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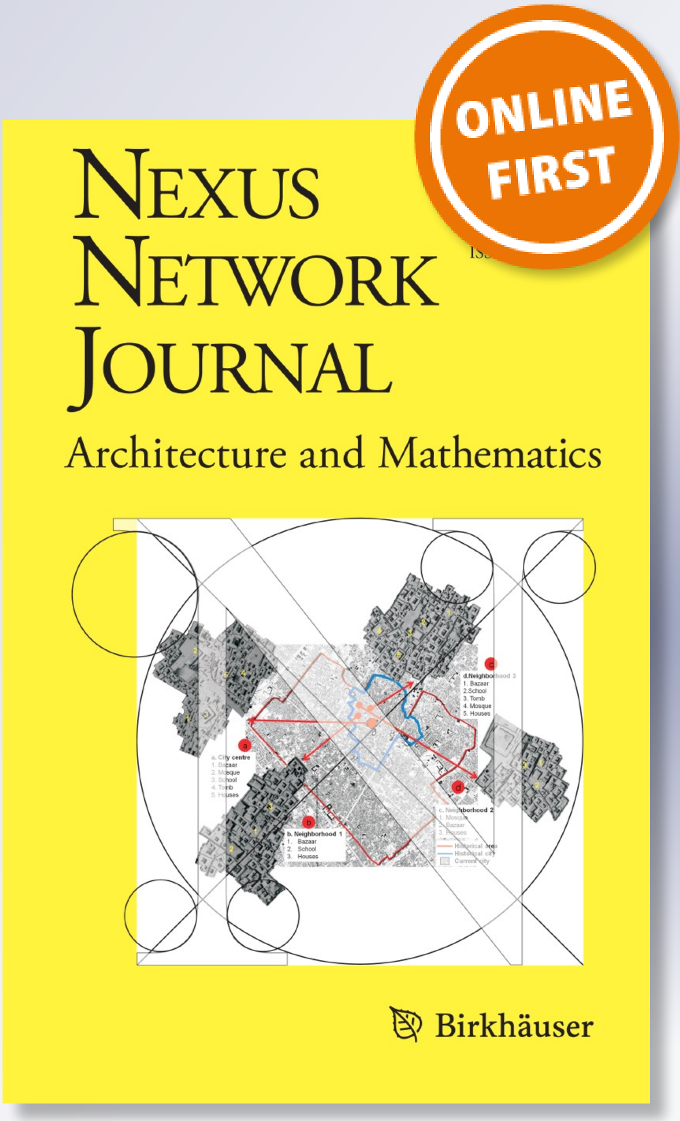

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RESEARCH

Folded Compositions in Architecture: Spatial Properties and Materials

Mauro Chiarella · Rodrigo García Alvarado

Abstract The two-dimensional unfolding of three-dimensional volumes allows architectural design and production methods to be rethought in a creative way. This paper reviews spatial and material properties of folded compositions in architecture, through a conceptual proposal based on professional and pedagogic experiences as well as new technologies for geometrical programming and digital fabrication, tested in five alternatives for one case study. The continuous and dynamic two-dimensional projection of a three-dimensional spatial situation provides a geometric relationship between the surface and volumetric configuration of a design, thus enabling a mathematical and operative connection between conditions of perception and production. The material expression of these configurations establishes a significant link between the conceptualisation of the design form, its geometric digital generation, its physical fabrication and overall appearance in a manner analogous to the design process used. The combination of folded compositions with the new technologies available further strengthens their potential, which embraces the fluid nature of human activity with continuous forms and delicately intricate geometries.

Keywords Design analysis · Structural systems · Geometry · Transformations · Folded compositions · Form making

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Introduction

Folded compositions in architecture allow design and production methods to be rethought in a creative way. The designer moves away from the prevalence and, to a certain degree, the historical determinism of graphical architectural thinking based on descriptive geometry, which has for many years enjoyed almost total stylistic control over the objects built. The continuous two-dimensional projection of a three-dimensional spatial situation provides an alternative geometric relationship between the surface and volumetric configuration of a design, thus enabling an operative connection between conditions of perception and production. As evidenced in the usual paper folding exercises, applied also by Josef Albers at the Bauhaus (Buri and Wein 2010), as well as in recent experiences with ruched wood in the Pavilion ICD/ITKE (Knippers and Menges 2011) or with metal sheets through the system Robofold (Peters 2011). The material expression of these configurations displays the capacity to control production methods and physically explore their spatial development. While this process also reveals aspects of scale and construction that limit the range of models produced, it establishes an important connection between the conceptualisation of the design form, its geometric generation, its physical fabrication and its overall appearance.

The potential of folded compositions in architecture has been exhibited in some of buildings by contemporary architects, (such as: Valleaceron Chapel, Spain by Sancho-Madridejos; Yokohama International Port Terminal by Foreign Office Architects; Maison Folie de Wazemmes by NOX; and Tod's Omotesando by Toyo Ito), all of which claim to have used folding design processes (James 2008; Chiarella 2009), developing new spatial and material configurations (Fig. 1).

