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Full-scale prototype of a lightweight and robotic incrementally formed copper facade system with standing seam connections

Paul NICHOLAS*, Dane VOORDERHAKE[a], Tim SCHORK[a]

* CITA | Centre for Information Technology and Architecture
Royal Danish Academy of Fine Arts, School of Architecture
Philip de Langes Allé 10, Copenhagen, Denmark
paul.nicholas@kadk.dk

[a]University of Technology Sydney
Faculty of Design, Architecture and Building
School of Architecture
PO Box 123 Broadway NSW 2007, Australia
tim.schork@uts.edu.au

Abstract

Incrementally formed thin sheet metal enables lightweight structures that integrate ornament, structure and skin - a trajectory of architectural and structural opportunity initialized by Prouve, Junkers, and LeRicolais. However, where previously the need for a mold has limited rigidization to contexts of mass production, mold-less Robotic Incremental Sheet Forming (RISF) provides new opportunities for customized and bespoke panels. This paper reports on the computational design and fabrication of a lightweight and highly differentiated copper façade system, using RISF. Central concerns are the challenge of integrating customized structurally responsive geometry with design constraints typical of a metal facade, and managing the material property changes induced by the fabrication process.

Where architectural models of material typically assume stability of physical properties, geometric change implies property change in the RISF process. This paper describes a multi-scale approach to predictive and generative modelling that incorporates these variables within the design process at material and structural scales, allowing for material and fabrication informed design of a 1:1 prototype.

Keywords: material computation, robotic incremental sheet forming, digital fabrication, lightweight facade system, copper, multi-scale modelling

1. Context and motivation

Metal facades are deployed within architecture to support the transmission of light and creation of shade, screen from wind and other climatic factors, resist weathering and can be highly expressive. Copper is an expensive however particularly sustainable choice of metal as it requires no further treatment once installed, is highly formable and expressive, and will last for hundreds of years. As increasing pressures of sustainability drive the need for increased material efficiency and lighter weight building practices, methods for increasing the structural performance of thin copper sheet can contribute towards stronger, thinner and lighter panels, decreasing the dead-loads carried by underlying structural systems.

Increasing the performance of thin metal sheet is possible through mechanical rigidization, which adds structural strength by increasing cross sectional depth. However rolling, extrusion and pressing processes for rigidization do not easily support the local customization of geometry in response to structural requirements. Robotic Incremental sheet forming (RISF), a flexible and mold-less fabrication process, is a way to enable the cost-efficient fabrication of metal panels with customized rigidization.

