Concepts and Methodologies for Multiscale Modeling

A Mesh-Based Approach for Bi-Directional Information Flows

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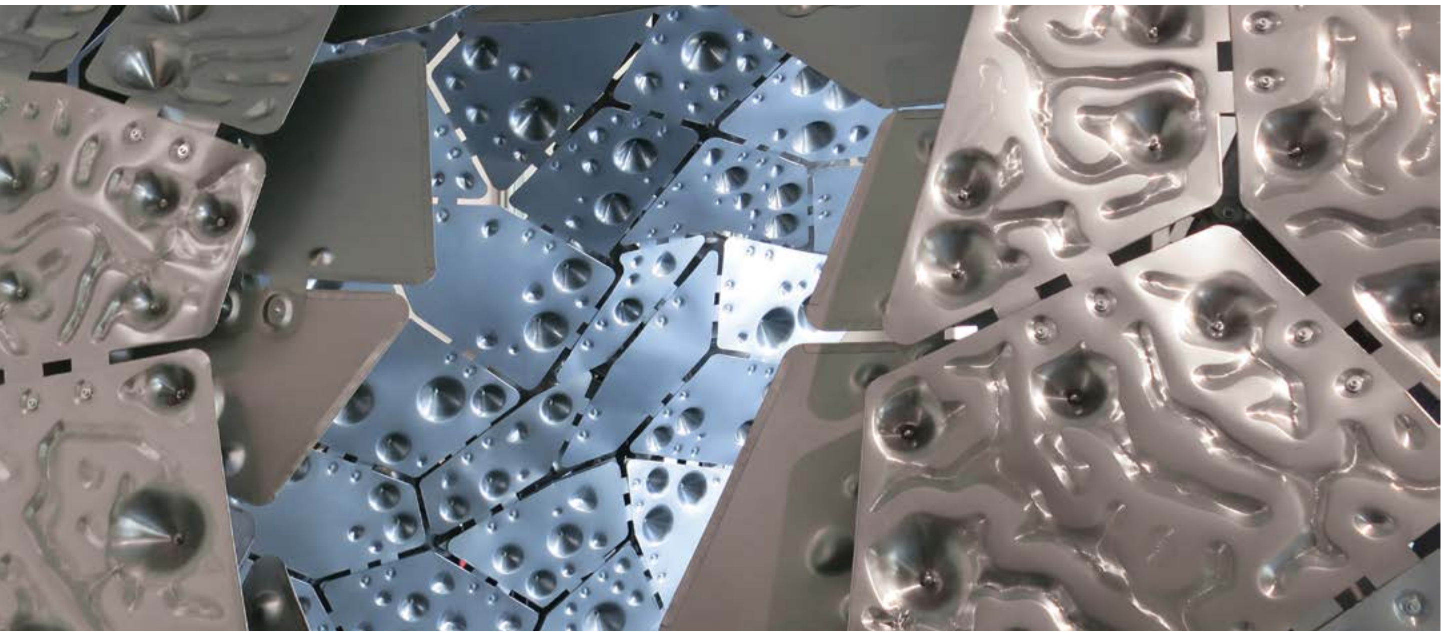

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1 The installation 'StressedSkins,' at the Danish Design Museum 2015.

ABSTRACT

This paper introduces concepts and methodologies for multiscale modeling in architecture, and demonstrates their application to support bi-directional information flows in the design of a panelized, thin skinned metal structure. Parameters linked to the incremental sheet forming fabrication process, rigidisation, panelization, and global structural performance are included in this information flow. The term multiscale refers to the decomposition of a design problem into distinct but interdependent models according to scales or frameworks, and to the techniques that support the transfer of information between these models.

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 and sequentially increase resolution to support structural analysis, panelization, 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 multiscale modeling approaches are substantiated through the production of structures and prototypes.

INTRODUCTION

Thin panelized 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, the development of skin-stiffening techniques marked the early history of metallic aircraft manufactuing (Hirschel, Prem, and Madelung 2012), and are currently applied within the automotive industry, where selective local differentiation of sheet thickness and yield strength combine with locally specific rigidizing geometries that increase structural depth.

