Deep Trails

Coupling of structural optimization and self-organization processes for the computational design of composite surface tectonics

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This research explores the constructive and expressive capabilities of stigmergic-based creasing patterns integrating structural and ornamental conditions in fibre-composite surface tectonics, generated by the reciprocal influence of multi-agent systems and Non-Linear Time History (NLHT) dynamic structural simulation. Building upon precedents on the use of agent bodies and behavioural tectonics such as the work of Roland Snooks, our approach employs NLTH simulation for the dynamical assessment of the structural failure modes to provide information for agents behaviour and a comparative assessment of the bodies pattern contribution. Considering the obtained results, insights gained on the structural behaviour of multi-agent composite surface tectonics while attempting to explore its embedded architectural, morphological and expressive qualities are discussed.

Keywords: Computational Design, Multi-Agent System, Ornament, Structural optimization, Fibre-composite materials, Stigmergy, Non-Linear Time History.

INTRODUCTION

This research explores the constructive and expressive capabilities of stigmergic-based creasing patterns integrating structural and ornamental conditions in fibre-composite surface tectonics, generated by the reciprocal influence of multi-agent systems and dynamic structural simulation. Notable precedents in the use of multi-agent systems and/or fibre-composite surface tectonics include Tom Wiscombe (2010), Marc Fornes [1] and Roland Snooks (Snooks & Jahn, 2016). The approach discussed leverages the latter author's use of behavioural formation, posing as a nonlinear algorithmic design methodology that seeds specific architectural purpose within the local interactions of multi-agent systems.

A foundational aspect of this research is the understanding of structures as assemblages of parts (DeLanda, 2016) where parts maintain individual identity but gain further properties in the whole. A first part can be classified as a surface, and a second one (which is itself an assemblage of parts) as a "performative ornament", not mere decoration but an integrated contributor to the structural and architectural performances of the whole (which are a result of the interdependency of both parts).

Discussing the concept of ornament is far beyond the scope of this paper, although it is important to clarify that its use here does not flatten towards the historical idea of "embellishment" (conflating it with detail) nor the postmodernist "cloak" (a dress to hide the naked structure). A third interpretation comes from what Spuybroek (2010) calls "self-ornament": an idea borrowed by John Ruskin from William Morris, that considers the ornament as that which connects tectonic relationships across multiple scales, or rather ornament as an expression of forces and processes acting on the material scale. Using it as a device for the integration of the consequences of certain architectural choices within the project provides a more elegant solution than stifling or denying these aspects.

Another key aspect involved is the computational investigation of multi-agent systems with stigmergic behaviour and their potential to generate morphological and organizational complexity: the operational translation of this principle implies the minimization of manual operations (such as modelling) in favour of computational methods for the generation of form through formation.

The third key topic is the computation of structural information by means of Non-Linear Time History (NLTH) dynamic simulation, both for the generation of data during the process and as an assessment of the structural performance of the generated system.

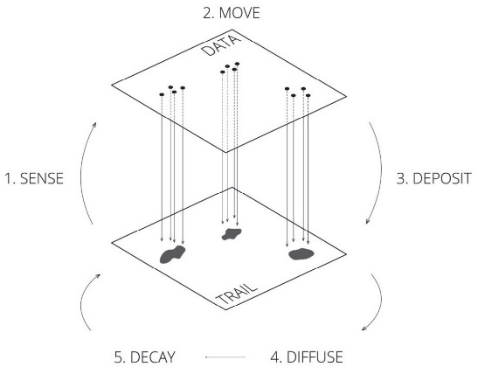


Figure 1
Multi Agent System feedback loop

SIMULATION FRAMEWORK

The digital simulation uses a multi-agent approach to build bottom-up dynamic transport networks (Jones, 2010), in which inter-agent communication occurs indirectly through the release of a mediator signal CS (simulating chemo-attractant traces) in the environment (Figure 1). In Jones' approach, agents emit a small amount of signal in the environment and are able to perceive it (autocrine behaviour), following its strongest concentration. At each iteration, three forward-facing sensors detect the CS concentration and the agent orients itself toward the sensor with the stronger signal value. This sensor offset morphology, coupled with simple, forward-oriented behaviours, CS diffusion (propagation in space) and evaporation (signal decay over time), produces the known phenomenon of stigmergic pathways reinforcement and typical emergent pattern formation, which, in the presence of fixed signal-emitting nodes (simulating food sources), converges over time into the shortest path network approximating a Steiner tree (Tero, 2010, Jones, 2011, [2]), a pattern that minimizes the total length of all possible paths among nodes. A significant simplification compared to the biological reference (Physarum Polycephalum) is that both food sources and changes in internal protoplasm flow are represented by the same chemoattractant signal.