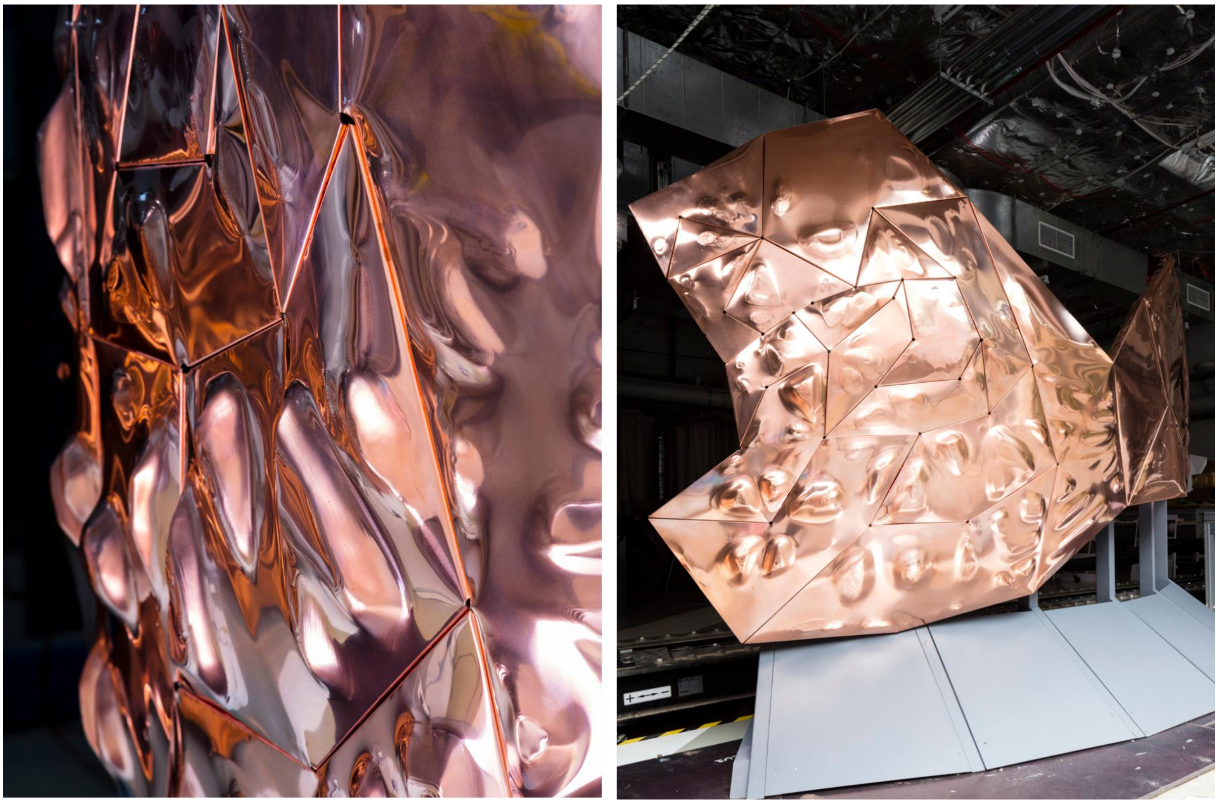

Figure 1: Completed 1:1 copper façade prototype

2. Research background

The research develops as part of an ongoing investigation into robotic sheet metal forming at CITA. The underlying drivers of this research trajectory are to investigate how digital design and fabrication tools support new material practices, to develop new methods that support designing across scales of resolution, and to establish design integrated modelling methods.

2.1. Robotics as means to extend architecture's material practice

Conventionally, design and representational approaches have privileged the geometric description of form over materiality (Lloyd Thomas [1]), while industrialization has brought both real and assumed standardizations of material. Digital fabrication has shrunk this gap between design and making, by connecting design environments to the instructional data that control machining operations. With the increased precision and control it is possible to create customized design solutions and better performing structures. Robotic fabrication, the leading edge of digital fabrication, supports even greater possibilities for design-integration, complex geometry and efficient mass customization.

However, digital fabrication requires a strong awareness of materiality and fabrication constraints, which aid the definition of the design space and provide productive resistances to support design exploration and development. This can be achieved by incorporating material properties within the design environment. In this research, the changes in sectional thickness induced by the fabrication process are predictively modeled within the design model, to 1) inform the designer of the formability of solutions and 2) inform structural simulation.

2.2. Extending application

Where previous research using RISF has investigated the fabrication of lightweight structures, such as arches and bridges (Nicholas et al. [2]), the use of a cyber-physical fabrication approach to manage positional uncertainty (Nicholas et al. [3]), and the use of machine learning methods to predict and manage forming tolerances (Zwierzycki et al. [4]), this research explores integrated modelling and fabrication methods for copper cladding applications, and a negotiation between customized geometries and the discretization, connection and detailing techniques typical for this application.

3. Method

The 1:1 scale facade prototype is formed via Robotic Incremental Sheet Forming (RISF), a variant of the flexible Incremental Sheet Forming (ISF) manufacturing process first developed in Japan in the 1980s and 1990s (Emmens et al. [5]). A manipulative process for imparting 3D form onto thin metal sheet through highly localized deformation, ISF differs from deep drawing and other common sheet metal forming techniques in that the final shape of the piece is fully determined by the movement of the tool. A simple tool, applied from either one or two sides, facilitates mold-less forming by moving continuously over the surface of the sheet causing a highly localized plastic deformation (Jeswiet et al. [6]). A single sided approach utilizes one tool and a blank, while double sided forming provides further flexibility for forming out of plane in opposing directions. The facade prototype was formed using a single sided approach (Fig. 2).