To improve the rigidity of thin skinned metal structures requires a modeling 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. 2015). This necessitates a multiscale perspective. In this research, much of the multiscale challenge is related to the fabrication technique used to form the steel sheet—robotic incremental sheet forming (ISF)—and the desire to connect information regarding localized material change that results from this process to the design and finite element analysis of the larger structure. This is accomplished through a transition between multiple mesh resolutions, and an approach to meshing that supports effective flows of information about both geometric and material properties. In this paper, we introduce these modeling frameworks through a description of the installation 'StressedSkins' (Figures 1–3).

The paper is organized as follows: section one describes a conceptual background for multiscale modeling, the ISF process, and the geometric and material transformations that it implicates. Section two describes our application of multiscale modeling, and presents two adaptive mesh-based approaches. The first supports predominantly unidirectional information flow and the second implements bidirectional information flow through a coupled meshing/tree traversal.

MULTISCALE MODELING

Most physical and social phenomena are multiscale, and exhibit what Cyril S. Smith has described as the "deep entanglement of macro and micro" (1981). We organize time into days, months, and years as a result of the multiscale dynamics of the solar system (E 2011). We understand materials to combine "macrocosm and microcosm consist[ing] of innumerable material objects… each material object capable of supporting and transmitting forces" (Otto 1992). Architectural structures can be

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2 The installation 'StressedSkins,' at the Danish Design Museum 2015.

3 Forming of connection and rigidisation geometries on the inner and outer skins enables stability and force transfer without a frame.

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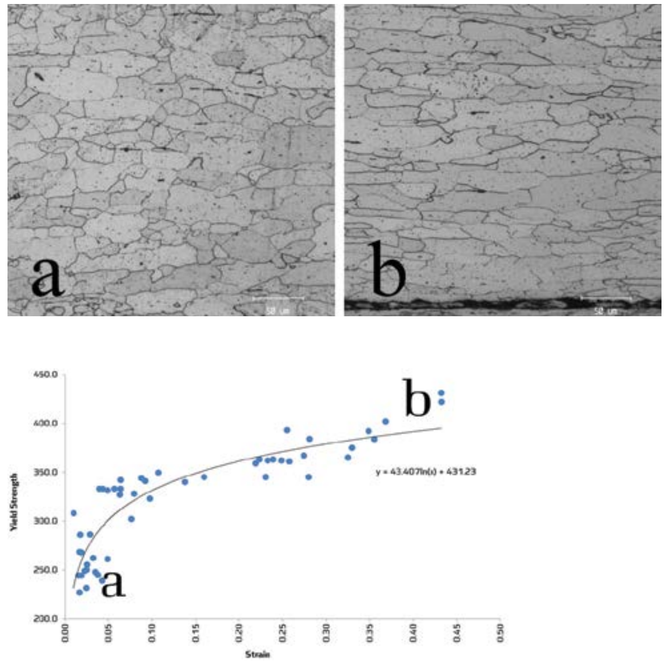

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thought of similarly, as nested organizations from which features, behaviors, and properties emerge on the basis of interactions across scales and systems. Macroscopic domains—often concerned with territories, topologies, and structures—provide environmental constraints for the micro-scale concerns—material distributions, loads, limits—that also inform them.

Modeling approaches in architecture typically follow traditional drawing practice: a focus on one scale at a time, and a gradual refinement from greater to smaller scales. Relations between scales work under the assumption that processes at any other scale are homogenous, or can be described via highly simplified linear relationships. But in other fields, including materials science, economics, and meteorology, alternate modeling approaches that support a different and less linear set of relations and flow of information have developed.

These modeling approaches—termed multiscale—simulate underlying phenomena that span a sequence of scales or, more accurately, frameworks (E 2011). They have developed on the basis of several realizations: 1) that no single model or framework is adequate on its own to capture the full behavior of a system, since the information and models that we have about the world are partial and bounded; 2) that modeling efficiencies can be gained by exploiting different levels of resolution; and 3) that high-resolution models quickly becomes intractable at larger scales. For example, molecular dynamics and quantum mechanics models can capture differentiation at the smallest scales, but because of computational issues, these simulations are currently constrained to approximately 107–108 molecules, or about fifty nanometers. The problem of modeling larger collections is not simply computational; the mathematical complexities are so great that it is impossible to apply them directly to common problems (E 2011). Given that architectural models—when attempting to model differentiation within the bounds of a single scale and a single model—are similarly constrained in computing dynamic information flows between large numbers of entities, multiscalar approaches become a promising architectural tool.

