

The droxel: A universal parametric construction component

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ABSTRACT

Recent disruptive advancements in the fields of robotics, advanced manufacturing and parametric design will transform the construction industry in the next decades. In this article, we take advantage of the possibilities offered by these technologies to develop a new family of universal construction components that we called "droxels". They bring together many characteristics that make them suitable for both robotic operations and traditional construction: they make it possible to materialize any 3D surface or volume with good structural stability, they allow an easy interlocking with a large laying tolerance, and they avoid scaffolding thanks to carefully chosen intermediate construction phases. Possible materials are polymers, timber, and concrete. In particular, polymers allow filling the droxels with water, or insulation, or sand, or recycled ballast. However, droxels have a complex geometry defined by eight parameters. The aim of this paper is to perform a comprehensive sensitivity analysis to characterize the influence of each of them on the characteristics of droxels and droxel-based engineering structures, such as the quality of interlocking or the feasibility of cantilevers. The methodology consists of an analytical and geometrical approach based on parametric design tools developed in Grasshopper. Finally, the results of the parametric study confirm that droxels can be used for many practical applications and a synthesis is given in order to guide the designer in the choice of the geometrical parameters, according to the characteristics of the structure and the construction process.

1. Introduction

As a result of the rapid evolution of robotics and electronic engineering fields, the way we build will fundamentally change in the next decades: robotic arms [1] and manipulators [2], 3D printers [3,4], exoskeletons [5], coordinated automated vehicles [6], Computerized Numerical Control machines (CNC) [7] and autonomous robots [8,9] will allow builders to develop new construction components and new construction processes. Automation opens new opportunities for the construction sector, in particular for structures with complex architectural features, which often require unreasonable time and cost when executed by traditional means. Regarding the construction components themselves, 3D printing, CNC machines, injection molding and robotic manufacturing now allow to create complex shapes in concrete [10], timber [11] or other polymeric materials [12] that were simply impossible to manufacture just a decade ago.

This paper will present a recently developed universal masonry block that can materialize complex shapes and structural forms without the

need of scaffolding and supports: the droxel. Masonry systems can be classified according to the utilized construction processes:

- With mortar: the joints are usually around one centimeter thick, which allows blocks with rough dimensions and a good structural connection. This approach is the most widely used in construction and traditional approaches are predominant in practice, and the research in the field is mainly devoted to optimization of the bricks and their mechanical behavior [13].
- Dry stacking: blocks require smooth dimensions and their manufacturing can be complex and expensive to manufacture. A good structural connection is not always possible. Notable examples of recently developed systems are the rubberized concrete masonry [14] or the so-called Putra block [15].
- With glue/adhesive mortar: this method yields a good bond between the blocks to withstand external actions but, since the glue layer is relatively thin, geometric inaccuracies must be reduced to a minimum [16].

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Nomenclature			
A, A^*	angle of a droxel such as defined in Fig. 8, with $\tan(A^*) = 1.4142 \cdot \tan(A)$	p	vertical distance between two theoretical contact points between 2 droxels (Fig. 16)
$A_0, A_1, A_2, A_{21}, A_{22}, A_{31}, A_{32}, A_4, A_{51}, A_{52}, A_{61}, A_{62}$	surfaces defined on a droxel (Fig. 9)	q	horizontal distance related to surface A_1 (Fig. 16)
B	height of the small droxel's hook (Fig. 8)	Q	a force that can be the resulting self weight of n droxels put in a cantilever mode
C	$=\cosinus(A)$	R	height of the big droxel's hook (Fig. 8)
C^*	$=\cosinus(A^*)$	S	$=\sin(A)$
C_r	chamfer of a droxel (Fig. 8)	S^*	$=\sin(A^*)$
d	lever arm of force Q . Q can be the resulting selfweight of n droxels put in a cantilever mode (Fig. 15)	S_w	self-weight of a droxel [kg]
D_1, D_2	Droxels n°1 and n°2	S_{aw}	sawing yield, equal to the ratio between the volume of a droxel and the volume of the smallest cylinder that can contain the droxel
E	droxel's main cross' width (Fig. 8)	T	$=\tan(A)$
F	scale factor ($0 < F < 1$) that defines the dimension of the below surface of the small upper hook with respect to the dimension of the upper surface of the big upper hook, such as $F= 11-9 / 11-13 $ (Fig. 8)	T^*	$=\tan(A^*)$
F_1, F_2	reactions forces at the contact surfaces between two droxels	$T1, T2$	Transition droxels (Fig. 27)
f_1, f_2, f_3, f_4	functions depending only on dimensionless parameters $L/H, E/L, R/H$ and T	V_{cyl}	volume of the cylinder in which a droxel is inscribed (Fig. 19)
H	Height of a droxel (Fig. 8)	V_{droxel}	volume of a droxel (Fig. 18)
L	Main cross' length of a droxel (Fig. 8)	V_{rect}	see Fig. 21
L_T	Laying tolerance, that defines the ease with which a droxel can be put in place	$VLTR$	vertical load transfer ratio. Ratio between the area across which vertical loads can spread and the area across which they could spread if the volume was completely filled with material
L_x, L_y, L_z	dimensions of a parallelepipedal volume	X	equal to $0.5H \cdot T$
n	number of droxels that can be hooked to a first droxel D_1 in a cantilever mode 1A (Fig. 15)	Y	equal to $R \cdot T$
		Y_v	volume filling yield
		α, α^*	minimum possible slope of droxels in mode 1A (Fig. 25)
		β	dimensionless parameter useful to calculate A_2 and A_2
		φ	material's friction coefficient

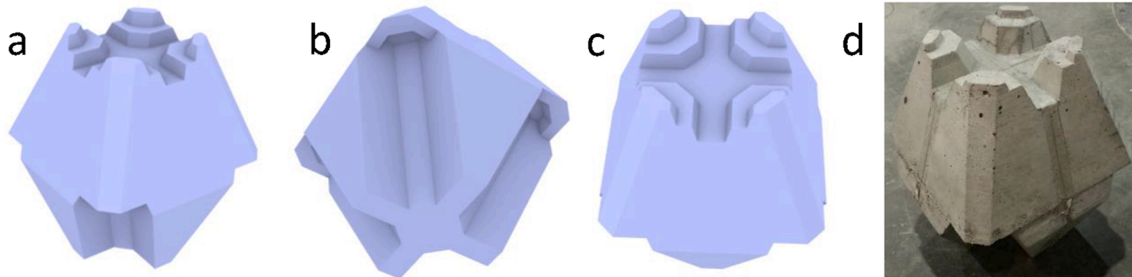


Fig. 1. The droxel, under one of its possible geometrical forms (a, b, c: 3D Rhino model, d: real concrete 15 kg droxel).

In each case, blocks can be hollow or solid, and can be filled with concrete and/or reinforcing elements (e.g., rebar or fibers), which allows for the required structural behavior.

Stackable blocks do not necessarily come from the wish of an automated construction, but rather from the development of systems compatible with fast construction from medium-to-low skilled workforce [17–19]. Researchers of the University Putra Malaysia [20] have developed dry stackable blocks, and focused on the structural global resistance, self-alignment, manufacturing and weight of the block for an easy handling. Tests were performed on small buildings. With the same objectives, K. B. Anand, E. K. Kunhanandan and K. Ramamurthy [21–23] have developed two types of interlocking blocks: the IITM SILBLOCK (solid blocks) and the IITM HILBLOCK (hollow blocks), filled with concrete and reinforcement. These blocks have the particularity of being composed, within the thickness of the wall, of two half-blocks, offset by a half level. The authors also carried out a comparative study of stackable blocks available on the market up to 2004. Other blocks such as the SPARLOCK [24] developed in Canada or the ARMO SYSTEM [25]

widely marketed in Mexico have similar interlocking features. The famous Belgian construction component STEPOC system [26] differs from the previous blocks since interlocking features don't exist for structural reasons, but only to facilitate the placement of the different blocks. The concrete and reinforcing bars allow for the structural strength and integrity. A common point between many interlocking blocks is that they have a small laying tolerance of a few millimeters only. However, a laying tolerance of several centimeters would constitute a great advantage, likely to facilitate both human work and automated processes with robots. A source of inspiration for this particular aspect is the CFRC interlocking block made of reinforced concrete with coconut fiber, developed by researchers at the University of Auckland to withstand dynamic stresses [27]. The inclined faces of these blocks allow them to return to their original position after displacements imposed by seismic events. The FCS interlocking block, marketed in the Philippines and in Thailand [28,29], is another stackable block that makes it possible to take up a laying tolerance of about one centimeter, depending on the dimensions of the block. Similarly, the Tanzanian

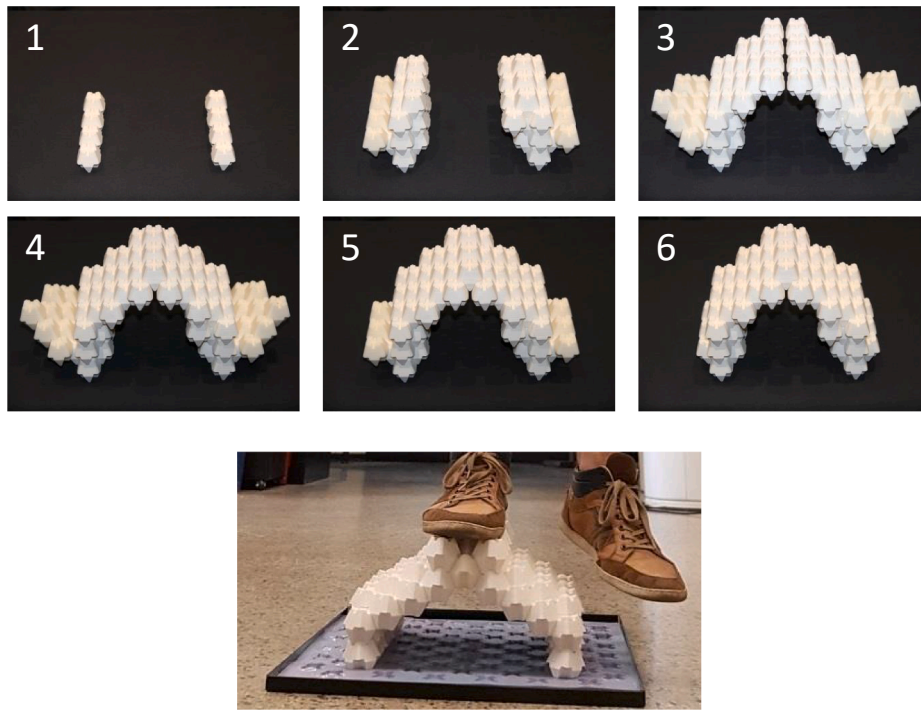


Fig. 2. The construction of an arch, with no scaffoldings.

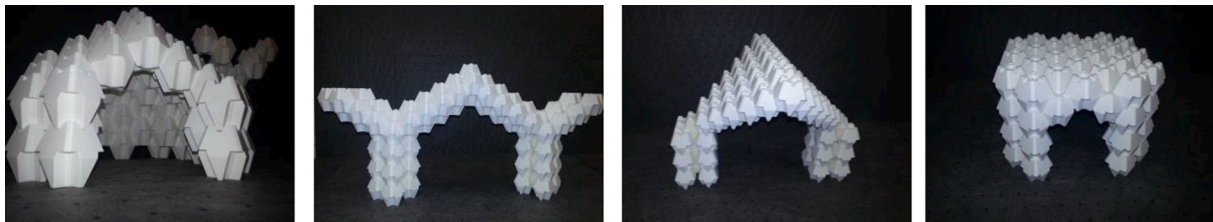


Fig. 3. A few structures composed of 3D printed droxels.