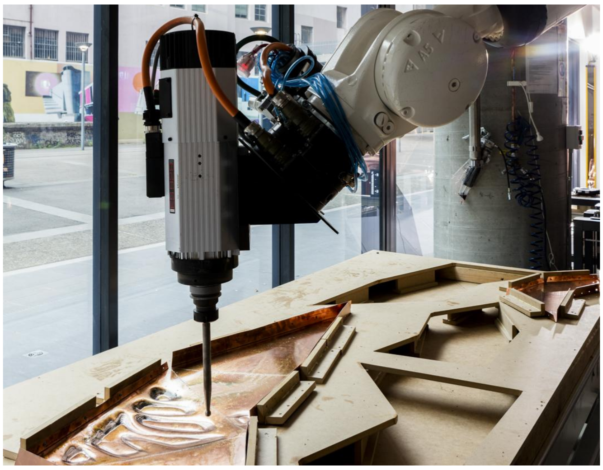

Figure 2: Setup of robotic single-point incremental forming process (RISF)

3.1. Informed digital models

Forming is the result of complex interactions between material behavior and construction technique, and has effects that are both geometrically and materially transformative. Geometry drives two parameters of material change - localized thinning and work hardening of the sheet. Of these, thinning is most important to the definition of forming limits. To establish forming limits, a hyperbolic cone geometry was formed until tearing (Fig 3, left). The cone was cut to allow measurement of wall thickness using digital calipers at known points along the section. A linear regression was performed to establish the relationship between wall angle and resulting thickness (Fig 3, right). When incorporated into the design environment, this custom model enabled fast evaluation of geometries via an equation-based model, dependent on the calculation of local wall angle at each node within the mesh defining the design geometry. Results from this model, as well as a simpler depth analysis, can be overlaid as a heat map onto the original mesh, allowing for easy visual inspection (Fig 4).

The generation of rigidization patterns occurred on a medium resolution mesh. To determine localized thickness values more accurately, particularly in areas of high curvature, the mesh was smoothed and its resolution increased by a factor of 10. Thickness values were calculated on this high resolution mesh and then averaged back to the medium resolution mesh for structural analysis.

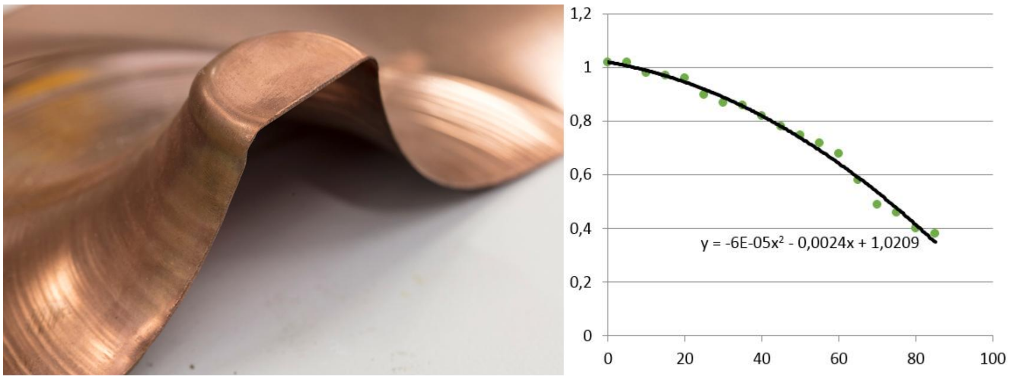

Figure 3: Wall angle forming tests (left) and plotted graph of measured wall thicknesses (right)

