Adaptive Meshing for Bi-directional Information Flows

A Multi-Scale Approach to Integrating Feedback between Design, Simulation, and Fabrication

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Abstract

This paper describes a mesh-based modelling approach that supports the multi-scale design of a panelised, thin-skinned metal structure. The term multi-scale refers to the decomposition of a design modelling problem into distinct but interdependent models associated with particular scales, and the transfer of information between these models. They are applied in this architectural context as a means to manage complex information flows between scales. We describe information flows between the scales of structure, panel element, and material via two mesh-based approaches. The first approach demonstrates the use of adaptive meshing to efficiently sequentially increase resolution to support structural analysis, panelisation, local geometric formation, connectivity, and the calculation of forming strains and material thinning. A second approach shows how dynamically coupling adaptive meshing with a tree structure supports efficient refinement and coarsening of information. The modelling approaches are substantiated through the production of structures and prototypes.

Keywords:
meshing, discrete models, tree, optimisation, multi-scale modelling

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1. Introduction

Thin panelised metallic skins play an important role in contemporary architecture, often as a non-structural cladding system. Strategically increasing the structural capacity – particularly the rigidity – of this cladding layer could offer significant savings for secondary and primary structural systems. Achievable through the specification of geometric and material properties, skin-stiffening techniques marked the early development of metallic aircraft (Hirschel et al. 2012), and are currently applied within the automotive industry, where selective local differentiation of sheet thickness and yield strength combine with locally specific rigidising geometries that increase structural depth.

To improve the rigidity of thin-skinned metal structures requires a modelling approach that guards against instabilities due to buckling at three distinct scales: buckling of the structure, buckling within panel elements which have to carry compressive load, and also buckling and tearing that can occur during the sheet forming process itself (Nicholas et al. 2016). In this paper we discuss a multi-scale approach in which a mesh connects distinct models associated with each of these scales. A particular challenge is related to the fabrication technique used to form the steel sheet. A robotic incremental sheet forming (ISF) process is used to form all connections and rigidising geometries in a given panel. The ISF process has material implications related to thinning and change in yield strength, which means that a panel cannot be accurately modelled as geometrically or materially homogeneous. This leads to a requirement for multiple mesh resolutions, which go beyond that of a typical architectural model, and for effective flows of information about both geometric and material properties.

The paper is organised as follows: Section 1 describes the ISF process as well as the geometric and material transformations that it implicates. Section 2 describes the multi-scale modelling approach. Section 3 presents two adaptive mesh-based approaches, the first supporting unidirectional information flow and the second bi-directional information flow through a coupled meshing/tree traversal.

2. Background: ISF Process

The modelling process addresses the design of a thin-sheet steel structure fabricated via a specific fabrication method – robotic ISF. ISF is an innovative fabrication method for imparting 3D form on a 2D metal sheet, directly informed by a 3D CAD model. In the ISF process, a simple tool moves over the surface of a sheet to cause localised plastic deformation (Jeswiet et al. 2005) (Fig. 1). The primary advantage of ISF is to remove the need for complex moulds and dies, which only become economically feasible with large quantities (Wallner & Pottmann 2011). For

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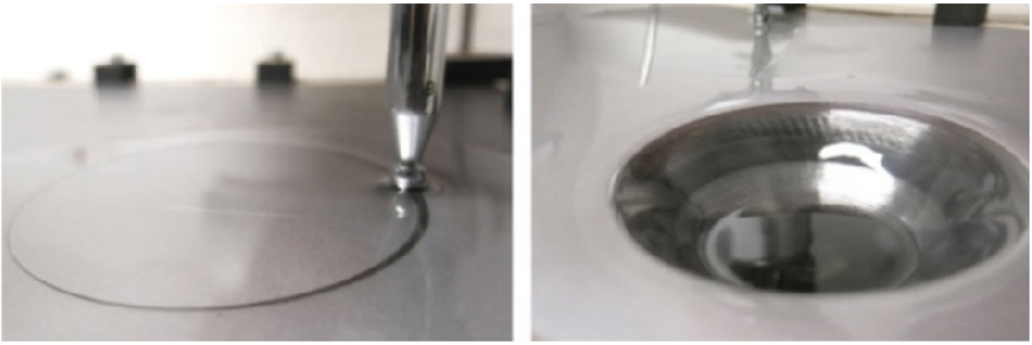

Figure 1. ISF process.