Our research builds upon the principles and simulation mechanisms of Jones (2010), translated for a 3D environment.

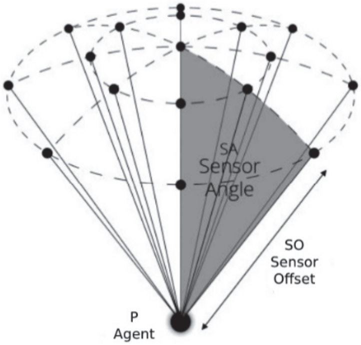
3D simulation

The environment is encoded as a 3D voxel grid, whose centres are associated with the scalar value, representing the local amount of CS. The environment incorporates diffusion and evaporation behaviours:

- diffusion propagates at each iteration a fraction of a vertex-associated value to its neighbours, according to established diffusion coefficients associated with each neighbour (Repenning, 2006);
- evaporation incrementally decreases the signal value by a given percentage at each iteration;

The agent occupies a single voxel of the environment; the 2D to 3D translation transmutes the sensor array from a triangular to a conical configuration, with seventeen sensors that sample environmental values at a given sensor offset distance SO from its position in the direction of movement, whose opening is adjustable through the sensor angle SA (Figure 2).

Figure 2
3D Agent properties

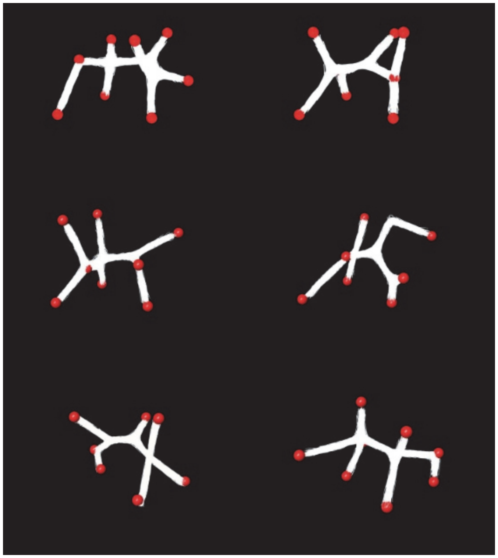


Cues

Pre-existing stimuli are specified by CS sources, named cues. They emit a continuous stimulus signal, whose strength is related to the intensity of the attraction exerted on agents and can be modulated by a weighting factor (stimulus value × weight) where the weight is typically within the range 0.01 to 0.1 (depending on the area of the stimulus source). Stimuli signals are subject to the same diffusion process that applies to the agents-emitted CS.

In the presence of cues, the network evolves forming stigmergic paths first (with minimal apparent cue influence), progressively removing redundant paths until it minimizes approximating a Steiner tree (Figure 4). Frei Otto (2009) arrived at the same pattern via material computation, with his minimal path system. The pattern minimization process exhibits quasi-physical surface tension effects (visible in [2]); this emergent phenomenon, not explicitly encoded in the algorithm, closely resembles those observed, again, by Otto (2009), in his soap films experiments and network path computation; Otto also completed the material computation observing how connecting paths under tension preferably form three-way nodes at 120-degree angles. Both of these observed behaviours prove that the algorithm can simulate energy minimization in the transport system.

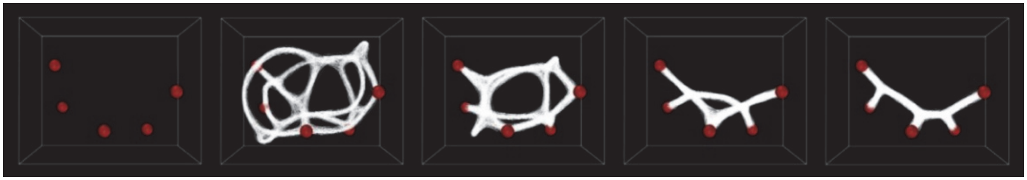
Figure 3
samples obtained by varying cues position



