Ceramic AM Gantry Structures

Discretisation and connections between beams and columns

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The manufacture of architectural components driven by digital design tools and Additive Manufacturing (AM) allows the achievement of highly evolved constructive systems, more integrated into a specific reality to which it is intended to respond, resulting in unique and adapted solutions with high geometric and material performances. Considering the application of these methods to common structural elements, namely beams and columns, for which there are already several examples demonstrating their feasibility, we find that it is necessary to provide a sound answer to an element that is fundamental for these proposals to function together as a single system - the moment of connection between beams and columns. In this sense, this paper proposes the design and test of a set of connections with adapted geometry between beams and columns, produced through ceramic Liquid Deposition Modelling (LDM), applying logics of topological optimization. This work foresees the development of a constructive system that incorporates reversible and irreversible connections, being formalised in a set of gantry structures formed by two vertical elements and a horizontal one, giving the comparative model between digital design and manufacture methods and the traditional ones.

Keywords: *Ceramic AM, Performative design, Computational design, Connections, Ceramic gantry structure*

1. INTRODUCTION

The potential that AM can bring to architecture has been highlighted during the last few decades. Traditionally called 3D printing, AM consists of the production of objects by the successive addition of material layer by layer, where it is necessary, making it a sustainable system, in contrast to subtractive methods where, generally, there is a big waste of material during production processes.

In addition to the potential benefit regarding the economy of means and sustainability, AM also allows for mass customization, without any restriction about the plurality of geometries that is possible to obtain. Since the material is only deposited where it is necessary, being this process controlled by a computer, the time and cost of producing different objects will not depend on the existence of accessory components (moulds), and it will take the same time to produce either they all have the same geometry or different ones. In fact, with AM the mass production of architectural components with unique geometries will have the same cost and take the same time as the mass production of identical copies.

Supported by computational design logics, AM allowed new fields of research and development in architectural design, building materials and construction industry, enabling geometric freedom that can result in the design of geometries with specific requirements, optimizing the design and functions of traditional systems (Sarakinioti et al., 2020).

In 2016, a report from the World Economic Forum (Renz et al., 2016) related to the future impact and likelihood of new technologies, based on the results of the "Future of Construction Survey", states that the "contour crafting of buildings" is unlikely and is considered to have a low impact on the construction industry. Comparatively, the probability of the production of components by AM and "advanced building materials" is considered moderate, and the production of prefabricated components is extremely high.

This may justify why many research teams are working in this field, using AM technologies to produce advanced materials and components "following a line of thinking that is based on discrete elements". With this logic, instead of the need for machinery covering a bigger area than the area of the actual building, each element is discretised according to project requests and existing machinery characteristics (Cruz et al., 2020). This idea is corroborated by Mario Carpo (Carpo, M., 2019), pointing that "instead of printing bigger and bigger monoliths, it may be conceivable easier to start with any number of parts, as many as needed and as small as needed".

Despite that, and all the improvements on the use of these technologies, there is still a lack of research on a fundamental aspect of construction, which is the connections between components, namely when they have a structural role. Examples of columns such as Concrete Choreography (Anton et al., 2020) or Modular Column [1] and beams and bridges like WASP Reinforced Concrete Beam [2] or the Concrete Bridge [3] present us with architectural elements that explore design and manufacturing logics that clearly demonstrate the potential of this process. However, these are isolated studies that consider both beams and columns independently, without the complementarity that exists in a real context.

The use of ceramic materials to produce advanced architectural components is not yet an effective reality and there are numerous issues that need further study. This research aims to contribute to the mitigation of these failures and to seek solutions so that the effective use of this technology/material is possible in a real context.

In this sense and based on the extensive knowledge resulting from previous research projects developed at the Advanced Ceramics R&D Lab, this investigation proposes the development of a set of ceramic gantry structures, with load-bearing capacity, composed by hybrid (ceramic in collaboration with other materials) beams and columns.

2. METHODOLOGY

Considering the implications associated with the LDM of ceramic materials, namely the need to fire the components and the limited working volume of the production/firing equipment, the entire system was discretized into smaller elements to meet these requirements. Thus, the methodology applied in this study begins by analysing the discretisation of the general model into components, proceeds to the interconnections between each of these components considering the material constraints and ends with the dynamic behaviour of the system when subjected to load-bearing efforts.