Instead of attempting a complete description within a single scale or model, multiscale approaches assemble a multiplicity of models, each capable of describing an important feature using a particular framework. These models are connected together, so that the output of a given model becomes the input for another. Multiscale modeling is therefore the identification and construction of suitable models and frameworks, together with the application of modeling techniques that relate or 'bridge' these models and frameworks (Elliot 2011) by coupling together different kinds of description.

Within architecture and engineering, one approach to multi-scale modeling is to link a macro-scale structural domain with a micro-scale material domain. With either design generation or optimization as a goal, each level is varied so as to achieve a specific global effect. In the simplest case, this involves the iterative solution of one problem at the macro level (stability, for example), and several problems (which together inform the best local configuration) at the material level (Coelho et al. 2008).

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4 The start and end states of the incremental sheet forming process, which induces 3D form through the application of a continuous localised plastic deformation.

5 Above left: The material implications of the forming process. Above right: the elongation of grain geometry under strains induced by forming is observable via optical microscopy. Lower: Graph of yield strength as a function of strain, derived from Vickers hardness testing.

6 The machine setup at CITA used for single- and double-sided forming.

Some multiscale models, including the approach described in this paper, include an intermediate meso-scale level, in this case related to an architectural component and its detailing. But because the type and level of detail of information is different for the different levels of description, multiscale models can easily be constrained by the need to translate information. For this reason, bridging or 'handshaking' techniques (Winsberg 2010)—which translate, coarsen, or refine information as it passes it between models—are central to the multiscale modeling process. The mesh-based techniques described in this paper directly address this issue.

Considering the Fabrication Process as a Site For Localised Material Property Variation

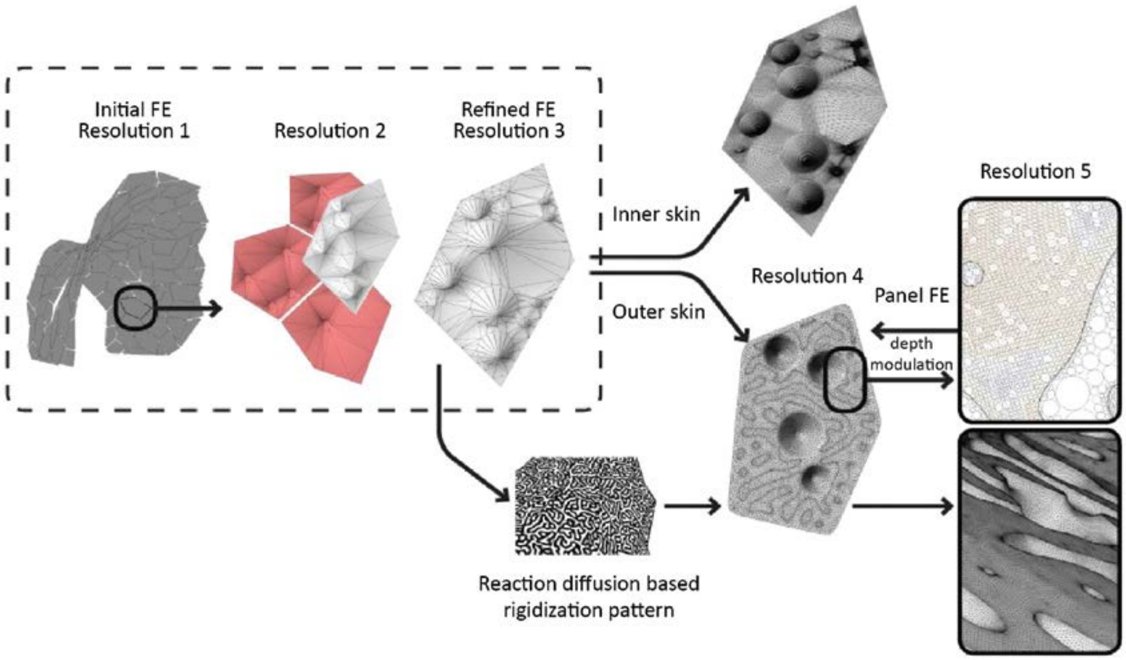
The modeling process addresses the design of a thin-sheet steel structure fabricated via a specific fabrication method—robotic incremental sheet forming. Incremental sheet forming (ISF) is an innovative fabrication method for imparting 3D form on a 2D metal sheet, directly informed by a 3D CAD model. In the ISF process, a simple tool moves over the surface of a sheet (Figures 4 and 6) to cause localized plastic deformation (Jeswiet et al. 2005). The primary advantage of ISF is to remove the need for complex molds and dies, which only become economically feasible with large quantities (Wallner and Pottmann 2011). For this reason, in contexts such as automotive fabrication, 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 customization, it provides an alternate technology through which to incorporate, exploit, and vary material capacities within the elements that make up a building system. Potential architectural applications have been identified in folded plate thin metal sheet structures (Trautz and Herkrath 2009) and customized load-adapted architectural designs (Nicholas et al. 2015; Kalo and Newsum 2014; Brüninghaus et al. 2013). Recent research has established ISF as structurally feasible at architectural scale (Nicholas et al. 2015; Bailly et al. 2015).