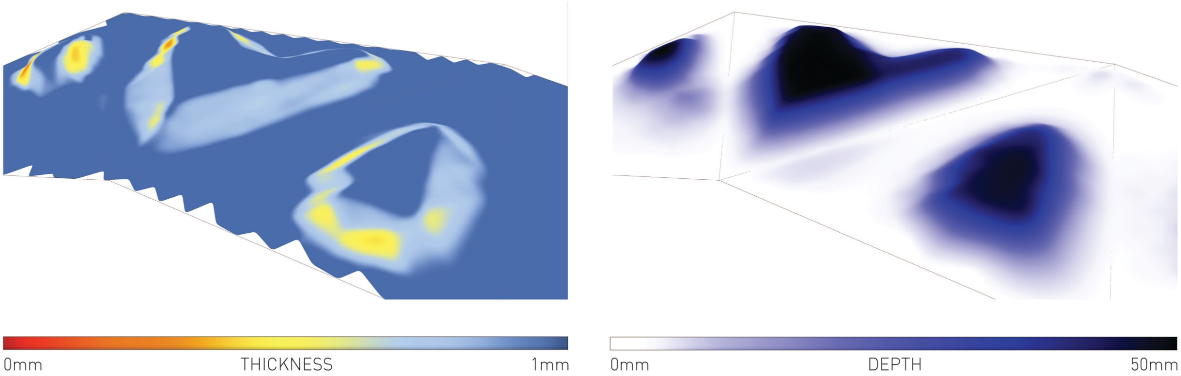

Figure 4: Wall angle and forming depth assessment graphing

4. Experiment

The copper facade was designed, prototyped, fabricated and installed by the authors at the University of Technology Sydney. The workshop made use of a KUKA KR120 R2700 HA on a 7000mm Linear Axis, a 2440 x 1220mm Vacuum Table as well as a 3-axis CNC Mill in the UTS Advanced Fabrication Lab. To ensure that the research addressed current industry practice, the process included input from a number of industry professionals including digital fabrication teams and sheet metal experts. This close relationship to industry workflows provided better, more applicable outcomes towards more seamless technology transfer.

300x300mm copper test squares were set in a reusable forming frame and teams were supplied with a digital fabrication pipeline capable of producing robotic instruction code (KRL) based on discretely modelled or parametric geometries. Emphasis was placed upon testing material, tool and workcell-specific limits. Physical limits tested included formed wall angle, global depth of depression, proximity to frame, step down and step over, tool size and length, feed, speed, and whether a supporting profile was used below. Standing seam details were investigated in parallel to forming tests. The standing seam has advantages over other sheet metal details in that by standing perpendicular to the sheet plane it stiffens by design. A basic detail was chosen that could be bent to shape using standard hand tools, and CNC engraving was tested along fold lines in order to increase accuracy of the edge and reduce tolerances. The intention of these investigations was twofold; to test and record how digital and physical fabrication variables affected material outcomes, and to familiarize students with process, material and tools.

