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Computational Optimization of voids on 3D woven Composites Truss Structures during Infusion

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***Abstract*—All the world is undertaken a low carbon emission process due to sustainability and the potential for composites to reduce greenhouse gas (CO2) is clear. Therefore, new composites truss structures materials with 3D woven continuous fibre reinforced composites will start to be used for civil, aerospace, automotive, and marine applications due to their lightweight, water resistance, their internal electrical conductivity and superior mechanical properties. The overall goal and attitude of this paper are to predict the fluid flow behaviour during the liquid infusion processes which are one of the most common manufacturing routes for composites and optimize computationally the high concentration of voids that may arise. Since experimentally this work is presented with high complexity and very expensive. The void formation can compromise the truss structure integrity and the final mechanical properties. The following research work tries to deal with the resin flow behaviour during impregnation affected by the preform properties, which are fibres orientation, and textile volume fractions, that can vary locally. Advanced composites truss structures are made of complex geometry which is made off 3D woven geometrically complex preforms, for better through-thickness properties. Thus making the impregnation process hard to control and potentially causing void defects in the manufacturing of the final component. Therefore, three-dimensional computational optimization scenarios are close realistic and can be used in the final manufacturing process of the truss structure.**

Keywords—Computational optimization; void formation; advanced composite materials; truss structures; liquid infusion;

I. Introduction

The computational liquid infusion process may be used to develop a macro-scale flow simulation technique able to predict possible manufacturing defects during resin transfer moulding (RTM). To achieve this, firstly, the isotropic finite element (FE) Truss node behaviour was studied with the 3D woven HTS40 F13 fabric permeability. Secondly, the fluid flow behaviour with and without void formation was investigated. Thirdly, generated a new 2D FE generic node models with mesh refinement and the truss sensitivity was studied.

An important aspect of the design process of any truss composite component is computational modelling. Predictive modelling and optimisation for material and geometric characteristics of the generic node are essential to avoid low-quality components due to defects (e.g. void formation) in the final composite material. There is a wide range of techniques available for the simulation of various manufacturing processes. Computational resources give a visualisation of how the component is infused during RTM processing. It also indicates any potentially critical areas inside the composite where a converging flow front may lead to void formations. This theoretical insight allows the optimised design of injection gates and venting configurations for the generic node based on predicted resin flow paths and any highlighted dry spots or resin-rich regions as reported in a study on void formation in multi-layer woven fabrics by Jinlian, H.*et al* [1]. Devillard, M. *et al* [2] studied online characterization of bulk permeability and race-tracking during the filling stage in the RTM process, while a numerical model for vacuum infusion manufacturing of polymer composites was presented by Anderson, H.M *et al* [3]. Hammami, A., *et al* [4] modelled the edge effect in liquid composites moulding while Sozera, E.M., *et al* [5] studied with online control the liquid composite mould filling process.

A successful prediction (as presented with gates and vents for liquid infusion seen on fig. 1(a), fig. 1(b)) of the node fluid flow can yield substantial savings for high quality and volume production components. The paper by Anderson, H.M, *et al* [6] focused on measuring composite textiles thickness variations in the vacuum infusion process with digital speckle photography. Gokce, A., and Advani S. G., [7] provided a paper on vent location optimization using map-based exhaustive search in liquid composites moulding (LCM) processes. Lawrence, J. M., Fried, P., Advani, S. G., [8] provided a research paper on automated manufacturing environment to address bulk permeability variations and race tracks in RTM by redirecting flow with auxiliary gates. Lawrence, J. M., *et al* [9] research approached couple mould design and online control to manufacture complex composite parts by RTM. Weimer, C., *et al* [10] on his part I edges paper: reported an approach to net-shape preforming using textile technologies for use in LCM processes. While Devillard, M., Hsiao, K-T., Advani, S. G., [11] on their paper studied flow sensing and control strategies to address race-tracking disturbances in the RTM process. Bickerton, S., Advani, S. G., [12] provided a paper on composites with the characterization and modelling of race-tracking in liquid composite moulding processes. Endruweit, A., *et al* [13] studied random discontinuous carbon fibre preforms by permeability modelling and resin injection simulations for the LCM process reported by Rudd, C. D., *et al* [15]. *Flow-*

induced alignment in composite materials was detailed with the experimental and analytical approach by Papathanasiou, T. D., and Guell, D. C. book research studies [16], finally Tucker, C. L., Advani, S. G., presented a research paper for *Processing of short-fibre systems* [17].