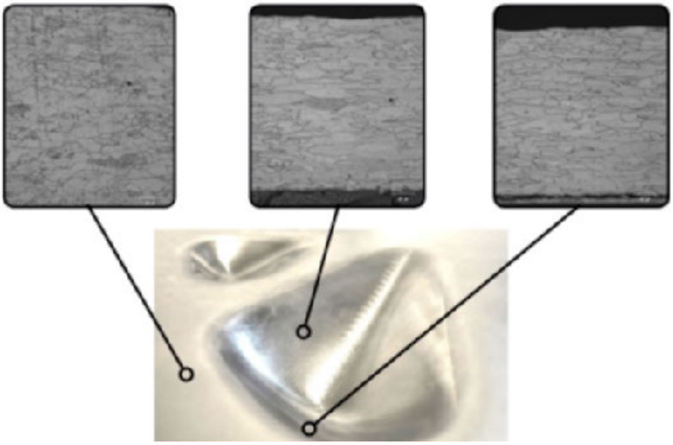

Figure 2. Grain elongation and thinning at selected wall angles.

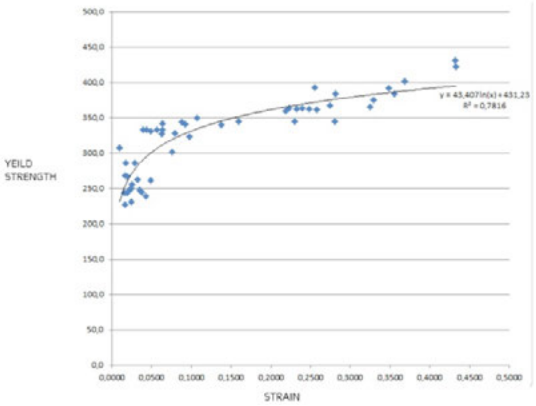

Figure 3. Increase in yield strength as a result of cold working during the ISF fabrication process.

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this reason, in contexts such as automotive, ISF is explored for its potential to dramatically reduce the costs of prototyping.

Transferred into architecture, ISF moves from a prototyping technology to a production technology. Within the context of mass customisation, it provides an alternate technology through which to incorporate, exploit and vary material capacities within the elements that make up a building system.

2.1 Transformative Implications of ISF

The ISF process has effects that are both geometric and materially transformative. Geometric features can be introduced by locally stretching the planar sheet out of plane. These increase structural depth and therefore increase rigidisation and can also provide architectural opportunities for connection and surface expression.

As the steel is formed, there is an increase in surface area and a corresponding local thinning of the material. It is important to calculate this change in thickness so that the material is not stretched too far and tears or buckles as the thickness approaches zero. Forming also activates a process of work hardening – a deliberate application of deformation that helps resist further deformation – with the effect of raising the yield strength of the steel. Depending on the geometric transformation, the effects of the material transformation are locally introduced into the material to different degrees, depending on the depth and angle attained through the ISF process. At an extreme, yield strength for steel can almost double, while material thickness can reduce to zero (Fig. 2, Fig. 3). Because the transformative implications of ISF fabrication are significant, it is very important to incorporate them into the design phase.

2.2 Design Application

The context of this research is the application of ISF to the forming of panels within unframed, panelised, stressed-skin structures. Stressed skins are lightweight, thin sheet structures in which the skin is structurally active, and bears tensile, compressive and shear loads as well as providing rigidity.

A full scale demonstrator was installed at the Designmuseum Danmark in May 2015 (Fig. 4), and prototype panels that also test the meshing methods described in this paper were produced afterwards. The panels are produced by robotic ISF based on production information drawn directly from the meshing methods described in Section 3. The basis of the customised toolpathing algorithm is the established method of a spiral descent (Jeswiet et al. 2005), which can be run on different levels of mesh resolution to achieve different aesthetic effects (Fig. 5), but extended to vary stepping and tooling speed in relation to wall angle, measured from the normal of the mesh face.

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Figure 4. Demonstrator in the Designmuseum Danmark.

