Robotic Bead Rolling

Exploring Structural Capacities in Metal Sheet Forming

Jared Friedman, Ahmed Hosny and Amanda Lee

Abstract The robotic workflow proposed analyzes the bead rolling process, its potential digital interpretation, and improved fabrication aspects that accompany such a translation. For this process, a robotic tool has been developed that integrates multiple variables observed from existing bead rolling machines, while simultaneously allowing further control. Material-informed decisions required a series of tests evaluating optimum tool and workflow design. While the process provokes a multitude of potentialities, it has been put towards a structural behavior testing scenario to demonstrate its validity. It attempts to bridge analysis methods with prototyping as means of direct performance testing and evaluation. Deeply rooted within a parametric modeling environment, the workflow creates a single digital interface that links several platforms that otherwise are not in direct communication.

Keywords Bead rolling · Forming · Metal · Robot tooling · Mechanism

1 Introduction

The research conducted over the course of this project looked at taking what is typically a very manual process and transferring it to a robotic work environment to allow for high degrees of control. Bead rolling is a process of metal forming

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W. McGee and M. Ponce de Leon (eds.), *Robotic Fabrication in Architecture, Art and Design 2014*, DOI: 10.1007/978-3-319-04663-1_6,

consisting of two rotating dies that a person maneuvers a sheet of metal through in order to create grooves in the sheet. The application is most typically used in the automotive industry and for decorative embossing in metal plates. The specificity of the process requires a person with a high degree of skill to accurately move a sheet in and around the dies in order to achieve a desired bead in the sheet. By transferring the process to a robotic work environment, this research looks at the potential opportunities that are granted as a result of the control, speed, and replicability allowed by industrial robotic processes. A series of tooling prototypes were developed to explore these potentials and gain a better understanding of the opportunities granted by the process. Through prototyping with both manual and robotic processes, the authors recognized that there was a correlation between the beading patterns and the structural capacities of the sheets. This was identified as one of the primary opportunities to explore, and one which can serve broader applications when applied at an industrial level. The use of metal sheet forming techniques to provide strength to an assembly has been most commonly used in constructing curved shells or folded plate structures. While the bead rolling process may sometimes result in slight deformations of the of the sheet, the authors' intent here is to maintain the flatness of the sheet while investigating both the structural and ornamental opportunities enabled by advanced CAD/CAM processes. A digital workflow has been developed that automates a beading pattern based upon specific structural criteria such as location and magnitude of a load to be applied to a surface. The design-to-fabrication workflow is done entirely within the Rhinoceros modeling environment, using various Grasshopper® components specific towards structural analysis and robotic fabrication. As prototypes continue to be developed, empirical testing is being used to determine the levels of structural improvements that the process is capable of at the current scale of application.

2 Analysis of Existing Bead Rolling Processes

Existing bead rolling processes have remained essentially unaltered since their inception. Because of the forces required to push a sheet of metal through the dies, bead rollers are typically very rigid and made of cast iron or some other homogenous metal assembly. Industrial bead rollers can typically bead up to 14 gauge aluminum or 19 gauge stainless steel, whereas more consumer models will be able to handle 16 gauge aluminum or 21 gauge stainless steel (www.mittlerbros.com/mittler-bros/bead-rollers/power-drive.html). While some machines require a person to manually push and direct the metal sheet through the dies, other machines use motors to turn the dies that drive the sheet through, but still require a laborer to direct the orientation of the sheet. A critical difference between the existing manual processes and the one explored in the research is that in existing processes the machine is stationary and a sheet is moved through, whereas in our process the sheet is held in place and the tool is moved along the sheet. In manual processes the worker moving the sheet is constantly providing variable amounts of pressure at different points in the process to counter deformations. By clamping the sheet in place, deformations in the sheet are limited thereby allowing the robot to access the plane of the sheet as a constant reference.