II. ISOTROPIC FLOW SIMULATIONS

Firstly an isotropic scenario simulation as presented, injections and venting gates for the 3D woven HTS40 F13 industrial preform with experimentally measured properties, was studied to extract information about the isotropic 2D and 3D flow behaviour of the generic node as shown in fig. 1 (a), (b) which also indicates 3D trial injection gate and vent locations as proposed by the tooling manufacturer. All simulation was done with ESI PAM-RTM® software. The same gates and venting were used in all simulations for the 2D injection simulations as requested from the industrial manufacturer partners of the node.

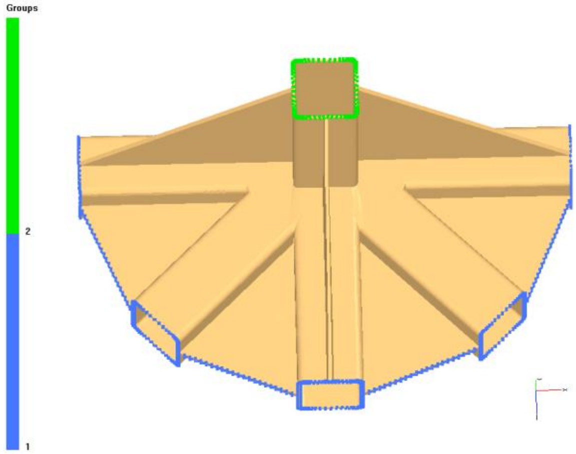

Fig. 1 (a): 3D scenario of injection gate (blue) and venting (green) locations used for 3D simulations (top view) done with ESI PAM-RTM® software [14].

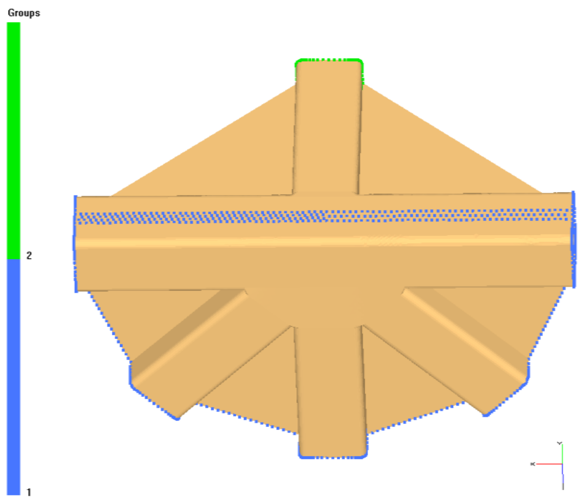

Fig. 1 (b): 3D scenario of injection gate (blue) and venting (green) locations used for 3D simulations (opposite side view).

The material properties used in isotropic and anisotropic simulations with HTS40 F13 3D woven preform are measured experimentally on separated research are presented in Table 1,

Table 1: Compaction tests power-law fitting.

Preform	Layers	H_{height} (mm)
ACTS fabric	4-layers	$2.6051\ P^{(-0.073)}$
ACTS fabric	3-layers	$1.9538\ P^{(-0.073)}$

And in Table 2 as follow:

Table 2: Preform permeability K_1, K_2, K_3 against volume fraction (V_f) that have been used in simulation tools.

a) In-plain K_1, K_2 experimental fitting equations:

Preform	K_1 fitting eq. (m^2)	K_2 fitting eq. (m^2)
3D woven HTS40 F13	$0.005V_f^{(-11.55)}$	$0.0013\ V_f^{(-12.41)}$

b) Through thickness K_3 experimental fitting equations:

