**Ouvrage: What's the Matter?** Materiality and Materialism at the Age of Computation

CHAPITRE

# Additive Manufacturing for the Development of an Assembling System for Gridshells

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The invention of the computer and of the numerous digital technologies that followed started what is now called by some the Digital Turn [1]. Although the turn is in some ways already behind us (for example through the omnipresence of computers, cameras and various digital technologies in our lives), huge potentials still remains unexploited, and a large part of the history of digital still has to be written. In particular in architecture, the Digital Turn lies ahead of us. Whereas already deeply discussed and explored by a few architects, researchers and historians of architecture, digital technologies are not yet widely applied in most of the world's architectural production.

The Digital Turn in architecture does not only concern technical matters, but also a conceptual change. The emergence of new digital fabrication techniques has been changing the fabrication of architecture, but the emergence of computer programming has also an impact on the conception of architecture. Architecture must open to the potential of digital and bond with otherdisciplines in order to accompany the Digital Turn. The work presented in this paper has involved architects, structural engineers and material scientists, in order to explore the potentials of additive manufacturing in architecture, particularly in the production of structural assembling systems.

# Additive Manufacturing

## Rise of additive manufacturing

Since its development in the 1980s, the use of additive manufacturing has kept increasing, and it is now considered as one of the most promising production technologies. Over the past years, several additive manufacturing processes have been developed and improved: extrusion and deposition, laser sintering, photopolymerization, etc. The number of printable materials has also risen to encompass most engineering materials: metals and alloys, thermoplastic and thermosetting polymers, cement, ceramics, paper and wood, even sugar and lately carbon fiber. Additive manufacturing is now used in many fields of application: aerospace and automotive industries, medical engineering, design, architecture, producing objects as diverse as motors, personalized smartphone cases, furniture, moulds, plaster casts, clothing, jewellery, and now buildings… To illustrate the current state of possibilities and applications of additive manufacturing, two examples can be detailed.

## Everyday Additive Manufacturing

One of the most widespread additive manufacturing processes is the extrusion and deposition of a molten material, in a large majority of cases thermoplastic polymers. The material is deposed in layers, and the accumulation of solidified material eventually forms the designed object. This technique has been used to develop affordable, easily usable 3D printers for everyday use, such as the famous Makerbot Replicator [2] machine. Given the price range of these printers (US$500 to US$2000 depending on the level of pre-assembling of the machine's parts), it is available to many people wishing to use additive manufacturing at home, in order to produce various everyday objects. Most of the time, files for these objects are found on the Internet, and therefore this kind of *everyday additive manufacturing* does not necessarily involve any form of creativity or innovation. It is used to produce mass customisation objects, such as smartphone cases, small items to repair other home objects, or toys, jewellery or other small everyday objects.

## Industrial Additive manufacturing

The second example, that can be deepened further in order to highlight the current state of additive manufacturing, is the case of selective laser sintering and/or melting of granular materials, which has been thoroughly developed for aerospace applications with specific powder metal alloys. Just like in the case of extrusion and deposition and other additive manufacturing techniques, the accumulation of solidified material eventually forms the object. The machines required by such process are much more advanced and expensive printers, and the applications are mostly reserved to industrial additive manufacturing. It is used for academic and industrial research and production in fields such as aerospace or automotive industries, mainly for prototyping, but more and more for production of items such as engine parts or moulds for foundry.

## A potential intermediary

This duality in application leads on the one hand to mediocre materials and printers producing mostly basic and non-challenging objects, mainly dedicated to mass customization, and on the other hand, to top-of-the-range printers and tailored materials producing expensive items in response to particular industrial problems. An intermediary between those two ways of using additive manufacturing could exist, it might be possible to use the average printers and materials usually reserved to mass customization to produce viable solutions for some research or industrial problems. In particular, that might be potential architectural applications for this kind of additive manufacturing. Despite the massive research conducted in order to increase the size of 3D printers, resulting in objects being the size of a building, most available printers still produce small or object scale items. This paradox of small 3D printing versus large architectural scale might be overcome by considering structural assembly. As a matter of fact, many types of architecture rely on structural part assembly, and this is one of the applications where the intermediary, architectural potential of additive manufacturing resides. While making an inventory of existing structures such as nexorades [3], gridshells [4] and geodesic domes [5], it appeared to us that gridshells could be an ideal case study, given the issues still remaining when building such structures, especially regarding the particular case of structural parts connections.