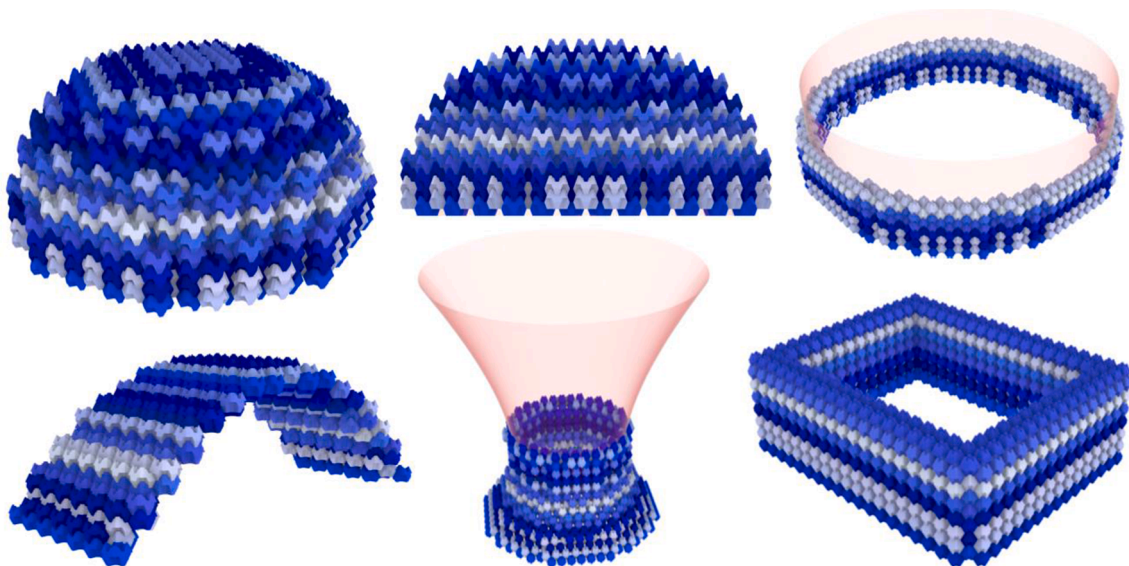


Fig. 4. Droxels allow covering a large range of structural shapes.

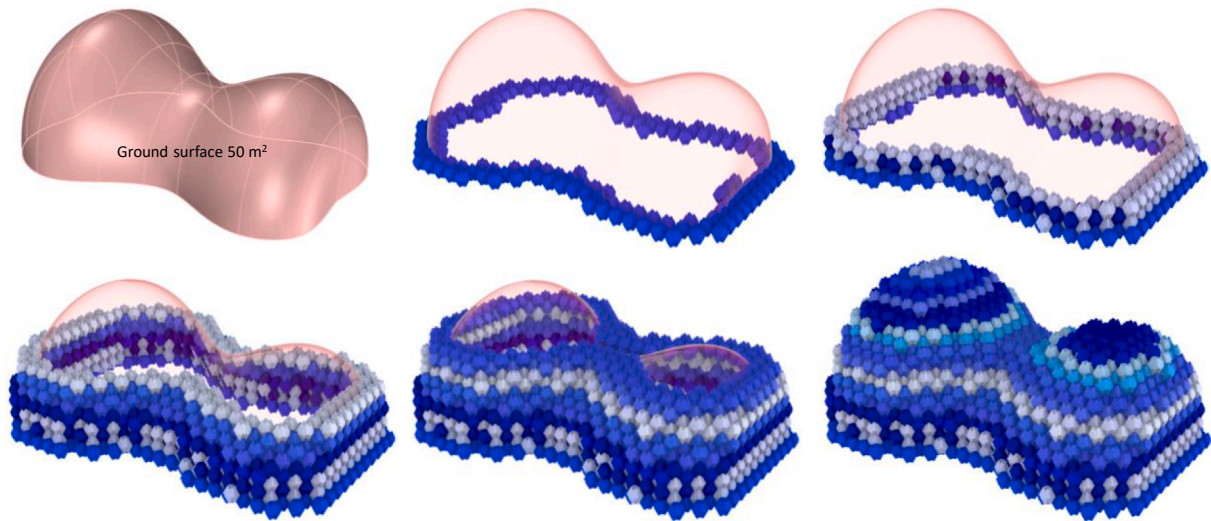


Fig. 5. The *droxelization* process for 3D surfaces.

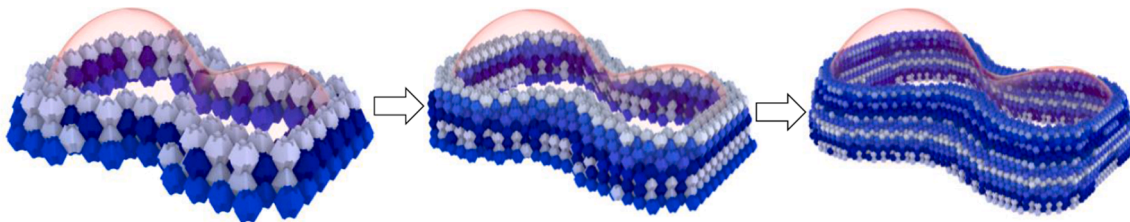


Fig. 6. The scale of the droxels can be adjusted to refine the inside and outside aspect.

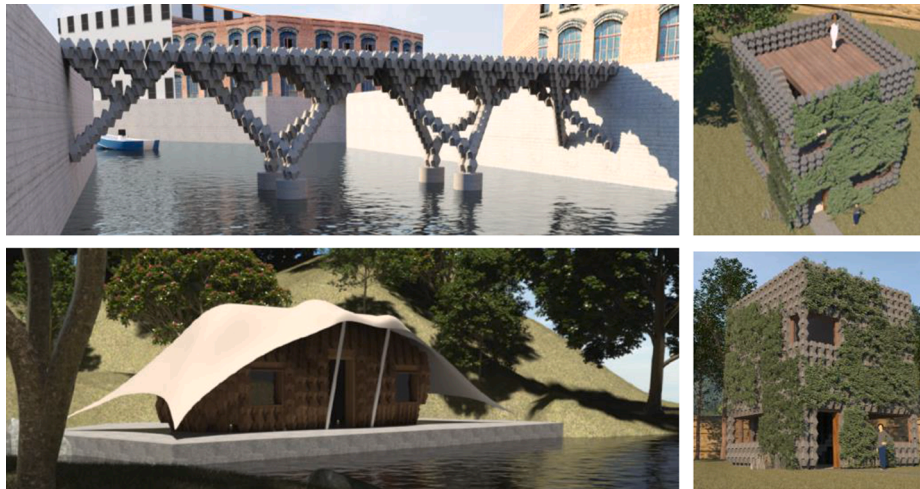


Fig. 7. Some structural and architectural possibilities that droxels offer: bridges and tiny houses. A short video about these structures can be retrieved from [39].

Interlocking Brick developed at the University of Warwick (United Kingdom) [30,31], is made of a mixture of soil and cement using a press. For retaining walls, huge stackable concrete blocks assembled by cranes are often used and produced all over the world [32]. They are equipped with devices allowing good stacking in view of the unavoidable geometrical inaccuracies related to the heavy lifting equipment used and the impossibility for the workers to guide the blocks precisely as a result of their weight. Researchers from the University of Western Australia developed many types of interlocking elements, such as the

“Osteomorphic blocks”, that allow for the construction of walls and slabs [33]. The Tetralocs, a block marketed in Australia, is an adaptation of this geometry [34].

In all the presented works, the weight of the blocks represents a critical design parameter. The two main solutions that previous works highlighted to obtain lighter blocks are: 1) use hollow elements, or 2) cast the blocks in lightweight materials (e.g., aerated concrete or argex concrete). The Ytong blocks, for example, are composed of aerated concrete with a density ranging from 400 to 600 kg/m³ and then glued

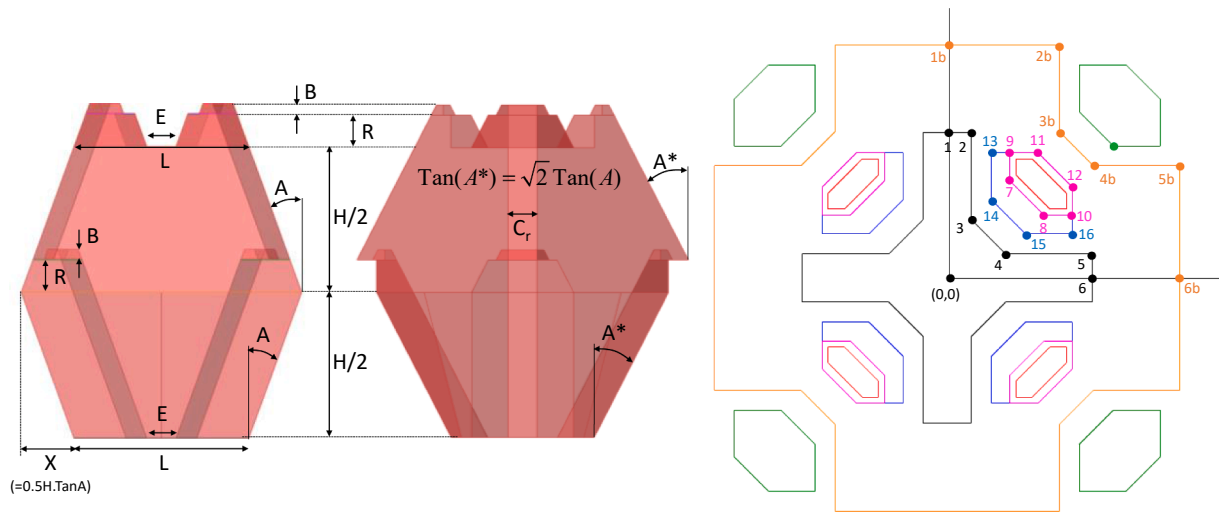


Fig. 8. The droxel's geometry depends on 8 parameters.

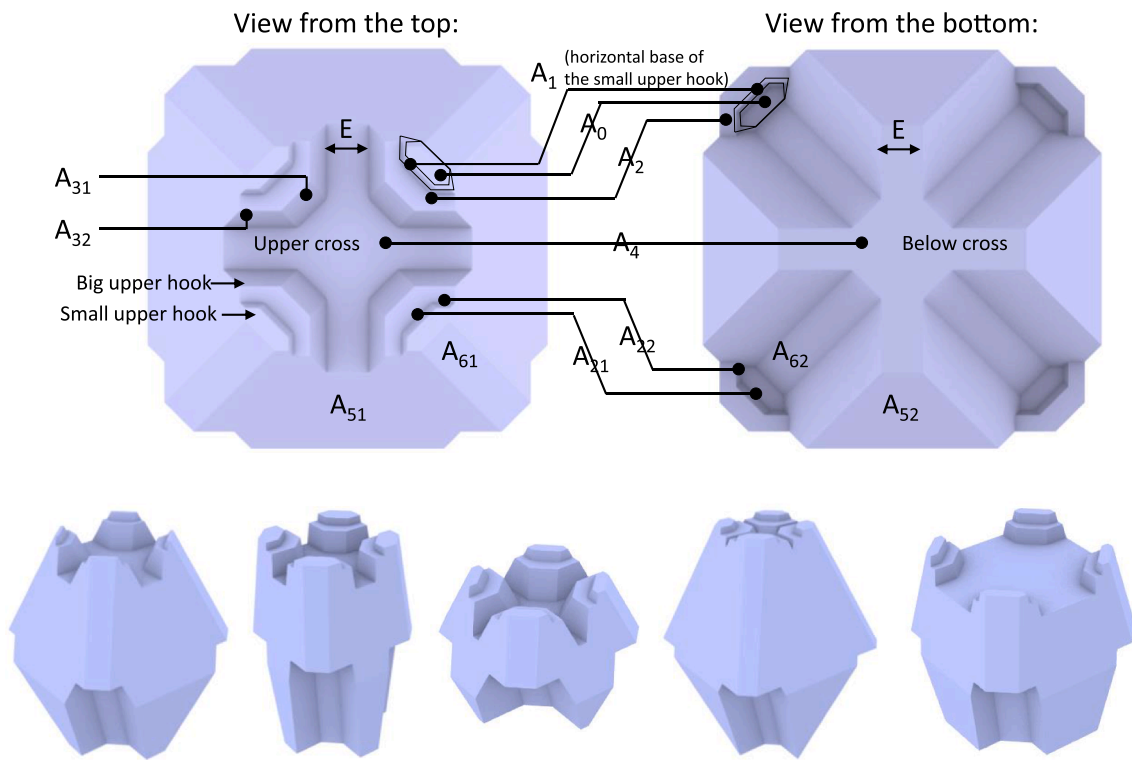


Fig. 9. Parameters L , E , C_r , A , H , R , B and F can materialize different droxel shapes.