Preform	K_3 fitting eq. (m^2)
3D woven HTS40 F13	$0.03789\ V_f^{(-4.481)}$

and their numerical values are as follows: mean permeability value reported by Endruweit, A., *et al*, [13] and presented in eq. **(1)** below *:*

$$K_e = \sqrt{K_1 K_2} \qquad \textbf{(1)}$$

K_e= 3.4 x10^{-10} m^2 (calculated assumed isotropic permeability from eq. (1)), permeability measured experimental values for the K_1=5.207x10^{-10} m^2, K_2=2.221x10^{-10} m^2, K_3=5.207x10^{-12} m^2, μ(MVR 444 industrial resin viscosity)=0.1 Pa s, P_i(injection pressure)=3 bar, P_v(vent pressure)=0 bar, d (density of carbon fibre)=1760 Kg/m^3, V_f (Volume Fraction)=0.55, Φ(porosity)=0.45.

III. RESULTS AND DISCUSSION

Firstly a series of different CAD models (with an increasing number of triangular elements according to the fluid flow behaviour if there is convergence at the increasing number of triangular elements then the all process is correct according to [7-11], [13-17]) for the computational study was generated and the flow behaviour of the node was modelled with a 2D CAD model, which was created and meshed with 6424 triangular elements as shown in Fig. 2.

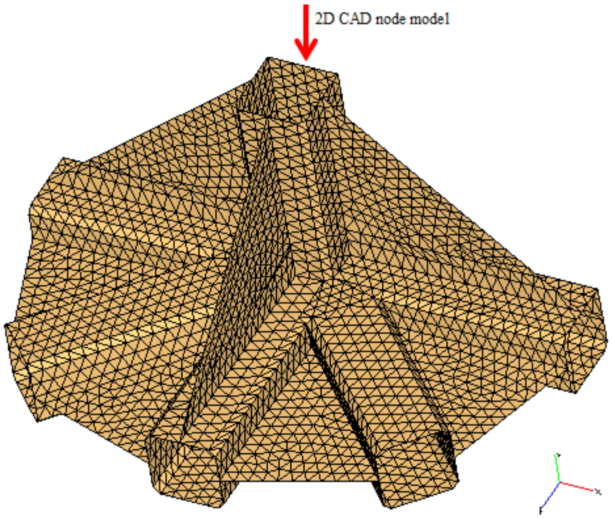

Fig. 2: 2D CAD node model meshed with 6426 triangular elements (red arrow shows the 2D geometry of the node).

The flow behaviour of the node was simulated thereafter with the ESI PAM-RTM software shown in fig. 3 (a), (b).

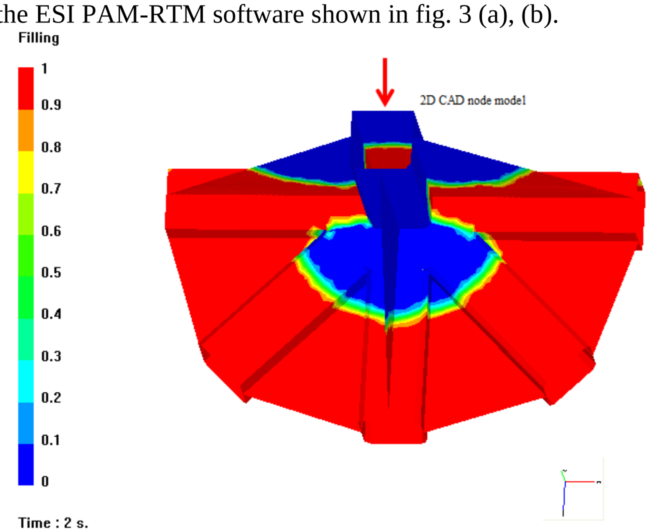

Fig. 3 (a): 2D node isotropic filling simulation (after 2 s.) top red colour filled area, blue unfilled, half-filled area any other colour. The blue down part of the figure indicates probably the formation of an unfilled area (void) at the upper part of the trust structure. However since is connected with the vent as shown fig 1 (a), fig 1 (b) the risk does not exist.