## Gridshells: Definition and Specifications

### Historical overview

The first gridshell was built by Frei Otto, a german architect and structural engineer, in 1975 in Mannheim, Germany [6], with the help of the Arup engineering team (Fig. 1). Frei Otto was looking for a way to build a large span, light structure, and he conceived the double curved wooden grid structures, shown in Fig. 1. The first built example is the Mannheim Multihalle gridshell, initially a pavilion for the horticultural show held that year in the city.

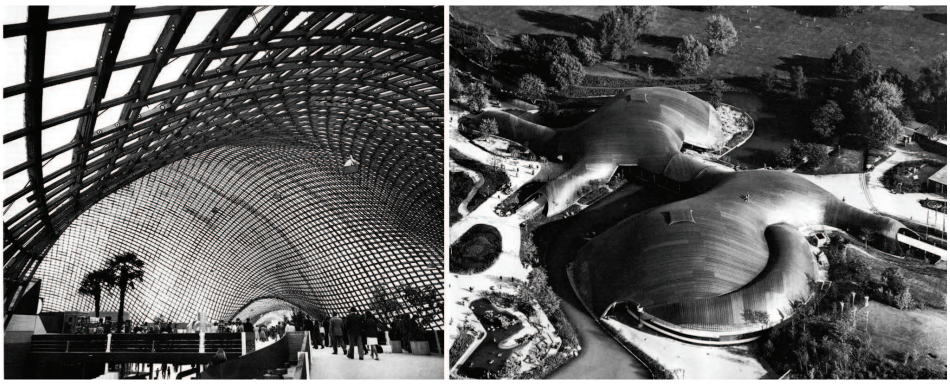


Fig. 1
Mannheim Gridshell.

Only a few other examples of built gridshells exist in the world, such as the Japan Pavilion at the Hannover Exhibition in 2000, by Shigeru Ban [7], and the Weald and Downland Museum gridshell, in 2002, by Edward Cullinan Architects [8], both with the help of Buro Happold structural engineering team. Except for a particular family of metallic grids which is not considered in this paper, the first gridshells were built with a grid consisting of wooden laths, but recent gridshells built by the Navier laboratory experimented the possibility of using composite glass fibre reinforced polymer (GFRP) tubes for the structure, such as the Creteil and the Solidays gridshells [9,10]. Despite the progress made in the knowledge we have of gridshells and in our process of construction of these structures during the building of these few examples, several issues remain in the conception and construction of gridshells, particularly regarding their connections.

## Characteristics

Gridshells' most spectacular characteristic lies in their shaping process. As it can be seen in Fig. 2, the grid is assembled flat by joining two perpendicular layers of laths and then deformed step-by-step unto its definitive position by raising the grid and bringing its borders to their place on the ground. The grid can either be assembled flat

Fig. 2
Shaping process.

on the ground and lifted, as it was made for most gridshells, or assembled flat on top of a scaffolding with its borders lowered, as it was made for the Weald and Downland Museum gridshell [7]. In some cases, the gridshell is made of four layers of laths instead of two, for structural improvement and for a better control of the final shape: it is a quite difficult process to master the deformation in order to bring the grid to its definitive form. Once in place, the structure is triangulated either by a third, or fifth, direction of laths, or by cables. Sometimes the triangulation is provided by the covering of the structure, in this case made of plates, as for the Weald and Downland Museum gridshell. In other cases, the cover is made of a tensile membrane and the triangulation has to be provided by one of other aforementioned solutions, as for the Mannheim gridshell. Initially, gridshell shapes stem from dynamic relaxation [11], a method used to find surfaces with a geometry such that all forces are at a state of equilibrium. Given this property, these are ideal shapes in term of stress and load transmission, but it confines gridshells to particular shapes depending on this form-finding method. In the last years, several form-finding methods have been developed, so that now almost every shape can be approximated and studied to be turned into a gridshell: these structures have now the same freedom in terms of shape than any other. Once the desired surface obtained through one of the now various existing form-finding methods, it has to be meshed, in order to obtain the grid that will form the structure. The usual and basic method is the so-called compass method, proposed by Frei Otto [12]. As it can be seen in Fig. 3, the shape is made of two main curves along the surface, crossing each other in one point, and a series of circles at each intersection between the curves and the circles. A net of points, corresponding to the intersections of the gridshell laths grid is therefore obtained.