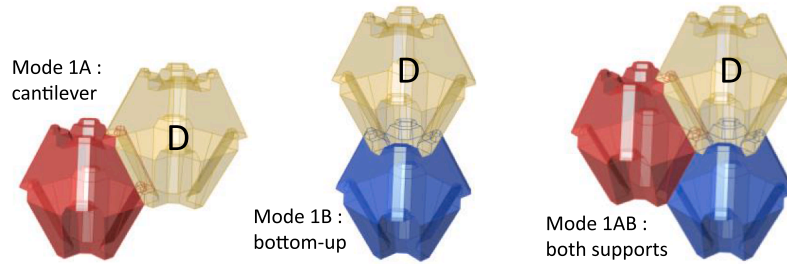
together. They also have an interlocking profile to facilitate proper alignment, allowing for a very fast building with good insulation.

Although being outside of the strict framework of construction elements, LEGO blocks [35], made of plastic, are toys that make it possible to build small walls. In order to stack two blocks, it is necessary to apply a relatively high force in relation to the weight of the block. The connection is however easy because plastic has the ability to deform a lot. As it is, this LEGO block concept is not applicable for concrete building blocks because this material has too high a modulus of elasticity, and no ductility. Examples of concrete blocks resembling LEGO exist in literature, however, the interlocking devices have been enlarged so that interlocking is still possible [32]. Novel interlocking plastic

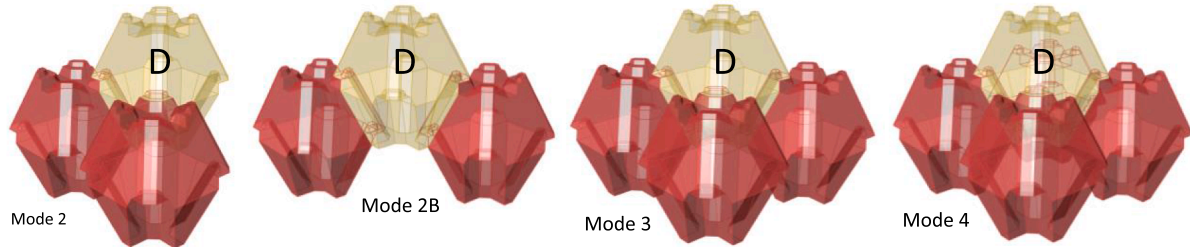
blocks were developed by architect Kengo Kuma at the Water Branch House exhibition in 2009 [36]. The plastic blocks filled with water allow for the construction of structural assemblies with spectacular shapes. These elements have the great advantage of allowing the cantilever structures without the need for intermediate support.

In this context, the work presented herein covers the multi-year development of a universal, easily stackable construction component that we called the droxel. The droxels (Fig. 1) were progressively developed during several research projects revolving around novel automated construction by means of Unmanned Aerial Vehicles (UAVs, commonly referred to as drones) [37] and robotic arms [38]. In the context of aerial operations, in fact, a very large laying tolerance is

Elementary modes 1A, 1B : droxel supported by another single droxel



Mode 2A, 2B, 3 and 4 : droxel supported by 2, 3 or 4 other droxels, in a partial cantilever mode



Modes 2AB, 2BB, 3B and 4B : combination of mode 1B with modes 2, 2B, 3 or 4

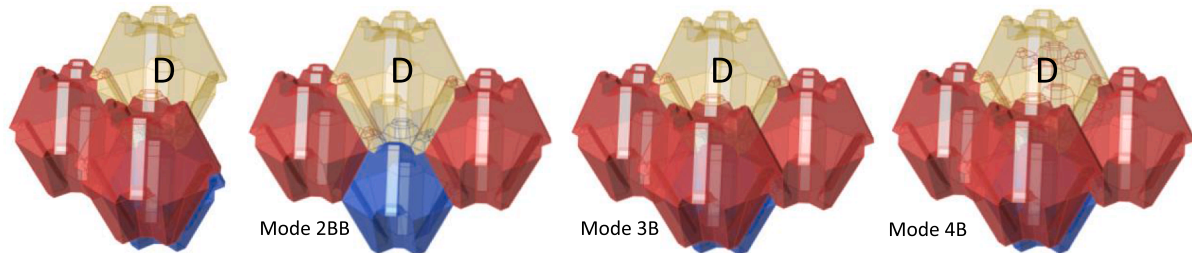


Fig. 10. A droxel D can be supported by its neighbors according to 11 different stacking modes.

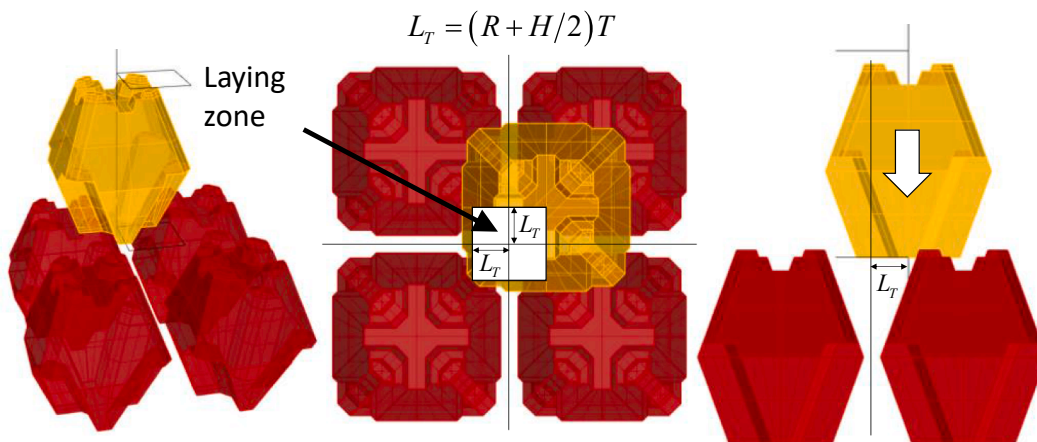


Fig. 11. Definition of the laying tolerance for stacking mode 4.

required, since several factors such as the wind and the guiding system do not always allow a perfect flight stabilization. During this research, the droxel was experimentally tested, but its geometrical and mechanical features were never studied in detail. Therefore, the aim of this article is to formally define the geometrical and mechanical features of droxel structures. The name *droxel* comes from the words drone and voxel, where *voxel* designates a three-dimensional pixel. The words

“*droxelize*” or “*droxelization*” are used herein to refer to the faithful reproduction of any given structural form, using *droxels* of given form and size.

The successive steps that lead to the definition of the geometry of a droxel are described in our previous works [37]. In brief, the droxel is a stackable block that has progressively evolved from the elementary cell of a bees' nest to a more complex geometry, such that it allows for the

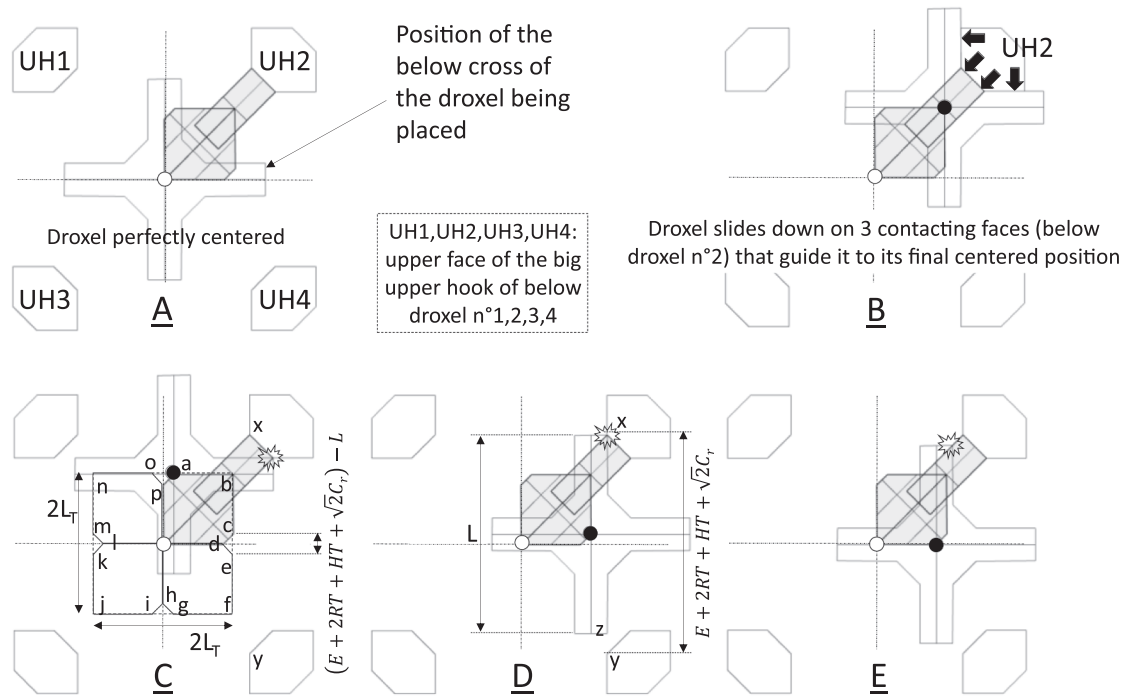


Fig. 12. Different possible situations when a droxel is placed between four other droxels (stacking mode 4). It is assumed that the bottom cross of the droxel is situated in the horizontal plane at level $H + R$ above the four below droxels' crosses.

Table 1

Laying zone for each mode (in grey).

Laying zone for each mode With $L_T = (R + H/2)T$			
1A	1B	1AB	
	Almost null		
2A/2AB	2B/2BB	3/3B	4/4B

droxelization of any 3D shape with the following salient characteristics [39]:

- A good laying tolerance in every direction.
 - The possibility of creating openings thanks to vault effects.
 - The possibility of creating perpendicular walls.
 - Interlocking features, in order to ensure a structural link between the droxels and the global stability and resistance of the whole structure.
- Fig. 2 shows an arch composed of 3D printed small-scale droxels, that withstands the weight of a person.
- No sharp angles, in order to allow the use of molded materials and formwork.
 - The possibility of creating cantilever structures without the need for scaffoldings.

The shape of the droxels is characterized by eight geometrical parameters that will be described in the remainder of the paper, and that

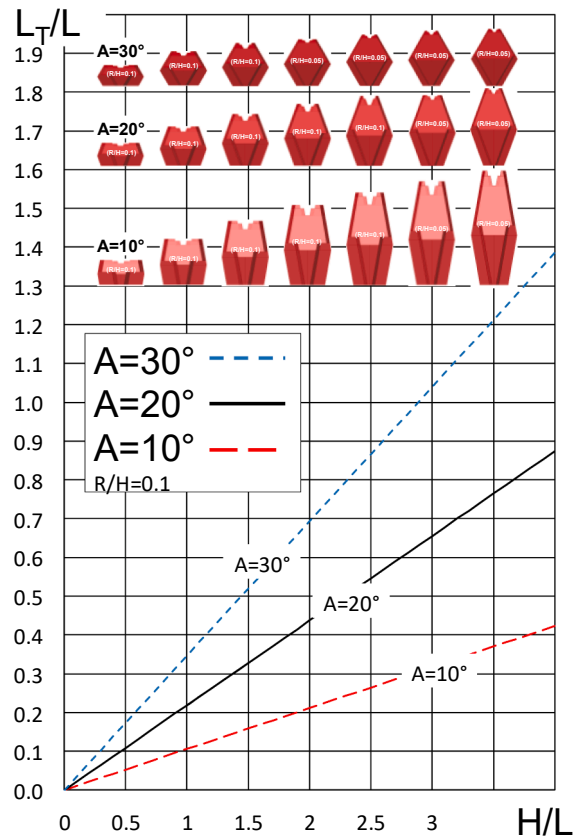


Fig. 13. Values of the laying tolerance $L_T/L = H/L(R/H + 0.5)T$.