3 Advances in Sheet Metal Fabrication Processes

The adaption of advanced CAD/CAM technologies by leading metal fabricators has opened up a new realm of potentials for sheet metal, which is being realized across multiple industries. Most applications of thin sheet surfaces are non-load-bearing, and tend to lend themselves towards compound curvatures. However, because of the molds and profiles that need to be created in cold-forming techniques, these processes are frequently quite cost prohibitive at a building scale (Schodek et al. 2005). If one were to remove the necessity for molds and secondary support systems, it may be possible to strengthen the economic argument for customized sheet metal components in building applications.

A number of precedents exist for the use of 6-axis industrial robots for various metal forming processes. One of the processes that has attracted much research is incremental sheet forming (ISF), a CNC die-less metal forming process that shapes metal by pressing a rotating spherical tool along pre-defined toolpaths.

The material may either be moved over a stationary forming tool or the tool may be moved while the material is fixed in place (Figs. 1, 2). Research out of TU Dortmund titled ‘Robot Assisted Asymmetric Incremental Sheet Forming: Surface Quality and Path Planning’ presented at Rob|Arch 2012 looked at Asymmetric Incremental Sheet Forming (AISF) as an architectural fabrication technique (Brüninghaus et al. 2012). The process outlined in this research shares similarities with robotic bead rolling in that it is a highly flexible process, and is best suited for small batches of customized parts. Another research direction with AISF is exploring the application of formed sandwich panels (Jackson et al. 2008). This application is relevant as it addresses certain geometric possibilities and potentials implied by the robotic bead rolling process. One of these geometric possibilities is the formation of patterns similar to that seen in an isogrid panel—a homogenous structure in which load-bearing ribs and the skin of the panel are milled from a single plate of aluminum alloy (Fig. 3). These types of panels have been developed by the aerospace industry for their strength and light weight, which are features that can be deployed for a variety of applications. While these panels deal with solid section corrugations involving a subtractive manufacturing process, shell corrugations—involving material expansion locally to increase overall depth—raise similar functional characteristics.

Fig. 1 Robotically controlled ISF processes (http://i1.ytimg.com/vi/xcg08U_Y4PI/maxresdefault.jpg)

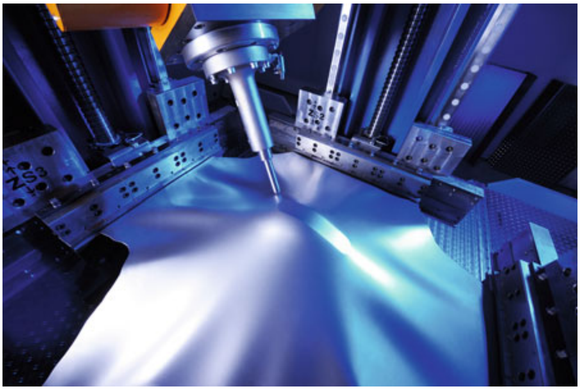


Fig. 2 Robotically controlled ISF processes (Taleb Araghi et al. 2011)

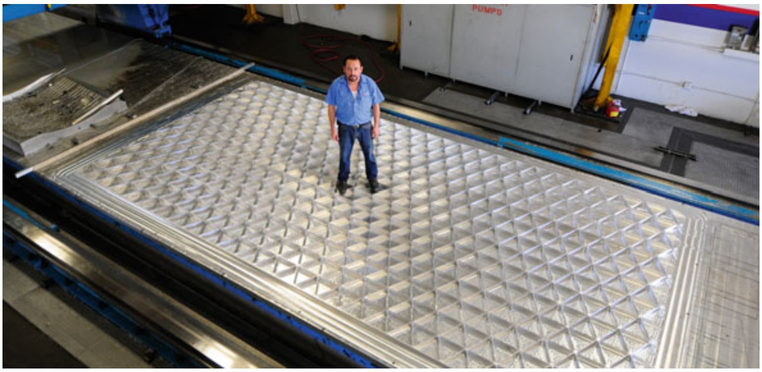


Fig. 3 Image of lightweight isogrid panel (http://www.amrofab.com/)