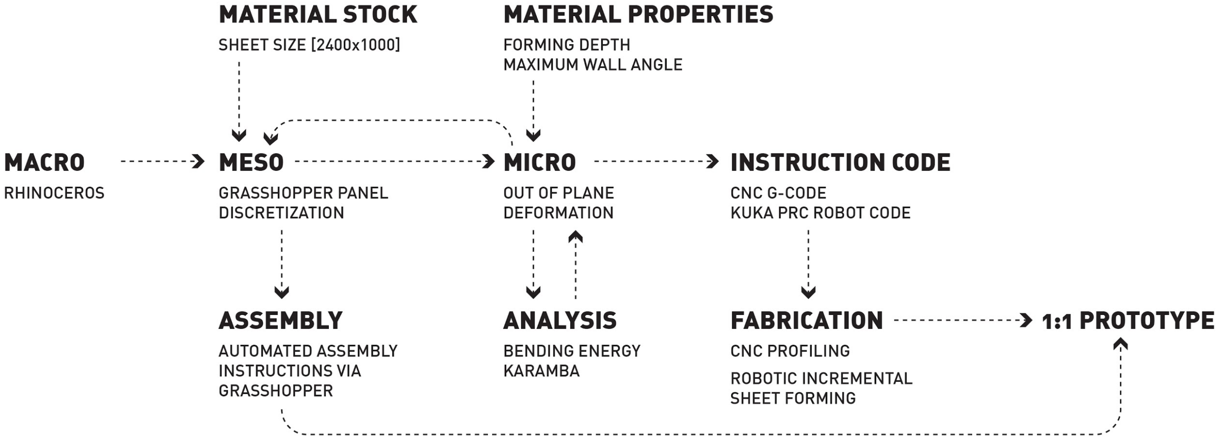

Figure 5: Project flow chart

4.1. Modelling

Design occurred in parallel at three distinct scales - macro (global form), meso (panelization) and micro (rigidization). Iterations were produced and assessed for fitness via a number of criteria derived from initial tests, prior knowledge and aesthetic value. They were produced in parallel at multiple scales and compared to each other in order to ensure compatibility between decisions at the macro, meso and micro scales. A synclastic doubly curved form was chosen for its departure from traditionally flat or singly-curved sheet metal facades. The global shape was extracted from a 16m diameter sphere, and was chosen as it allowed for consistent intersection angles between panels. A mesh-walking algorithm was adapted to panelize the input mesh, whereby the underlying subdivision could adapt based on structural input. This definition accounted for maximum and minimum panel sizes, triangulated subdivision and individual panel orientation. The scale of each panel was limited in order not to exceed a manageable size for two people to lift and install it, to fit within a 2400 x 1000mm stock sheet and to not deviate too far from industry-standard facade panel dimensions. Panel orientation and subdivision were optimized to ensure the bulk of standing seams ran near parallel to bending forces, making the most effective use of the stiffening effect of the detail.

Pattern generation produced out of plane deformations via a reaction-diffusion algorithm generated based on structural logics. An initial structural analysis is performed on the panelized geometry and includes points of restraint and self-weight. The results of the analysis - specifically the bending energy measured in each mesh face - are seeded as values within an isofield. Indentations push further out of plane as more stiffening is required to counteract higher bending forces. The algorithm maintained awareness of inter-panel edges and internal face to face bends, and would interpolate between full and zero deformation to allow a bend to occur. Forming was simultaneously reduced near panel edges to avoid tearing due to forming directly onto an MDF support panel edge.

4.2. Prototype

A full scale prototype was formed and assembled in order to test digital and physical fabrication processes, orders of operation and stability. Various strategies were tested through the design and fabrication of a selection of panels, with a couple of failures that led to key adjustments in the process. A small 2000x1000mm subsection consisting of three panels was digitally simulated and instruction code was generated for both CNC pre-profiling and RISF. All standing seam tabs were pre-drilled for use in hold down during the incremental forming process and a portion of tabs were scored between tab and panel face to assist in seam folding, the remainder were left untouched. The panels were nested into a 2440x1220mm panel and 16mm MDF was CNC cut for use as a support template including 10mm wide beams to run below coincident edges and 12mm holes used to locate the MDF onto dowels embedded into the supporting frame on the vacuum table. The reusable supporting frame was held down via the vacuum and allowed forming to occur up to 70mm below the MDF voids before collision with the table.

