SIMULATION OF ARTICULATED COMPRESSION RESIN TRANSFER MOLDING

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ABSTRACT

Liquid Composite Molding (LCM) is increasingly used in industry to manufacture high performance composites. This technology encompasses a family of composite manufacturing processes that consist of injecting a resin through a fibrous reinforcement. The latter can be placed in a rigid closed mold (*Resin Transfer Molding* – RTM) or covered by a flexible membrane (*Vacuum Assisted Resin Infusion* - VARI). In order to accelerate the resin flow, the mold cover can also be moved to compress the reinforcement (*Compression Resin Transfer Molding* – CRTM and *Articulated Compression Resin Transfer Molding* – ACRTM). The present effort focuses on ACRTM and emphasizes the main advantages of the technique. Unlike CRTM where the mold cover is usually made of a single part, ACRTM can be considered as a generalized version, in which the mold cover contains several pieces that can be articulated separately. Once enough resin is injected, each segment of the mold cover is compressed to complete the impregnation of the reinforcement. Numerical modeling and simulation is used to show how only the impregnated zones of the reinforcement need be compressed, therefore minimizing the total load on the mold cover while ensuring a complete impregnation of the reinforcement in a timely manner.

KEYWORDS: Modeling, Articulated Compression Resin Transfer Molding

INTRODUCTION

Composite materials are used in a large number of industrial applications ranging from high performance automotive and aerospace structures to common consumer products. Because composites combine high mechanical performance, low weight and good resistance to corrosion, further increase can be expected in their industrial usage. Five major ways to manufacture composites are presently in use: hand lay-up, autoclave, pultrusion, filament winding and liquid composite molding (LCM). A tradeoff between manufacturing cost, performance and geometric complexity governs the choice between the above processes. When the part geometry becomes complex as often encountered in the automotive and aerospace sectors, LCM remains the only reasonable alternative. LCM actually represents a family of composite manufacturing processes that consist of injecting a reactive liquid resin through a fibrous reinforcement. Among the several existing LCM techniques, Resin Transfer Molding (RTM) uses closed and rigid molds. The RTM process is well suited to manufacture complex small to mid-size parts. However, a problem arises with RTM for composite parts with a high fiber content. Indeed, the permeability of the fibrous reinforcement drops drastically with an increase of the fiber content. Consequently mold filling is completed after a much longer period of time, resulting not only in a low overall throughput of the process, but sometimes in a non uniform impregnation of the reinforcement. One way to overcome this limitation is to design a mold with a thicker cavity to let the injected resin flow above the fibrous reinforcement (Fig. 1a). Once enough resin has filled up the cavity, the injection is stopped (Fig. 1b) and the upper part of the mold is pushed towards the fibrous reinforcement to compress the fibers, hence achieving a complete impregnation and reaching the desired fiber volume content (Fig. 1c). This technique is commonly called *Compression Resin Transfer Molding* (CRTM). It was studied extensively by Pham et al. [1], who modeled the process and developed a numerical algorithm to simulate injection and compression of the fibrous reinforcement in the case of displacement control of the mold cover. This work was further extended by Pham and Trochu [2, 3] for thin shells, then to include the case of pressure control in bladder assisted injection. More recently Achim et al. [4] have generalized this work to the case of an articulated mold cover.

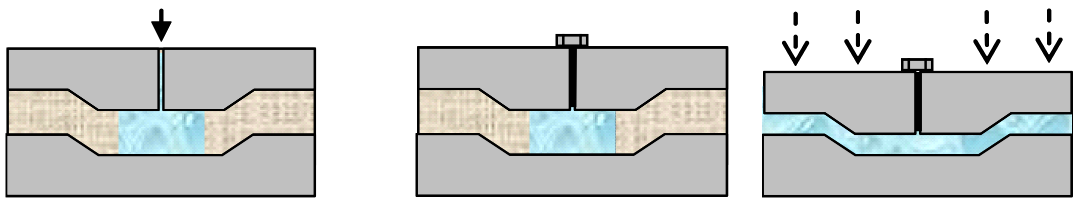


Fig. 1 Main steps of Compression Resin Transfer Molding (CRTM)

In this paper a generalized version of CRTM commonly called ACRTM is presented. Unlike CRTM where the mold is made of a single piece, ACRTM compresses the reinforcement with a mold cover made of several pieces that can be articulated separately. Using modeling and simulation, it will be shown how the wet zones of the reinforcement are compressed to complete the impregnation process in a timely manner.