The used methodology follows a set of rules considered fundamental to reach relevant data for the definition of fully functional systems, capable to respond to mechanical requests, be easy to produce and assemble, as well environmentally friendly comparing to systems with similar behaviour. For that and taking into consideration the restraints that ceramic LDM have, namely geometric deformations, on these initial tests the system must be as simple as possible, both functional and geometrically, focusing on the definition of joints and overall structural scheme.

In addition, the discretization methods that may vary in future conceptions are strict to simple slices of the overall component, avoiding unnecessary complexity, that could compromise the results of prelaminar tests.

2.1. Problem definition

Considering the problems related to the use of ceramic AM on architecture and construction, that goes from material composition to the limited built volume of the production equipment, this study aims to contribute with solutions in some specific fields, trying to produce real scale high-performance ceramic gantry structures.

In this sense, and since we are dealing with elements at different scales (discretised component and full structural system), there is a need to make these two scales compatible. For that, it is important to study the reaction that the material has when increasing or decreasing the size of the components as well the response of the assembled systems when subjected to efforts.

Additionally, there is a common issue conditioning the use of ceramic materials on the construction of structures which is its fragile condition and the bad behaviour when submitted to traction efforts.

2.2. Material

The material used to produce the ceramic components was a fine stoneware paste (130-MP) without chamotte and with 35% of water content, as it proved to be the most suitable and compatible with the type of extruder present in the production equipment (Lutum® 4.0XL). Tests carried out on previous studies show that this specific material when fired at 1260ºC can reach up to 175 MPa of compressive strength (Cruz et al., 2019).

For the execution of the necessary additional components was defined a material palette that could compensate the previously mentioned ceramic downsides, like its fragility, and help to get the better behavior of the entire system. Wood (laser cut oak), rubber (SBR), mortar (Sika adhesive mortar for ceramic), glue (acrylic adhesive) and concrete (C-30), as well metallic elements for the nodes and post-tensioning were tested. These materials are used either to separate ceramic pieces, to glue them together or to give resistance to traction efforts.

The manufacturing method presented below and the computational models for the generation of geometries follow these material configurations and any change to the composition or type of material results in the necessary adaptation of method and geometry.

2.3. Fabrication

LDM comprises the formation of objects from a paste material that is extruded on a regular or irregular basis, layer by layer. The extrusion of the ceramic material is controlled by a rotating spindle that regulates the outflow of material. The material intake system uses compressed air to compact and transport the ceramic material to the extruder, where the automated spindle is located. Depending on material characteristics the equipment settings, fundamentally the deposition flow, speed, layer high and layer thickness must be changed accordingly. The production equipment allows the control of each parameter automatically (from the numerical control code) and manually in real-time (from the machine's control interface).

The produced ceramic components use basic configurations for the execution of mid-size components. Extrusion thickness of 3mm and 1,5mm height. The pressure applied to the ceramic paste on the cartridge was 5,0bar with a printing speed of 50mm/s. These values, namely the air pressure, have in consideration the plasticity of the ceramic paste.

3. PROTOTYPES

During the investigation, several prototypes with the objective of solving the problems mentioned above were developed. The executed elements were used to classify the materials as to their effectiveness or degree of complementarity in relation to ceramic materials, either to serve as a separate element of ceramic components or as a traction or post-tensioning element for the built set. Prototypes to study the structure of beams and columns components were also made.

3.1. Complementary materials

The first set of tests was carried out having in mind the search for the best material to serve as a separating element between ceramic components, something fundamental considering that ceramic is a material that, although extremely resistant to compression efforts, is also very fragile, especially if the applied tension is not uniform, which can cause early ruptures, jeopardizing the integrity of the system.

For this purpose, cylindrical ceramic pieces with approximately 70mm in diameter and 40mm in height were developed, consisting of three 3mm thick walls, where the inner wall rise above the remain two in height, serving as a connecting element. Later, these pieces were associated with materials that could serve as separation elements (Figure 1).

As previously mentioned, the inclusion of other materials was tested, namely wood, rubber, mortar, glue, and concrete. Based on this aggregation, a series of test specimens were developed, comprising: a) simple ceramic element; b) two stacked ceramic elements; c) three stacked ceramic elements; d) two ceramic elements stacked with a layer of separation material; e) three ceramic elements stacked with two layers of the separation material; f) two ceramic elements filled inside with concrete; g) three ceramic elements filled inside with concrete; h) cylindrical test pieces of solid concrete; i) cylindrical hollowed concrete test specimens (Figure 2).