Agent planes and implicit surface

Agents have been described so far as points, for which positional information sufficed for their

Figure 4
Network evolution under cues influence



individuation; the goal, however, is to give agents three-dimensional bodies. To determine the orientation of a body in 3D space a position and three rotations are needed. Mathematically, this leads to transformation matrices; in our case, this low-level implementation can be skipped by leveraging local coordinate systems predefined in CAD systems, also called reference planes, and the related transformations. Planes relate to bodies much like a tray upon which an object is glued: as the tray moves in space, the object rigidly follows. Once the stigmergic pattern defined by agents trails is computed, agent planes are distributed in the bounding volume and start interacting with each other and the pattern.

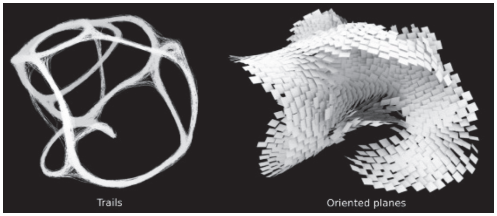


Figure 5
Transition from stigmergic trails to oriented planes

Agent planes are encoded with behaviours that adapt from Reynolds' (1987) flocking and steering behaviours: curve cohesion, frame alignment, implicit surface cohesion.

- Curve cohesion: agents move towards the closest point to the nearest trajectory in a given radius;
- Frame alignment: each agent coordinate system tripod axis aligns with the corresponding frame axis at the closest point of the nearest trajectory;
- Implicit surface cohesion: each agent computes the positions of neighbour agents in range in its own coordinate system, and moves along its Z axis towards the average point;

The behavioural combination provokes a self-organization process in the system: the planes wrap the stigmergic trajectories stabilizing into an implicit surface when the system reaches equilibrium (Figure 5). For geometric consistency and to perform structural analysis later on, planes must undergo a translation into a mesh geometry: a point cloud of planes origins (Figure 6-1) is first converted into a triangulated mesh using the ball pivoting algorithm (Bernardini et al, 1999 - Figure 6-2), and then re-topologized and re-meshed in order to obtain a quad mesh (Figure 6-3), the optimal topology for finite element analysis.

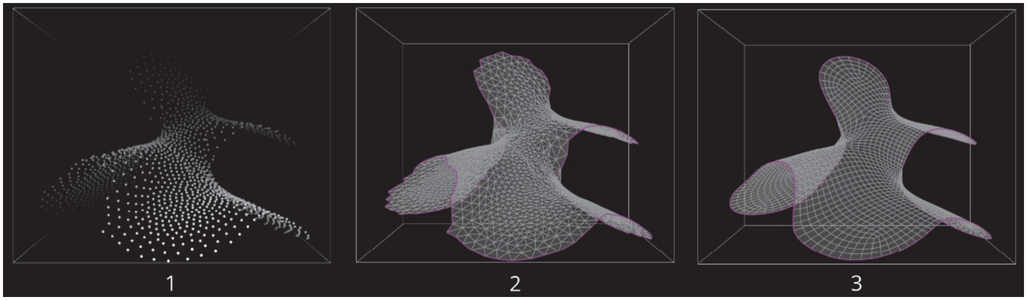


Figure 6
Workflow – from point cloud to topologically adjusted implicit surface

STRUCTURAL SIMULATION

Structural simulations have been carried out using the commercial software Oasys LSDyna®, an advanced general-purpose multiphysics simulation software. While the package contains an extensive toolset for the calculation of many complex, real-world problems, its origins and core competency lie in highly nonlinear transient dynamic finite element analysis (FEA), using explicit time integration.

Shell

In order to simulate the behaviour of fiberglass surfaces, a fidelity model version of the composite layers is created: each face of the mesh is considered as a single-layer shell element with two integration points through the thickness, each representing a single fiberglass sheet, for a total thickness of 4mm (Figure 7).

