Structural Architectural Elements Made of Curved Folded Sheet Metal

Vlad Andrei Raducanu¹, Vasile Danut Cojocaru², Doina Raducanu³
¹National University of Arts Bucharest, FDADD Design Department
²³University Politehnica of Bucharest, Faculty of Materials Science and Engineering
¹http://unarte.org/national-university-of-arts-bucharest.php
²³http://www.upb.ro/en/
¹zoster.ar@gmail.com ²dan.cojocaru@mdef.pub.ro
³ac_doina@yahoo.com

To deviate from conventional metallic structural elements is not an easy achievement, especially if free forms with curved surfaces are wanted. One approach that makes sinuous volumetric metallic shapes accessible is curved folded sheet metal. The aim of the current application is to create a reinterpretation of the classical column, an architectural element which is both decorative and structural. This is achieved through curved crease folding of steel sheet metal. To aid the form-finding process, a virtual simulation of the bending process is done using computational means.

Keywords: curved crease folding, metallic material behaviour, computational design, digital stress analysis

INTRODUCTION
In architecture, metallic structures are used increasingly due to their low weight, slim profiles, easy (dis)assemblage and facile recycling. The usual structural elements consist of extruded profiles such as H or I beams which also usually lead to conventional architectural displays. Making less standardized, freeform structural elements, that could contribute to the architectural aesthetics of the built environment, does involve at the present time major costs if metallic three-dimensional printing is considered. A cost-effective alternative is to use sheet metal that can be folded in order to achieve sinuous, aesthetically pleasing shapes, that through digital and physical analysis can be tweaked for structural performance. The sheet metal development can be processed by more accessible technology, such as 3-axis CNC milling machines or CNC punch presses.

STATE OF THE ART
Curved crease folding (Huffman 1976) is an expanding research domain that is still in development, hence options to digitally simulate curved crease folding designs are limited (Bhooshan et al. 2015). Due to the cumbersome process of digitally simulating the deformations that arise when folding sheet material along curved lines, working with physical models is often the cornerstone in the development of a curved crease design. The design alterations often go from the physical model to the digital one and not the other way around (Tachi and Epps 2011), yet the (folded) digital counterpart is necessary for en-
semble visualization and especially if structural and other types of digital analysis are desired in order to inform the form-finding process.

The most basic way to achieve curved folded designs is to generate the fold lines as intersections of a developable surface with a cutting plane, the result being the reflected geometry of one of the two sides (Mitani and Igarashi 2011) (see Figure 1), a method that can be seen in David Huffman's famous designs (Demaine et al. 2010). In this cases, a fully digital simulation, without feedback from a physical model, is possible, but the design spectrum can be fairly limited.

For more complex shapes, the following method of virtual simulation of curved folding process can be used within Grasshopper (Tachi and Epps 2011):

1. A design solution is searched through the use of physical models (usually paper models).
2. Once a plausible idea emerges, the development is digitally reproduced, preferably in an algorithmic manner, so that the folding pattern can be easily altered in order to optimize the solution.
3. The simulation of the folding process takes place using a rationalization of the original development as a rigid origami pattern (see Figure 2). Rigid origami uses polyhedral planar plates joined by rectilinear hinges (Miura 1970) rather than a continuous elastic sheet like paper or sheet metal. This conversion needs the ruling lines of the folded shape. These lines can be "discovered" on the physical model (one way of doing this is by using a ruler - Figure 3). A certain development (in its original fluent form) doesn't describe a single folding outcome, it depends on the way the different strips get bent (see Figure 4). The outcome is nevertheless a ruled surface which therefore is developable and has ruling lines. Different configurations of the same development display differently oriented ruling lines. This means that the rulings pattern determines the way the development gets folded digitally. These ruling pattern can be digitally generated, by defining an algorithm based on the physical model examination (rather than manual reproduction from scanned flattened models).
4. Analysis - the rigid plate interpretation is a mesh that can be subject to different analyses, be it structural or otherwise.

Figure 1
Curved crease folding through plane reflection.

Figure 2
The reinterpreted development as rigid origami pattern (quad mesh).

Figure 3
Discovering ruling lines on the paper model using a ruler.

Figure 4
Two resulting surfaces (with different rulings) based on the same development.
CURVED FOLDED DESIGN DEVELOPMENT

The goal was to investigate diverse shapes that could work as both structural and ornamental architectural elements, such as the columns used in the classical orders. We intended to use sheet metal that can be very effective from a structural point of view but also generates pleasing reflections when curved. Several curved crease folding column designs were developed at model scale (see Figure 5), each with its own advantages and disadvantages regarding different aspects of aesthetical, practical and structural nature. The chosen design (see Figure 7) references the entasis and the fluting found in the classical architectural orders (see Figure 6) in addition having a hexagonal section better illustrates the idea of a circular section, which is specific to the concept of column. The design needed to include new characteristics compared to the classical or even contemporary columns, hence the idea of transparency arose. This was achieved by splitting the column, and later on also the option of using inner light that accentuates the shape of the column in dark environments and further enhances the ornamental aspect of this structural element (see Figure 7).
ALGORITHM

The column is based on a number of 6 strips. The individual strips have a symmetrical arrangement of fold trajectories, which eases the determination of the ruling lines needed for the digital folding simulation (see Figure 8). There are a few principles (Fuchs and Tabachnikov 1999) that relate the orientations of the ruling lines to the way the developments gets folded (see Figure 9). These principles were implemented in the algorithm, and the digital simulation does return an acceptable approximation of the physical model. In this way, the algorithm includes an automated adaptation of the ruling lines pattern that generates the development and thus fine-tuning the design requires fewer physical models. The physical models are still necessary at times, since sheet material doesn't conform exactly to its digital representation due to different aspects, like the fact that the creases do have a tendency to resist folding after a certain angle, whereas in the digital simulation the folding lines are free-moving hinges.