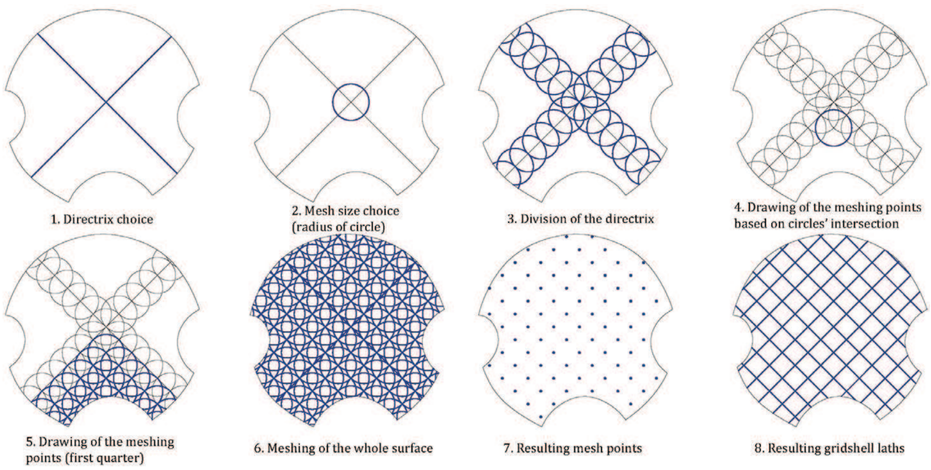



Fig. 3
Compass method.

## Specifications

The strength of the structure, and therefore the possibility to have very large spans, comes from the doubly-curved shape. As their name indicates, gridshells are wooden grids behaving like shells, with stress distributed on the whole structure. Therefore, we have a good knowledge of the structural behaviour of the global structure of a gridshell. However, uncertainty remains regarding the mechanics of gridshells: the exact determination of the stress state exerted on each node remains challenging, first during the deformation of the grid, and then during the life of the structure. Nevertheless, a conservative worst-case-scenario estimate of the stress state within the nodes can be given, thus yielding mechanical specifications to be respected when design of an assembling system. We also established a list of required geometrical specifications for a gridshell node to be fully functional. In order to achieve the peculiar installation of a gridshell structure, the nodes connecting the two layers of laths must allow them some movements; some degrees of freedom must be free, whereas some other must be prescribed to prevent unwanted displacements. First, the node position, along the two laths it connects, must not vary (Fig. 4). The deformation of the grid would not take place properly with such translations. Furthermore, the form of the grid being pre-defined, it would change it if the laths were not well fastened together, and the final shape of the structure would be impossible to obtain. Secondly, while the node cannot translate along the lath, it must be able to rotate around it, in order to allow the necessary movement freedom for the grid deformation. Thirdly, for the same reason, both laths must be able to rotate around the node axis.

Finally, as mentioned earlier, since gridshells can be made of 2, 3, 4 or 5 (or even more) layers of laths, various types of triangulations and covers can be thought of. The ideal connection would take these elements into account, and its geometry should allow an easier implementation and adaptation of the assembling system. The connection mechanism and function should also be reversible, so that gridshells could be assembled and disassembled.

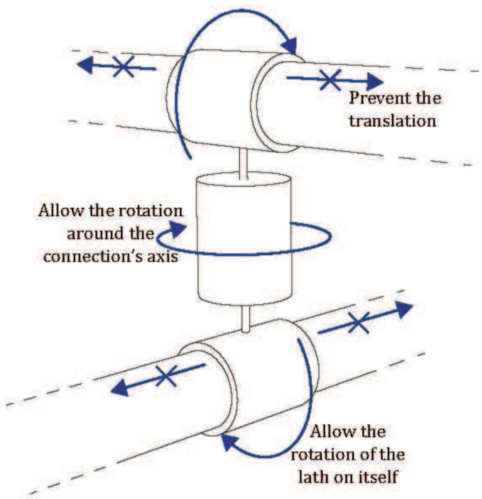



Fig. 4
Geometrical specifications.