The possibilities of folded compositions in architecture have also been explored and defined in experimental exercises and diverse teaching activities (Vyzoviti 2003, 2006; Saito et al. 2009; Tachi 2010; Chiarella 2011). However, the spatial and material properties of this method have not been fully explored in terms of the possible production processes for a more generalised application. If folding compositions are to become more widespread in architecture, the potentials and conditions of the method must be characterised so that it can be integrated into both teaching and professional practice. This article, based on activities from the research project FONDECYT 3110025, sets out a relationship between the spatial and material properties of folded compositions in architecture, illustrated in strategies developed with parametric programming and digital fabrication, in order to foster the application and use of these new design technologies.

Spatial Properties of Folded Compositions

Folded compositions can be defined as the transformation of a physical form, to double a flat structure (according to the Merriam-Webster Dictionary), as can be seen from the primary experiences (Buri and Weim 2010), to contemporary (Iwamoto 2009; Knippers and Menges 2011; Peters 2011). However, they also offer wider possibilities in the spatial and material elaboration of building design, from

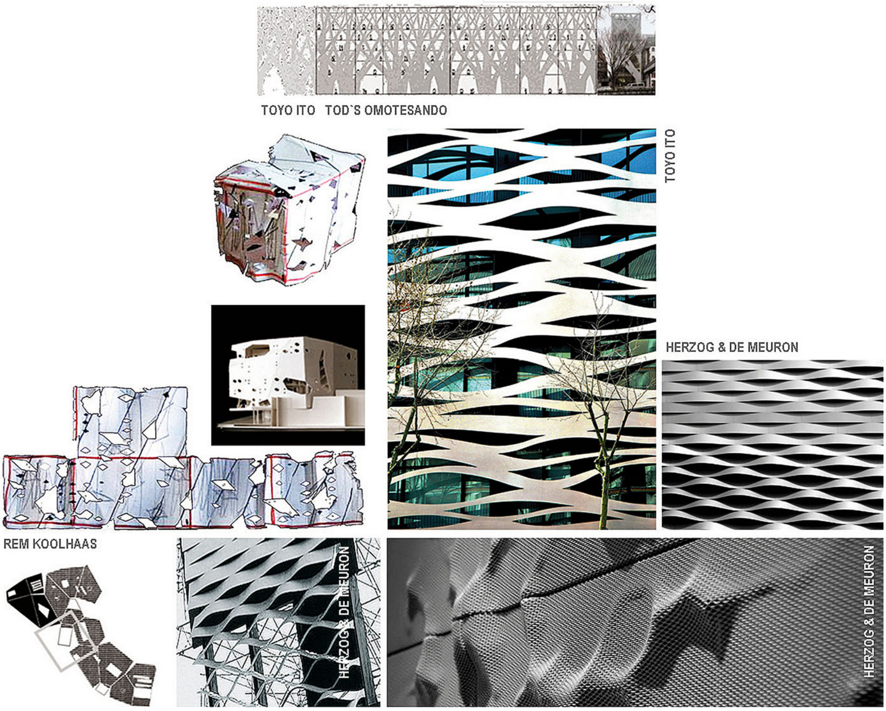

Fig. 1 Examples of professional and experiences of folded compositions in architecture

abstract conception of the project and the visual continuity of the architectural volume, to dynamic action or resistance capacity of folded surfaces. Generally, the size of an architectural building demands structural stability with a large number of rigid elements. However, folded compositions can play a role in the design of such configurations, as demonstrated in the examples shown in (Chiarella 2009), particularly in the treatment or shape of specific components or in more complex projects that make use of new materials and construction systems. Thus, folded compositions in architecture can be understood initially as a mechanism for formulating a design, and then increasingly as a manufacturing solution. This method clearly displays a form-finding process of evolution, where a surface is transformed into a volume with spatial conditions; the resulting inherent geometric complexity in some ways conditions its use but also expresses its creative potential.

Folded compositions possess some of the following form-related characteristics: geometric surface development, transformation of planes and edges, modulation, fragmentation, curvature, etc. All these features can be identified in certain elements of the natural world. They have been widely tested with materials on a small scale and in some cases on a larger scale (such as tensile fabric construction) and partially implemented with computer programming and digital production (Spuybroek 2009). Some specific technical advances have been identified (such as an increase in structural resistance due to folding and enhanced acoustic resonance and light

Table 1 Spatial properties folded compositions in architecture

Spatial properties			
Volume defined by overall outline	Diverse articulation of surfaces	Partial or total containment	Visual continuity of surfaces

dispersion), but clear recognition of the perceptual and physical conditions for a wider architectural application is still lacking.