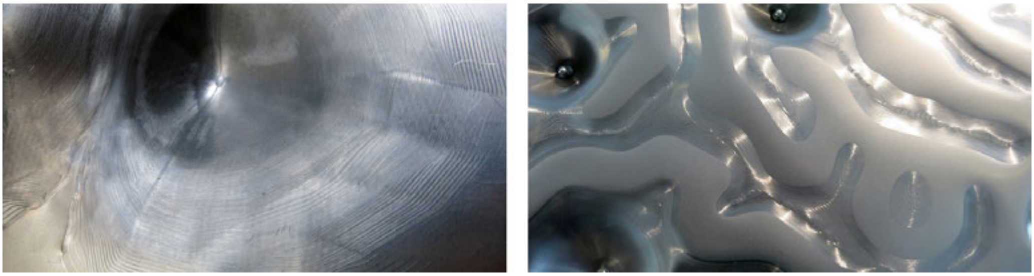

Figure 5. Toolpath generated from different levels of mesh resolution.

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3. Method: Multi-Scale Modelling Approach

The design context described above necessitates a multi-scale approach. Multi-scale models aim to describe a problem by separating it into discrete models, typically of different type (E 2011). They leverage that, for some applications, a model does not require the full complexity of the object. Each model addresses a particular feature of the design problem (Nicholas et al. 2012). These models parameterise one another, either sequentially or simultaneously. A key concern is therefore those techniques that enable the information generated within each of these models to flow to others.

The modelling framework for StressedSkins defines three scales – macro, meso, and micro – that coincide with the considerations regarding rigidity outlined above. In addition, the macro-scale encompasses the resolution of global design goals, overall geometric configurations, a full-scale understanding of structural performance and discretisation, and is informed by the available scale of production. The meso-scale considers the project at an assembly and sub-assembly level, and is concerned with material behaviours tied to geometric transformation, detailing and component-level tectonic expression. The micro-scale is concerned with relevant material characteristics at the most discretised level. To act as a communicative substrate and efficiently bridge between different levels of resolution to capture the required dynamics, small-scale geometry and scale-sensitive calculations, the adaptation of a non-structured grid is pursued. This mesh supports all relevant outputs for form-finding, analysis, fabrication and representation.

3.1 Communication Across Scales Through Half-Edge Mesh Structure

The first approach focusses on incrementally refining a mesh subdivision so that one mesh can support understandings of coarser topological relationships between individual panels, granular understandings of local material behaviours, and refined geometries for defining digital fabrication drivers and toolpaths. The basis of the approach is a half-edge (or directed-edge) mesh data structure. Half-edge meshes enable the deployment of N-gon faces (rather than more standard triangulated or quadrilateral faces). This opens up the possibility for designing with more complex topologies.

The sequential increase in resolution is shown in Figure 6. Initial increases in resolution are achieved through node insertions related to specific geometries, and later refinements by Loop subdivision (Loop 1987). The refinement of the mesh maintains anchored nodes, seams, and creases as they are established at different levels of resolution. At a first resolution, two layers of pentagonal tiling are distributed across a base surface. The nodes of this base mesh are positioned

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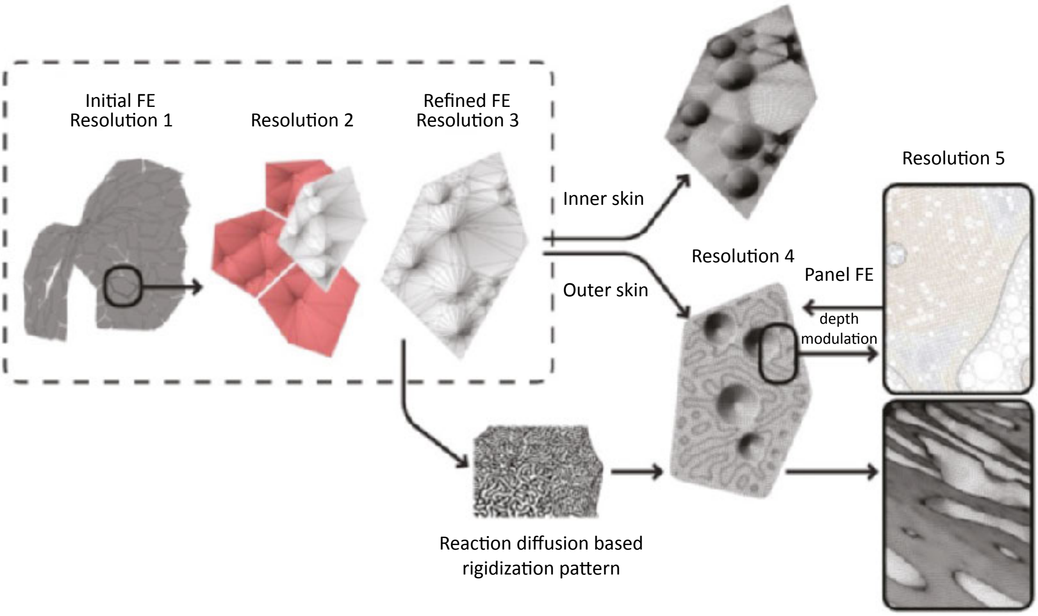