The 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 rigidization, 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. This change in thickness is important to calculate so that the material is not stretched too far, and does not tear or buckle 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 differing degrees, depending on the depth and angle attained through the ISF process. At an extreme, yield strength for steel can almost double (Figure 5), while material



7 Flow of information across multiple scales of resolution within the design process.

thickness can reduce to zero. Because the transformative implications of ISF fabrication are significant, it is very important to incorporate them into the design phase.

DESIGN APPLICATION

The context of this research is the application of ISF to the forming of panels within unframed, panelized, 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. ISF is particularly suited to this application, as it provides a method for customizing each panel so that it can be informed by local, performance driven requirements for rigidization and connection, as well as by the geometries needed to negotiate these conditions in a seamless manner. In our design application, ISF is used to make all out of plane geometric features within a panel, including connections between the inner and outer skin, as well as the rigidization geometries that are applied to the outer panels.

A full-scale demonstrator was installed at the Danish Design Museum in May 2015, and prototype panels that also test the meshing methods described in this paper have been produced afterwards. The basis of the customized tool-pathing 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, but extended to vary stepping and tooling speed in relation to wall angle, measured from the normal of the mesh face.

METHOD

One of the main problems in the design of thin-skinned metal structures is to ensure rigidity, and to guard against instabilities due to buckling at three distinct scales: buckling of the structure, bucking within panels which have to carry compressive load, and also buckling that can occur within the sheet-forming process itself. This design context necessitates a multiscale approach and the development of techniques that enable the information generated within models to flow to others.