Folded compositions generally possess four significant spatial features (Table 1):

1. The configuration of an irregular volume diffusely defined by its overall outline, which varies according to different viewpoints. In contrast to regular geometric compositions, the complete shape and its exact dimensions cannot easily be deduced by visual perception alone, calling for a detailed recognition of the whole volume.
2. The articulation of the surfaces of the volume, with a discrete layout of faces and edges (with differing angles) or curving planes in undulating volumes. A certain degree of modulation of the surfaces or repetition of some features develops with either partially regular or totally irregular geometric characteristics. There is a degree of concordance in the dimensions and surface conditions between the planes, but the overall treatment remains heterogeneous.
3. A partial or total sense of containment resulting from the irregular concavity of some parts of the surfaces, generating a variable spatial perception of the volume which sometimes defines interior and sometimes exterior spaces depending on the configuration of planes in the volume. This stands in contrast with regular geometrical volumes that provide a clear exterior and interior place, with a clean definition of spaces.
4. The continuous perception of surfaces, combining different textures, lighting, openings, fissures, treatments or material compositions. However, a certain similarity between surfaces is maintained, particularly a differential patterning depending on face type, thus enabling an overall understanding of the shape. Despite differences in proximity, geometry, shadowing and openings, this tectonic extension is essential to the volume's spatial quality.

These spatial features offer a diverse and far-reaching creative potential for architecture, as demonstrated by the teaching experiences and a developing body of built works. Regular geometric compositions possess more structured spatial properties (with recurring forms, regulated relationships, perceptual homogeneity, etc.) that have determined the rationale of developments in construction technology. Folded compositions, in contrast, possess variable qualities that foster diverse and meaningful spatial experiences, although progress must be made to define these compositions and make them more operative if they are to have a wider application. Materiality, in particular, must be explored and determined, to enable further use of folding in works of architecture.

Material Properties of Folded Compositions

Due to their inherent complexity, folded compositions have mainly been developed on a small scale, with their dimensions and folding procedures determined by the material used, usually paper. An actual work of architecture demands a significant change in scale from the design model to the built form, with a corresponding change in materials used, and this represents a significant obstacle to the architectural use of folded compositions. In fact, it is the very properties of the material to be used that determine the form (Stavric and Wiltsche 2014). It is thus essential to characterise the physical conditions necessary to develop a folded design proposal to be realized at full architectural scale.

The material properties of folded compositions (Table 2) can be differentiated firstly in terms of edges (the contour of each straight or curved surface) and faces (each surface), and secondly according to their subsequent development in the fabrication and use of the building.

1. The edges possess two main conditions: their own configuration and relationship to the faces, that is to say, the continuity or modification of materials with regard to the neighbouring planes (sometimes adding new components); and the mobility between faces if they maintain a degree of flexibility. Curved forms maintain the same materiality with some linear areas possessing smaller radii, lending these the quality of edges.
2. The faces reveal properties of the enclosure itself, which may be similar for all the faces, combined or different for some faces. These material characteristics depend on the physical composition, dimensions and form of production and can be characterised as transmittance capacities (thermal, acoustic, lighting, visual), resistance capacities (tension, compression, traction, torsion), appearance aspects (colour, texture, etc.) and durability (related to materiality, context and period of use).
3. In the fabrication and use of folded compositions, the resistance to tension of the faces and edges (regardless of whether they are continuous or added elements) are particularly significant. Modifications made to the resistance of edges and curvatures are key features that can increase or reduce structural capability and even deteriorate over time or with movement. Likewise, the resistance of surface planes depends on geometric size (the distance between edges); a larger distance may produce partial torsion that modifies the overall

Table 2 Material properties folded compositions in architecture

Material properties			
Edges	Faces	Fabrication	Use
Linear configuration Relation to Faces	Transmittance Resistance Appearance Durability	Execution size implies different structural capabilities	Temporal exposure produces different alterations by faces

shape or smaller modular volumetric designs may be used to compensate. Also, exposure to site conditions or usage may alter durability, lighting, transparency and so on.

This physical characterisation reveals a considerable variety of relevant factors according to the elements used and their spatial layout at different scales. Step-by-step experimentation with different materials and applications is essential in order to connect design ideas with real constructive possibilities and architectural results.

Parametric Geometries and Digital Fabrication

Parametric design introduces geometry from a mathematical-algorithmic viewpoint (Woodbury 2010). It proposes the generation of a geometry based on the definition of a family of initial parameters of dimensions and the relationships between them. In the design process, algorithms and advanced computing resources are not simply used to represent forms and control complex geometries but to create dynamic and variable design possibilities. The result is not a single solution but rather a family of possible solutions. The variables and algorithms create a tree or matrix of geometric relationships by calculating the range of possible design solutions according to the variability of the initial parameters and components selected.