Figure 6. Information flow. Mesh resolution is adaptively increased to support scale specific computational processes.

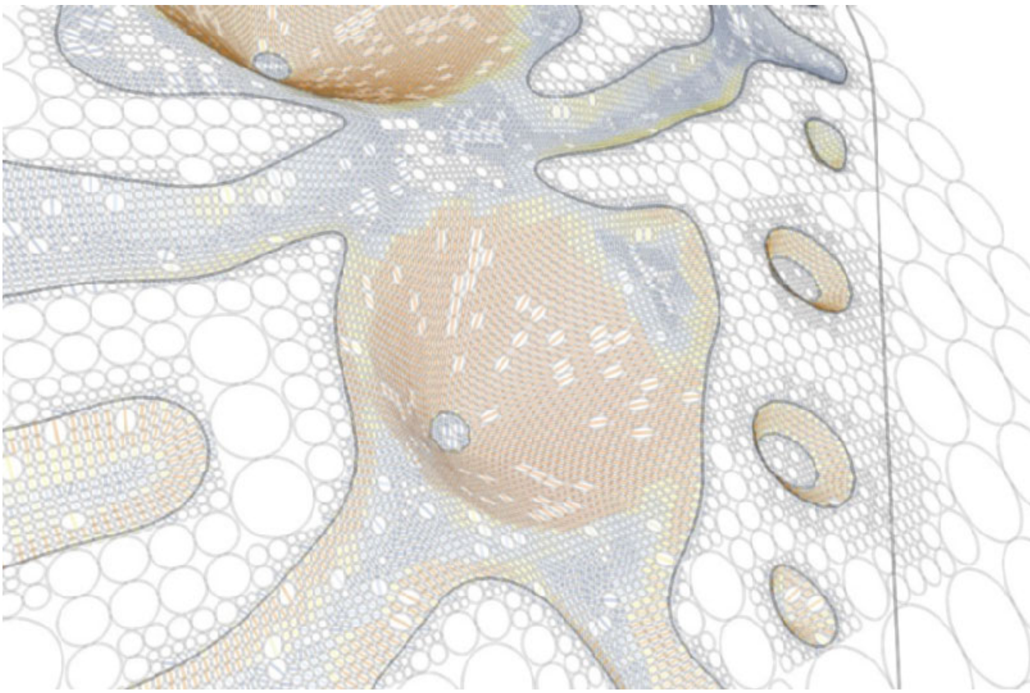

Figure 7. Calculation of strains and material thinning.

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so that edges are oriented to minimize any global hinge effects using constraint based form-finding. At a second resolution, nodes describing low-resolution details related to connection are added to the mesh. These conical geometries are integrated with the panels and connective faces – with inherited data structures – into a coarse triangulated mesh. An iterative process of finite element analysis performed upon this mesh refines the number and distribution of connection elements, which are located in as great a number as possible near high-shear forces, and aligned perpendicular to them.

A third resolution introduces new nodes that more accurately describe all connection geometries, and the mesh is then subjected to finite element analysis. The results of this analysis – utilisation and bending energy – directly drive the tectonic patterning of the skins, which introduces a fourth resolution. For this, utilisation forces within each panel are used to drive the depth of either oriented dimples or a non-orientated pattern within the structure.