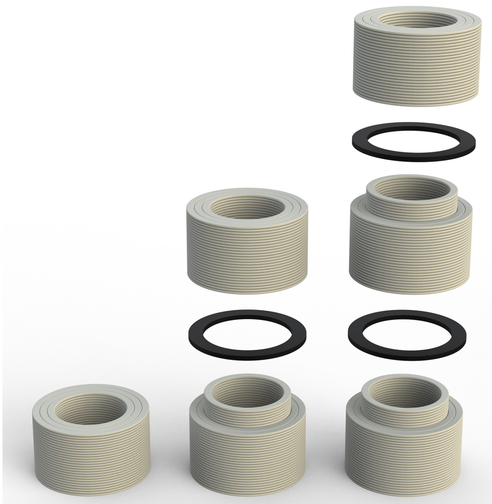

Figure 1
Cylindrical stacked ceramic pieces and separation material.

Three test pieces were developed for each series, making a total of 51 test specimens. The main objective of these tests was to determine which material is best suited to work together with ceramics having as a base point the results obtained by the concrete specimens. The concrete used in the test specimens was a traditional C-30 mixture.

Figure 2
Complementary materials test specimens.

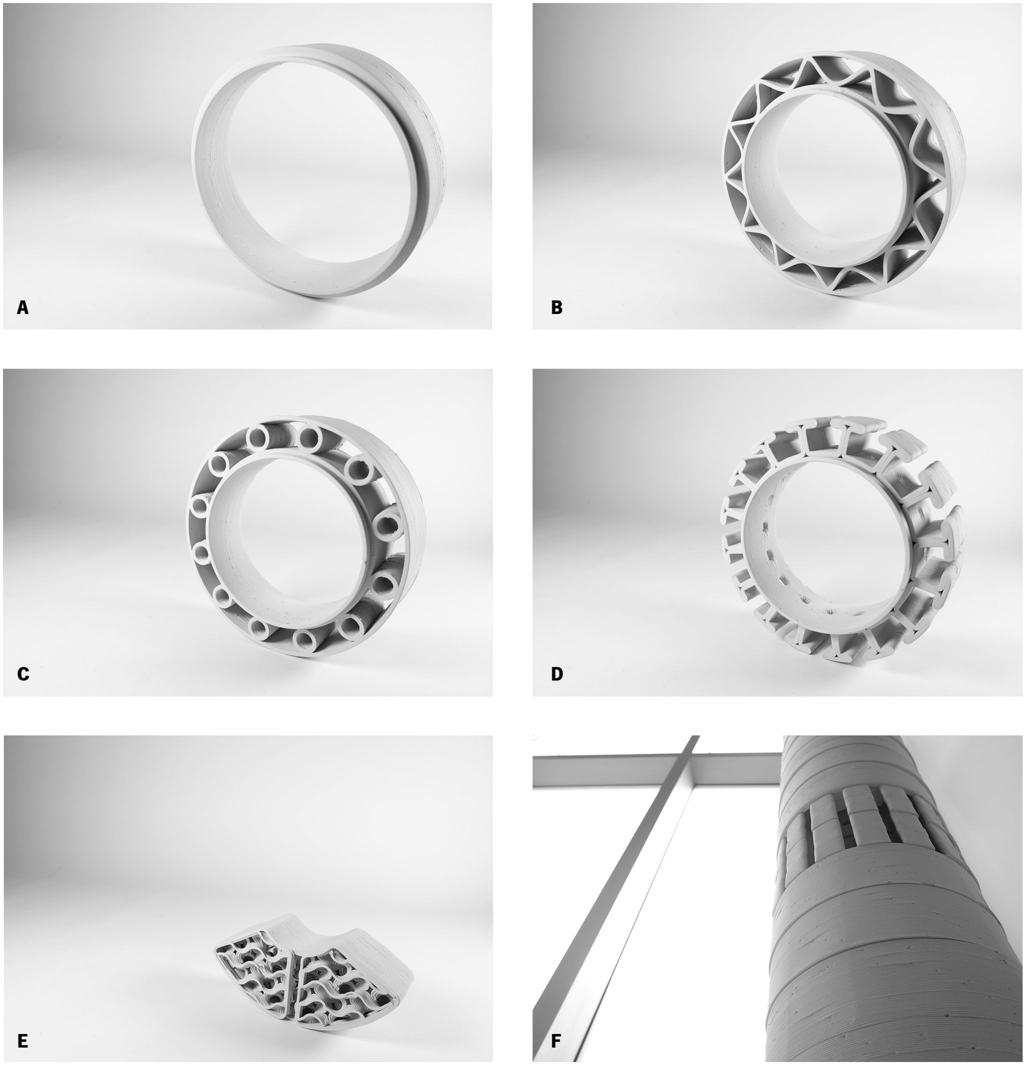

Figure 3
Column prototypes.
A - Structural reinforcement; B - Thermal insulation; C - Infrastructures; D - Ventilation; E - Compound stave (second type of discretization); F - Example of column assembly.

3.2. Columns

During the investigation, 5 types of columns were developed (Figure 3), each having a different purpose and representing an additional performative function. Although they are presented as being of different types, in their constitution and form of operation there is no change, being the formal variation an element that points to the study of the possible addition of functionalities.

The columns, in addition to the structural role, which later will relate to the beam, there was also a demand to give these elements functions that were not limited to the load support, as are the cases of a) structural reinforcement; b) thermal insulation; c) passage of infrastructural networks; d) ventilation.

Additionally, two types of discretization were also tested: a) one component at each level; b) three components per level. Here, on columns prototypes, the focus was mainly on the functional issue and on the increase in the performance of ceramic architectural components, leaving out the structural performance since the responses to this performance are expressed by the tests presented in 3.1.

3.3. Beams

This research points to the development of a set of beams composed by discretized ceramic elements tensioned using post-tension steel cables and tensioners or static elements resistant to traction efforts such as wood. Each of these types of stresses will result in a different materialization as the structural scheme varies according to the characteristics of the stress/aggregation elements (Figure 4).