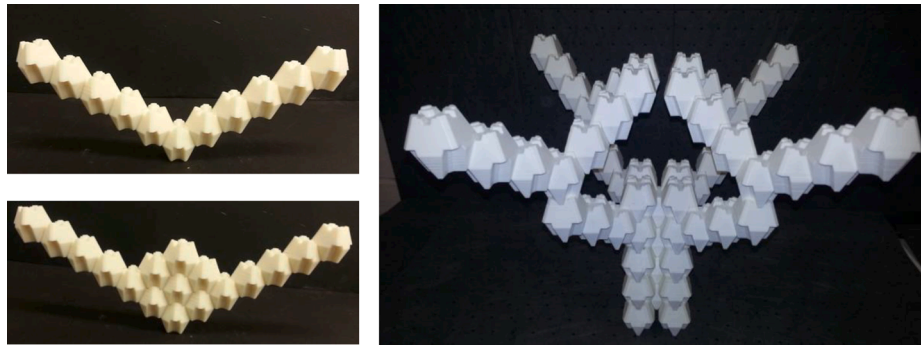
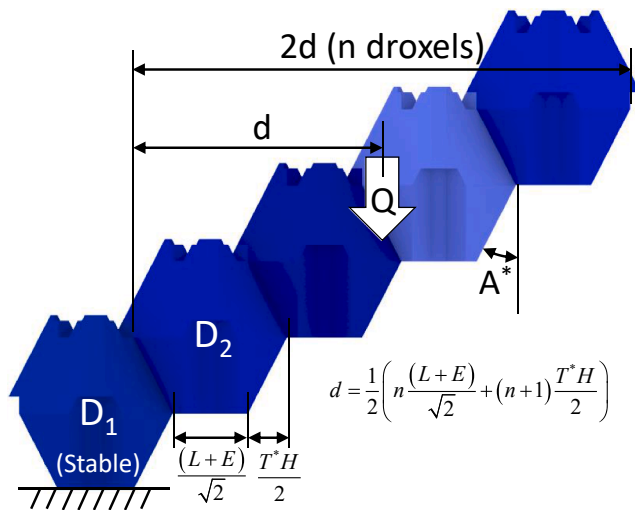


Fig. 14. Experimental tests with 3D printed droxels.

Fig. 15. $n = 4$ droxels in a “multiple mode 1” situation.

can drastically change its appearance, interlocking characteristics and the aspect of the droxelised structure. Fig. 3 shows a few examples of structures composed of 3D printed droxels. Droxels allow to create complex architectural forms without the need of any formwork or supports. In the example of Fig. 2, an arch made out of 3D printed droxels is first equilibrated by temporary droxels put at both extremities, which can be removed once the connection at the top is finished. Fig. 4 shows several 3D structures that can be droxelized, such as water tanks, spheres and arches.

Fig. 5 shows an example of the *droxelization* of a 50 m^2 shelter, composed of 2042 droxels of volume 26.10^{-3} m^3 . Fig. 6 shows that the same structure can be composed of droxels of smaller size, in order to refine the aspect of the structure or, at the contrary, composed of droxels of bigger size to reduce the total number of blocks and construction time.

This article presents the results of the first step of our research that focuses on both the geometrical and interlocking characteristics of the droxels, as well as the geometrical characteristics of droxel-based structures. Other essential aspects will be described in future articles, such as the algorithms for the global stability check, the calculation of the flow of forces and stresses between droxels, and the search for the best scenarios of construction that ensure a global and local stability at each step of the construction. Initially, droxels have been developed in order to allow the construction of 3D structures with flying robots capable of assembling construction components having the largest laying tolerance. Then, it became apparent that droxels also have the potential to cover a wider range of manufacturing applications (automated construction, garden shelters, temporary structures, emergency structures after natural disasters, military structures, artistic structures,

tiny houses, bridges, residential buildings etc.) and even be used as STEM-based activities for primary and secondary level students. Fig. 7 shows 3 droxels-made structures such as a tiny house and a bridge.

2. The droxel's geometry

The geometry of the droxel comes from reasoning that was discussed in [37], and from which 8 parameters naturally follow to completely define the block's geometry. These 8 parameters are reported in Fig. 8 and are the following:

- L and E are the main dimensions of the basic cross [mm].
- C_r is the size of the chamfer [mm].
- A is the characteristic angle of the droxel and has a great influence on the installation tolerance and the possible structure geometries. The angle A^* is such that $\tan(A^*) = \sqrt{2}\tan(A)$, with the following notation: $C = \cos(A)$, $S = \sin(A)$ and $T = \tan(A)$ and $C^* = \cos(A^*)$, $S^* = \sin(A^*)$ and $T^* = \tan(A^*)$.
- H is the total height of the droxel, except for the size of the upper growths [mm].
- R is the height of the large upper protrusions [mm].
- B is the height of the small upper protrusions [mm].
- Factor F governs the horizontal size of the four small upper hooks of height B , and in particular the ratio between distances [11-9] and [11-13] (Fig. 8).

Each combination of these 8 factors creates a unique geometry, having its own interlocking properties and its own 3D features and possible applications. A few examples of the versatility of the blocks and possible shapes that can be materialized are reported in Fig. 9.

3. Connection modes between droxels

Fig. 10 shows that a droxel can be supported by a number of other droxels variable between one and five, according to eleven different stacking modes:

- Modes 1A and 1B are the fundamental support modes, while mode 1AB is a combination of the previous.
- Modes 2A/2B correspond to a situation where droxel D is supported by 2 others. In mode 2B, the 3 droxels are aligned in the same vertical plan. In mode 2A, droxel D is offset from the two lower droxels.
- Modes 3 and 4 correspond to a situation where droxel D is supported by 3 or 4 others, respectively.
- Modes 2AB/2BB, 3B and 4B are similar to the modes 2A/2B, 3 and 4, but with an extra droxel added directly underneath the one to be placed.

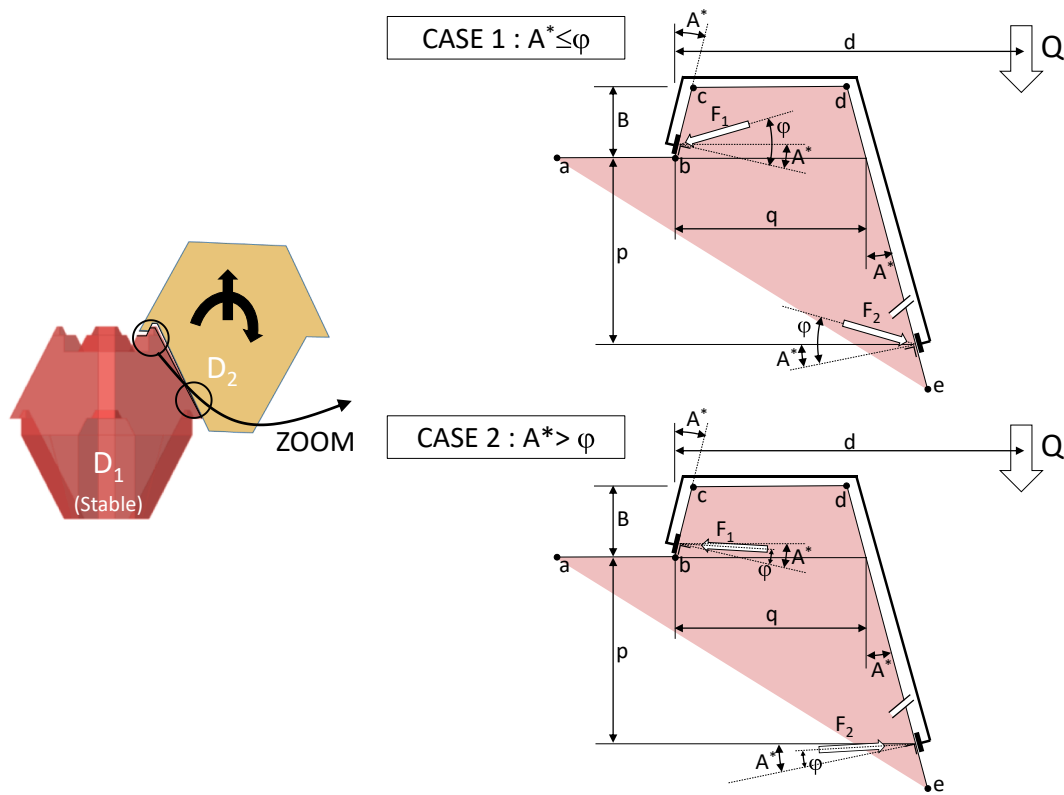


Fig. 16. In a cantilever mode, the instability comes from an uprising from droxel D_2 .

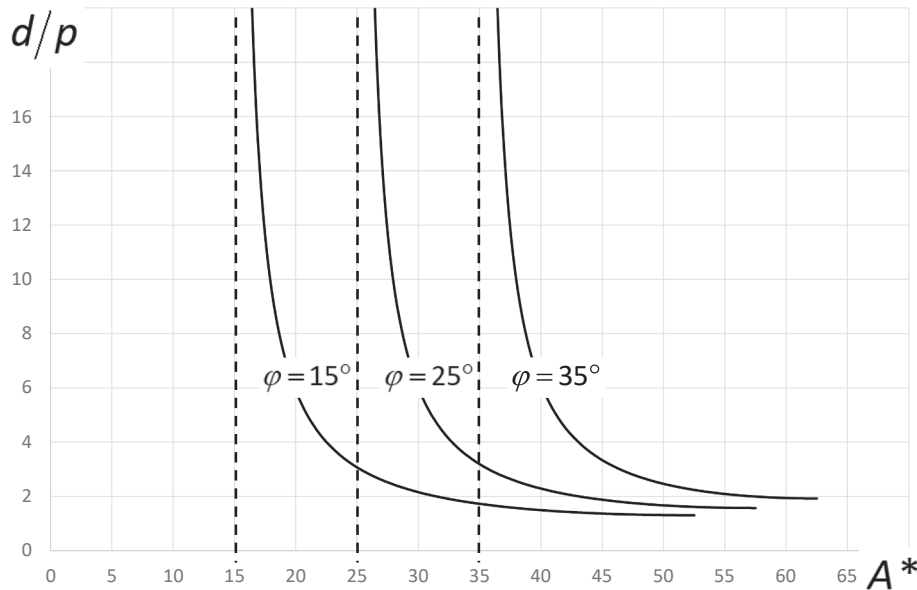


Fig. 17. Maximum value of the cantilevered distance “d” for given values of A^* and φ .

4. Laying zone and laying tolerance L_T

Droxels differ from all other stackable blocks not only because they allow an infinite number of structural shapes (and not only straight walls), but also because they have a very large laying tolerance, which makes construction easier, whether it is robotic or manual. The laying zone is defined as the horizontal area inside which the center of a droxel can be dropped, while still guaranteeing a perfect interlocking with the surround droxels (it is assumed that the axis of symmetry of a droxel to

be placed is kept parallel to the ones of the droxels already placed). Fig. 11 shows the laying tolerance L_T for mode 4 (Fig. 10), with L_T being the half of the square's size that defines the laying zone. A good approximation of the laying tolerance is given by the following equation, which shows that L_T increases with the values of R , H and T increasing (or L_T/L increases if R/H , H/L and T increase): $L_T = (R + 0.5H)T$, or $L_T/L = (H/L) \cdot (R/H + 0.5)T$.