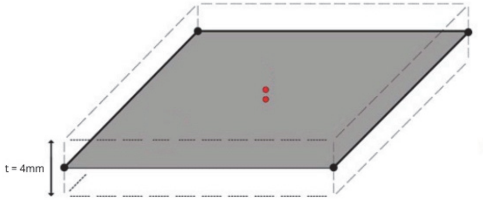


Figure 7
Shell configuration

Material

LSDyna material *MAT_Plastic-Kinematic* is used for modelling the fiberglass sheet (Table 1). A benefit to this material type is the built-in strain rate dependence, based on the formulation proposed by Cowper and Symonds (1957), that changes the yield stress of the material along with the strain rate. However, this may be of limited use for the glass fibre reinforced plastics (GFRP) used in our experiments. While the polyester matrix exhibits some plasticity, the glass fibres fail in a brittle manner, without passing through a yielding point and plastic deformation. Even so, the complexities of delamination, fibre debonding and subsequent pull-out, lend a degree of 'synthetic plasticity' that can be captured, phenomenologically, through a plasticity model.

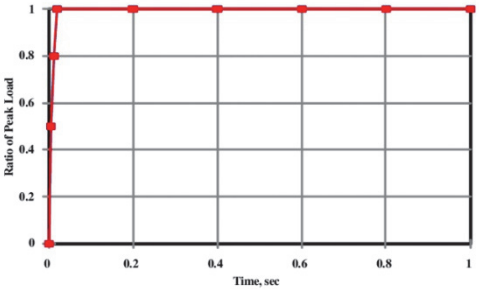


Figure 8
Gravity load curve

Load

The Gravity Load configuration is applied to all nodes of the element. The load force is released gradually in the first instants of the simulation to dampen the eventual deformations that would otherwise cause a total release of the gravity force intensity at the zero instant of the simulation (Fig. 8).

A set of 94 geometries were tested; these are obtained as the multiple possible orientations of the meshes computed by the multi-agent systems previously described, by varying the cues distribution in space. For each mesh from a different cues distribution, all coplanar boundary points are tagged as supports, orienting their common plane as an XY ground plane over which the mesh leans. Cues distribution criteria are subject to some considerations regarding curvature and mesh topology consistency.

Table 1
Material parameters

Variable	Density (Kg/m^3)	Elastic Modulus (Pa)	Poisson's Ratio	Yield Stress (Pa)	Tangent Modulus (Pa)	Hardening Parameter, β
Value	1950	$1.3 * 10^{10}$	0.284	$2.35 * 10^9$	–	1.0
Variable	Cowper-Symonds C	Cowper-Symonds P	Failure Strain	Viscoplastic Formula Flag		
Value	1520	13.43	0.02	1		

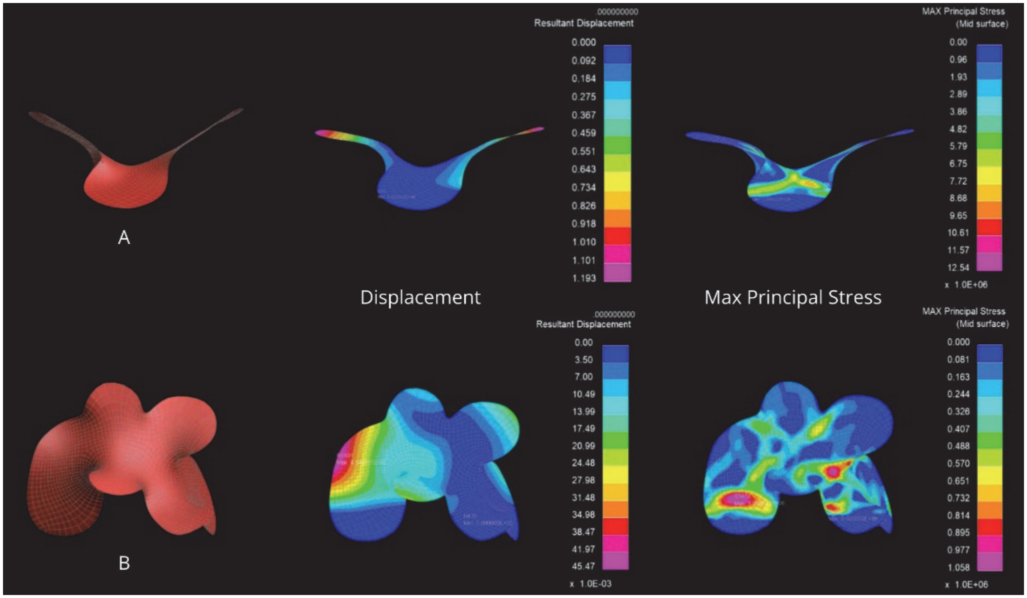


Figure 9
NLTH analysis on
two sample meshes

Curvature plays a key role in stiffness and stability: in cases where local single curvature conditions are present, the surface fails to have sufficient structural stiffness to keep the system in equilibrium (Figure 9-A); in cases where double curvature conditions are distributed to maximize differentiation of radii and direction (a condition described by Marc Fornes as "intensive curvature" [1]) low displacement values were maintained (Figure 9-B).