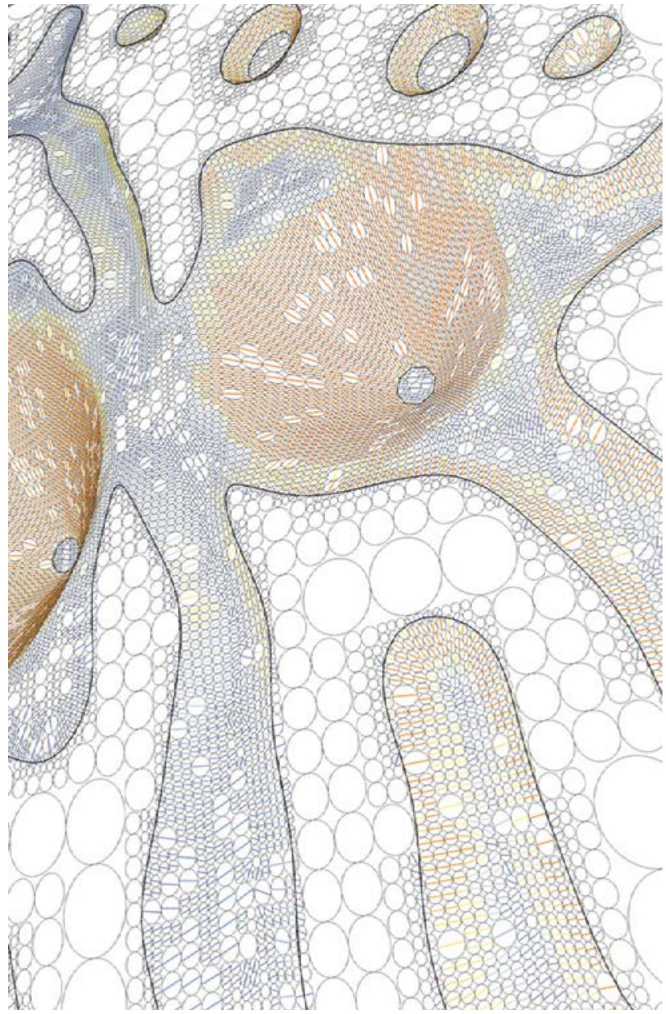
The modeling framework for StressedSkins defines three scales—macro, meso and micro—that coincide with the considerations regarding rigidity outlined above. In addition, the macro scale encompasses the resolution of global design goals, overall geometric configurations, a full-scale understanding of structural performance and discretization, 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 behaviors tied to geometric transformation, detailing, and component-level tectonic expression. The micro scale is concerned with relevant material characteristics at the most discretized 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.

Communication Across Scales Through Half-Edge Mesh Structure

The first approach focuses 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 behaviors, 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 7. 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, a generative pentagonal tiling algorithm arrays a double skin of pentagonal tiles across a base surface. The nodes of this base mesh are positioned 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. The 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.

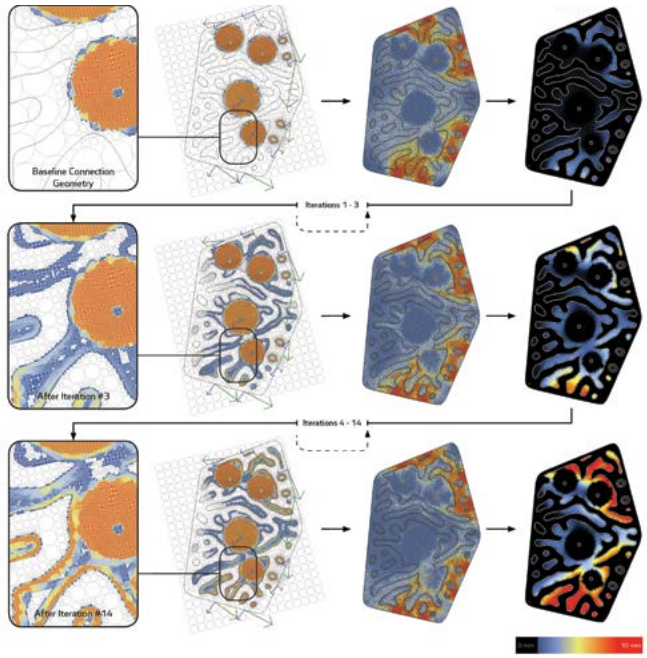
A third resolution introduces new nodes that more accurately describe all connection geometries, and the mesh is then subjected to finite element analysis. The results of this analysis—utilization and bending energy—directly drive the tectonic patterning of the skins, which introduces a fourth resolution. For this, utilization forces within each panel are used to drive the depth of either oriented dimples or a non-oriented pattern within the structure (Figure 9). The complex geometries that result are informed by the calculation of thinning (Figure 8) and increased yield strength, on the basis of strain measurement via circle projection 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 synthesized, and each panel systematically arrayed for extracting toolpaths.