The complex geometries that result are informed by the calculation of thinning and increased yield strength, on the basis of strain measurement via circle projection (Fig. 7) and numeric models generated from Vickers hardness testing. Empirical testing provided a means to accurately inform the model at this scale, as available theoretical models such as the sine law do not yet provide accurate models (Ambrogio et al. 2005). A final skin fabrication model at a fifth scale of resolution is synthesised, and each panel systematically arrayed for extracting toolpaths.

3.2 Communication Across Scales Through Coupled Meshing/Tree Traversal

The second communication approach is focussed on refining two phases of the modelling process: mesh subdivision and data transmission between different scales.

As experienced with the first modelling workflow, the geometries produced by subdivision can become computationally expensive, whereas their high resolution is necessary only locally within each panel, specifically where the out-of-plane deflection occurs. To reduce the mesh density without coarsening the geometry, an adaptive Loop Subdivision algorithm (Pakdel & Samavati 2004) was implemented and further developed to incorporate additional constraints. The subdivision method was extended to support creases (chains of edges which break the curvature continuity) and anchor points (points that stay in place during the process), which are utilised to efficiently and precisely model the deformation. Using this adaptive subdivision strategy, the resolution of a typical mesh used in the first demonstrator can be reduced by up to 30%, yet still maintain the shape (Fig. 8). Structural analysis occurs at different mesh resolutions/scales: The structural efficiency of the global shape is optimised at the macro level, where

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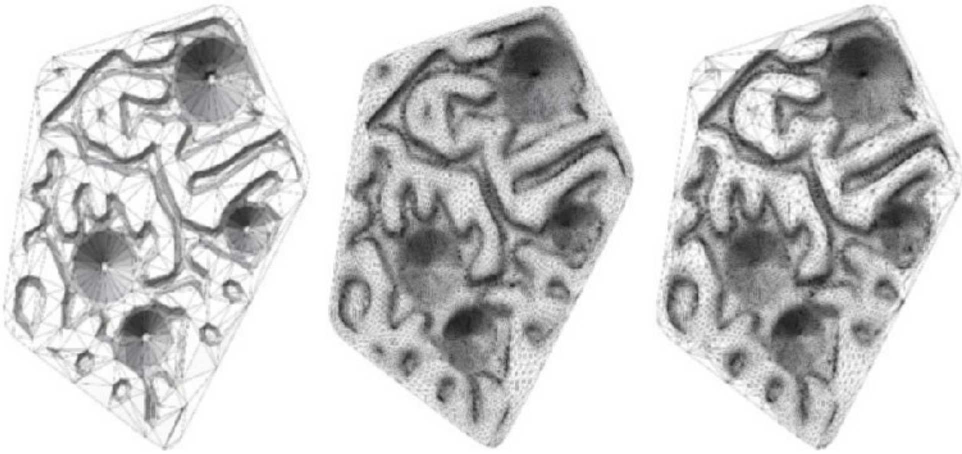

Figure 8. Face count comparison. From left: original mesh, Loop subdivision, adaptive Loop subdivision.