ARTICULATED COMPRESSION RESIN TRANSFER MOLDING (ACRTM)

In CRTM the mold cover is usually made of a single rigid part, so the pressure applied during compression is uniformly distributed over the mold cover. Consequently, the mechanical press used in the process needs to provide an increasing force to overcome the resistance of the resin flow caused by the decrease in permeability of the reinforcement during compression. However, it is possible to minimize this effort if the mold cover is made of several pieces that can be articulated separately. This alternative is called ACRTM and consists of compressing only the newly impregnated part of the reinforcement. To illustrate the concept, Fig. 2 shows a mold made of four different pieces where the resin is injected from the left side. In the first step (Fig. 2a) the resin is injected underneath the first segment of the mold cover. Segment 1 is then pushed toward the base plate of the mold until the desired thickness is reached. In the meantime segment 2 is moved upward to let the resin accumulate underneath it (Fig. 2b). The same operation is repeated with the remaining segments (Fig. 2c, d, e).

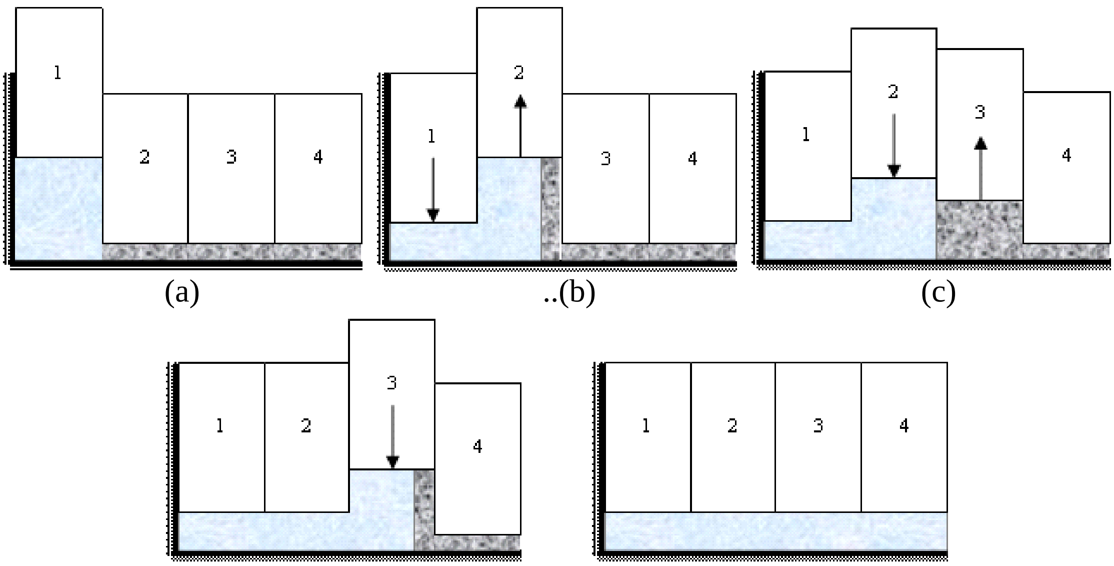


Fig. 2 Main steps of Articulated Compression Resin Transfer Molding (ACRTM)

