temperatures. The results obtained from such analysis can act as a guide for the development of a representative vascular system for experimental validation.

In summary, we contend that vascular networks have significant potential to improve the cure quality of parts. Our results demonstrate significant improvements are possible, however the impact on structural performance has not been considered. We believe that additional refinement of the optimisation process will increase the robustness of this approach when handling more complex multi-vascular systems. A multi-objective approach, considering cure quality, structural performance and post cure vascular multi-functional uses, can be developed using our approach as a foundation. Such an approach could lead to the development of high performance composites systems with *multi*-multi-functional capabilities.

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