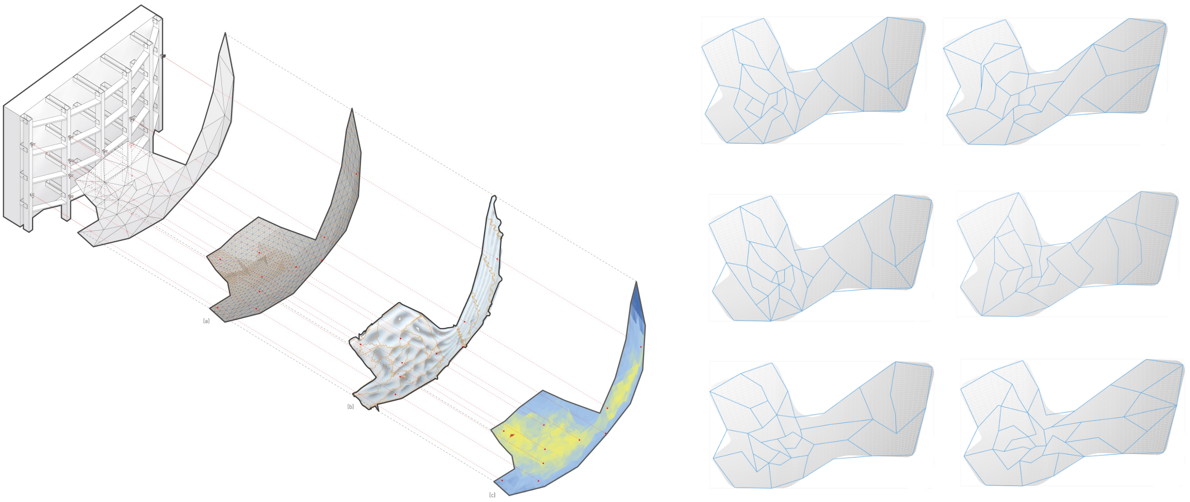

Figure 6: Structurally informed micro patterning (left) and example discretization options (right)

A short robotic routine was run to check the accuracy between the digital simulation and the physical objects (MDF support, forming voids, Robot and RISF end effector) before the precut copper panels were mounted atop the MDF support templates and fixed with screws through the pre-drilled holes in the standing seam tabs. A series of toolpathing methods were tested and assessed both for speed and aesthetic resolution. It was discovered the best fidelity of fine patterning was had with a level-first layer-by-layer toolpath, however, due to a tight production timeline a depth-first continuous spiral toolpath was ultimately chosen.

During fabrication the pre-drilled holes used to secure the panels became a point of failure. The RISF process produced too much stress upon too few points which resulted in undesirable stretching in the standing seam tabs. The etched guides for bending the standing seams were very successful in achieving low tolerances for assembly, however, the hold down deformation made for difficulty in some seams. A new strategy was developed whereby seams were pre-bent to a 90 degree angle and screwed into wooden blocks that were then affixed over nested, panel specific voids in the CNC cut support MDF panel. This folded copper flange on all sides stiffened panel edges, counteracting the forces of RISF which resulted in more accurate incremental deformations, reduced stretching of seam tabs and highly accurate standing seams.

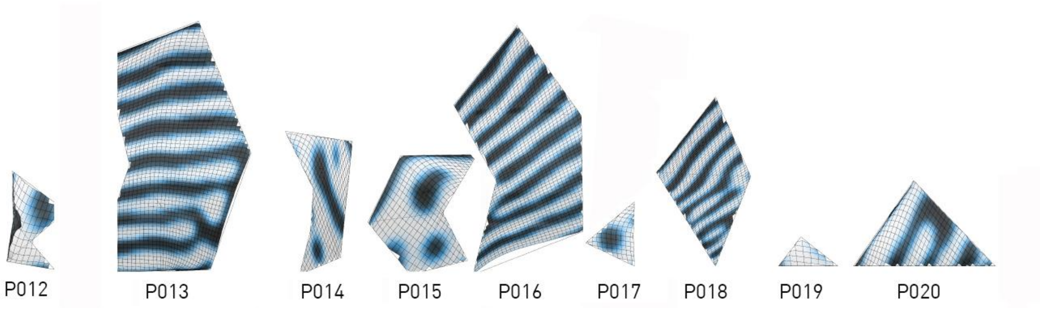

Figure 7: Rigidization pattern on individual panels

Figure 8: Prototype of standing seam connection

The cross supports on coincident edges were successful in that they did not structurally fail, however, produced an undesirable creasing between mesh faces that gave the prototype a 'pillowed' aesthetic. For the final installation these were removed to increase the continuity of global pattern.