GOVERNING EQUATIONS

The injection of a liquid resin through a fibrous reinforcement is generally considered as a flow through a porous medium and consequently governed by Darcy's law. The latter relates the average fluid velocity $\mathbf{v}$ (Darcy's velocity) to the pressure gradient ∇P as follows:

$$\mathbf{v} = -\frac{[\mathbf{K}]}{\mu}\nabla P \tag{1}$$

where $[\mathbf{K}]$ is the permeability tensor of the porous medium and μ is the resin viscosity. Darcy's velocity is related to the resin velocity via the porosity ϕ of the porous medium by:

$$\mathbf{v} = \phi\ \mathbf{v}_r \tag{2}$$

and Darcy's law may be reformulated as:

$$\mathbf{v}_r = -\frac{[\mathbf{K}]}{\phi\ \mu}\nabla P \tag{3}$$

The continuity equation for the liquid phase in a deformable porous medium leads to the following global mass balance [3, 4]:

$$div(h\phi \mathbf{v}_r) = -\frac{\partial h}{\partial t} \tag{4}$$

Using Eqn. 3, Darcy's law for compressible porous media is finally obtained:

$$div\left(h\frac{[\mathbf{K}]}{\mu}\nabla P \right) = \frac{\partial h}{\partial t} \tag{5}$$

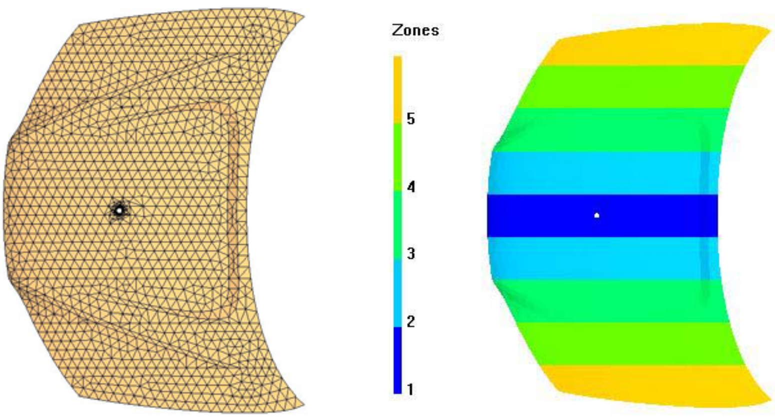
In the case of CRTM or ACRTM processes the term of the right hand side of Eqn. 5 is set by the imposed displacement of the mold cover during the compression stage. The equation may therefore be rewritten as:

$$div\left(h\frac{[\mathbf{K}]}{\mu}\nabla P \right) = \mathbf{v}_{\mathbf{Cover}} \tag{5}$$

where $\mathbf{v}_{\mathbf{cover}}$ is the velocity of the mold cover during compression. The governing equations are solved by the finite element method [5].

FILLING OF AN AUTOMOTIVE HOOD

In order to fill the automotive hood of Fig. 3a by ACRTM, the mold mesh is divided into several segments (see Fig. 3b). The injection port is located in the center of the part while vents are set at the bottom and top right corners.



(a) (b)

Fig. 3 The mold cover is split into segments in order to carry out ACRTM

The inlet pressure is set to 10^5 Pa to inject a resin of viscosity 0.1 Pa.s and the vents are kept at 0.28 10^5 Pa. The initial height of the mold cavity is 12 mm and the initial fiber content is low (16%). Since the fiber content will vary during compression, the variation of permeability as a function of the fiber volume content is provided in Fig. 4.