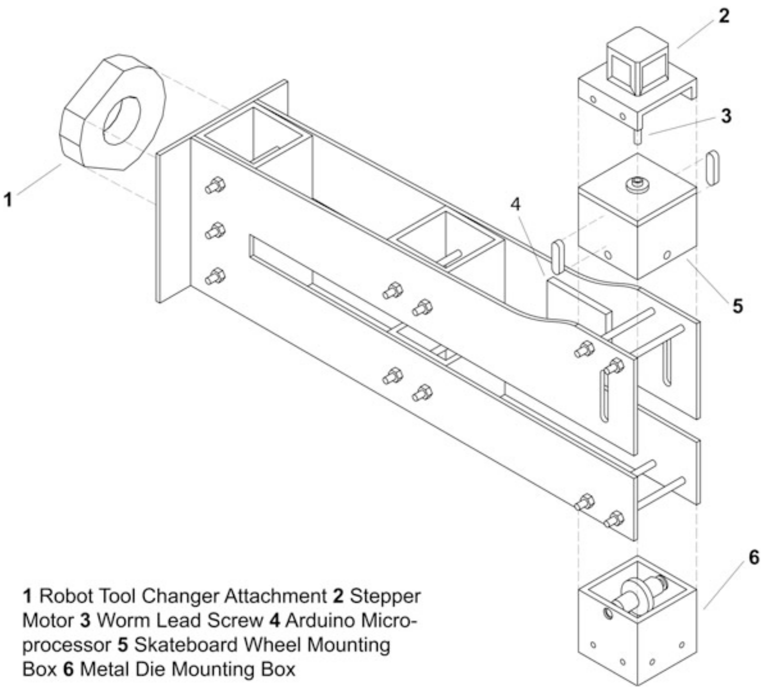


Fig. 4 Diagram of tool affixed to robot

4 Tooling and Process

4.1 Tool Development

With limited precedents surrounding variations of the traditional bead rolling machine, a trial and error approach was applied during the design of the tool (Fig. 4). Early prototypes in plywood reveal that there was a heavy amount of torque on the tool itself when a sheet is pushed through. Additionally these tests proved that the process requires both wheels—above and below the sheet—to spin in order to avoid scratching the surface of the sheet metal. To add more flexibility to the process a rubber skateboard wheel was tested in order to allow for variations in the bead depths. An added benefit of this process is that it allows for a bead being rolled into a sheet to intersect with existing beads without destroying the profile. This ability opens up opportunities for improvements in the structural performance of the sheet, as well as expands the lexicon of pattern possibilities. In later iterations of the tool, more attention was focused on how to provide varying depth to the beads, and exploring the possibilities of having rotating wheels. A lead screw mounted on top of the casing for the top wheel pushes down onto the casing, which drives the rubber wheel into the metal die. This process is now automated so

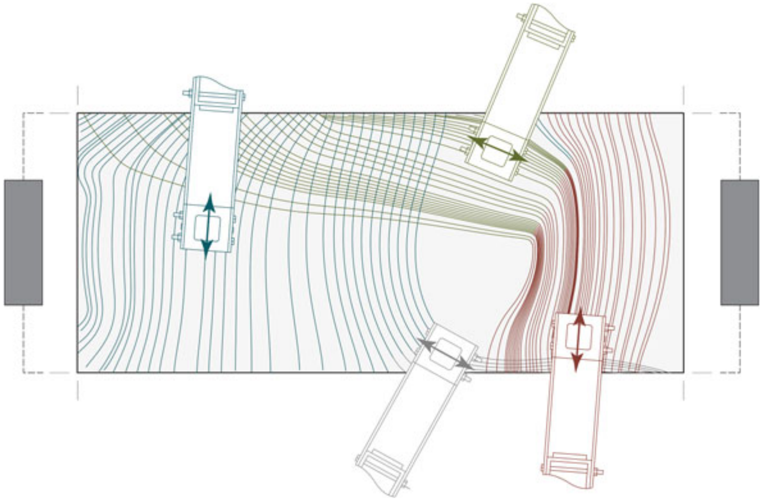


Fig. 5 Diagram displaying the directionality of the lines that are achieved with a 90° rotation of the wheel casings

that a Bluetooth device is connected to an Arduino that remotely controls the stepper motor that drives the lead screw into the wheel casing.