Considering the characteristics inherent to the ceramic material, which normally presents a good response to compression efforts and poor performance when exposed to tensile forces, care was taken to make a mass distribution that followed the structural scheme in each situation, resulting in a higher concentration of ceramic material in areas expected to be compressed and materials resistant to traction in areas where this type of request is more prevalent.

The structural scheme that results in the distribution of masses and the consequent distribution of types of material, as a function of the applied forces, is obtained using a topological optimization algorithm that after making a global analysis of the elements (column, beam and load), makes the reduction of the initial volume of the beam and presents the areas that will be in compression or traction. The reduction of mass applied to the test models was 60% of the initial volume of the analysed element.

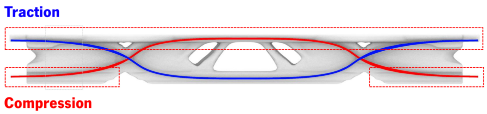

Figure 4
Beams topological optimization with the type of applied forces.

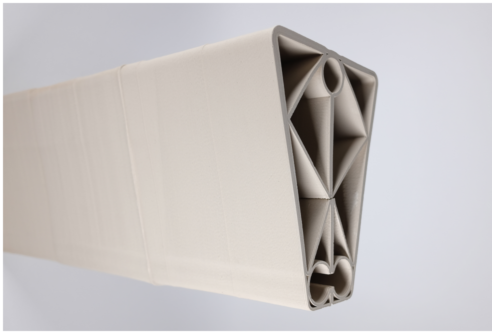

Figure 5
Example of the beam using the first type of structure to build the components.

Figure 6
Shell and internal structure geometries for load compression tests.

Additionally, to study the most suitable geometry for the shell and internal structure of the ceramic staves that make up the beam, three alternative possibilities were defined (Figures 5 and 6). The first stands out for the use of straight walls to define the contour of the part and internal structure, and an inner cylindrical channel for the passage of post-tension cables. The second examines the use of a triple wavy contour wall that alternates between two external walls with an internal and an external wall with two internal, forming a latticed alveolar structure. There is no internal structure in this component. The third format consists of the use of an alveolar corrugated wall and an internal structure defined by a triply periodic minimal surface.

For each of these structural drawings, the compression will be tested in two directions in order to understand the behaviour of the component in a real situation. These tests simulate the force exerted by the post-tension (longitudinal direction of the beam) and by the applied loads (vertical direction).