Still regarding mode 4, Fig. 12 shows the possible positions of the droxel to be placed, with respect to the four droxels underneath (Only

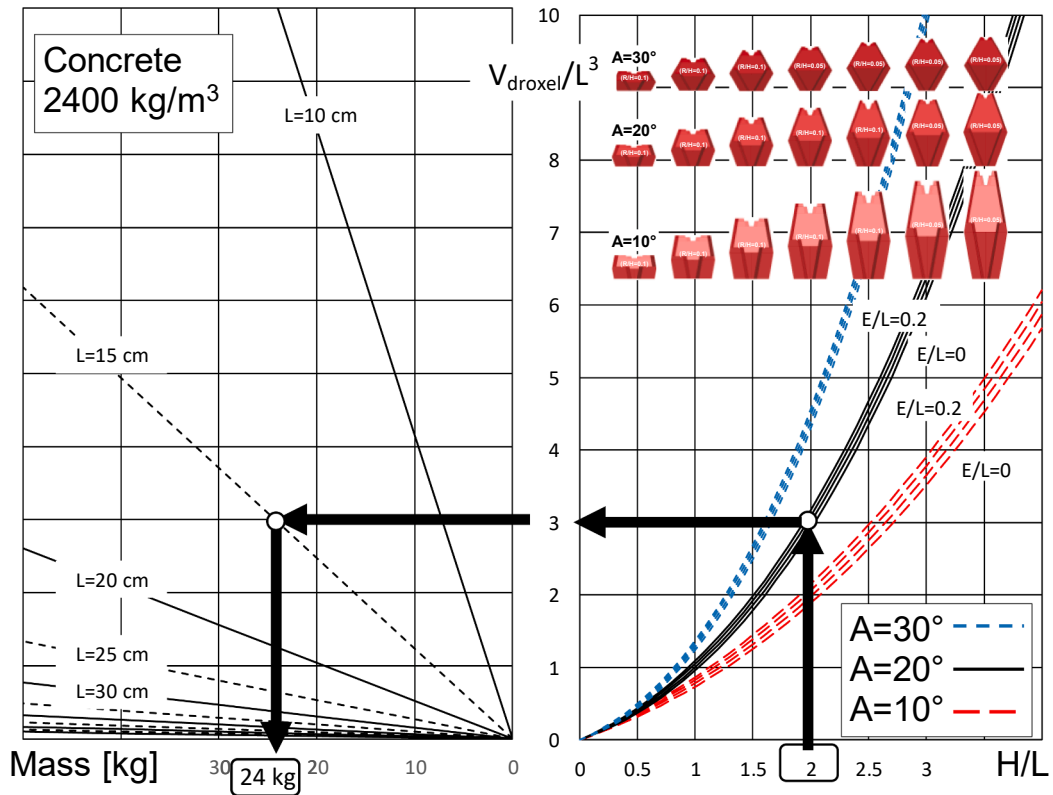


Fig. 18. Mass of concrete droxels. The choice of H/L and angle A of the right figure, combined with the choice of L on the left figure uniquely determine the mass of a droxel. The example given for $H/L = 2$, $A = 20^\circ$, $E/L = 0,1$, $L = 15$ cm leads to a mass of 24,3 kg.

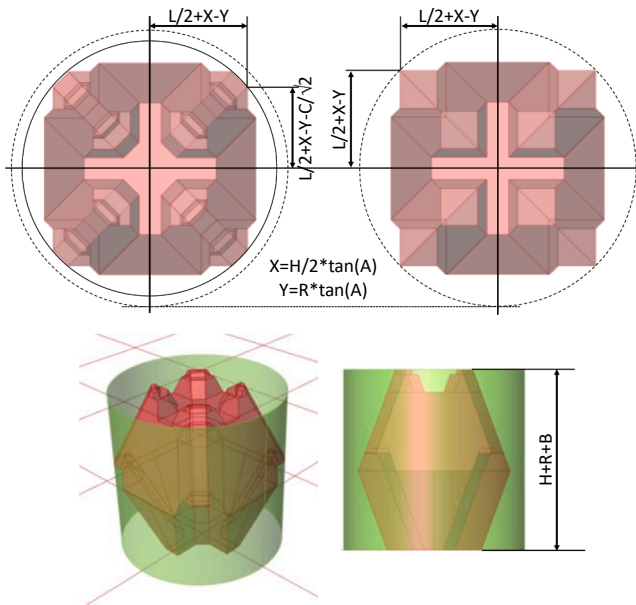


Fig. 19. Dimensions of the cylinder in which a droxel can be inscribed.

the top face UH1, UH2, UH3 or UH4 of one of their four big upper hook is drawn):

- Fig. 12A shows the ideal situation, with a droxel that is dropped perfectly centered. It fits exactly in the space between the other four, without any relative sliding between faces in contact with each other.

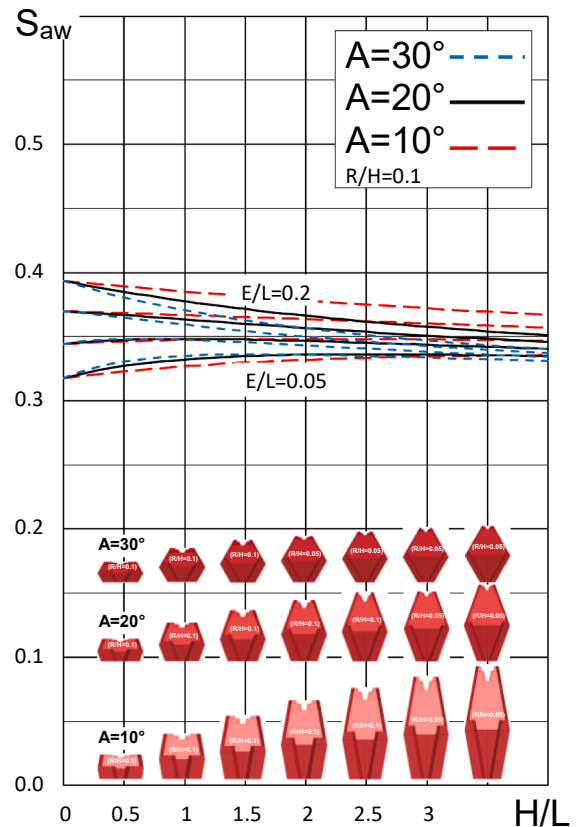


Fig. 20. Sawing yield S_{aw} for $A = 20^\circ$ (B and C_r neglected).

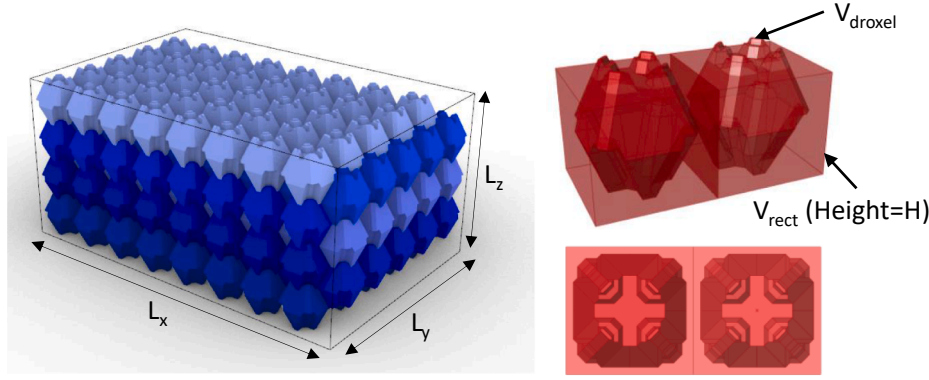
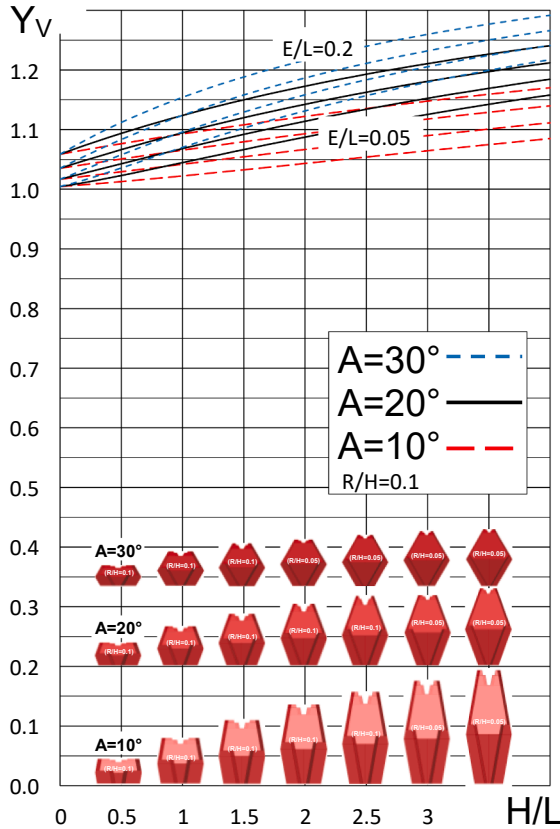


Fig. 21. Filling a cubic volume with droxels.

Fig. 22. Volume Filling Yield Y_v .

- Fig. 12B shows the situation where the (center of the) droxel is dropped at the upper right extremity of the laying zone. It is then still guided by the chamfer C_r and slides down on 3 contacting faces that guide it to its final, centered position.
- Fig. 12C, 12D and 12E are borderline situations where the lower cross of the droxel to be placed hits a chamfer face of one of the lower droxels without the possibility of sliding between faces, making it impossible to “guide” the droxel downwards. In other words, the laying zone may not always be represented by a perfect square of size $2L_T \times 2L_T$ but by the contour a-b-c-d-e-f-g-h-i-j-k-l-m-n-o-p shown in Fig. 12C. However Fig. 12D shows that this only happens if distance L is lower than distance $|xy|$ (note that $L=|xz|$). Indeed if $L > |xy|$, the droxel to be placed is always guided by two of the lower droxels and

in this case the laying zone remains a perfect square of dimensions $2L_T \times 2L_T$. It is easy to deduce from Fig. 8 that $|xy|=E + 2RT + HT + 1,41C_r$.

In conclusion:

- The laying criterion $|xy|=E + T(2R + H) + 1,41C_r < L$ should always be respected in order to guarantee an easier nesting. In this case, the laying zone is a square of size $2L_T$ with $L_T=(R + H/2)T$;
- Since $|xy|$ is also equal to $E + 1,41C_r + 2L_T$, the only way to respect the laying criterion without decreasing the laying tolerance is to have the lowest possible values of E and C_r .

Table 1 shows the laying zone for all the other modes, while Fig. 13 gives the values of L_T/L .

5. Equilibrium of droxels in cantilevered modes

Droxels can be stacked in cantilevered modes (Figs. 14 and 15), thanks to the small upper hook of height B (see Fig. 9). However, tests on 3D printed droxels have shown that the number of droxels that can be placed in a full cantilever mode is limited. The instability mode, shown in Fig. 16, is always the same, with a cantilever droxel D_2 that rises, turns and falls, with a sliding on faces “bc” and “de”.

Fig. 15 shows a multiple stacking mode 1 situation with a number of 4 droxels placed on top of a base droxel D_1 , which is considered as stable. The aim is to describe the equilibrium of cantilevered stacking modes and evaluate the number n of droxels that can be supported. Two cases must be considered (Fig. 16), depending on the respective value of the friction coefficient φ and the angle A^* . In case 1, where $A^* \leq \varphi$, the equilibrium equations in the horizontal and vertical directions are, respectively:

$$\begin{cases} F_1 \cos(\varphi - A^*) = F_2 \cos(\varphi - A^*) \\ F_1 \sin(\varphi - A^*) + Q = F_2 \sin(\varphi - A^*) \end{cases} \quad (1)$$

This system has no physical solution, which means that it is not possible to have an instability when $A^* \leq \varphi$, (when the friction coefficient is high, or the droxels straight ($A^* \rightarrow 0$)). In this case, Q and/or d and/or the number of droxels in the cantilever mode are not limited by a possible instability, but only by stresses between the faces in contact with each other.