Various tests have been conducted to determine the benefits of allowing the wheels to freely rotate in order to allow the wheels to self-adjust to the movement of the robot in any direction. The mechanics of this process have proven to be somewhat unpredictable, and have caused errors due to the amount of force required to push down on the top wheel. As an alternative, the current tool is designed to allow the wheel to be mounted either parallel or perpendicular to the face of the tool, but without free rotation (Fig. 5). This flexibility in the tool was able to be sacrificed because of the flexibility granted by the movements of the 6-axis industrial robot. The latest iteration of the bead rolling tool provides a larger slot depth, and contains the remotely controlled motor that allows for exiting the material within the sheet.

In addition to the bead rolling tool developed for mounting to the robot. A jig has been constructed that holds the sheet in place during the robotic beading process (Fig. 6). By holding the sheet vertically as opposed to horizontally, the sheet stays flat. This is critical so that the tool can predict the location of the edge of the sheet.

Fig. 6 Jig ensuring sheet material is in place during the robotic beading

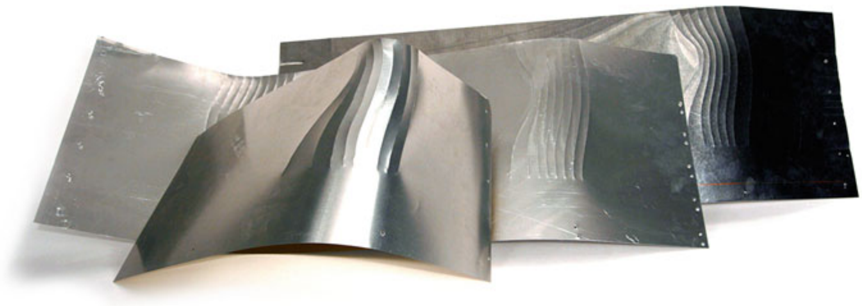


Fig. 7 Beading effect on sheets of different gauges

4.2 Material Testing

The majority of the material testing up to this point in the research has consisted of various gauges of aluminum sheets ranging from aluminum flashing to 20 gauge sheets, with 20 gauge being the most common due to its wide availability. This material is relatively cheap and malleable when compared to other stock metal sheets. 24 gauge mild steel has also been successfully tested during our prototypes. By altering the depth of the sheet through the process, further rigidity and strength are provided without the need of altering the chemical properties of the metals. While our prototypes have primarily used thinner and softer metals, at an industrial scale, thicker and stronger sheets would certainly be plausible for this process. Figure 7 illustrates the resulting sheet deformations from beads rolled in aluminum flashing, 20 gauge aluminum, and 24 gauge mild steel.

5 Robotic Workflow

5.1 Overview

Finite Element Analysis is performed on sheet metal samples given a set of user-defined load parameters and boundary conditions. The outcome is a series of stress vectors acting on the sample. These are hence identified as locations of weakness and where bead corrugations are introduced as means of enhancing the sample's structural performance towards a specific loading condition. Vector direction is translated into a toolpath and fed into the robotic controller while vector magnitude drives the corrugation depth through the tool-mounted microprocessor.

5.2 FE Analysis Results as Input

To demonstrate this workflow, Millipede, a Grasshopper® plugin developed by Sawako Kaijima and Panagiotis Michalatos, was explored as an analysis tool. Using a library of structural algorithms, Millipede performs Finite Element Analysis on linear elastic systems. It generates a set of statistical data simulating material behavior under different loading and boundary conditions. Basic assumptions are fed into the plugin including, geometry: planar material of constant thickness and density with dimensions that fit within the maximum workable domain of the operating tool; support regions: designating an area of structural support; and load regions: designating an area and vector value of load application. These parameters are ideally an output of a parametrically generated model allowing for quick prototyping of a wide range of conditions. An analysis model is thus generated in the form of a mesh which is then passed on to the Finite Element solver. While Millipede outputs several analysis types, the authors' interest lies first in principal stress vectors as curves travelling through the material, with either positive values for tension and negative for compression; and second—the Von Mises stress at points along these curves as a measure of combining both principal stress values (Figs. 8, 9). These vectors (curves) and their corresponding values simulate force lines used in visualization of internal forces in Solid Mechanics.

