



Two Year Exposure of 3D Printed Cementitious Columns in a High Alpine Environment

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Abstract. While digital fabrication technologies with concrete have focused primarily on process development and compressive strength in terms of performance, more recently studies evaluating the durability performance of 3D printed cementitious materials have started to appear. To date, however, no field performance assessments have been published regarding 3D printed cementitious materials. In this study, we present the condition of bespoke 3D printed columns that have been exposed to the high alpine environment of Riom-Parsonz, Switzerland, for a period of two years. Damage levels are variable from column to column, often appearing as vertically oriented cracks that can also track along weak layer interfaces. The damage is conjectured to be linked primarily to freeze-thaw damage and/or thermal or differential shrinkage strains. The link between column design and damage is discussed in depth, in particular as it relates to the current predominant use case of 3D printed cementitious materials as a lost formwork.

Keywords: 3D printing · Digital fabrication · Concrete · Durability · Field exposure

1 Introduction

The recent interest in digital fabrication with concrete, on an academic and industrial level, has led to a growing number of practical applications and demonstrations of the technology in the real world [1]. Much research attention until now has been focused, understandably, on process development to ensure successful production of digitally fabricated structures. The link between processing, properties, and performance, however, is also of vital importance, and in this sense, most performance related research of digitally fabricated concrete has focused predominantly on the property of strength, and especially the anisotropy that can be induced by the process [2]. No less important, however, is the performance with respect to durability.

Of prime importance in any reinforced concrete structure when it comes to durability is the protection of the steel reinforcement from agents that can lead to corrosion, thus the transport properties of the cover layer of concrete must be understood to predict when corrosion could be initiated. Until now, because of difficulties introducing traditional

steel reinforcement bars into printing processes, the layered extrusion method has been used primarily to print lost formworks, in which hollow cores are printed where steel reinforcement is inserted and structural concrete is later cast [1]. This raises interesting questions of using the printed concrete not just structurally but also as a “durability” layer to help protect the steel reinforcement (for example, from carbonation). It is clear that the layer-by-layer fabrication method has the potential to introduce “channels” where transport is enhanced, as has been determined in some studies [3, 4]. Additionally, a recent study has demonstrated worse behavior of printed concrete with respect to cast concrete in terms of freeze-thaw performance [5].

Until now, field studies of printed structures are nonexistent, due to the paucity of their existence until just a couple years ago. We present here a first look at field performance of 9 structural scale printed components exposed in a high alpine environment after two years. These structures represent the typical use case of a lost formwork and can already give some insight into how the component construction design, material, and process can have critical impacts on the performance.

2 Concrete Choreography

The design, production, and installation of 9 concrete columns for a dancing stage of the Origen Cultural Festival in Riom, Switzerland, has been described in detail elsewhere [6]. The 3D printed material is a cementitious mortar with crushed limestone aggregates ($d_{\max} = 2 \text{ mm}$), printed with a CEM I binder with 8% silica fume and 15% fine limestone substitution accelerated by a ca. 5% substitution of a calcium aluminate cement paste. Each column is approximately 2.7 m in height and each was printed in approximately 2.5 h on a hardened concrete slab.

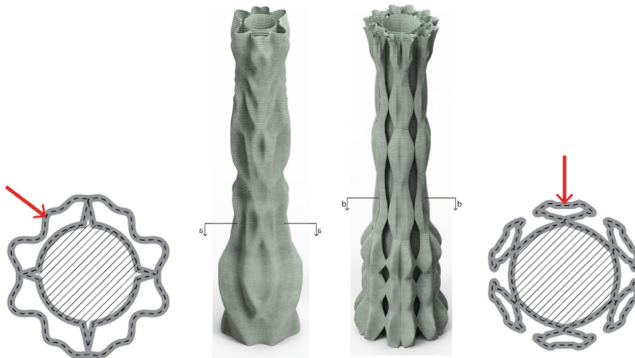


Fig. 1. Column typologies in Concrete Choreography, with example cross section: (left) trigonometric function design engine, and (right) mesh subdivision design engine. The central dashed and circular section indicates the part into which structural concrete was cast.