## Connections

The connections in various examples gridshells considered so far are all different (Fig. 5). The Mannheim gridshell node is made of a metal part piercing through the wood layers and maintaining them together. The main problem of this connection is that by removing matter in order to place the node, it weakens the structure at its most loaded locations: intersections. In Hannover, the connection is as peculiar as the gridshell: the structure is made of cardboard, temporary connections were used during the shaping process of the structure and then replaced by nodes made of adhesive rope. For the Weald and Downland Museum, the node is made of metal platforms placed between each lath layer and fastened together by bolt and screws. Although allowing the grid-shell to be shaped, the geometrical specifications are obtained in a very approximate way. The Creteil and Solidays gridshells build by the Navier Laboratory use a different

Fig. 5

Previous connections.

material for the laths, which therefore changed shape: initially wooden rectangular struts, the laths are in this case GFRP round tubes. This change in strut section geometry allowed the use of a particular object as connection: steel scaffolding elements. These are made of two openable rings with a circular junction enabling the rotation of the two tubes around the axis of the node. Although this connection is much closer to the geometrical requirements than the others, it still exhibits drawbacks that could be overcome with a 3D printed connection. The geometrical requirements are not perfectly met, and could therefore be improved by designing a new, tailored geometry rather than using an object initially designed for another purpose.

Additive manufacturing is making any geometry possible, even enabling to produce objects unbuildable with any other technology, such as a ball in a closed hollow sphere. The secondary requirements mentioned earlier (adding laths layers, fixing the triangulation and the cover) are not taken into account by the scaffolding element, and by designing a new node, one could anticipate these steps in order to ease the implementation and speed up the process. Optimized solutions for each aspect of the node can be conceived, prototyped and implemented with additive manufacturing in order to improve the gridshell assembling system. Last but not least, the scaffolding elements are extremely heavy when compared to the weight of the lath structure. Each of these connections weights about 1 kg, which represents up to 2/3 of the total weight of the structure. A change of material and a new design could solve this issue and considerably relieve the structure. Gridshells seem like a challenging case study: specific problems still remain unsolved regarding their connections, and yet these problems could be solved by considering the geometric possibilities offered even by, even low-cost, additive manufacturing, possibilities offered by no other technologies until now and the characteristics of the materials usually shaped by this kind of printers.

## Material Choice and Manufacturing Process

### Material selection approach

This leads us to the second part of this study: which material would be relevant for the gridshell assembling system? The previous connections, as explained, were made of steel. As a material, steel exhibits high performances, as shown by its very common application in every field of production, especially when considering structural connections. But as said, a particular manufacturing process was chosen, dictating us a pre-selection of materials, and steel was not a part of this pre-selection. Steel was therefore not an option. Moreover, some of the problems raised by the steel connection could be resolved by changing the material, in particular with regards to its weight. The geometrical requirements of the structure could easily be solved by the use of additive manufacturing. Although steel is one of the most efficient materials available, it is relatively expensive to manufacture this way.

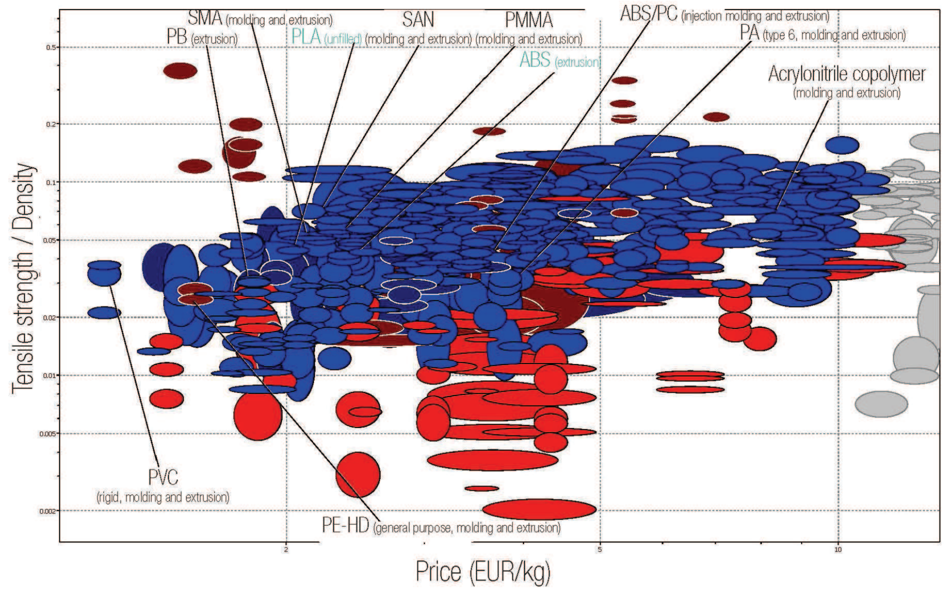



Fig. 6

Material selection diagram.