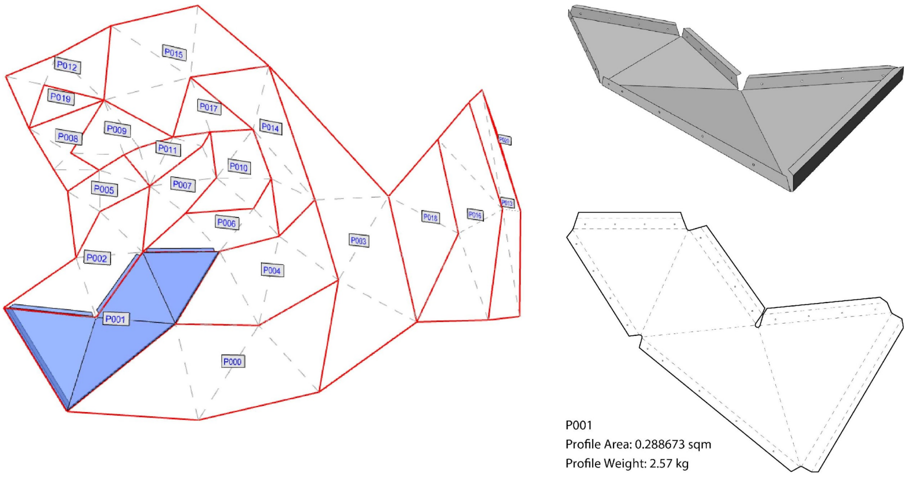

Figure 9: Automatic generation of fabrication and assembly information

4.3. Machine workflows

Design, prototyping, production and assembly all occurred simultaneously and used a KUKA 6-axis robotic arm as well as a 3-axis CNC Router. A multi-machine workflow was employed to take advantage of each machines' strengths and avoid bottlenecks during fabrication. The utilization of the CNC for preparation of parts (engraving, profiling and drilling of MDF and copper sheets) left the Robotic Arm free for incremental sheet forming. The multi-machine workflow allowed experimentation to continue right up until final production began. Whilst panels were finalized and cut by the 3-axis machine the robot could continue forming prototype panels with new information easily fed back into digital simulations for inclusion into final production instruction code. This agility of production, multi-machine utilization and pre-folded seam meant that parts emerge from the RISF process assembly-ready. It is worth noting that the size of the KUKA robotic arm used had a huge impact on the toolpath feed rate and subsequent production speed as compared to previous investigations by the authors. *Stressed Skin* and *A Bridge Too Far* both utilized a smaller robotic arm [in the realm of 12-20kg payload] for the RISF process and the feed rate reflected this. With a 120kg payload the KR120HA achieved straight line feed rates of 1m/s, with the potential for further increases utilizing full-automatic mode. Where previous projects' panel production took up to 30 days, all 20 copper panels were formed over a 3 day period.

5. Discussion and evaluation

This project has demonstrated that customized forming can be combined with an industry-standard approach to facade detailing in an integrated manner, to produce novel façade systems. The workflow that is developed includes the constraints of the facade approach, related to dimensioning, seaming and folding lines, as well as material and fabrication parameters within the digital design and simulation process. The research implies that the approach could be integrated to add value to existing metal cladding, by supporting the addition of optimized and customized geometries to flat sheet products, increasing material stiffness and reducing material use. With the increased forming speeds demonstrated using a larger industrial robot arm, the forming times required for a typical facade become reasonable. A principal limit was found to be the restrictions upon the location and continuity of incrementally formed geometries implied by the folding lines required within each panel. While these restrictions are removed in the case on 2D surfaces - the majority of typical wall and roof conditions - further work aims to explore how the need for folding lines might be removed to better achieve complex 3D surface applications.

6. Acknowledgements

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