Once the rationalized development is generated, a planar quadrilateral mesh can be based on it and digitally folded (Kergosien et al. 1994). The deformation can be performed using specific origami software, such as Freeform Origami and Rigid Origami Simulator (Tachi 1999) [2], but the Kangaroo plugin for Grasshopper can also simulate the deformations, which is more convenient since the same software (Rhinoceros + Grasshopper) can be used for a larger part of the project and tweaked to specific needs.
Kangaroo 2 was used in the simulation with the following settings: the quads needed to retain their planarity as much as possible, also their perimeter and diagonals needed to remain the same length, in order to prevent deformation. No hinge restrictions were implemented at first. This made the digital model have a different final shape in the middle section compared to its physical counterpart, where the two lateral strips are more open due to the tendency of the sheet material to resist bending, therefore the next step was to implement this resistance in Kangaroo. This however made the initial approach, where one end got folded and the rest came into place perfectly (see Figure 8), less than ideal, since the fold didn't propagate to the other end (see Figure 11). In the end, virtual banks were used to fold the digital module (see Figure 12). Another problem that arose is that the two ends of the module didn't remain collinear (this can be seen in both the digital and the physical models - see Figure 10). When used as an ensemble in reality, they do remain collinear the ends being fixed together (see Figure 13). Making them collinear however generates a pinching effect in the middle of the module, where it is at its narrowest, which is a weak spot, as can be seen both from physical tests as well as digital analysis (see Figure 13). To counteract this, local embossing of the sheet metal will be explored (see section Further Developments).

Prototype
A 1:3 prototype was build using 1mm pickled steel sheet metal that was welded after the folding process (see Figure 14). A CNC punch press (Durma RP6) was used to create different hole patterns for the creases (see Figure 15). The folding process was made using a press brake. Preliminary tests showed that a small dent in the middle portion of the crease contour is needed (using the press brake locally) so that the metallic sheet folds along the creases when the extremities are folded all the way to their final angle.
POST-FOLDING ANALYSIS

**Mechanical Structural Testing**

The prototype was mechanically tested for compression with an increment of 0.5 KN using an Instron 3382 machine (figure 16). The force/displacement variation was linear for all tests. The tests were stopped at a force of 5KN (500Kgf) that exposed a compression of only 0.39mm, which indicate a very good mechanical behavior of the design. Further tests will be made to test it's absolute limit.

**FURTHER DEVELOPMENTS**

The next stage involves implementing embossed "dimples" using the same punch press to modify the material properties. Strategic dimple patterns will be generated digitally depending on the distribution of loading forces resulted from the smooth surface prototype analysis.

Micro-scale testing of the results will be made in order to obtain relevant material characteristics around dimples; the local increase in strength is monitored using mechanical tests coupled with hardness tests. Some preliminary tests were made at a small scale. Samples were prepared to be examined by a scanning electron microscope (Tescan VEGA II - XMU) which allows us to examine the local deformations (Figure 17). Further testing will be used to observe the influence of stress hardening through different embossing patterns on the column as an ensemble. Metallic materials behavior will be studied from the point of view of structural properties as well as their influences upon fabrication. Further prototypes and samples will undergo similar tests, in the end a 1:1 scale column is to be build.
CONCLUSIONS

Regarding the topic of the 34th eCAADe Conference - "Complexity & Simplicity", the output of the research presented in this paper leans towards simplicity, from a geometrical point of view, but some of the most satisfying designs rely in fact on simple shapes, such as Oscar Niemeyer’s buildings (Figure 18). As sculptor Constantin Brancusi said, “Simplicity is complexity resolved”. On the other hand, intensely complex designs, such as Michael Hansmeyer’s columns are just as fascinating (see Figure 19). Advanced computational design methods are tools and should be seen as such, they don’t dictate a classification of the outcoming results, but simply are means to explore possibilities that were less tangible before.

ACKNOWLEDGEMENTS

The work was supported by a grant of the Romanian National Authority for Scientific Research, CCCDI-UEFISCDI, project number 316/2014.

Special thanks to Gregory Epps and the members of Robofold [17] for welcoming me at their studio and showing me the methods they use to manage curved folding designs.

REFERENCES

Bhooshan, S, Van Mele, T and Block, P 2015 'Discrete funicular structures with curve-crease-folded moulds', Proceedings of the International Association for Shell and Spatial Structures (IASS) Symposium, Amsterdam


Mitani, J and Igarashi, T 2011 'Interactive Design of Planar Curved Folding by Reflection', The 19th Pacific
Conference on Computer Graphics and Applications, Kaohsiung, Taiwan, pp. 77-81


Tachi, T 2009 'Generalization of Rigid Foldable Quadrilateral Mesh Origami', Proceedings of the International Association for Shell and Spatial Structures (IASS) Symposium 2009, Valencia