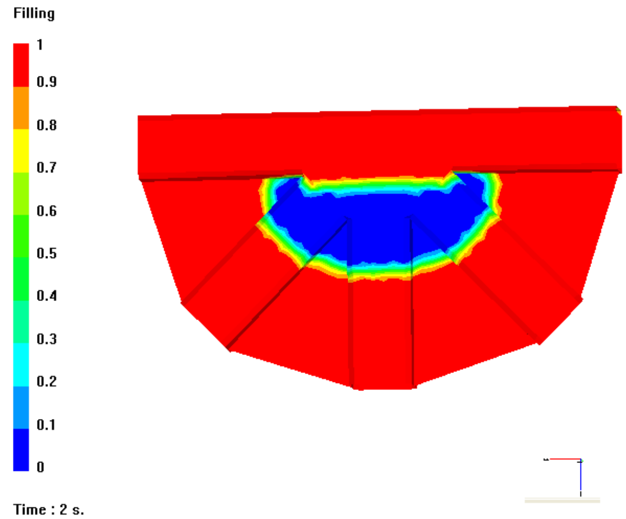

Fig. 3 (b): 2D node isotropic filling simulation (after 2 s.) opposite side (down) red colour filled area, blue unfilled, half-filled area any other colour. The blue down part of the figure indicates probably the formation of an unfilled area (void) at the lower part of the trust structure.

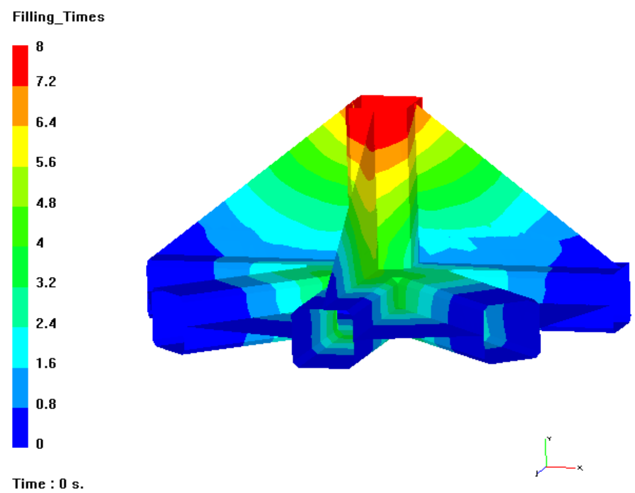

Fig. 4: 2D filling times simulation of the node gives the variation of pressure seems to be critical at the top end of the node-red area.

The 2D FE model filling time simulation was 8 seconds as presented in fig. 4. Filling and filling times simulations were then compared with the 3D FE node to verify flow behaviour and filling times.

IV. Results and Discussion

A series of the 3D CAD model of the node generated with different mesh density and the isotropic case scenario was simulated for each model. Two 3D CAD model of the node as shown in Fig. 5 (a) and (b) meshed with 16377 and 111240 tetrahedral elements.

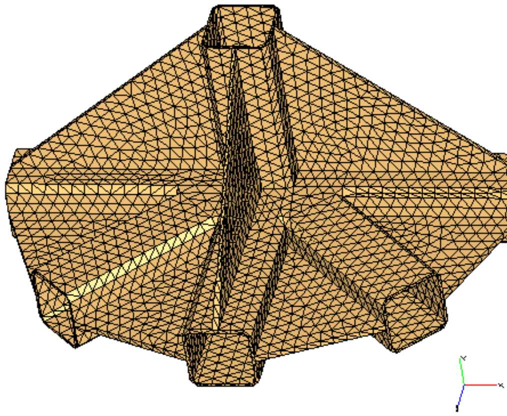

Fig. 5 (a): ACTS node coarse mesh with 16377 tetrahedral elements.

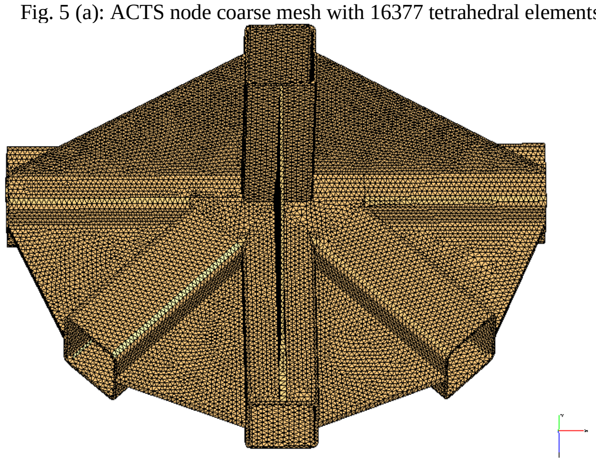

Fig. 5 (b): ACTS node fine mesh with 111240 tetrahedral elements. CAD model with a higher number of elements increasing the accuracy of the prediction and so the optimisation process according to [2-15].