The strategic incorporation of mathematical calculation in the geometric definitions based on parametric modelling has proved to be a determining factor in the spatial and morphological configuration of the contemporary experimental works of architecture (Hauschild and Karzel 2011; Hensel et al. 2006). A general geometric manipulation of non-uniform rational B-spline (NURBS) surfaces, isomorphic polysurfaces, hypersurfaces and genetic algorithms has concentrated efforts not only on conceiving and controlling these spatial possibilities but also on developing coherent construction techniques with relevant and consistent criteria (Meredith 2008). The age-old inertia of architectural tradition and the inability of traditional building materials to fulfil the demands of these new spatial developments are the main challenges to integrating the design and simulation technologies of the post-mechanical age with the inherited industrial and pre-industrial building techniques. The new forms of architectural production face the challenge of embracing the complexity of these new design projects and integrating digital fabrication techniques and procedures to ensure the complexity lies in the resulting geometry alone and not in the building design and construction process (Gramazio and Kohler 2008).

Digital fabrication technologies are classed according to the processes acting upon the physical and/or chemical properties of the materials used. These are: additive procedures, subtractive procedures and formative procedures (according Kolarevic and Malkawi 2003), and joining procedures (Schodek 2005).

In the CAD/CAM additive (pre-formed) procedures the components are produced from amorphous materials (small particles). Chemical and physical processes create solid bodies with the material qualities the product requires based on amorphous input materials such as liquids, powders, gases, fibres or shavings.

Examples include moulding processes (for prefabricated concrete elements), robot-aided handling (used to assemble individual elements) and large-scale 3D printers.

Subtractive procedures break down the cohesion of the material at specific places in the initial component. The particles are separated from the prime material reducing the final volume of the construction material. Different cutting, manufacturing and elimination processes can be used, for example, CNC laser cutting, CNC jet cutting, CNC hot wire cutting, CNC milling and jointed-arm robotics.

Formative procedures conserve the cohesion of the material and generate different parts through altering the form of the original components to optimise their initial characteristics (by improving rigidity or adapting a piece to a specific geometry without changing its volume). These can be divided into cold-forming and hot-forming procedures, for example, CNC bending edges, CNC punching and nibbling and pressure forming.

Application Strategies

A number of workshops and design exercises were developed to study these spatial and material properties of folded compositions either with one or with several of the different digital fabrication procedures available locally (Figs. 2, 3).

Here we present a graphic summary of five alternatives applied to the development of an actual design task on a small-scale: a permanent piece of urban furniture to be installed at the entrance to the Industrial Engineering School of the Universidad del Bío-Bío in Concepción, Chile. The experiment of using folded compositions with new technologies was put to test in the development of an element designed to symbolise the teaching and professional activity of the school while also providing a functional solution for students and other people entering, leaving and passing the building. The object was to serve as sculpture, furniture and shelter; that is, as an "unfolding" of human activity and architectural expression, it sought to articulate the limits of architecture and of people's perception as they walked past. The design took on a formality of a monumental nature while also serving as an informal resting place; more precisely, it was an expression of the doubling up of traditional functions and the dissolving of the limits between building, work of art and accessory, between sign and structure. The design could be used for only a moment but also recognised as a timeless symbol. Different development and production strategies were explored to create an element that represents the deeper meaning of architectural folding.

With regard to material properties, experiments were made folding the different conventional materials found in the construction market in Chile (steel, PVC and polycarbonate) in the form of sheets, laminas, solid blocks and tubes. Numerous design interpretations were created to cover a surface (a complex three-dimensional geometry with double curvature designed for the project) based on the construction of different components created from the folded material, then either soldering, fusing or joining each piece to make the whole. Both flexible and rigid joints were incorporated to achieve structural continuity (in most cases) avoiding the use of external support elements.

Fig. 2 Tests of folded components manufacturing with marine plywood and polycarbonate, Universidad del Bío-Bío, Chile, 2012

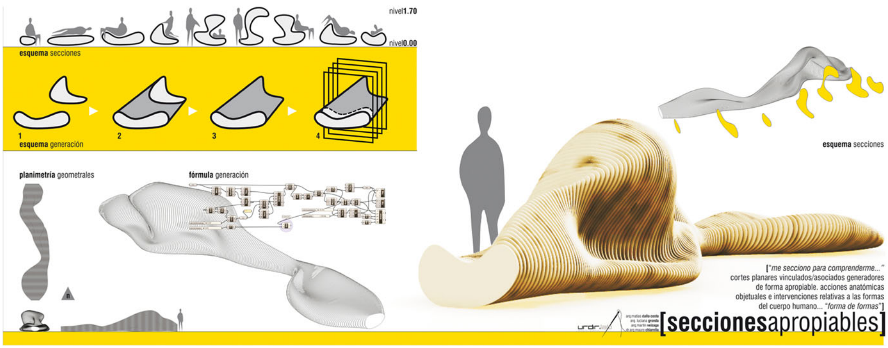

Fig. 3 Strategy spatial and geometric design of alternative 1: Generating spatial envelope by folding from the survey of 9 body positions. Urdir.Lab. FADU. Universidad Nacional del Litoral. Santa Fe-Argentina. February 2012 (Authors: Matias Dalla Costa; Martin Veizaga; Luciana Gronda; Mauro Chiarella)