8 Calculation of strains and thinning are achieved using circle projection and a measure of deformation.

Communication Across Scales Through Coupled Meshing/ Tree Traversal

The second communication approach is focused on refining two phases of the modeling process: mesh subdivision and data transmission between different scales. As experienced with the first modeling 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 and 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 which stay in place during the process), which are utilized 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



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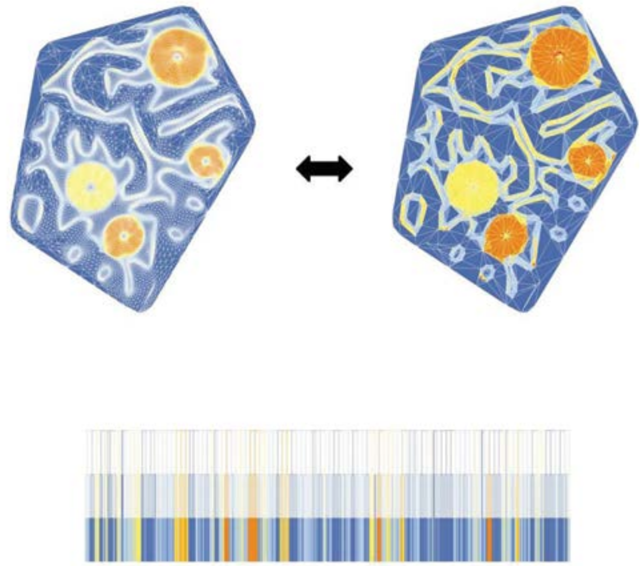

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by up to 30%, yet still maintain the shape (Figure 11). Structural analysis occurs at different mesh resolutions/scales: the structural efficiency of the global shape is optimized at the macro level, where the low resolution mesh is sufficient. On the other hand, the plastic deformation is computed at the micro level, being analyzed for a single panel at a time. The meso-level information accounts for joinery and analysis of relationships between panels. It is highly desirable to tie the analysis information with the discrete model produced by the subdivision algorithm, as that way, the efforts to transition data back and forth between different models/scales should be made much less noticeable. The ultimate goal is to consider multiple various scale representations as a single model.

The HNode Class

The HNode Class is developed to support continuity of information between different resolutions. The modeling framework is based on Grasshopper, where the principal collection type is called Data Tree. 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 which can be traversed efficiently. As with tree structures, all of the data is 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 that 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. 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 of the examples of upstream data propagation is the minimal wall thickness information gained from strains calculation. This process happens at the lowest level of the tree (the highest density mesh), 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 visualization (Figures 10).

Two major 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 nodes (both 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 became clear that for the sake of

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9 Multi-directional data propogation to improve panel performance. From left: Base panel with translation (blue) and rotation (green) vectors at connection nodes; Calculation of local material proerties; Utilisation calculated via structural analysis; Change to depth of rigidisation geometry; Continue loop.

10 Bidirectional data propagation between low and high resolution.

11 Face count comparison. From top left: original mesh; Loop subdivision; adaptive Loop subdivision.

computational efficiency and clarity, the passive method seems more appropriate.

The HNode library is written in .NET, and our implementation wraps it up as a data type compatible with Grasshopper. The generic nature of this collection type likely makes it 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.

REFLECTION & CONCLUSION

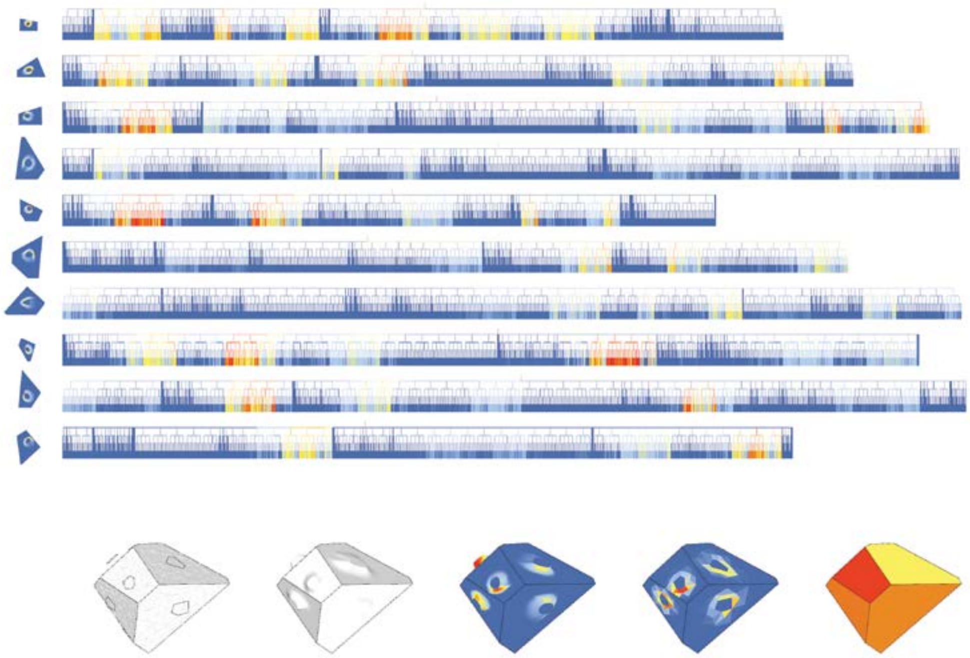
This paper examines adaptive mesh-based modeling as a means to support the computational design of panelized thin sheet structures built using the ISF fabrication process. Fabrication parameters are not usually included within architectural modeling or simulation even when, as is the case with ISF, they have significant impacts on material properties. A greater awareness of these impacts, together with a greater capacity to include them within simulation models, provides just one motivation for the greater use of multiscale approaches within architectural design.