The flow behaviour of the node as shown in Fig. 6 (a), and (b), was studied with the PAM-RTM® software for the same 3D woven textile material properties (Tables 1 and 2) following the method as of section 2.

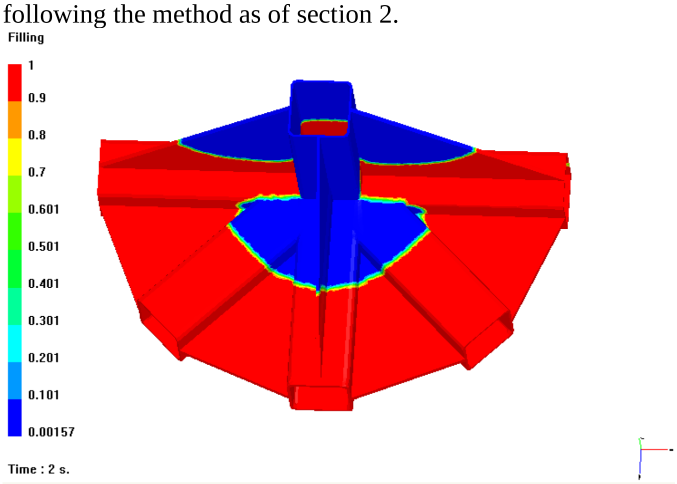

Fig. 6 (a): 3D node isotropic filling simulation (after 2 s.) top view red colour filled area, blue unfilled. The blue down part of the figure indicates probably the formation of an unfilled area (void) at the upper part of the trust structure. However since is connected with the vent as shown fig 1 (a), fig 1 (b) the risk does not exist.

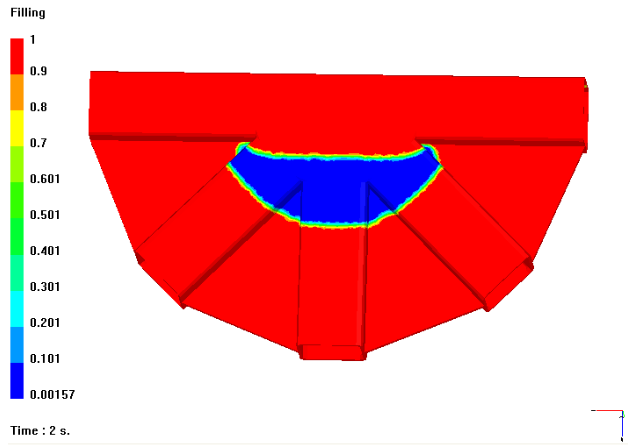

Fig. 6 (b): 3D node isotropic filling simulation (after 2 s.) opposite side red colour filled area, blue unfilled. The blue down part of the figure indicates probably the formation of an unfilled area (void) at the lower part of the trust structure.

3D FE model filling time simulation presented in fig. 6 (c), fig. 6 (d).

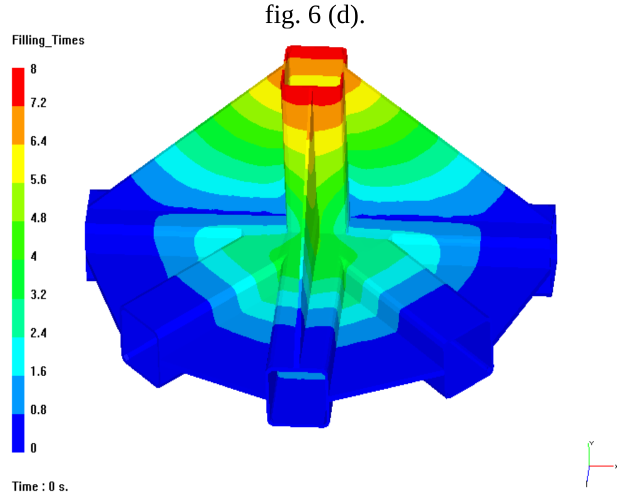

Fig. 6 (c): Filling times, for the upper view of the node the variation of pressure seems to be critical at the top end of the node-red area.