As the model is discretized into a smaller finite number of elements through meshing, internal surfaces to which the principal stress direction is perpendicular are identified. Numerical Integration of stress on each of these surfaces then allows for the visualization of overall distribution of stress patterns across the entire geometry. As the research has focused testing on planar sheets of material, the decision has been made to accept the marginal differences between stress and bending moment vectors for planar surfaces. If the analysis was to move into the curved surface realm, bending moment vector values would be of prime importance.

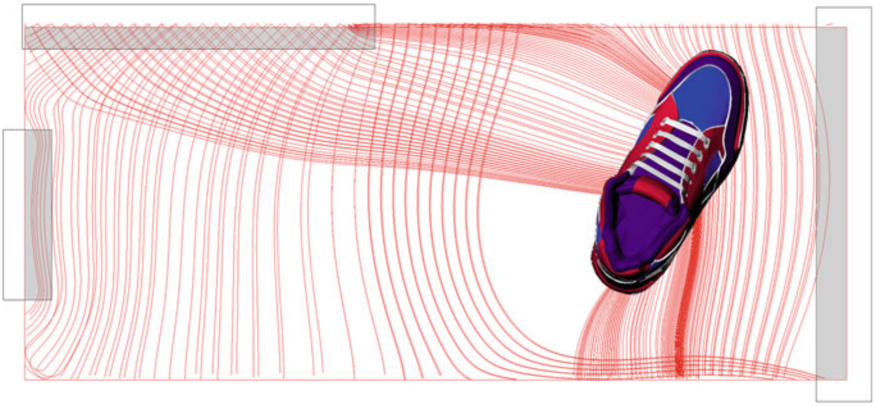


Fig. 8 Stress lines generated in millipede based on specific boundary conditions

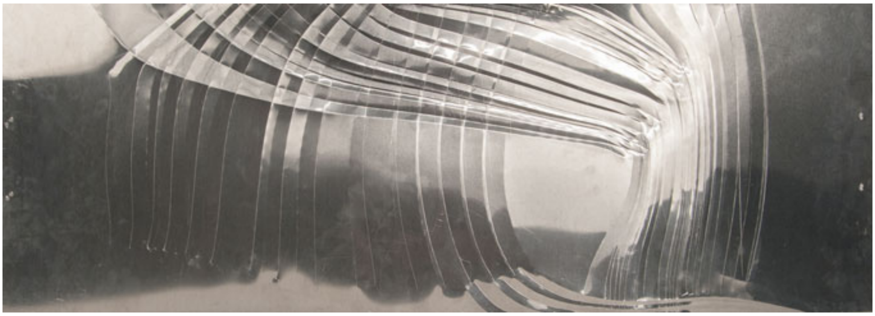


Fig. 9 Sample panel produced from millipede output curves

5.3 Digital Robotic Interface

With this data in hand, an interface processes the information into recognizable formats by other components down the workflow (Fig. 10). Principal stress curves are converted into toolpaths and used to feed HAL Robot Programming and Control—a plugin for Grasshopper® developed by Thibault Schwartz—eventually outputting the required RAPID code. Positive and negative values inform the corrugation directionality: outward corrugations resist tension while inward corrugations resist compression. As the majority of mechanical forces acting on a structural beam are concentrated at its upper and lower surfaces, the direction to which material is redistributed or corrugated becomes essential in resisting these forces. This is deemed particularly evident when testing two sandwiched planar metal sheets with tension on the upper sheet (outward corrugations) and compression on the lower (inward corrugation) (Fig. 11). The RAPID code is thus programmed in such a manner so as to allow tool disengagement from the