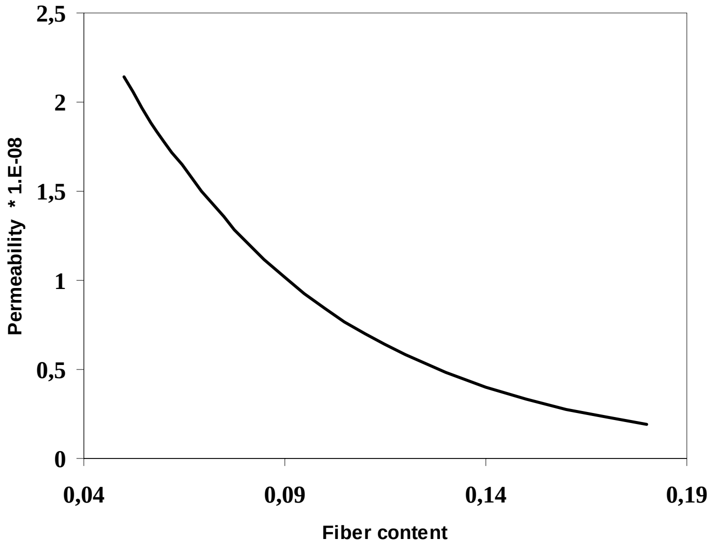
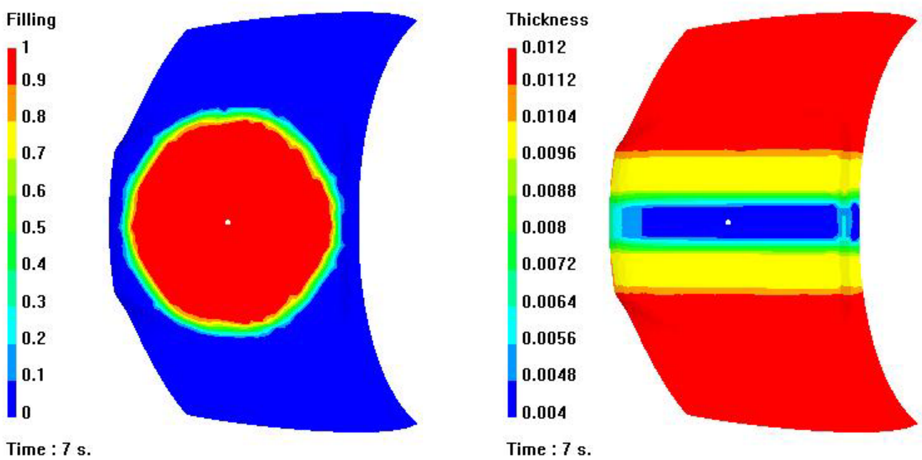


Fig. 4 Permeability vs. fiber content for the reinforcement used in the simulations

After 7 sec, the resin is already transferred underneath the 3 central segments of the mold cover as depicted in Fig. 5a and enough resin has been injected to fill up the entire cavity. The compression of the central segments starts as seen in Fig. 5b and a decrease in thickness of the corresponding zone is observed. The thickness keeps on decreasing with compression of the segment until it reaches a value of 4 mm, then the adjacent segments of the mold cover are moved down to continue the compression (see Fig. 6).



(a) (b)

Fig. 5 Beginning of the compression process after 7 sec of filling: (a) flow front at 7 sec; (b) thickness distribution at 7 sec