3.4. Connections between beams and columns

The connections between beams and columns are perhaps the most sensitive element in a frame structure like the one this research aims to develop. In addition to serving as a transfer point for any loads that are being applied to the beam, the connecting element also has the task of ensuring the stability of the assembly by providing the blocking of rotation efforts in the various possible directions.

This preponderance manifests itself mainly in structures composed of several independent elements, as is the case presented here, of a system composed of discretized ceramic elements, in contrast to a reinforced concrete structure in which the efforts of the joining moment can be easily diluted in the system. In this specific case, with the use of either steel cables to tension the ceramic pieces, or wooden beams in articulation with ceramic components, the tops of each of the composite elements, beams and columns, are also the moments of consolidation of the composed element, giving extra complexity.

In this sense, four structural schemes were conceived materializing different conditions to the structure. The first type (Figure 7a) is the simplest and is based on the support and direct discharge of forces (with separating material between ceramic pieces), without any type of structural blocking. The beam and the column remain independent and are the gravity and inertia of each one of them to provide the balance of the system.

The second type (Figure 7b) is characterized by the use of the tensioning elements as load transferors for the column, with no direct contact between the main (ceramic) body of the beam and the column. In this case, there is the use of a special piece on top of the column to receive the tensioning elements and transfers the loads. There is a structural blockage in at least one axis of rotation.

The third type (Figure 7c) provides blocking in one direction and is characterized by the use of metal pieces to connect beams and columns and a wood frame on top of the column to receive the beam.

Type fourth type (Figure 7d) consists of a wooden interconnection that enters beam and column elements in cavities specially developed for the purpose. The design of the wood elements that go inside the beam is conceived to be deformed according to deflection and avoid stress points on ceramic components.

For all previously mentioned types, the components positioned next to the connections are reinforced with concrete inside. The wood material used is birch plywood considering its bidirectional fibers and uniform composition, by opposition to natural raw materials.

4. RESULTS AND DISCUSSION

The developed system, the principles that rule it and the set of practical results obtained during the prototyping of the various models, renew the conviction that it is possible and feasible to produce medium-scale ceramic architectural components and their subsequent application in a real context, redefining the built environment, making it more consistent and environmentally friendly.

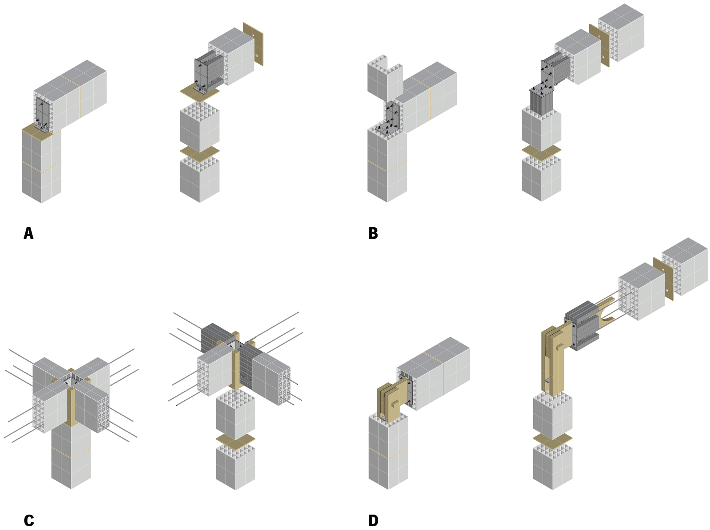

Figure 7
Types of connection between beams and columns. A - first type; B - second type; C - third type; D - fourth type.

The results obtained during the compression tests presented in 3.1. clearly show the potential of using this material in structures with bearing capacity (Figure 8). Based on the values achieved by concrete, the most used material for the construction of supporting structures, we realize the enormous difference in the capacity that exists between both ceramic and concrete. Even without the introduction of elements to separate ceramic pieces, as are the cases of C2 (approx. 80mm height) and C3 (approx. 120mm height), respectively with two and three stacked components, which could reduce drastically the capacity of the ceramic set, the resistance values (in MPa) were substantially higher than those presented by the equivalent concrete specimens, CM/CH80 and CM/CH120.