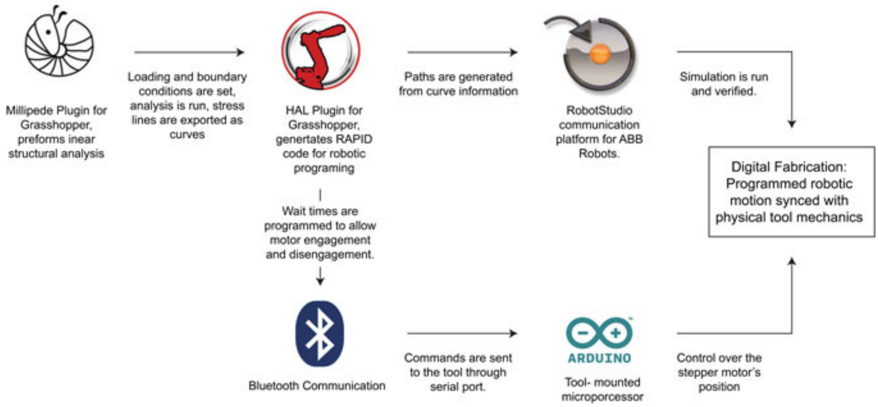


Fig. 10 Workflow for toolpath generation and motor control

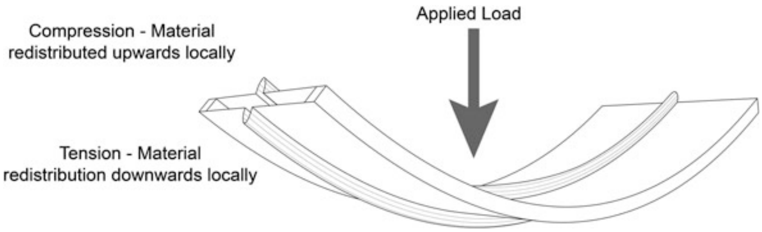


Fig. 11 Sandwiched planar metal sheets with bead corrugations

material, full 180° rotation, and re-engagement in order to flip corrugation directions.

On the other hand, Von Mises stress scalar values are remapped along a new distance domain in millimeters. These are supplied into Firefly, another Arduino control plugin for Grasshopper® developed by Andy Payne, allowing the tool-mounted stepper motor to travel accordingly. A higher stress value is translated into a larger motor pin displacement pushing the rubber wheel and metal die closer to one another and thus creating a deeper corrugation. Syncing the RAPID program with the Arduino component has proven to be challenging since the robot's travel time involves acceleration, deceleration and constant speed making it difficult to quantify. In current testing, the stepper motor is manually controlled via Bluetooth from a serial port while RAPID is being executed. The user is then able to control whether the two wheels are engaged (corrugations executed) or released (corrugations not executed), in addition to the corrugation depth. Future improvements include utilizing the ABB Robot Reference Interface as it allows for the periodic exchange of actual robot position data and other RAPID multitasking options through TCP. Such data is then received by the Arduino microprocessor prompting the execution of code and thus precise control. Within this closed loop system, robot movements would, in turn, be triggered upon feedback from the tool. This allows a fully automated, pre-programmed fabrication process.

5.4 Fabrication Environment

The jig to hold the metal sheets is designed in such manner so as to clamp the sheets along three sides with an exposed fourth side for tool access. Breaks are introduced in the RAPID to manually rotate the sheets. Careful consideration went into allowing safe distances between the clamps and the tool and avoiding collisions. A future iteration of the table could potentially involve a rotating base that allows automatic rotations of sides staying within the robot's maximum reach. Other iterations could support a number of sheets and allowing a larger set of prototypes to be produced within one robotic session. Over the course of prototyping, human intervention during the fabrication process has decreased with potential in reaching full automation as the research concludes.