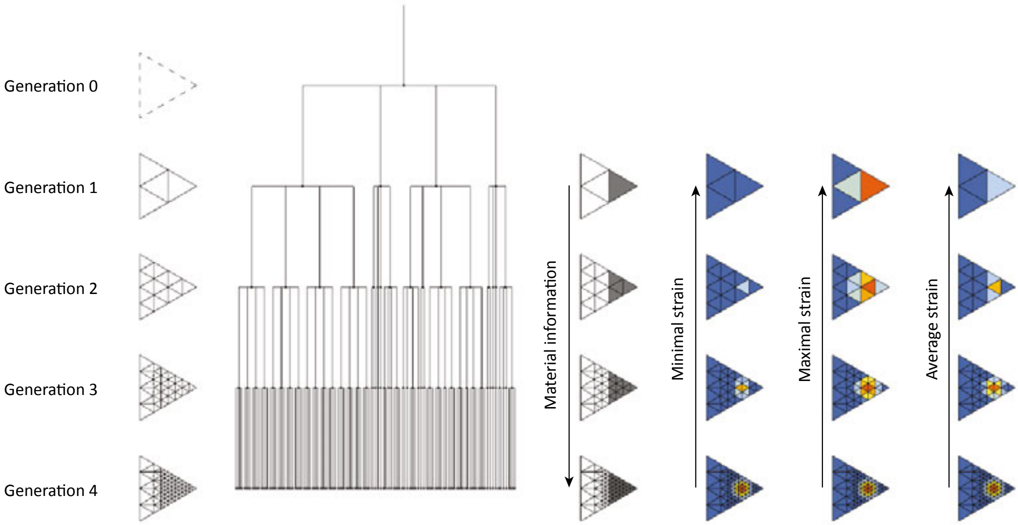

Figure 9. Bi-directional data propagation between low and high resolution.

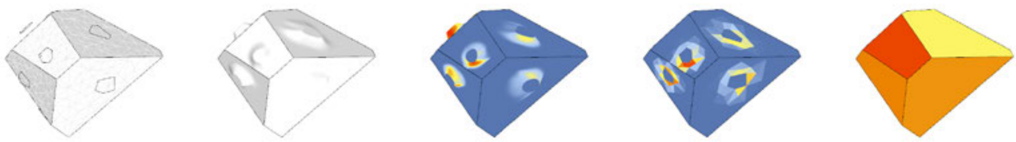

Figure 10. Upstream data propagation result. From left: original mesh, subdivided mesh, strain calculation, results propagated up the subdivision tree, colourizing the panels with respect to the maximal strain value.

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the low resolution mesh is sufficient. On the other hand, the plastic deformation is computed at the micro-level, being analysed for a single panel at a time. The meso-level information accounts for connections between layers and analysis of relationships between panels. It is highly desirable to tie the analysis information with the discrete model produced by the subdivision algorithm, since the efforts to transition of data back and forth between different models/scales should be minimised. The ultimate goal is to consider multiple various scale representations as a single model.

The HNode Class is developed to support continuity of information between different resolutions. The modelling framework is based on Grasshopper, where the principal collection type is called DataTree. Contrary to its name, this object is not a proper tree-like collection (rather a dictionary), as it doesn't have a query method for parent and child nodes. A custom-tailored class provides a better foundation to accomplish geometry-data coupling through a recursive tree object. The HNode Class (Hierarchy Node) is a type of a tree data structure that can be traversed efficiently. As with tree structures, all of the data are stored in the root-level node. In our case, the root represents the complete demonstrator structure composed of multiple panels, which are stored separately as the second level of the tree. The third level represents the initial low-resolution mesh, where each node keeps information for each mesh face. To keep track of different resolutions, the subdivision algorithm introduces new layers to the tree: For each subdivided face, multiple children are added (2-4 for adaptive loop subdivision), and to keep the tree easy to read and manipulate, the nodes of the faces which are not subdivided are given a singular child. Additionally, to storing information about its children, an HNode collection can store and/or convey some more information just like a binary tree (Fig. 9). Contrary to that kind of structure, the values are decoupled from the topology of the tree (in our case the topology is derived from the subdivision process) and come from structural analysis at various levels. As the analysis can be done for any of the levels of the tree at any time, various upstream and downstream methods of propagation have been implemented.

One example of upstream data propagation is the minimal wall thickness information gained from strains calculation. This process happens at the lowest level of the tree, and to visually inspect the results it is easiest to recursively query each top-level parent to get the lowest value of each of its children. At this highest level, this results in an easy to verify visualisation (Fig. 10).

Two ways of keeping the data up to date within the tree have been tested: active and passive. The active way means that the value of dependent parents and children is updated automatically each time any value in the tree is changed; the passive method requires the user to manually trigger the upstream or downstream propagation from a selected level of the tree. During the tests, it came clear that the passive method is more adequate for computational efficiency and clarity.