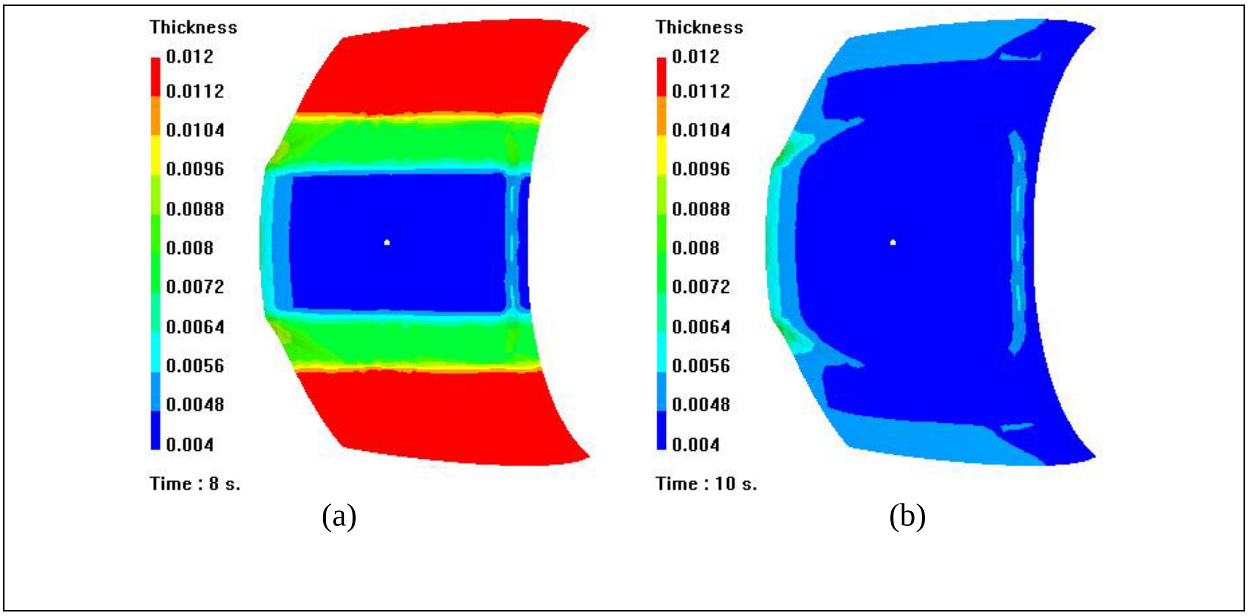


Fig. 6 Thickness variation during compression (ACRTM): (a) at 8 sec; (b) 10 sec

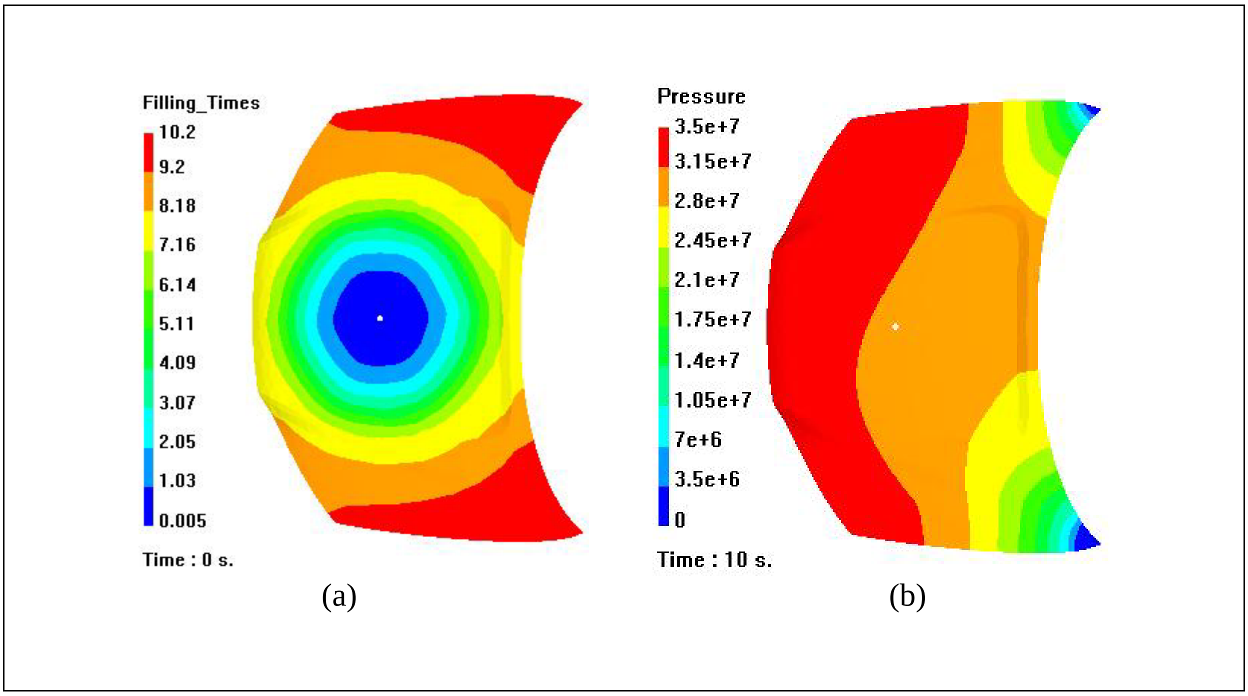


Fig. 7 Filling of the hood by the ACRTM process: (a) filling time distribution; (b) pressure distribution