6 Industrial Applications

6.1 FE Analysis Applications

Conventional use of FE structural analysis involves (a) The development of an initial model based on a structural engineer's experience or a designer's concept, and (b) Analyzing the model as means of providing a feedback loop informing what design decisions are to be made. The initial model is thus reiterated and continues to be analyzed until it has been optimized satisfying all design parameters. This iterative process includes both addition of structure to areas of high stress concentration and elimination at areas that lack stress forces. The input workflow outlined here aims at flattening this two-step process with its associated feedback loop into a single step procedure by using the FE analysis results as initial design criteria. By approaching material stock as an empty canvas and only treating areas that require additional strengthening, a smoother and simpler workflow is achieved. Additionally, in contrast to topology optimization that deals with altering material distribution, simplifying the core problem into 2D flat mono-material studies allowed the authors to move away from the additive/subtractive nature of the existing workflow to a more transformative one. Parameters beyond structural performance including manufacturing constraints and heat flux amongst others could then all be added to early FE analysis. While these constraints are quantitative, varying their degrees of compliance could then allow for a set of design iterations—all within the acceptable quantitative threshold—on which

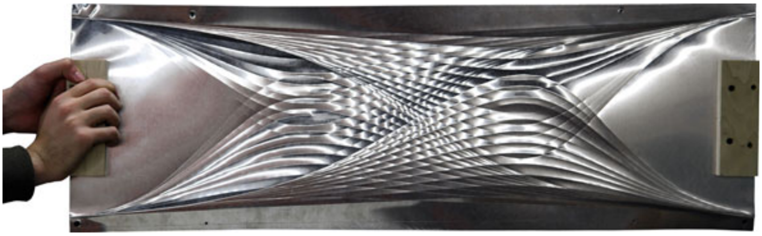


Fig. 12 20 gauge aluminum sample produced by robotic bead rolling process

qualitative aesthetic judgment can be made. This instigates new formal languages that arise out of pure functional and numerical investigations.