The first alternative (Fig. 4) involves the following tasks: (a) Generation of a surface with curved sections and geometric parametric control; (b) Extraction of curved level sections (ribs), with projection onto the plane XY and representation by overlaid steel tubular profiles; (c) Geometric development of parts for production. These are produced with CNC Bending, which involves exposing the material (steel bar or tube) to mechanical pressure by passing it through three or more flexion rollers. This cold-forming process does not cause any chemical changes in the material. The material undergoes plastic deformation (it suffers irreversible

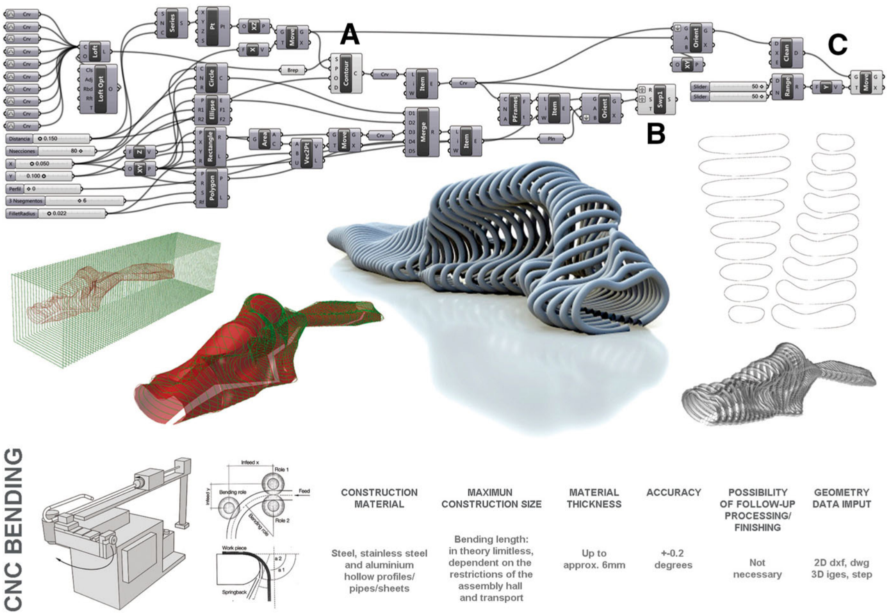

Fig. 4 Alternative 1

thermodynamic changes) and does not return to its original form once the pressure is removed. Benefits include: (a) better resistance of the component through change in the geometry and recrystallization of the material; (b) the possibility to create complex 3D geometries; (c) good precision in both dimensions and shape with little loss of material (compared to CNC Milling); (d) continuous production of construction elements without additional connectors such as rivets or welded screws (this depends on the dimensions of the design); (e) excellent possibilities for automatized production of different components.

Alternatives 2 and 3 both used steel sheeting. In alternative 2 (Fig. 5), the geometric strategy was to inscribe adjacent tubular hexagons into the external surface, thus defining the structural continuity with a reticulate plan. In alternative 3 (Fig. 6), the double curvature geometry was adapted to plane surfaces, providing the basic geometry for the folded component under development. In practice, this strategy takes advantage of the structural rigidity of the folded surfaces to form a geometric continuity wherein the components themselves are structural.

The subtractive CAD/CAM procedures are used to separate planes of prime material with little variance in sheet thickness. The main advantage of jet cutting is the low level of loss of material along the cutting edge and the speed with which it can be used. The procedure of CNC Folding is carried out without separation of material and with plastic deformation. As a consequence of this state of traction-compression the material tends to spring back slightly after folding, making it necessary to form a slightly stronger fold to compensate. The process causes deformation of the metal along a single line of folding. By following this with