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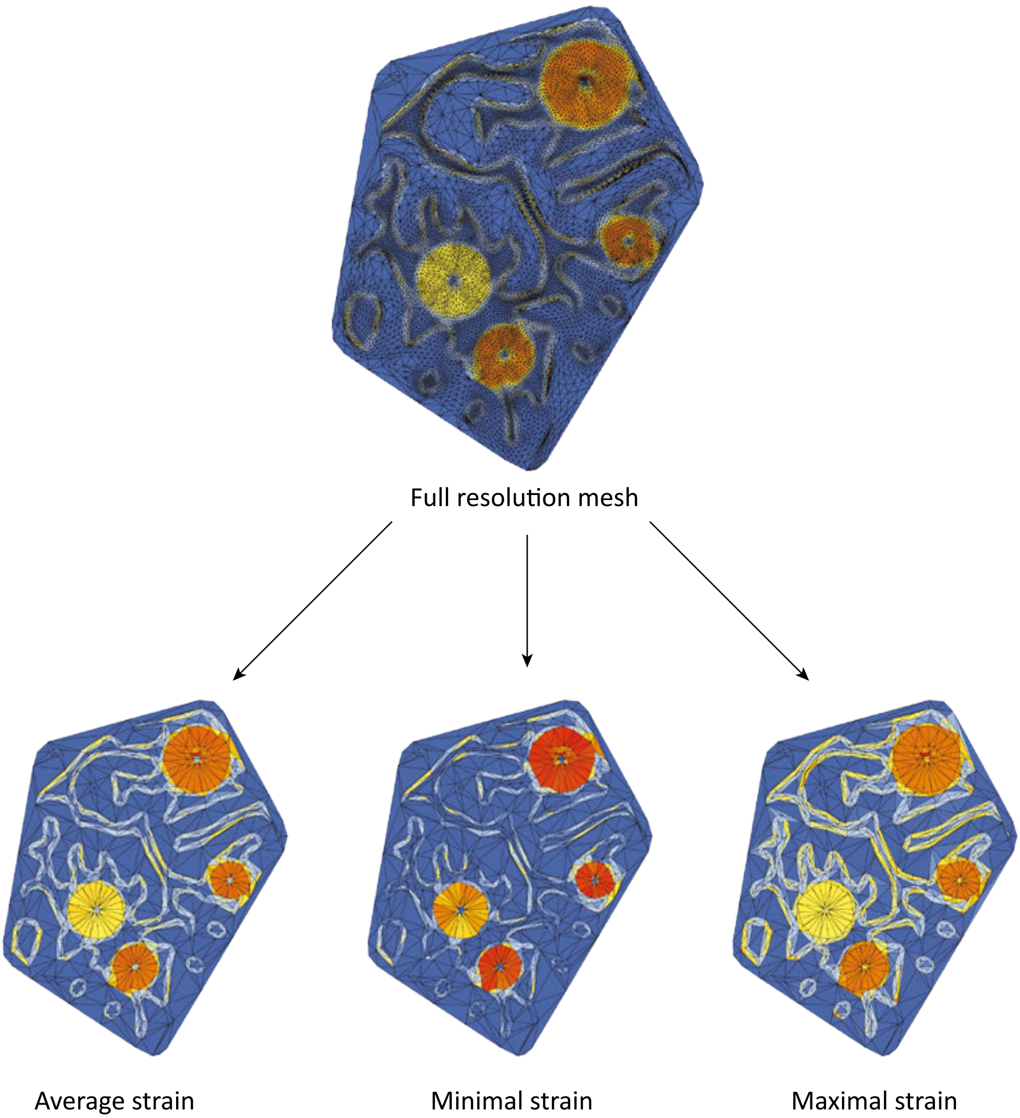

Figure 11. Various methods of data propagation.

The HNode library is written in .NET, and the implementation wraps it up as a data type compatible with Grasshopper. The generic nature of this collection type bears a premise of its being useful in other applications, where keeping track of dependencies and relationships might not be as easy to achieve with the native to Grasshopper Data Tree collection because of the previously stated dictionary-like characteristics.

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4. Reflections and Conclusions

This paper examines adaptive mesh-based modelling as a means to support the computational design of panelised thin-sheet structures built using the ISF process. Two approaches are described: The first is characterised as unidirectional and the second as bi-directional. The context of the research exemplifies the need for a back and forth between fabrication, design, and analysis. With multiple scales of material organisation – multiple parts, highly heterogeneous in terms of their shape, their surface geometry, and their material properties, modelling necessitates a discretisation for reasons of control, accuracy and workability. However, a successful discretisation relies on retaining as many possibilities for information flow as possible, and on an efficient and effective organisation of that information flow.