A first selection had been made by the choice of the manufacturing process, but a large range of available materials still remained. By applying a materials selection approach [12] to the materials which can be processed through 3D printing, the most adequate materials were short-listed. This first materials performance map, shown on Fig. 6, corresponds to thermoplastic polymers spread according to their Young modulus (Y-axis, in GPa) versusspecific price (X-axis, in US$.kg$^{-1}$).

From this map, several materials are selected because of their good performance and are gathered in Table 1. Comparison is made for their supposed price, real market price, and their initial avaliable shape. Polylactic Acid (PLA) and Acrylonitrile Butadiene Styrene (ABS) both stand out, most notably because of their availability as strand, the shape needed for common 3D printers, meaning there is no need to reshape the feedstock before printing products: it saves money by reducing the production time.

Table 1

Materials comparison.

| Material | Supposed price | Tensile strength | Density | Glass transition temperature | Usual shape | Real market price |
|---|---|---|---|---|---|---|
| ABS | 2.30 - 2.50 €/Kg | 30 - 50 MPa | 1.02 - 1.08 10^3 kg/m3 | 88 - 120 °C | Strand | 18 - 30 €/Kg |
| ABS-PC | 3.40 - 3.80 €/Kg | 40 - 51 MPa | 1.07 - 1.15 10^3 kg/m3 | 137 - 145 °C | Sheet | |
| A/MA/B (Acrylonitrile copolymer) | 6.80 - 8.40 €/Kg | 78 - 86 MPa | 1.14 - 1.16 10^3 kg/m3 | 80 - 100 °C | Granules | - |
| PA | 3.60 - 4.00 €/Kg | 33 - 40.2 MPa | 1.13 - 1.15 10^3 kg/m3 | 44 - 56 °C | Strand | 25 - 30 €/Kg |
| PB | 1.80 - 1.90 €/Kg | 26.2 - 30.3 MPa | 910 - 925 kg/m3 | -38 - -24 °C | - | - |
| PE-HD | 1.40 - 1.60 €/Kg | 22.1 - 31 MPa | 952 - 965 kg/m3 | -125 - -90 °C | - | - |
| PMMA | 2.20 - 2.40 €/Kg | 48.3 - 72.4 MPa | 1.17 - 1.2 10^3 kg/m3 | 100 - 110 °C | Sheet | 5,5 €/Kg |
| PLA | 1.80 - 2.10 €/Kg | 48 - 60 MPa | 1.21 - 1.25 10^3 kg/m3 | 56 - 58 °C | Strand | 18 - 30 €/Kg |
| PVC | 1.10 - 1.20 €/Kg | 41.4 - 52.7 MPa | 1.3 - 1.49 10^3 kg/m3 | 80 - 88 °C | Sheet | 7,5 €/Kg |
| SMA | 2.10 - 2.30 €/Kg | 53.2 - 58.6 MPa | 1.05 - 1.08 10^3 kg/m3 | 106 - 122 °C | - | - |
| SAN | 2.00 - 2.20 €/Kg | 69 - 82.1 MPa | 1.06 - 1.08 10^3 kg/m3 | 102 - 110 °C | - | - |

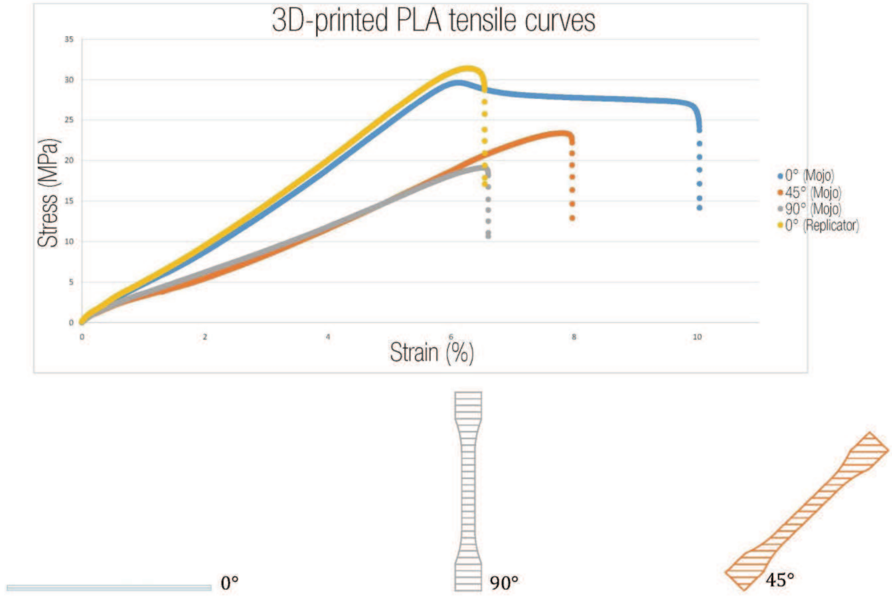



Fig. 7
Orientation of the layers and tensile test characterization.