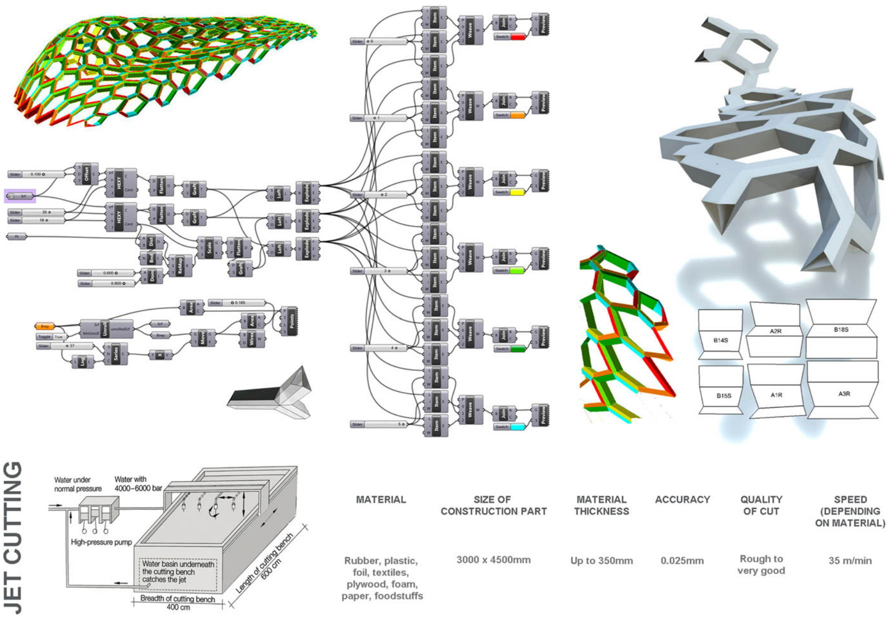

Fig. 5 Alternative 2

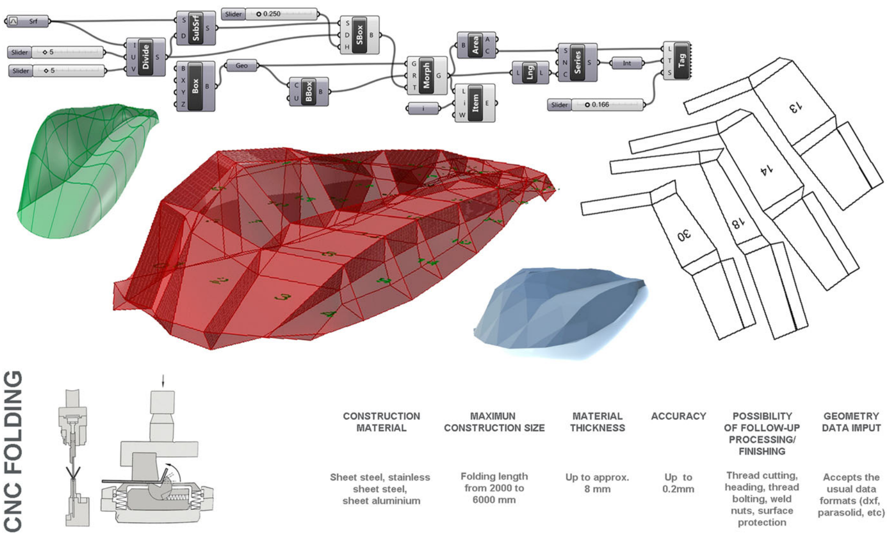

Fig. 6 Alternative 3

further folds, complex pieces can be created that increase the rigidity of the metal without losing its continuity.

The strategy in alternative 4 (Fig. 7) consists of randomly filling the space marked out by the double curvature space with hollow prisms (a variety of

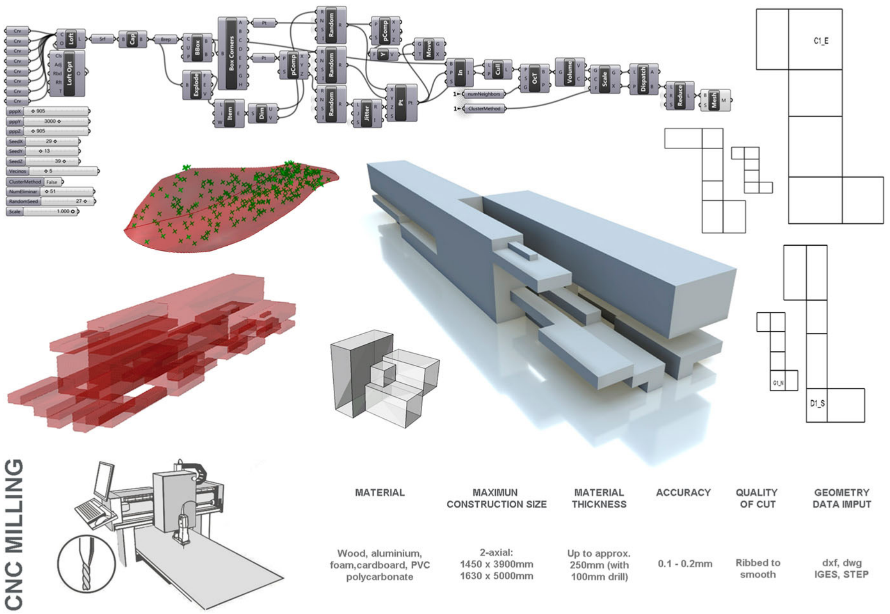

Fig. 7 Alternative 4

components created by folding), diversifying the proportions and dimensions of the pieces while maintaining their proximity.

This distributes a cloud of points over the initial containing surface, which belong to the origin edges of each parallelepiped represented by the borders of solid objects (B-Rep). Alveolar polycarbonate and CNC Milling are proposed to make cuts in the components and create folded edges. This is the most time-consuming of the subtractive procedures but also the most accessible for softer materials both in terms of equipment costs and ease of use. The milling head is determined by the material to be used, mostly timber and plastics. These procedures use optimised component distribution software both to make efficient use of the sheets of material used and to minimise cutting times.