The total filling time obtained is nearly 10 sec (see Fig. 7a) and the maximum pressure reached in the mold cavity is 3.5 10^7 Pa.

In order to illustrate more clearly the advantages of ACRTM, it is interesting to compare the previous results to those of a CRTM simulation. The same properties of the resin and the reinforcement are therefore considered. The variation of permeability as a function of the fiber volume content is given by the same curve as in Fig. 4. The initial height of the mold cavity is 12 mm. No compression is carried out until enough resin to fill up the entire mold cavity has been injected. The compression starts 7 sec after the injection began. Fig. 8 shows the thickness variations during compression. Note that the thickness is not uniform since the mold cover is moved vertically while the automotive hood is not perfectly planar. Figures 9a and 9b depict respectively the progression of mold filling in time and the final pressure distribution attained in the mold cavity. It is important to note that the final pressure of 6.4 10^7 Pa reached in CRTM is twice as much as the one of ACRTM. For the same compression pressure, ACRTM would give a smaller filling time.

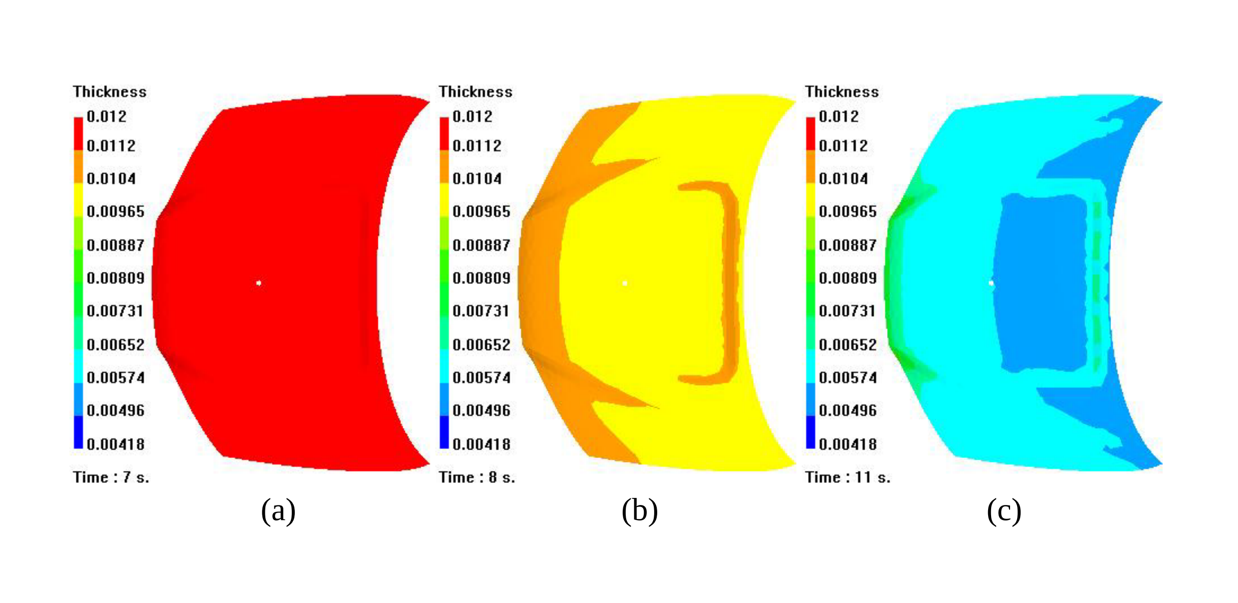


Fig. 8 Thickness variation during filling: (a) at 7 sec; (b) 8 sec; and (c) 11 sec