Also, the results obtained from test pieces that used rubber (C2R1/C3R2) and acrylic glue (C2A1/C3A2), as a separating element between ceramic pieces, show the instability that these two materials give to the system by causing accentuated deformations and misshapen settlements, leading to total rupture of the ceramic pieces. In contrast, the materials studied by specimens C2M1/C3M2 and C2W1/C3W2, respectively mortar and wood, present very positive values in the way they avoid part of the weaknesses of the ceramic material and can present resistance values higher than those presented by concrete specimens.

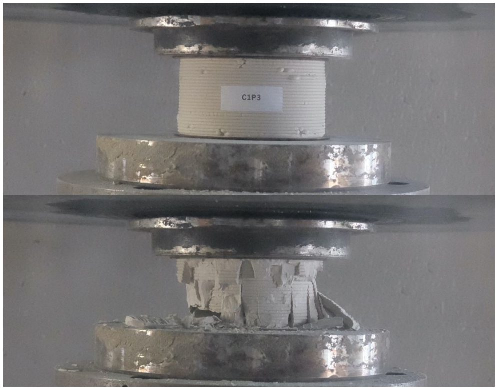

Figure 8
Example of the compression tests carried out during the research.

Regarding the tests of shell geometry and internal structure to be applied to each component, it is important to report the deformations presented by the test pieces that use linear elements as being quite expressive which, in some cases, as reported by Figure 9, lead to the uselessness of the component, under pain of compromising the structural integrity of the system.

As future work, looking to the conclusion of the present study, we aim to carry out the remain listed tests, namely regarding the definition of the geometry of each component and effective full-scale test of the complete system.

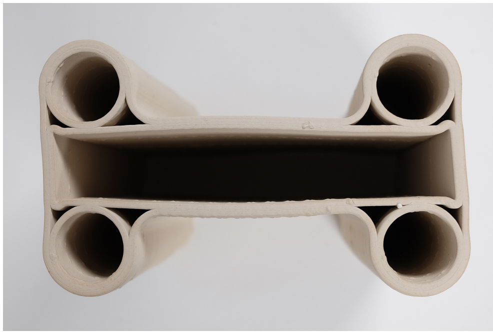

Figure 9
Beam component exploring the use of linear shell and with cavities for the introduction of wood connection elements and post-tensioning steel cables. Here is possible to see the deformations after firing.

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Table 1
Complementary material compression test results.

Code	Test probe	Connection Heigh [mm]	Connection Section area [mm2]	Average Load [KN]	Standard Deviation [MPa]	Standard Deviation [%]	Average Load [MPa]
C1	Ceramic [1]	0	1870	313,1	12,9	7,7%	167,4
C2	Ceramic [2]	0	1870	120,1	15,8	24,6%	64,2
C3	Ceramic [3]	0	1870	57,5	8,5	27,7%	30,7
C2M1	Ceramic [2] & Mortar [1]	3	1870	78,2	8,8	21,1%	41,8
C3M2	Ceramic [3] & Mortar [2]	6	1870	78,2	8,3	19,9%	41,8
C2A1	Ceramic [2] & Acrylic adhesive [1]	1	1870	67,7	8,1	22,4%	36,2
C3A2	Ceramic [3] & Acrylic adhesive [2]	2	1870	71,5	5,1	13,4%	38,2
C2R1	Ceramic [2] & Rubber [1]	2,75	1797	80,3	8,4	18,8%	44,7
C3R2	Ceramic [3] & Rubber [2]	5,5	1797	51,0	6,4	22,5%	28,4
C2W1	Ceramic [2] & Wood [1]	6,08	1690	165,3	5,9	6,0%	97,8
C3W2	Ceramic [3] & Wood [2]	12,16	1690	128,0	28,7	37,9%	75,7
C2C80	Ceramic [2] & Concrete [80]	1 (acrylic adhesive)	1870	189,0	10,8	10,7%	101,1
C3C120	Ceramic [3] & Concrete [120]	1 (acrylic adhesive)	1870	124,3	12,0	18,0%	66,5
CM80	Concrete Massive [80]	no connection	5026	129,1	6,3	24,5%	25,7
CM120	Concrete Massive [120]	no connection	5026	107,3	3,7	17,4%	21,3
CH80	Concrete Hollowed [80]	no connection	2211	47,5	3,3	15,3%	21,5
CH120	Concrete Hollowed [120]	no connection	2211	40,3	6,4	35,2%	18,2

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