Finally, alternative 5 is an example of combining diverse procedures and materials (Fig. 8). To maximise the possibilities of using different techniques together a separation is made between the structural ribs and an independent envelope that encloses and is supported by it.

The potential benefits of this strategy lie in defining the materiality of the envelope based on the possible development of a variable geometry that responds to external environmental data and constitutes active components with adjacent electronic mechanisms. The addition of an electronic microcontroller (such as Arduino) could facilitate the programming, allowing synchronisation between different sensors, physical mechanisms and geometric parameters, thus enhancing design efficiency.

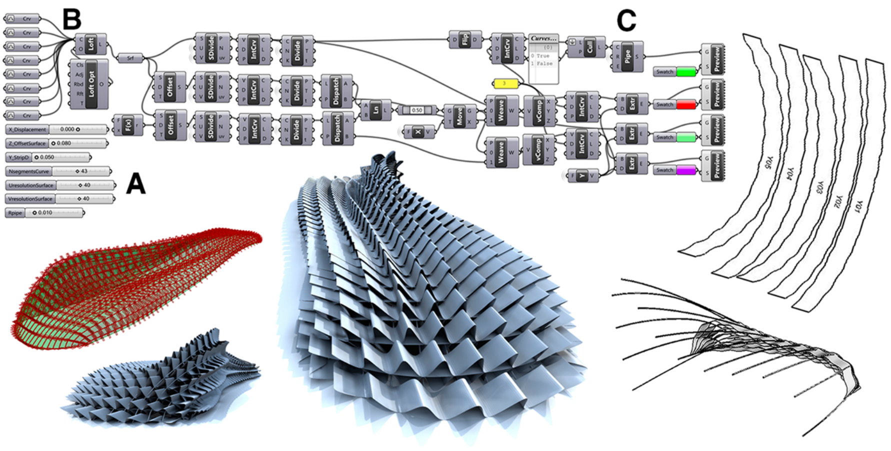

Fig. 8 Alternative 5

This case study tests the identified spatial and material properties of folded compositions in architecture, using new methods of parametric geometry and digital fabrication. While demonstrating such properties, they also open up new possibilities for the control and development of the design. The properties described for configuration and articulation of the spaces are fully present but the sense of containment and overall understanding of the volumes is most developed, particularly in the methods used in alternatives 1, 2 and 5. The material capabilities of the edges and faces also appear separated according to the construction strategy used, with a transformative development in practically all the procedures. Consequently, the application of these technologies expands the spatial and material properties detected while providing operational support to both design and construction. This constitutes a considerable step forward in resolving the problems of scale previously faced in the folded compositions in architecture. The new parametric and digital fabrication methods permit continuity between the conception and manufacture of the folded form. However, they also demand an exhaustive study and formalization of the processes and the different methods available. These are summarized in Table 3.

Material Execution (Alternative 1)

Parametric design software allows geometric control of non-conventional execution processes, to automate elaboration of variable components similar to industrial standardization. Although this possibility of mass customization has not been verified at all, research works suggest this potentiality. To carrying out execution of complex geometries requires rationalization criteria and to review the relationships between material tasks and shape definition, by CAD/CAM integration. In Latin America these process are used in manufactured products, while building sector has

Table 3 Evaluation of technologies applied in alternatives 1–5

	Parametric programming	Digital fabrication	Evaluation
1. Wire bending	Surface generated by profiles and extraction of parallel sections	CNC bending of tubes by plastic deformation	Good physical resistance Complex geometries Good precision without waste Continuous elements Complete automation
2. Hexa tubular	Transformation of surfaces in regular hexagons and edges in tubular flat pieces.	Jet cutting of pieces with folding	Plastic deformation Regular production Automation of cutting
3. Box morph	Transformation of surfaces in continuous flat plates with an irregular grid	Jet cutting of pieces with folding	Plastic deformation Regular production Automation of cutting
4. Pixel 3D	Randomly filling with hollow prisms	CNC Milling to cut alveolar polycarbonate	Time-consuming procedure Most accessible
5. Strips waves	Structural ribs and independent curved envelope	CNC bending, cutting of sheets, folding and assembly	Multiple procedures Responsive geometry Professional integration

Fig. 9 BANCAPAR. Parametric installation under construction, Concepción. Chile

low automation. Most of construction tasks are based in handcraft procedures due socio-economic conditions as well as historical traditions.

The material execution of the design explored in this research was supported by a grant from the Regional Endowment for Arts (FONDART) and developed according alternative 1 with mixed procedures due the local conditions (Fig. 9).