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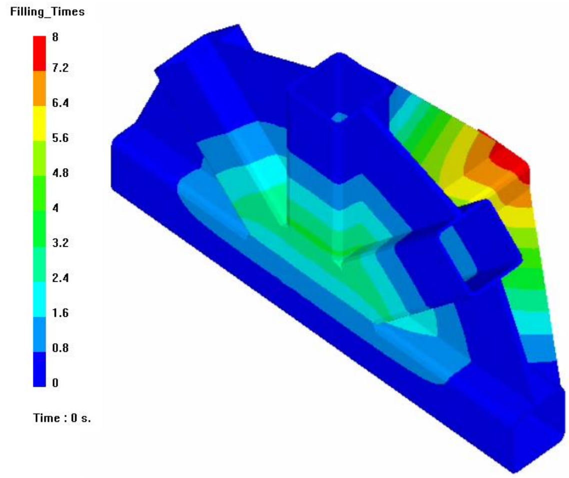

Fig. 6 (d): Filling times, for the lower view of the node the variation of pressure seems to be critical at the top end of the node-red area.

V. Results

In this section 3D, numerical simulations of the RTM process were performed with ESI PAM-RTM® to validate the 3D sensitivity of the generic node for the isotropic case. Filling times results against the number of tetrahedral elements from each 3D node model simulation are presented in Table 3.

Table 3: Filling times results against the number of tetrahedral elements for the 3D node model.

3D node model (Num. of the tetrahedral elements)	**Filling times(s)**
16377	8.52
37777	7.81
50671	7.72
111240	7.7

Above table 3 show that by increasing the mesh density of the 3D node model there is the convergence of filling time (s) at 7.7 (s) for 111240 tetrahedral elements. Since the node is of complex geometry, there is no analytical solution mathematically for comparison with the finite element/control volume (FE/CV) method. However, the convergence of the filling times 7.7 (sec) following the theory for complex geometry problems as reported as well by Devillard et al [2] for different geometric problems

VI. Discussion

From the whole investigation came out that 2D, 3D node simulations predicted nearly the same filling time 8 and 7.7 seconds respectively.

Both the 2D and 3D FE CAD node models revealed similar isotropic behaviour. Comparison between figures 3(a), (b), 4 and Fig. 6 (a), (b), (c), (d), suggested that the flow fronts converge in the centre of the component on the upper and opposite side. As a result air entrapment may be observed in this region of the node. This may lead to the void formation in what is bound to be a critical area within the node complex geometry.

So in this research paper, 2D CAD and 3D CAD node models have been studied for isotropic cases for void formation optimization. The flow pattern in the isotropic scenario for the 2D case was the same as the 3D case. This indicated that both models were build up correctly. The filling scenario for the 2D case with 6426 triangular elements and the 3D case with 111240 tetrahedral elements indicated a converging flow towards the centre of the generic node on both top and opposite sides. Which indicated that the presence of gates/vents on these moulder's area during the infusion process will be sensible and will optimize the voids (due to converging flow on this area) of the advanced composite truss structure.

VII. Conclusions

A novel numerical approach for computational optimization with composites truss structures made of 3D woven carbon fibres and an epoxy resin system was developed. The study based on this technique provided important insights into flow filling variations, void formation and optimization on a generic advanced composite truss structure.

The model optimization technique developed from this work (and requested from the industrial manufacturing partners) can be used for future work to account for the defects of any other truss composite component at the macroscale level. The predicted flow front data can complement experimental data to enhance flow simulations at the component scale. The future scope of this research is an addition to the flow behaviour in advanced composites truss structures CAE/CAD geometries to be able to predict converging flow behaviour in more advanced composites geometries and avoid void formation during liquid infusion manufacturing.

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