Cues distributions are filtered in order to obtain a valid mesh from the surface construction algorithm. All configurations where three of the cues form a bifurcation (cues laying on the same X, Y or Z coordinate) lead to a non-manifold mesh in the intersection area, and should therefore be avoided.

Meshes are chosen for further analysis according to four parameters: maximum surface area, minimum stress, minimum displacement and maximum horizontality; the horizontality parameter is defined as the percentage of mesh faces parallel to the XY plane within a given angle and elevation thresholds.

The most promising configuration (with the highest parameter values overall) is then selected for the agent body implementation.

AGENT BODY

Many multi-agent systems implementations, such as Reynolds (1987) boids, treat the agent as a point in Cartesian space. Our implementation endows agents with hierarchical geometric structures described as Agent Bodies.

The Agent Body conceptualization simulates the logic of ant bridges (Reid et al., 2015), where the interconnected geometry of ant bodies forms redundant, adaptable structural wholes (Vernerey et al., 2018). Body-to-body connections emerge through interrelations of body-specific behaviours among neighbouring agents within the generative algorithm. These behaviours include pattern-making, surface constraining and resistance to structural stress such as deflection and bending moments; the patterns generated by the Agent

Bodies emerge from the negotiation among the importance of each behaviour.

By agent body, we mean the spatial model with a specific topology through which the typical swarm relations are realized in higher-order geometric structures. The agent body is a dendritic network of lines, consisting of a fixed core and parts that reach out from the core, named tentacles; their tips can move, stretching the tentacle during the simulation. Tentacles tips of neighbour agents seek each other according to the proximity rules characteristic of cohesion behaviour: each tip searches for other tips in a range and field of view. If the nearest tip is already connected to another tentacle, the seeking tentacle moves towards the next closest tip in range. Behavioural interactions produce a distributed displacement (Figure 10) of the individual tips that tend to migrate toward common midpoints. The resulting pattern is a structurally coherent line network, whose expression can be modulated by acting on the body's behavioural parameters.

Figure 10
Pre and post locking patterns

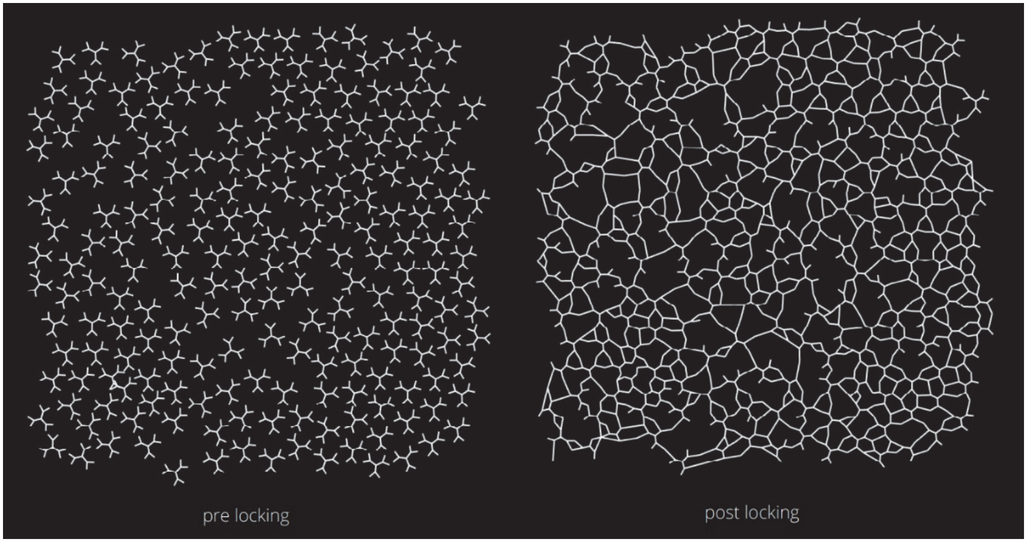
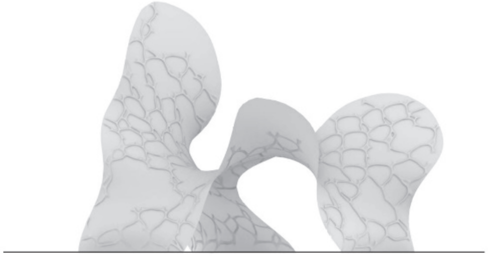