Alternative 1 was chosen for its feasibility for manufacturing and clear design strategy. The installation, called BANCAPAR, was proposed with a double aim: urban furniture and public art. The design detailing was carried out in a collaborative process between researchers in Chile and Argentina, and it was based on nine ergonometric curves to provide different body supports. Each curve was located in line with one meter of separation and related with a sequence of folded steel bars to give diverse functions (different height to sit with or without back, resting or supporting to stand). The transition between the curves defined the geometry of the overall volume. This process generates a parametric shape according to the geometric procedure used, without giving explicit cues about its uses, and thus fulfills a condition of an art work. This ambiguity between visual decoration and useful element was sought to promote the design exploration.

The material execution of this work was carried out in Concepción, Chile, based on parametric design, but without a complete digital manufacturing. The geometric programming was developed to produce graphic profiles of curves and the folding steel bars were elaborated by mechanical machines with manual control, through a rationalization of the 106 metal pieces measuring 50 × 6 mm, all of different shapes, with a cutting and bending process defined by a geometric sequence and manual manufacturing with tools and benches. The use of 3,000 kg of steel, the folding, installation and finishing with galvanized treatment involved a budget of nearly 23,000 dollars.

The folding of steel plates means that material properties (in particular the appearance and resistance of the pieces according to size) are relevant for the shape definition. Each component is similar providing visual continuity and identity to the installation. The folded bars contribute to its spatial condition and meaning, to suggest functions and expression. The final work is an open-process to be used and interpreted in different ways. The geometric programming makes it possible to create different designs for new installations for other uses, sites or materials. In keeping with contemporary thinking, this experience is not about a unique object, but is rather a methodology for variables shapes.

However, a particular challenge in Latin America is to continue working towards the connection of creative technologies with fabrication process. New production systems should allow the complexity of these designs, with integration of digital manufacturing, without necessitating a complex process of execution. Thus, modularity of pieces is required with non-series assembly for design tasks.

Conclusions

Folded compositions in architecture have progressively emerged as a new design possibility, as experienced in a variety of teaching experiences and contemporary works. In order to take full advantage of the perceptual and physical features of folded compositions in architecture, design and construction processes have been developed and tested to prove or (in some cases) disprove their respective attributes.

We have reviewed the spatial and material properties of these configurations, examining their use in architecture with parametric design and digital fabrication techniques so as to generalise transfer and communicate their procedures and conditions. Folded compositions in architecture have inspired creative design work, but have long faced the dilemma of the change in scale (and materials) necessary between the design idea and final construction. It is a growing challenge for architectural work to progress from the initial explorations with folds in paper and sketched ideas by hand or computer modelling, towards a clear definition of the volumetric geometry and physical construction. In this process it is essential to define the spatial and material attributes proper of these designs. Folded compositions in architecture involve a material form, an operative action and a sense perception. Their spatial properties are linked to the volume as a whole and the surface treatment; they arise from a folded form and take on both a functional role (by creating a shelter for activity) and an emotional one (by awakening sensations in the observer). In material terms, this demands a variety of aspects—connections, structural behaviour, and containment—to consider and regulate in order to achieve an effective result.

In this way, the folded volumes of variable sections proposes the development of flexible structures ranging from an enclosing envelope supported by structural ribs and geodesic structures to a variety of structural surfaces such as laminas of reinforced concrete, prefabricated panels, semi-fabricated supporting systems and inflatable formwork. In practice, two strategic construction models have been defined according to the basic structure of the design: the first (simplified in alternative 5) uses the supporting ribs as structural bones to support an independent envelope, as in the H_2O Pavilion by NOX, Santa Caterina Market by EMBT Associated Architects, and Kunsthaus Graz by Peter Cook; in the second (simplified in alternatives 1, 2, 3 and 4) the containing envelope has sufficient rigidity to itself become the structural element, as in the Japanese Pavilion at Expo 2000 by Shigeru Ban. The material elaboration of alternative 1 demonstrated a process from geometrical programming to execution in sequential metal bars, folded by mechanic devices. The development of polymers, polyester resins and epoxy or PMMA (poly methyl methacrylate) can provides solutions with considerable lightness and flexibility and these materials can be moulded to adapt to different geometric forms. The computer numerical control (CNC) production machines, widely used in industrial design and engineering, are slowly being incorporated into architecture and offer the promise of a continuous construction process (the so-called "digital chain"), without the need for intermediaries, since each structural element is cut by computer with previously calculated mechanised layouts for final assembly (Chiarella et al. 2013).

By connecting the CAD/CAM procedures with the physical properties arising from folded compositions in architecture through the use of parametric design we can creatively rethink some of the production and construction processes currently available, by mathematically and operatively connecting production and perception. Describing the conceptual and functional characteristics of folded compositions with the new technologies available further strengthens their potential. However, a clear disparity arises between this new technology and the traditional design and construction processes using Cartesian representation and pre-industrial technology (such as orthogonal masonry, or concrete or timber frames) that has predominated in the professional fields for centuries. This new scope and potential for design and construction capabilities requires a new attitude of cultural development in order to give rise to fresh architectural experience that embraces the fluid nature of human activity with continuous forms and delicately intricate geometries.

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