## Performance tests

The typical performance of both ABS and PLA suit our needs for the structure nodes. However, ABS and PLA test specimens are usually not manufactured by 3D printing. Hence, mechanical characterization of 3D printed samples was conducted in order to compare their performance to, typically injected, ABS and PLA specimens. The orientation of the layer construction is also of prime importance, as depicted on Fig. 7, showing the tensile behaviour of 3D printed samples for 3 different orientations: 0°, 45° and 90°.

These results show that the best orientation for the layers is 0°, meaning that a node produced with such a machine should be optimized to be printed with the layer construction direction oriented along the direction of maximum stress. Fig. 7 compares also the mechanical performance of the same sample (same orientation, same material), but printed with two different machines: a Makerbot Replicator and a Stratasys Mojo [13]. The most remarkable feature in these results is the presence of ductility for the Mojo specimen, i.e. irreversible plastic deformation, as expected from a thermoplastic polymer sample, whereas it vanishes for the Replicator-printed specimen. Those tests give an idea of the performances of PLA when shaped by a 3D printer as well as an insight on the inherent variability of material properties depending on the printer considered. When compared with the design requirements for the assembling system/gridshell connection, both 3D printed ABS and PLA are appropriate, whether shaped by a mid-range or low-cost 3D printer, respectively the Mojo and the Replicator printers. This capacity, along with the geometrical possibilities offered by additive manufacturing makes this technology very promising for solving problems posed by gridshell assembling.

## Designing the Assembling System

### A node divided in parts

In the second part of this paper, several geometrical specifications for gridshells, that need to be respected while conceiving a node, were presented. In order to properly inspect each geometrical problem and find a solution to it, they were separated, as well as the parts of the connection responsible for each specification. Several intuitive potential solutions were investigated. Although this work is still in progress, some of these solutions are currently being tested. Designing the node that way, in several parts, allowed us to solve, or partly solve several problems from the beginning. The idea was to conceive a half-node, locked around one lath and connectable to other half-nodes. One could therefore stack them easily, and use the assembling system for as many lath layers as wanted. The triangulation and cover fixation could also be solved, by adding one last piece on top of the stacked half-nodes, a different part that would allow the necessary fixations of the cover and triangulation in a better way that what was previously proposed, avoiding the wear and possible failure of the cover because of the nodes rubbing against it.

### First requirement:
### No translation

The first requirement, as explain in the second part of the paper, was to prevent the translation of the node along the lath, as well as to allow its rotation around it. In order to achieve this, two different systems were considered, either internal, or external. The external one would consist of two rings, fixed on each side of the node around the lath and preventing it to glide. We explored several options for the material these stop rings could be made of, retaining two solutions: steel or heat-shrinkable sheath (the same as the one used for cables). The node itself, trapped between the stop rings, would be free to rotate and to translate, but kept from gliding by the rings. This solution has already been tested on the Navier laboratory gridshells, with metallic rings and has proved itself efficient. But it is an additional step in the implementation of the node that could be avoided by the invention of an internal system. This system could for example consist of a double ring, with a bearing system in-between. The first ring is fixed to the lath in a way preventing it from moving, whether by rotating or translating. The second ring is free of rotating around the first, but is kept from translating by the bearing system. This solution would be quicker to implement, but more complex and longer to design and using more material, therefore more expensive; and a question still remains: how to guarantee the adhesion of the first ring to the lath.