Figure 11
Surface and ornament assembly



The naked mesh stress data derived from LS-DYNA is then used by the agent bodies simulation for the generation of the performative ornament pattern; the line network is integrated with the surface via isomeshing in order to constitute a unique structure (Figure 11).

Two different types of fibre composites were chosen for the structural simulation: fiberglass for the surface and carbon fibre for the pattern. Carbon fibre, although barely stronger than fiberglass in raw form, becomes incredibly strong when combined with the proper epoxy resins (stronger than many metals in some cases). For this reason, it was chosen for the bodies pattern, as it is subjected to critical stress values. Fiberglass is more flexible than carbon fibre, and about 15 times less expensive; an apt choice for the surface base, left naked in lower stress areas.

Figure 12 displays a comparison of the LS-DYNA analyses pre- (Figure 12-A) and post- (Figure 12-B) ornament, clearly showing how the ornamentation system actually manages to take on most of the stress, as it constitutes the most rigid zone of the structure, with a resulting displacement that reduces from about one meter to 10 cm under load conditions.

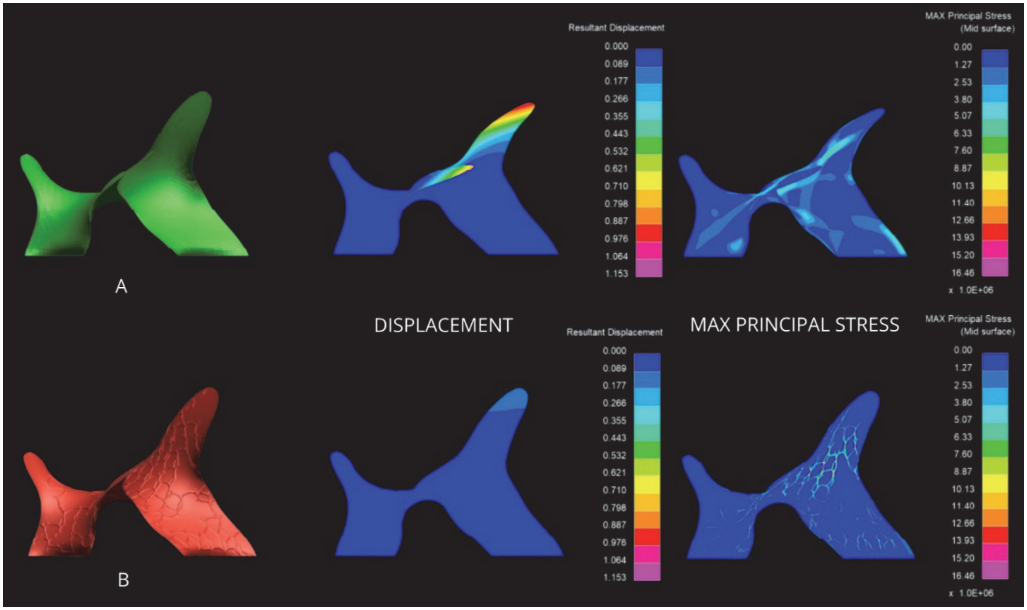


Figure 12
Final comparison

CONCLUSIONS

The research explored the architectural potential of fibre-composite surface tectonics through a combination of self-organizing processes and structural optimization.

In light of the obtained results in the development of the generative process, it is possible to read the first part of the research regarding stigmergic interaction and implicit surface formation as contributions to extend the expressive, morphological and constructive potentialities deriving from multi-agent systems towards the field of architectural exploration.

We can consider the method strong in introducing high degrees of spatial complexity without the aim of predetermining goals in the formal domain. Although cues pattern modelling speeds up the guided generation of complex surface geometry with intrinsic coherence, there are limitations, especially in the relationship between the stigmergic pattern and the stability of the obtained surface. Some manual mesh cleaning is also sometimes required for finite element analysis.