Two approaches have been described in this paper: the first is characterized as unidirectional and the second as bidirectional. The context of the research exemplifies the need for a back and forth between fabrication, design, and analysis. With multiple scales of material organization—multiple parts, highly heterogeneous in terms of their shape, their surface geometry, and their material properties—modeling necessitates a discretization for reasons of control, accuracy, and workability. However, a successful discretization relies on retaining as many possibilities for information flow as possible, and on an efficient and effective organization of that information flow.

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 any given model, computation time, and workability, there is a greater issue of simplicity. The generation of unnecessary data can render a design workflow unusable, or can generate subsequent filtering activities that displace effort.

The first approach sequentially varies a single mesh topology to manage the complexity of bridging scales and functions while maintaining continuity of information flows down scale. However, a realization of this approach is that for each scale, there is some data that we want to pass up or down. This is because a model does not necessarily have the possibility to recognize 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 described approach, the bidirectional workflow ties multiple scales together in a more consistent and manageable



12 Example of upstream data propagation. From lower left: original mesh, subdivided mesh, strain calculation, results propagated up the subdivision tree, colorizing the panels with respect to the maximal strain value. Above: results propagated up the subdivision trees.

way compared with the previous method. 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 higher- or lower-level information. Future research will connect this bidirectional workflow with an automated feedback loop, and develop visualization techniques that allow analysis and comparison at different resolution levels.

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IMAGE CREDITS

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Mateusz Zwierzycki is an architect, designer, Grasshopper user, and co-author of the projektowanieparametryczne.pl (the first Polish website about parametric tools in architectural design). He is also the author of the Starling, Squid, Anemone, and Mesh Tools plugins for Grasshopper, and many more disassociated scripts scattered all over the Grasshopper community, as well as the founder of the Milkbox group, a long time workshop tutor, teacher, and a parametric design populariser.

David Stasiuk's academic research exists within the larger framework of CITA's 'Complex Modeling' project, which investigates the digital infrastructures of design models, examining concerns of feedback and scale across the expanded digital design chain. His work discusses adaptive reparameterisation, focusing on the dynamic activation of data structures that allow for model networks to operate holistically as representational engines in the realisation of complex material assemblies.

He is currently the Director of Applied Research at Proving Ground, a technology consultancy for architects, engineers, and manufacturers, which focuses on the development of advanced computational tools that facilitate data-driven design and project collaboration.

Esben Clausen Nørgaard is an educated civil engineer with a specialty in architectural design from Aalborg University in 2014, and joined CITA after graduation. His primary research and interest lies within prototyping, fabrication, and rationalization. Since joining CITA, his primary focus has been on fabrication with industrial robots and how this can be used to create relationships between traditional craftsmanship and digital environments.

Mette Ramsgaard Thomsen is head of the Centre for Information Technology and Architecture (CITA). Her research centres on the intersection between architecture and computer science. During the last 15 years, her focus has been on the profound changes that digital technologies instigate in the way architecture is thought, designed and built.

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