## Second requirement: Junction of the parts

The second issue in the designing of the node was the junction of the node parts (two or more, as explained). Three different solutions were considered, all based on the same plug system: each half-node would possess a male and a female part, and could be plugged to two other half-nodes, making the stacking of elements and the accumulation of lath layers possible. For a good answer to the stress, the junction had to be as short and large as possible. It also had to allow the rotation of both laths. The first plug was a plug to clip, with a gap allowing it to shrink and then to expand. The other part of the plug was first slim and then larger. When implemented, the shrinking and then expanding of the plug would allow it to be clipped inside the other part and then locked in it. Despite a very easy implementation, this plug was the longest junction of the three and the chosen material's stiffness made the allowance to shrink more difficult to obtain. The second plug was made of several side wings and the host to this plug was designed to match the side wings, organised in a particular way: it could only be plugged or separated in one position, and in case of a sufficient rotation to place each wing in front of an exit, the organisation of the wings would keep it from falling apart. But despite this technique, if the plug rotated enough to be in a dangerous position, only the hooks would be supporting the stress, and the plug could break much more easily. In order to know which angle between the wings and therefore which number of wings would be the less dangerous and the most efficient, the angles formed by the laths of two of the Navier laboratory gridshell were studied. As shown in Fig. 8, three wings seemed to be the safest solution for this kind of plug, but it is still a fragile option. The third junction considered to link the different parts of the node was made of a bolt and screw system. To make the rotation of the laths possible, the two parts would not entirely be screwed together: the pressure of the laths would make the junction a little further screwed or a little unscrewed, therefore authorising this necessary movement. Although tests are necessary to make sure it would work even in torsion, and although it is a little longer to implement, this system is still easy to put in place and the variants possible in the screw thread would allow several improvements: a solid enough screw thread to support the stress without breaking, a shorter junction.

## Third requirement: Implementation and fastening of the nodes

The last question addressed in this work is about how the half-node would be placed on the laths, and then maintained. In the previous connection, it was necessary to use a bolt and screw system, to fix the node to a given position on the lath and force it to stay

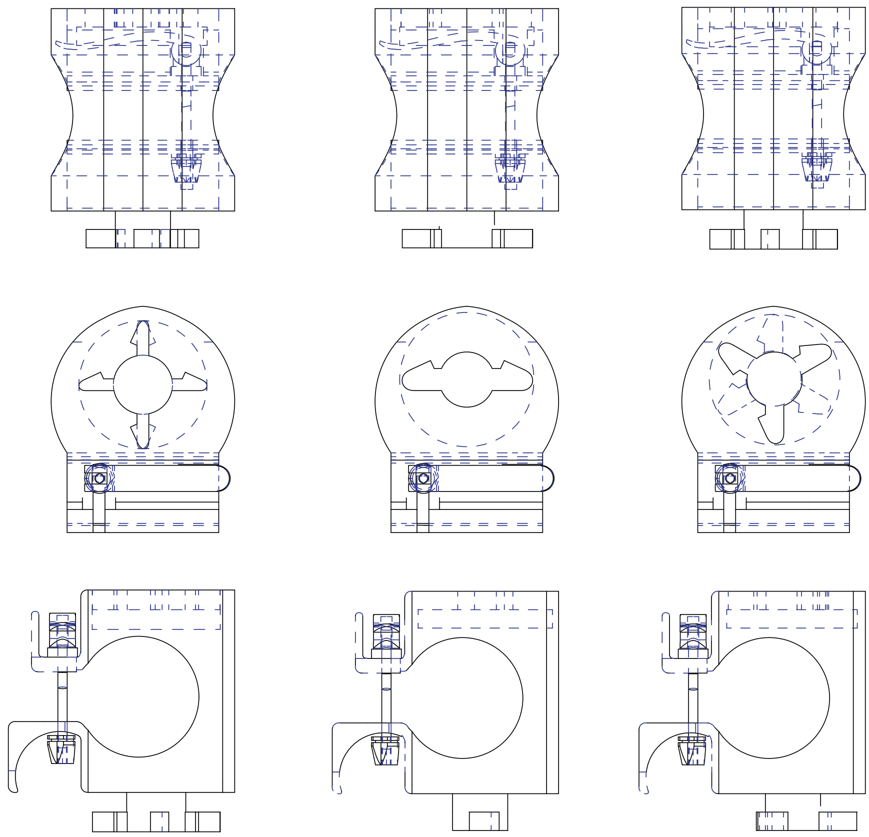


Fig. 8
Junction of the parts: side wings solutions.

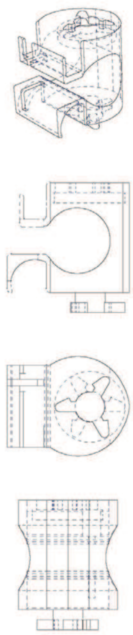
in place. It had the disadvantage of damaging the laths if not protected, and to be rather empiric: a compromise between fixing the node in position well enough to keep it from sliding and avoid crashing the lath by doing so had to be found for each junction. In this study, one goal of the node was to guarantee the set position of the node without having to squeeze it on the lath, so that is would not need a bolt and screw system. The node could be placed on the lath by clipping it on it, and then fastened with a simple closing system, inspired by a bike saddle fixing system for example. We could either design a connection with a closing system already part of it, a simple one that would only need to be clipped during the implementation of the node, or design a connection with a host for an external closing element, such as a bike saddle fixing or a zip-tie.