Figure 13 Architectural speculation

The second part of the research provides a solid demonstration of the structural performance contributed by the ornamentation system. Unfortunately, given the scarcity of information retrievable on precedents or alternative methods for the particular subject (structural simulation of pattern-integrated fibre-composites surfaces), it was not possible to draw comparisons. Further restrictive conditions imposed by the pandemic curbed the initial ambitions of producing physical demonstrator prototypes.

The work positions itself in continuity with the current research thread on surface tectonics and fibre composites. Despite the described limitations, the achieved results can be considered satisfying, and we hope they can further stimulate the research on performance integration, so that the architectural design can benefit both in terms of aesthetics, feasibility and resource utilization.

AKNOWLEDGEMENTS

The authors would like to thank families and all those who contributed in any way to the research. Special thanks to ARUP Italy for permitting software use and knowledge support during the research development.

REFERENCES

Bernardini, F et al. 1999, ‘The ball-pivoting algorithm for surface reconstruction’, *IEEE Transactions on Visualization and Computer Graphics*, vol. 5, no. 4, pp. 349–359.

Braitenberg, V 1984, “Vehicles: Experiments in synthetic psychology”, MIT Press, Cambridge, MA.

Cowper, G.R., and Symonds, P.S., Strain Hardening and Strain Rate Effect in the Impact Loading of Cantilever Beams, Brown University, Division of Applied Mathematics Report, 1957

DeLanda, M 2016, Assemblage Theory, 1 edition, Edinburgh University Press, Edinburgh.

Jones, J 2010, ‘Characteristics of Pattern Formation and Evolution in Approximations of Physarum Transport Networks’, Artificial Life, vol. 16, no. 2, pp. 127–153, viewed 5 January 2022,

<https://direct.mit.edu/artl/article/16/2/127-153/2650>.

Jones, J 2011, 'Influences on the formation and evolution of Physarum polycephalum inspired emergent transport networks', *Natural Computing*, vol. 10, no. 4, pp. 1345–1369.

Otto, F 2009, Occupying and connecting: thoughts on territories and spheres of influence with particular reference to human settlement, Edition Axel Menges, Stuttgart.

Reid, CR et al. 2015, 'Army ants dynamically adjust living bridges in response to a cost–benefit trade-off', *Proceedings of the National Academy of Sciences*, vol. 112, no. 49, pp. 15113–15118.

Reiser, J + Umemoto, N 2006, "Atlas of Novel Tectonics". Princeton Architectural Press, New York.

Repenning, A 2006 'Collaborative Diffusion: Programming Antiobjects', OOPSLA 2006, ACM SIGPLAN International Conference on Object-Oriented Programming Systems, Languages, and Applications, Portland, Oregon

Reynolds, C. W. (1987) Flocks, Herds, and Schools: A Distributed Behavioral Model, in Computer Graphics, 21(4) (SIGGRAPH '87 Conference Proceedings) pages 25-34..

Shiffman, D 2012, The nature of code: simulating natural systems with processing, Version 1.0, generated December 6, 2012, Selbstverl., s.l.

Snooks, R and Jahn, G 2016a 'Stigmergic Accretion', Robotic Fabrication in Architecture, Art and Design 2016

Spuybroek, L 2008, The Architecture of Continuity: Essays and Conversations, V2_ publishing, Rotterdam, NL

Spuybroek, L. (2010) 'The Matter of Ornament' in Brower, J. (ed.) The Politics of the Impure, Rotterdam, V2_publishing, pp. 232-267

Tero et al. (2010). 'Rules for Biologically Inspired Adaptive Network Design', *Science* 327(5964), pp. 439-442. Available at: https://doi.org/10.1126/science.1177894

Vernerey, FJ et al. 2018, 'How do fire ants control the rheology of their aggregations? A statistical mechanics approach', *Journal of The Royal Society Interface*, vol. 15, no. 147, p. 20180642.

Wiscombe, T 2010, Extreme Integration, in AD: Exuberance: new virtuosity in contemporary architecture, vol. 80, pp. 78–87, Wiley, Chichester, UK

[1] https://theverymany.com/art-of-the-prototypical

[2] https://vimeo.com/123547307?embedded=true&source=vimeo_logo&owner=4323989