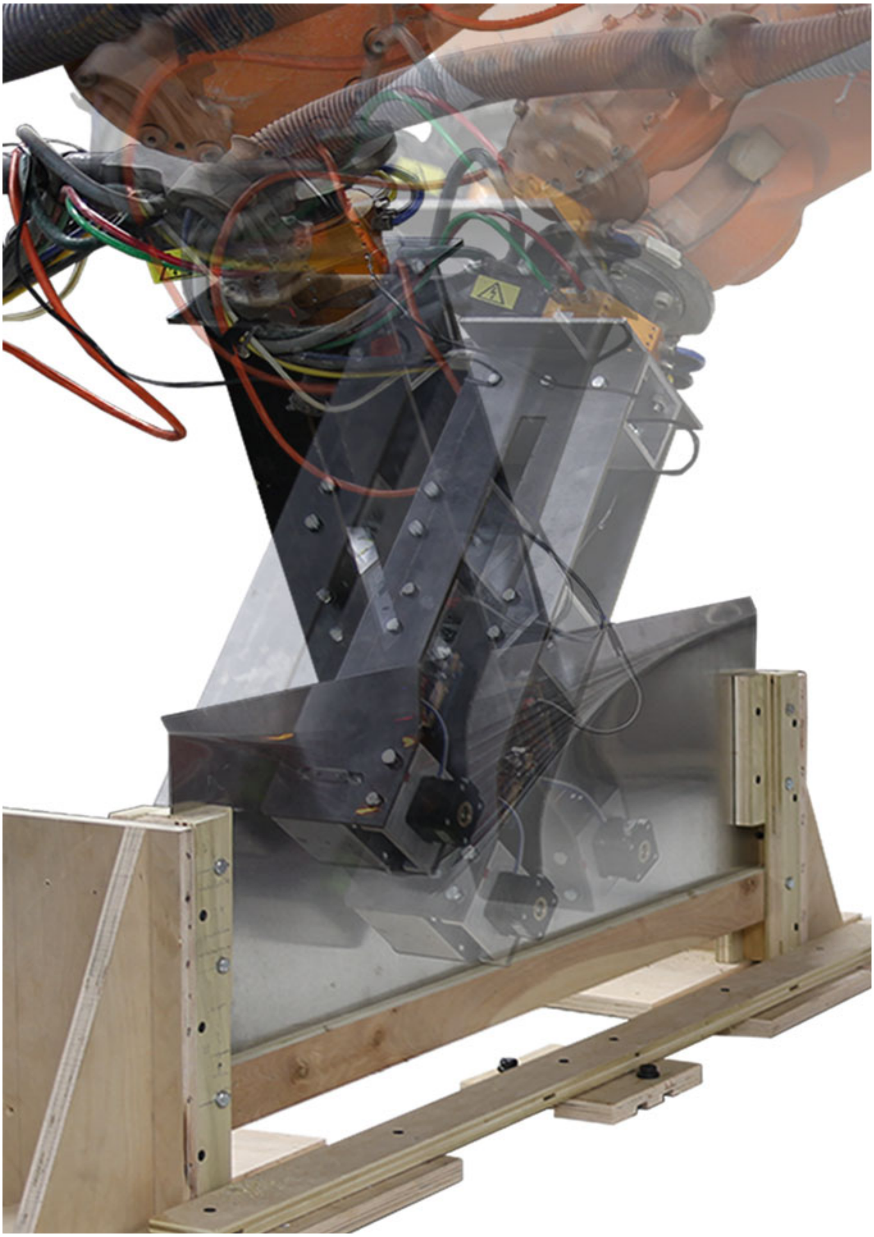
6.2 Robotic Bead Rolling Applications

Stressed skin surfaces, as stand-alone elements in monocoque arrangements or in tandem with structural members in composite systems, demonstrate a high performance capacity through their use in ship building and aerospace industries (Bechthold 2008). From building cladding panels to interior book shelves, stressed skin fabrication via robotic beading provokes a wide range of applications on various scales. This is due to the fact that it provides structural integrity to sheet metal and increases its rigidity. The authors, however, have recognized that these structural improvements do not reach the extents of using high gauge metal sheet as primary support in an assembly. Therefore, an added-value that comes with the application of such a technique would be allowing for lighter substructures resisting less mechanical forces. In the case of building facades, laminating multiple flat sheets that have gone through this strengthening process suggests that the desired visual flatness can be maintained while a structural layer on the underside supplies the rigidity.

While the authors have chosen to focus on analytical methodologies, bead rolling as an aesthetic impression and its associated play of light across corrugations is also a valid potential application of this process (Fig. 12). By varying the input mode beyond the suggested FE results, any algorithmically generated pattern could be easily formalized in the form of a rapid visual prototype. Bead corrugations in such prototypes do contribute to structural rigidity alongside pure aesthetics. This is due to the increase in the overall active structural depth, regardless of specific bead locations. Further directions of research would enable the 3d digital modeling of beads into a given geometry before production is carried out. This allows visual pre-verification as means of simulating fabricated outcomes. Assuming the reliability of digital testing matches its physical counterpart, this added function would also eliminate the need to physically test samples as further analysis, if required, could then be run on digital models.

7 Conclusion

Ongoing research has focused on digitizing certain elements of the traditional bead rolling process to allow for improved control and precision, while enabling novel formal possibilities that would have proved either difficult or impossible through manual processes. An automated process from digital form-creation to physical robotic fabrication has been developed entirely within the Rhinoceros environment. Toolpath input ranged from stress vectors produced through FE analysis to parametrically generated curve patterns. While both of these approaches added structural rigidity to the samples, further mechanical testing of samples is necessary to verify if there are significant structural differences between approaches. This type of analysis would allow the authors to then modify the manufacturing variables accordingly. Results from the panels produced throughout the research demonstrate that some appropriate applications include assemblies requiring load transfer through skins or lightweight sandwich panels. Additionally, the decorative possibilities enabled by the process have proven very provocative.



Acknowledgments This research was conducted under the guidance of instructor Andrew Witt and fabrication specialist Burton LeGeyt during the course: Expanded Mechanism/Empirical Materialisms at the Harvard University Graduate School of Design; Cambridge MA; Fall 2013.

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