The tree-based approach we have described avoids the separate storage and lookup of information, as this can be produced directly from the hierarchy. The approach is generalisable. For example, although applied here to a technique of manipulative fabrication, the methods we described would also support material specification and optimisation for additive fabrication, specifically within the emerging territory of functionally or mechanically graded materials. Because digital fabrication offers increasing possibilities for bespoke material design that corresponds to desired performances, complex information flows between design, specification, and analysis at multiple scales become required.

One could ask why it is necessary to have multiple scales of resolution and not simply compute every aspect at the highest level of resolution. Beyond pragmatic reasons, which include limitations of computation time and legibility, there is a greater issue of efficiency. The generation of unnecessary data can render a design workflow unusable, or simply displaces effort into subsequent filtering.

The first approach sequentially varies a single mesh topology to manage the complexity of bridging scales and functions while maintaining the continuity of information flows down scale. However, a realisation of this approach is that, for each scale, there is some data that the designer wants to pass up or down. This is because a model does not necessarily have the possibility to recognise or even correct a problem within the model itself. Instead, geometry needs to be passed to another level of resolution for its implications to be tested accurately. Equally, something can be learnt on a lower level that forces adjustment on the upper level, which cannot be tested for at the resolution of prior levels. This cannot be well addressed by a unidirectional model.

In the second approach described, the bi-directional workflow ties multiple scales together in a more consistent and manageable way compared with the previous method. The ability to reference the data through common interface to other levels makes an element on one level aware of information at any other level of the tree. This enables adaptation of any particular element based on

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higher or lower-level information. Future research will connect this bi-directional workflow with an automated feedback loop, and develop visualisation techniques that allow analysis and comparison at different resolution levels.

References

Ambrogio, Giuseppina, Luigino Filice, Francesco Gagliardi, and Fabrizio Micari. 2005. “Sheet Thinning Prediction in Single Point Incremental Forming.” *Advanced Materials Research* 6-8: 479–86. doi: 10.4028/www.scientific.net/AMR.6-8.479

E, Weinan. 2011. *Principles of Multi-Scale Modeling*. Cambridge University Press.

Hirschel, Ernst Heinrich, Horst Prem, and Gero Madelung. 2012. *Aeronautical Research in Germany*. Berlin Heidelberg: Springer. doi: 10.1007/978-3-642-18484-0

Jeswiet, J., N. Alan, F. Bramley, J. Micari, J. Duflou, and J. Allwood. 2005. “Asymmetric Single Point Incremental Forming of Sheet Metal.” *CIRP Annals – Manufacturing Technology* 54, 2: 623–49. Accessed at http://opus.bath.ac.uk/2137/

Loop, Charles Teorell. 1987. “Smooth Subdivision Surfaces Based on Triangles.” *Department of Mathematics, The University of Utah, Masters Thesis*. Accessed at http://research.microsoft.com/apps/pubs/default.aspx?id=68540

Nicholas, Paul, David Stasiuk, Esben Nørgaard, Christopher Hutchinson, and Mette Ramsgaard Thomsen. 2016. “An Integrated Modelling and Toolpathing Approach for a Frameless Stressed Skin Structure, Fabricated Using Robotic Incremental Sheet Forming.” *Robotic Fabrication in Architecture, Art and Design 2016*, 62-77, doi: 10.1007/978-3-319-26378-6

Nicholas. Paul, and Martin Tamke. 2012. “Composite Territories: Engaging a Bespoke Material Practice in Digitally Designed Materials.” *eCAADe – Digital Physicality*, Prague 2: 691–699.

Pakdel, Hamid-Reza, and Faramarz Samavati. 2004. “Computational Science and Its Applications.” In *ICCSA 2004: International Conference, Assisi, Italy, May 14–17, 2004, Proceedings, Part III*. Ed. by Antonio Laganá, Marina L Gavrilova, Vipin Kumar, Youngsong Mun, C J Kenneth Tan, and Osvaldo Gervasi, 237–46. Berlin, Heidelberg: Springer. doi: 10.1007/978-3-540-24767-8_25

Wallner, Johannes, and Helmut Pottmann. 2011. “Geometric Computing for Freeform Architecture.” *Journal of Mathematics in Industry* 1, 1: 4. doi: 10.1186/2190-5983-1-4

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