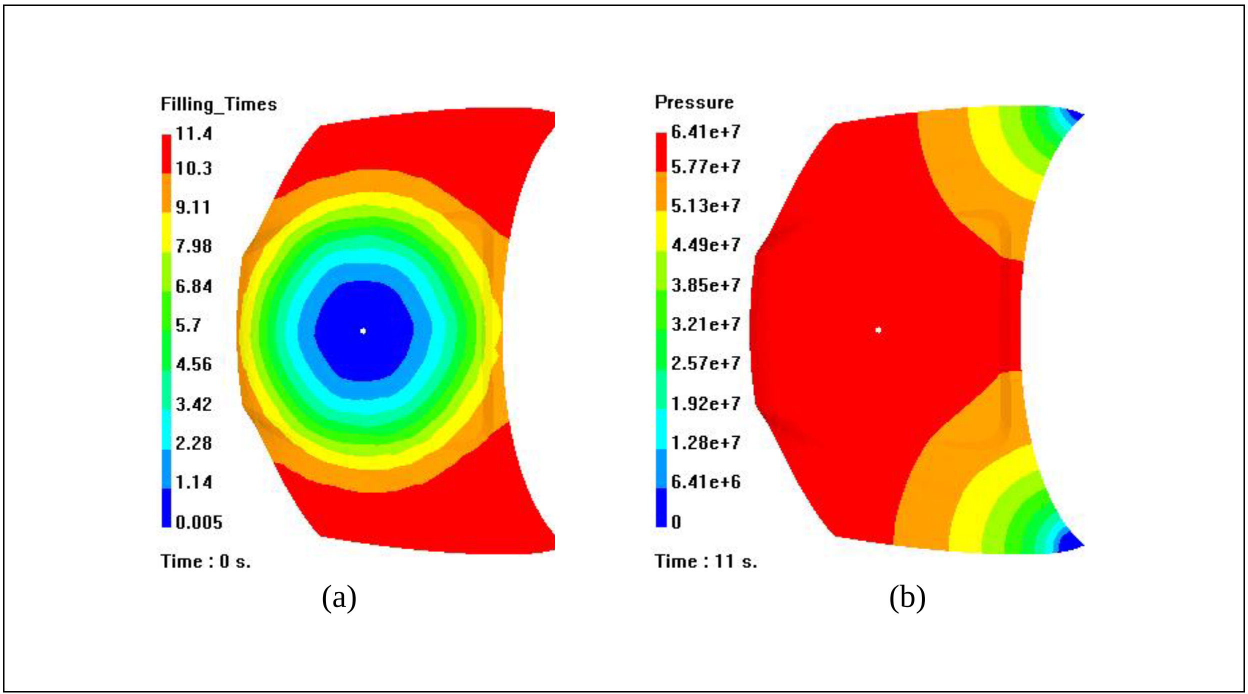


Fig. 9 Filling of the hood by the CRTM process: (a) filling time distribution; (b) pressure distribution

CONCLUSION

A model of Articulated Compression Resin Transfer Molding (ACRTM) was developed based on the general Darcy equation for compressible porous media and the resin continuity equation. The final form of the governing equation was solved for complex parts using the finite element method. The filling of an automotive hood was considered to illustrate this approach. It was shown how the mold cover can be divided into several segments intended to carry out the compression process. Simulation results were compared to those of CRTM. ACRTM used less energy to transfer the resin for the same range of filling times. For the same compression pressure, this process would allow filling parts more quickly than RTM or CRTM. However, like in CRTM one difficulty remains for parts with nearly vertical walls: it is not possible in that case to impose a uniform compression to the reinforcement. In addition, an articulated mold will necessarily be more complex, and hence more expensive than a rigid one.

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