On the one hand, the value of q is relatively small, as it is related to the small upper hook and it is equal to distance $|8-12|$, as shown in Fig. 8. On the other hand, the value of p is strictly related to the total droxel's height H , and thus always much bigger than q . In case 2, where $\varphi < A^*$, and, considering that $q \ll p$, the 3 equilibrium equations lead to:

$$F_1 = F_2 = \frac{Q}{2 \sin(A^* - \varphi)} \quad \text{and} \quad \frac{d}{p} \approx \frac{1}{2} \left(\frac{1}{\tan(A^* - \varphi)} + \tan A^* \right) \quad (2)$$

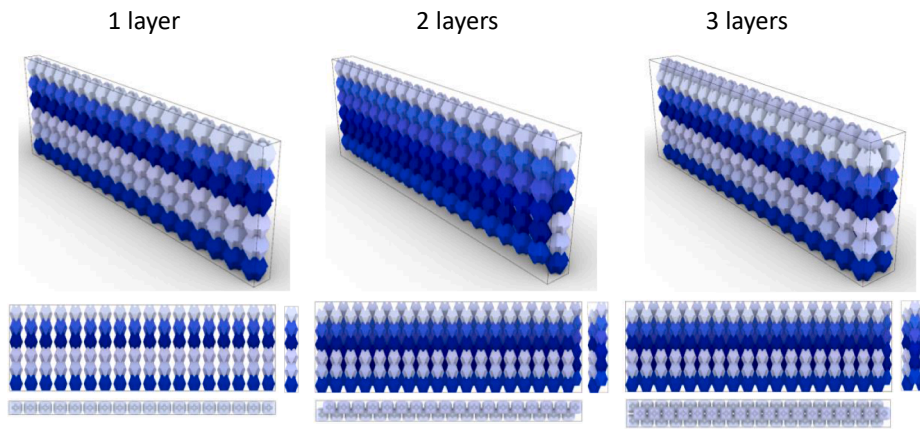


Fig. 23. A straight wall composed of 1, 2 and 3 vertical layers of droxels, respectively.

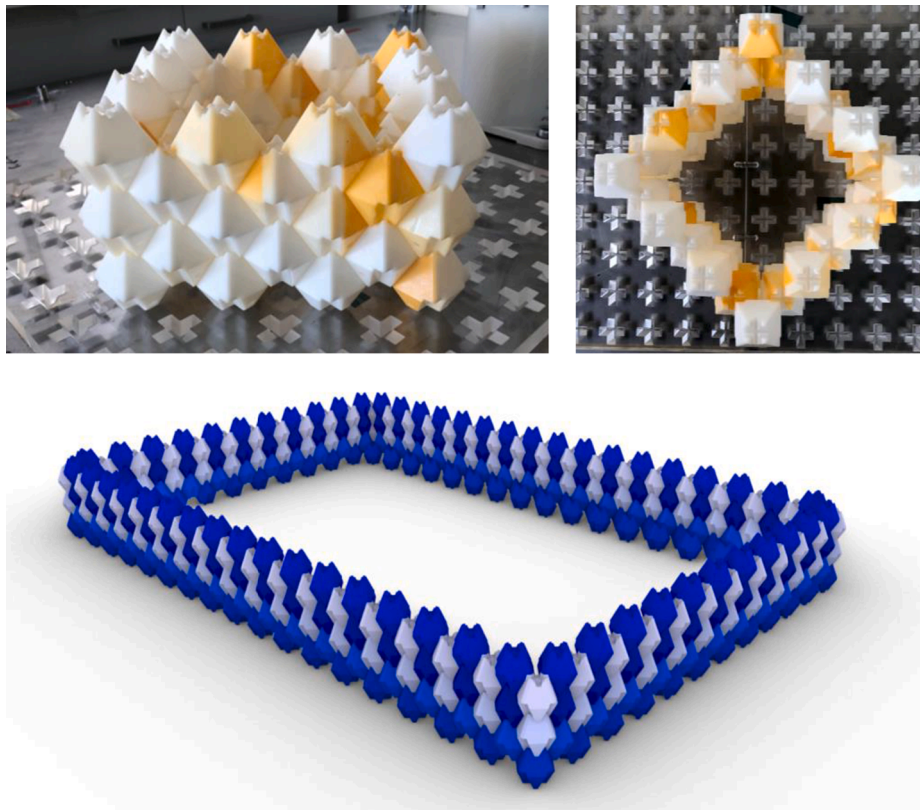


Fig. 24. Straight walls constructed with droxels at a 45° angle with respect to the horizontal axis of the walls.

These equations show that an instability doesn't come from Q (i.e., the self-weight of the droxels), but only from a value of d that is too high. This is shown in Fig. 17: for $A^* \leq \varphi$ no instability can occur, while for $A^* > \varphi$, an instability can occur if d grows over a certain value. Fig. 17 becomes even more explicit with the assumption $p \approx H/2$. From the previous findings, we can conclude that:

- If $A^* > \varphi$, the cantilever length is limited by the stability of droxel D_2 and decreases rapidly when A^* increases.
- If $A^* \leq \varphi$, the cantilever length is only limited by stresses between the faces in contact. In particular, surface A_1 must be sufficient to withstand shear.

$$A_1 = \left(\sqrt{2} (C_r/L) \beta F + (\beta F)^2 \right) L^2, \text{ with } \beta = 0,5 \left(1 - E/L - 4T(R/H)(H/L) - \sqrt{2} C_r/L \right) \quad (3)$$

6. Volume and mass of a solid droxel

The total volume of a solid droxel is equal to:

$$V_{cyl} = \pi(H + R + B) \left(\left(\frac{L}{2} + X - Y - \frac{C_r}{\sqrt{2}} \right)^2 + \left(\frac{L}{2} + X - Y \right)^2 \right) \quad (5)$$

$$V_{droxel} = L^3 f_1 \left(\frac{H}{L}, \frac{E}{L}, T \right), \text{ where } f_1 \left(\frac{H}{L}, \frac{E}{L}, T \right) = \left(\frac{H}{L} \right) \left[\frac{T^2}{3} \left(\frac{H}{L} \right)^2 + T \left(\frac{H}{L} \right) + \frac{1 + 2E/L - (E/L)^2}{2} \right] \quad (4)$$

Function f_1 is illustrated in Fig. 18, which shows that the mass of a droxel will decrease if H/L , A and E/L decrease. Fig. 18 (left) gives the corresponding mass for concrete but can be trivially adapted for any given material.

7. Sawing yield for timber

If droxels are made from timber with a CNC machine or a robotic arm, out of a piece of trunk, it is of deep practical interest to calculate the loss of material for each droxel (i.e., the sawing yield). Fig. 19 shows that the volume of the cylinder in which the Droxel can be inscribed is equal to:

where $X = 0.5HT$. By neglecting the effect of C_r and B , this expression simplifies to:

$$V_{cyl} = L^3 f_2 \left(\frac{H}{L}, \frac{R}{H}, T \right) \quad (6)$$

$$\text{Where } f_2 \left(\frac{H}{L}, \frac{R}{H}, T \right) = \frac{\pi}{2} \left(\frac{H}{L} \right) \left(1 + \left(\frac{R}{H} \right) \right) \left(1 + T \left(\frac{H}{L} \right) - 2T \left(\frac{R}{H} \right) \left(\frac{H}{L} \right) \right)^2$$

The ratio S_{aw} between the volume of the droxel and the volume of the cylinder is then equal to the following expression, which contains only the dimensionless parameters H/L , E/L , R/H and T :

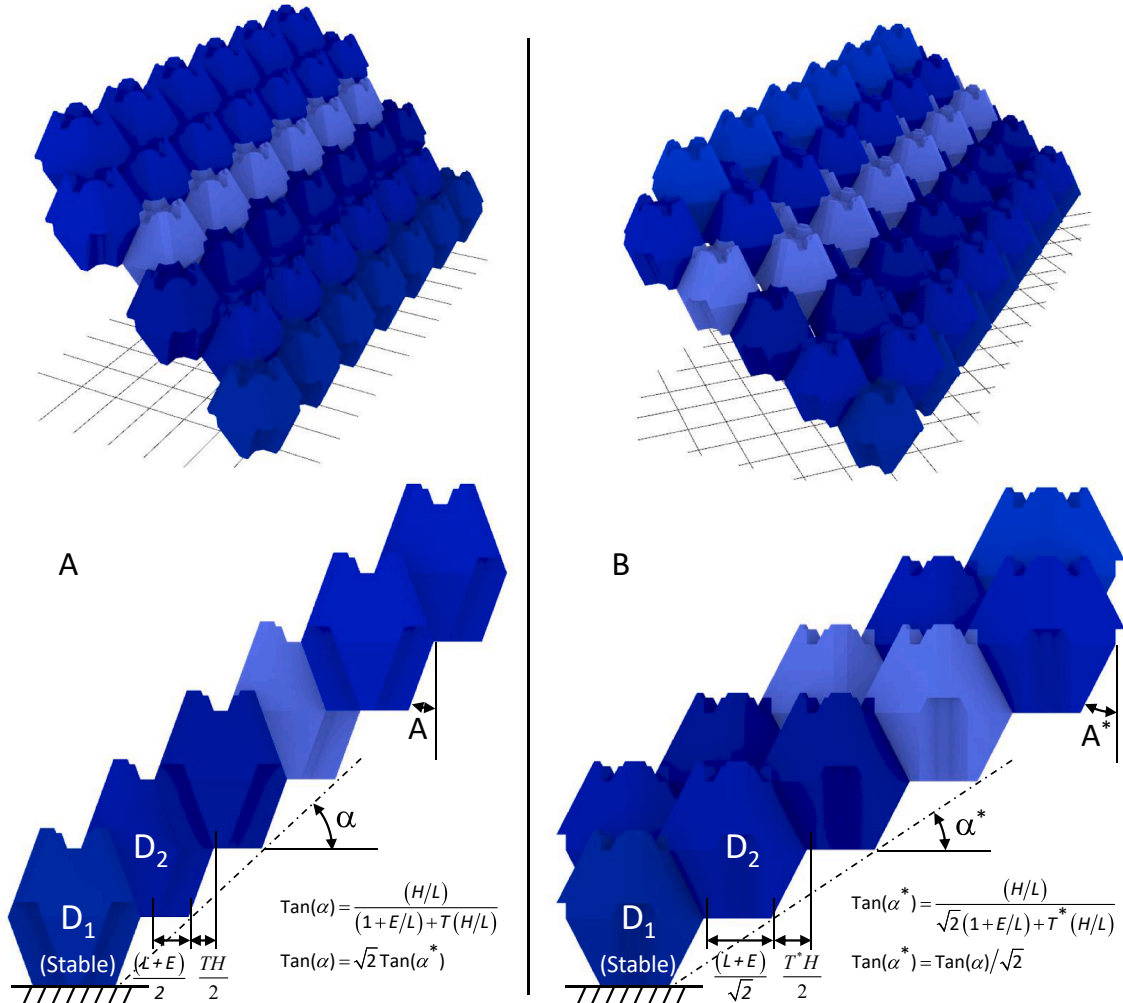


Fig. 25. For a given droxel geometry, the possible slope of a wall varies between α and α^* , depending on the position of the grid used for the droxelization.