## Further research

The multiple solutions considered in this work for the assembling system are gathered in Table 2 for comparison, in order to determine if one of them really stand out and if

Table 2
Assembling system solutions.

| ENVISAGED SOLUTION | ADVANTAGES | DRAWBACK |
|---|---|---|
| BLOCK RINGS | Less material use, less expensive, already tested and efficient solution, possibility to put in place before bringing to the work site | Longer to put in place, two different pieces for the connection |
| BEARING SYSTEM | Possibility to put in place before bringing to the work site, quick and easy to put in place | Complex and longer to elaborate, more material use, more expensive, problem of adhesion between rings and lath |
| WINGS LOCK | Quick and easy to put in place, reversibility | Low resilience |
| SCREW JUNCTION | Quick and easy to put in place, strong junction system | More material use, more expensive, problem of reaction to torsion load |
| CLIP LOCK | Quick and easy to put in place | Low resilience, complex reversibility, size of the crack |
| CLIP FASTENING | Quick and easy to put in place | Low resilience, complex reversibility |
| BIKE FASTENING | Easy to manipulate, resilient system | Longer to put in place, two different pieces , origin of the fastening |



some of them fitted better together than others. The next step will consist in producing several node prototypes resulting of several combinations, testing and comparing some of the solutions proposed here. Finally, the assembling system will have to be implemented on an actual 1:1 scale gridshell structure.

## Conclusion

This project results from the collaboration of architects, structural and material scientists. It consists in a multidisciplinary, collective design method, based on the deep relations between material selection, process selection, as well as geometrical and mechanical requirements. Our contribution illustrates the very promising possibilities of 3D printing as a means to solve various issues and innovate in architecture, structural engineering and materials science.

This potential raises the question of the role additive manufacturing already has today, and of the role it will have in the next years. Since its appearance, this technology has been presented as a key item to a new industrial revolution, and the many breakthroughs in the materials or processes used and in the first applications found for additive manufacturing seem to guarantee, even if not an industrial revolution, a leading role for additive manufacturing in prototyping and production processes at every scale of fabrication. Along with the potentials of this manufacturing process left to explore and the applications left to invent are also issues to be solved, such as finding a cleaner, more respectful to the environment, way of printing.

**References**


1. Carpo, M et al. 2013, *The Digital Turn in Architecture 1992-2012*, John Wiley & Sons.
2. Lipson, H & Kurman, M 2013, *Fabricated: the New World of 3D Printing,* John Wiley & Sons.
3. Baverel, O & Nooshin, H 2007, 'Nexorades Based on Regular Polyhedra', *Nexus Network Journal*, 09/2007, Vol. 9(2), pp. 281-298.
4. Hennicke, J, Matsushita, K, Otto, F et al. 1974, *Gitterschalen Grid shells,* Institut für Leichte Flächentragwerke (IL).
5. Popko, E 1968, *Geodesics*, University of Detroit Press.
6. Happold, E & Lidell, WI 1975, 'Timber lattice roof for the Mannheim Bundesgartenschau', *The structural engineer*, Vol 53, pp. 99-135.
7. Miyake, R & Luna, I 2009, *Shigeru Ban: Paper in Architecture*, Rizzoli.
8. Harris, R, Rohmer, J, Kelly, O & Johnson, S 2003, 'Design and construction of the Downland-Gridshell', *Building Research & Information*, Vol 31(6), pp.4 27-454.
9. Douthe, C, Caron, JF & Baverel, O 2010, 'Gridshell structures in glass fibre reinforced polymers', *Construction and Building Materials*, Volume 24, Issue 9, pp. 1580-1589.
10. Douthe, C, Baverel, O & Caron, JF 2007, 'Gridshell in composite materials: Towards wide span shelters', *Journal of the International Association for Shell and Spatial Structures*, 48, pp. 175-180.
11. Day, AS 1965, 'An introduction to dynamic relaxation', *The engineer*, Vol. 29, pp. 218-221.
12. Hennicke, J, Matsushita, K, Otto, F et al. 1974, 'Gitterschalen Grid shells', *Institut für Leichte Flächentragwerke* (IL).
13. Ashby, M 2010, *Material selection in mechanical design*, Butterworth-Heinemann, 4th edition.