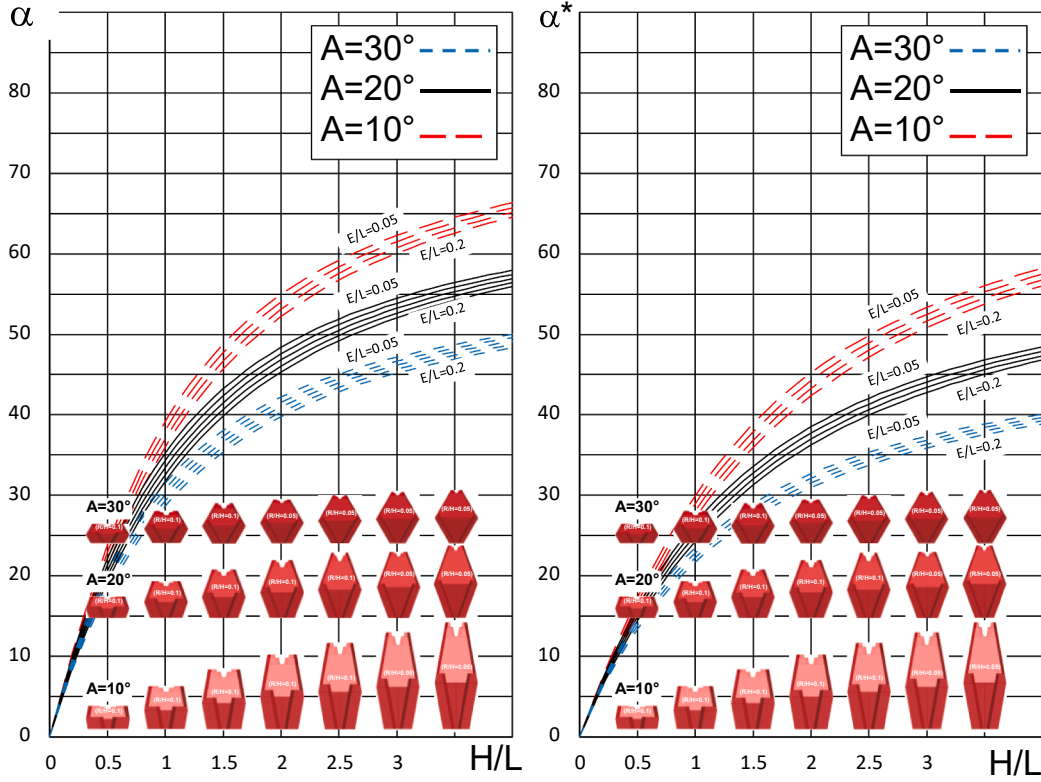


Fig. 26. Values of the minimum slope α^* and α (in degrees) for $E/L = 0.05$ to 0.2 (step 0.05).

$$S_{aw} = \frac{f_1\left(\frac{H}{L}, \frac{E}{L}, T\right)}{f_2\left(\frac{H}{L}, \frac{R}{H}, T\right)} = f_3\left(\frac{H}{L}, \frac{E}{L}, \frac{R}{H}, T\right) \quad (7)$$

Values of S_{aw} for $A = 10^\circ$, 20° and 30° are shown in Fig. 20 and show values ~ 0.35 for common values of E/L , which means that such a process induces a considerable waste of material.

8. Volume filling yield Y_V

The *Volume filling yield* $Y_V > 1$ is the ratio between the volume of a rectangular parallelepiped of dimensions $L_x \times L_y \times L_z$ (i.e., the 3-D bounding box) and the volume (nV_{droxel}) of the n droxels that compose a given assembly (see Fig. 21). The distance between the centers of two neighboring droxels belonging to the same layer is $(L + E + HT)$, and each layer of the 3D box is composed of $(L_x/(L + E + HT)) \times (L_y/(L + E + HT))$ droxels. $H/2$ being the distance between 2 layers, the number of droxels included into the “box” is equal to:

$$n = (L_x L_y L_z / L^3) [(H/L) f_4(H/L, E/L, T)]^{-1} \text{ with } f_4(H/L, E/L, T) \stackrel{def}{=} \frac{1}{2} (1 + T(H/L) + E/L)^2 \quad (8)$$

$$\text{Which yields: } Y_V = \frac{L_x L_y L_z}{n V_{droxel}} = \left(\frac{H}{L}\right) \frac{f_4(H/L, E/L, T)}{f_1(H/L, E/L, T)} \quad (9)$$

Fig. 22 shows that Y_V is always higher if H/L , E/L and A are high.

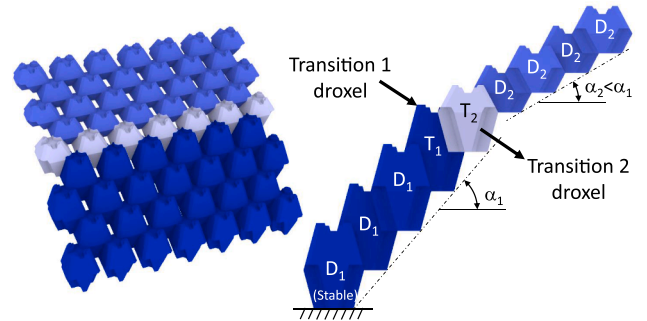


Fig. 27. Slope variation.

9. Straight walls with droxels

There are several means to create walls with droxels. Firstly, if one were to choose one vertical layer of droxels stacked together as shown in

Fig. 23A, no continuity would be attained, and therefore the global stability of a straight wall is only possible for at least 2 vertical layers of interlocking droxels (Fig. 23B and C).

A second way to build straight walls is to place the droxels at a 45° angle with respect to the horizontal axis of the walls. This allows walls

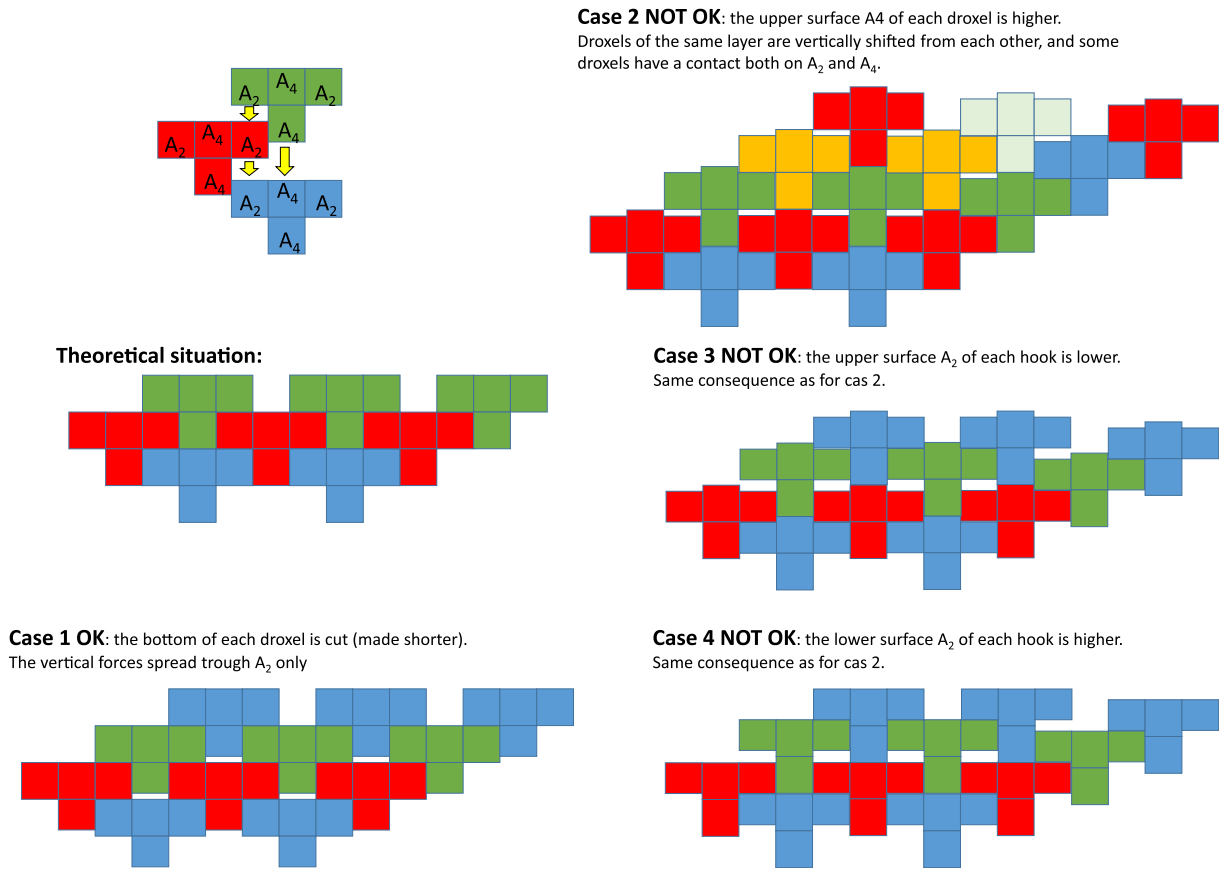


Fig. 28. Four ways to “force” the vertical forces to spread only through A₂ or only through A₄.

with a single vertical layer of droxels (Fig. 24).

$$\tan(\alpha) = \frac{(H/L)}{(1 + E/L) + T(H/L)} \text{ and } \tan(\alpha^*) = \frac{(H/L)}{\sqrt{2}(1 + E/L) + T^*(H/L)}, \text{ with } \tan(\alpha) = \sqrt{2}\tan(\alpha^*) \quad (10)$$

10. Slope's range for inclined droxelized walls

The droxelization of a spatial shape refers to the transformation of its geometrical form into a structure composed of droxels. This task is performed by means of parametric design software, such as Grasshopper, by defining a grid in the horizontal plane. Each intersection point of the grid represents a vertical axis passing through the center of the droxels that compose the structure. The dimension of a square of this grid is therefore $L + E + HT$. During the droxelization, the three main inputs are: the shape to be droxelized, the shape of the droxels (governed their 8 geometrical parameters), and the relative position of the grid with respect to the shape to be droxelized. The choice of the relative position between the grid and the spatial shape is completely arbitrary but can lead to different solutions.

A given droxel geometry determines the minimum possible slope for the walls of a structure. According to the relative position between the structure and the grid used for its droxelization, the slope can be between α and α^* (see Fig. 25). Fig. 25A shows an inclined wall that intersects the base grid at one of its main axis. Fig. 25B shows the result of the droxelisation performed with respect to a 45° rotation of the base grid (this can also be seen as a three-dimensional abstraction of the 45° straight wall example presented earlier).

Angles α and α^* are given by the following relations, and illustrated in Fig. 26:

Fig. 26 show that a small slope is associated to a low value of H/L and high values of E/L and A . It is important to notice that if H/L decreases, the laying tolerance decreases significantly.

The possible slope range $[\alpha \rightarrow \alpha^*]$ can change from a layer to another in order to better fit more complex structural geometries (Fig. 27). Droxels of different sizes and aspects are then required, and two families of droxels with a special shape need to be included:

- “Transition 1” droxels (T_1): shape similar to D_1 , but with a top adapted to the bottom of D_2 .
- “Transition 2” droxels (T_2): a bottom half compatible with D_1 and an upper half to transition to D_2 .

Droxels D_1 and D_2 must have the same parameters L and E . Furthermore, values of H/L and A must be such that $(H/L)_1/(H/L)_2 = T_2/T_1$.

11. Flow of forces and fabrication tolerances

The aim of this paper is neither to study in details the flow of forces and stresses across droxels, nor to set up a calculation method, which is a

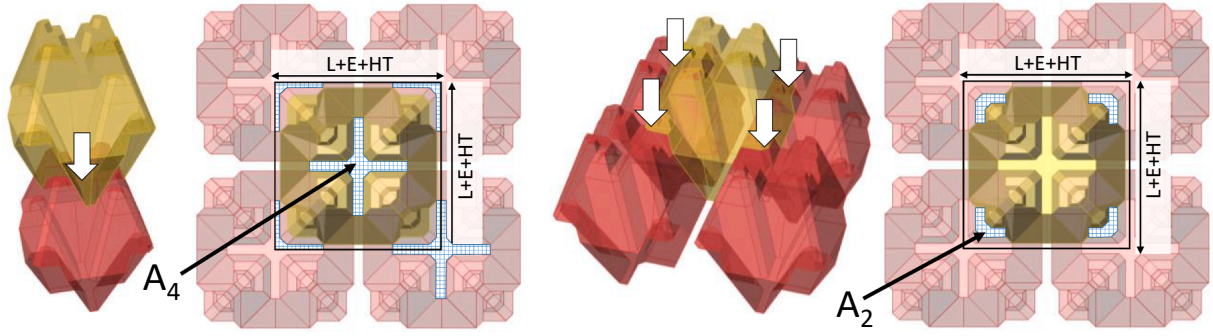


Fig. 29. Flow of vertical forces only through A_4 (left) or only through A_2 (right).

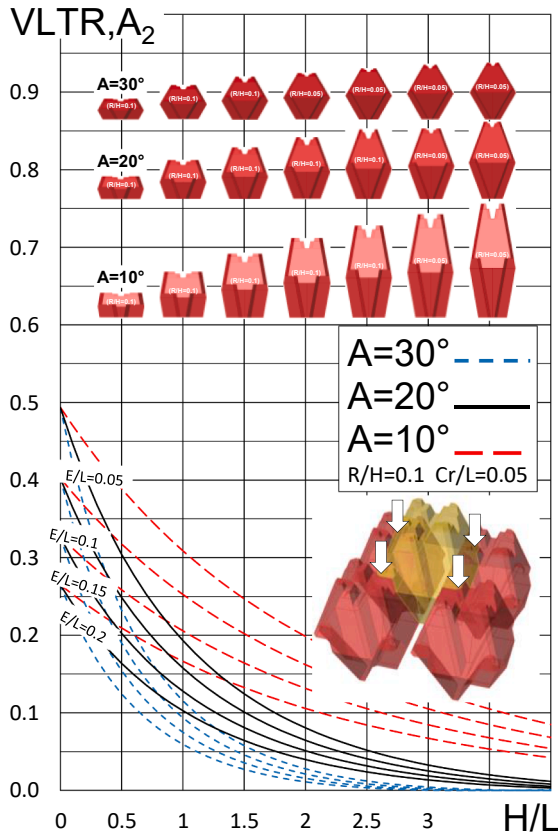


Fig. 30. Values of VLTR, A_2 for range of $E/L = 0.05–0.2$, with the assumptions $R/H = 0.1$ and $F = 0.6$.

Table 2

Influence of each parameter on the structural performance of droxels. The sign $\uparrow$ means that an increase in the value of the considered parameter (given in the column) has a positive influence on the considered characteristic (given in the row), and conversely for symbol $\downarrow$. A double sign ($\uparrow\uparrow$ or $\downarrow\downarrow$) indicates a stronger influence.

	Chamfer C_r/L	Base cross E/L	Big upper hook's height R/H	Small upper hook's height B/H	Small upper hook's F factor F	Angle A	Geometrical aspect H/L
High laying tolerance L_T	$\downarrow$	$\downarrow$	$\uparrow$			$\uparrow\uparrow$	$\uparrow\uparrow$
Low slope α and α^*		($\uparrow$)				$\uparrow$	$\downarrow\downarrow$
High cantilever length (number of droxels in cantilever mode)				$\uparrow$		$\downarrow\downarrow$	
High vertical Load Transfert Ratio VLTR, high value of A_2	($\downarrow$)	$\downarrow\downarrow$	$\downarrow\downarrow$		$\downarrow\downarrow$	$\downarrow\downarrow$	$\downarrow\downarrow$
High shear resistance of small upper hook (cantilever mode) - high value of A_1	($\downarrow$)	$\downarrow\downarrow$	$\downarrow\downarrow$		$\uparrow\uparrow$	$\downarrow\downarrow$	$\downarrow\downarrow$

whole subject apart. This section is therefore dedicated to general considerations on the structural features of droxel assemblies, in an attempt to describe the full range of their possible applications. Fig. 10 shows that eleven supporting modes are possible for a droxel and, for each of these modes, some of the surfaces shown in Fig. 9 are in contact with each other. It is therefore not straightforward to predict through which surfaces the inter-blocks forces will flow. For instance, for mode 1A (shown in Fig. 10), the vertical forces can flow, depending to fabrication tolerances and imperfections in the blocks, either through surfaces A_0 , A_2 , or both (A_0 and A_2 are shown in Fig. 9).

In order to avoid this uncertainty, and to lay trustful hypothesis for the calculation of droxelled structures, a solution would be to “force” some fabrication tolerances, in such way that the contact between some chosen surfaces is imposed. For the cantilever mode 1A for instance, height B and parameter F of the small upper hook and its female equivalent could be adapted, in order to avoid any contact between surfaces A_0 , and force the contact on surfaces A_2 only.

For the other modes, forcing the transmission of vertical forces only through A_4 or only through A_2 would be relevant for the same reason. However, Fig. 28 shows that forcing the flow of forces trough A_2 , thanks to a slight cut of the droxels' bottom, is the only possible solution (Case 1). The only disadvantage in this case occurs for a rare and not particularly relevant case, which corresponds to the realization of a column made up of a stack of droxels entirely constructed by means of Mode 1B. In this case, the cuts will accumulate and produce a column whose real height is shorter than the theoretical height.

If vertical forces only spread through four surfaces A_2 as shown in Fig. 29, the ratio between area $4A_2$ and the area across which the vertical forces would spread if the material were filling the whole space can be measured through the parameter VLTR (Vertical Load Transfer Ratio), which is equal to:

$$VLTR = \frac{4A_2}{L^2}(1 + E/L + T(H/L))^{-2} \quad , \text{ where : } \quad \begin{cases} A_2 = \left(\sqrt{2} (C_r/L) \beta (1 - F) + \beta^2 (1 - F)^2 \right) L^2 \\ \beta = 0,5 \left(1 - E/L - 4T(R/H)(H/L) - \sqrt{2} C_r/L \right) \end{cases} \quad (11)$$

Fig. 30 shows that the VLTR ratio is higher if H/L , A and E/L are small.

12. Influence of each parameter on the structural performance of droxels

The size of the construction project, as well as the desired aspect ratio of the structure (i.e., the droxelisation resolution) will determine the dimension L or the dimension H at the beginning of the design process. This is the reason why geometrical parameters such as C_r , E , R , B have been related to L and/or H in the previous developments through the following ratios: C_r/L , E/L , R/H and B/H .

Table 2 presents the influence of each parameter on the droxels' performances and allows to draw the following guidelines:

- **The chamfer C_r** should always be as small as possible. Depending on the value of L , the following values are recommended, based on our experience on small and big size 3D printed droxels and 15 kg concrete droxels: $C_r = 3 \text{ \AA} 5 \text{ mm}$ for timber, poured materials with no aggregates and polymers, and $C_r = 10 \text{ mm}$ for concrete. In any case, ratio C_r/L could always be limited to 0.05 (see Table 3).
- **The base cross width E** should also be as small as possible, as shown in Table 2. Another reason is that E is responsible for small openings that are visible in Fig. 27 and may be incompatible with some structural applications (This will need a special attention, depending on the characteristics of the project, in particular for insulation and waterproofness). However, a low value of E will produce very thin walls at the base of the droxels, which on the one hand weakens the blocks, and on the other requires a concrete mix with a specific granulometric curve to be cast properly. Generally, a value of E/L close to 0.1 is recommended (see Table 3).
- **The big upper hook's height R** : its utility is to avoid relative horizontal movements between stacked droxels. High values for R are generally not necessary, and even not recommended, although they might slightly increase the laying tolerance. Indeed, the smaller R is, the higher surfaces A_1 and A_2 can be, which are essential for the transmission of vertical forces (A_2) and horizontal forces in cantilever mode (A_1). A recommendation is to limit the values of R/H to the minimum admissible value, possibly between 0.05 and 0.1.
- **The small upper hook's height B** : the highest possible value of B is recommended in order to make the transmission of friction stresses

in cantilever mode easier and more effective. However, making this hook too sharp may not be compatible with some materials: a minimum value for surface A_0 is therefore needed.

- **The small upper hook's F factor**: a high value of F is good for the resistance of the upper small hook but can decrease the transmission of vertical forces through surface A_2 . Its value should thus be tuned according to the forces to be resisted by the droxels. A recommendation would be to choose F in such way that A_1 and A_2 are similar (e.g., $F = 0.6$).
- **The angle A** : as shown in Table 2, the best fit for the value of A is not trivial to identify and will generally depend on the preferred criterion. A compromise can be found. A high value of angle A has a good influence on the laying tolerance (which becomes null for $A = 0$) and on the lowest possible angle α/α^* . However, a high value of A decreases advantages related with the sliding of droxel with each other, the transmission of forces, and the cantilever stacking mode. For these reasons, values of A between 10° and 30° are recommended.
- **The geometric factor H/L** has also a major influence on the laying tolerance and should be as high as possible. However, just as for A , a compromise has to be found: increasing the laying tolerance reduces automatically both the lowest possible slope and the quality of the transmission of forces.

13. Conclusions and perspectives

The droxel would have been out of any construction reality and possible industrial manufacturing until just a decade ago. However, robotic operations and parametric design tools have changed the field, as well as the designers' perspectives on what is possible to accomplish with modern design tools. It is now feasible (both technologically and economically) to create droxels in polymer, concrete, or timber by leveraging capabilities granted by 3D printing, CNC machines and injection molding. The parametric shape of the droxels allows for the creation of virtually any kinds of complex structures. They also open new possibilities both for automated construction processes and for manual work (including self-building). Polymers can allow for hollow droxels to be cast, which opens new possibilities to fill the blocks with various materials: water for storage or stability, sand and ballast for stronger structures such as military shelters, food for shelters in case of natural disasters, etc. Concrete opens possibilities for many kinds of structures and is particularly adapted to a fast and easy construction of

Table 3
Suggested values for C_r , E and C_r/L , E/L .

Suggested values for C_r (mm)					Suggested values for E (mm)				
Timber, poured material without aggregates, polymers			Concrete		Timber, poured material without aggregates, polymers			Concrete	
L (cm)	Recommended values for C_r (mm)	C_r/L	Recommended values for C_r (mm)	C_r/L	L (cm)	Recommended values for E (mm)	E/L	Recommended values for E (mm)	E/L
10	3	0.03	–	–	10	10	0.10	–	–
15	3	0.02	–	–	15	15	0.10	–	–
20	5	0.03	10	0.05	20	20	0.10	30	0.15
25	5	0.02	10	0.04	25	25	0.10	30	0.12
30	5	0.02	10	0.03	30	30	0.10	30	0.10
35	5	0.01	10	0.03	35	35	0.10	35	0.10
40	5	0.01	10	0.03	40	40	0.10	40	0.10
45	5	0.01	10	0.02	45	45	0.10	45	0.10
50	5	0.01	10	0.02	50	50	0.10	50	0.10

straight walls (Fig. 24). Timber would create nice interiors for tiny houses. This list is not exhaustive, and the reader is referred to reference [39], which shows several other examples.

This publication focused on the geometrical characteristics of droxels and the building possibilities they offer. Ongoing research is focusing on the mechanical properties of droxelised structures, in particular the numerical and experimental identification of the best assembly sequences that guarantee both the local and global stability at every step of the construction process. The flow of stresses has also to be investigated in order to evaluate the construction limits in terms of spans and height for different materials, particularly in view of the complex dynamic actions resulting from automated placement of large-scale droxelised structures.

CRedit authorship contribution statement

Pierre Latteur: Conceptualization, Methodology, Supervision. **Alessandro Fascetti:** Methodology, Investigation. **Sébastien Gossens:** Conceptualization, Investigation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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None

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