The columns consisted of a central, circular void (approximately 25 cm in diameter) with an ornamented, aesthetic exterior design based on a computational generative design algorithm. Two design algorithms were used for the columns, one based on

trigonometric functions, and one based on mesh subdivisions, each producing a distinct design typology, noted in Fig. 1. The cross sectional profiles of the design typologies are also seen in Fig. 1, showing how the inner structural core is linked to the decorative exterior for the respective design typologies.

Steel reinforcement cages were inserted and the inner core was cast with a standard C25/30 concrete between 7 and 30 days after printing. Casting took place in two sessions, with half of the core filled first, and the rest of the core filled two days later. The columns were then transported via truck from the production site to their installation site in Riom, Switzerland in early June 2019. The columns were initially left open on the top, accumulating rainfall during the summer of 2019, before having a bituminous layer applied on top to seal them. The bituminous layer has degraded over the two years on certain columns, likely due to wildlife and moisture (Fig. 2).



Fig. 2. Concrete Choreography columns in Riom, Switzerland, in June 2019. (Photo: Benjamin Hofer)

3 Exposure and Damage Observation

3.1 Exposure

Riom is a small community in the Surses Valley of the canton of Graubünden, Switzerland, sitting on the east facing side at an elevation of about 1250 m, surrounded by the 3000 m peaks of the Swiss Alps. Most relevantly, the climate is classified as Dfb in the Köppen classification, typical of the Swiss Alps, with cold, snowy winters and warm summers with distributed precipitation: average highs and lows in January are 1 °C and −8 °C, respectively, and in July, 22 °C and 9 °C. Average snowfall amounts for Savognin, a ski resort town within 1 km of Riom, are approximately 250 cm annually, and total precipitation for the year is approximately 1400 mm. The columns sit on an exposed wooden platform, receiving direct sunlight with little protection from the wind. Snow removal is done manually, without the use of deicing salts.

3.2 Description of Damage

Two trips to record observations of the columns were taken, one in October of 2020 and one in August of 2021. Observations during both trips showed three primary types of damage, with differing levels of severity from one year to the next. The three types of damage were: 1) macrocracks, often vertically oriented, 2) superficial granular disintegration, and 3) efflorescence, sometimes associated to the macrocracking and granular disintegration.

The vertically oriented macrocracks have been observed in the first trip, with a small increase in number on the next trip, depending on the type. These cracks are predominantly associated to the columns that have been designed via trigonometric functions, tend to be closer to the bottoms of these columns, and tend to track within depressions. A particularly severe example is shown in Fig. 3 (left). On the columns of the mesh subdivision typology, macrocracks are much less common, but tend to be associated to the top of the columns (Fig. 3, right), especially where moisture can accumulate. This type of damage is also observed on the tops of some of the trigonometric typologies, but only where the moisture can pool.



Fig. 3. Macrocracking damage observed on columns. (left) Vertically oriented crack near foot of a trigonometric typological column. (right) Cracks near the top of mesh subdivision typological column, in areas where moisture could pool.

Superficial granular disintegration is depicted in Fig. 4 (left). This type of damage is rather widespread on all columns and not generally associated to macrocracking, but is sometimes more severe in specific areas, such as specific layers, and of note is that this particular column suffered a production pause of 45 min where the damage is the highest. Similar to the granular disintegration, efflorescence was observed globally, especially in the first trip. However, strongly localized efflorescence could be observed in some macrocracks, as seen in Fig. 4 (right). A scraping and subsequent analysis of the efflorescence revealed predominantly alkali carbonates. These high concentrations of efflorescence also tended to be associated with darker spots on the cracks of the columns, indicating high local moisture transport.



Fig. 4. (left) Superficial granular disintegration, where filament protrusions can be seen to have eroded. The high damage zone on the bottom is associated with a cold joint. (right) Efflorescence in a vertical macrocrack, with dark zone indicating moisture.

4 Discussion

The observed macrocracking of these columns is most likely due to one of two reasons: 1) thermal or shrinkage cracking, or 2) water pooling and freezing. Both of these mechanisms are most likely at play, depending on the design. For example, large, vertically oriented macrocracks tended to be associated only with the trigonometric typology, and one can see in Fig. 1a that the external shell is rather far from the core, with a very high effective diameter, and only connected by a few “spokes”. As this exterior shell shrinks, its only restraint comes from the concrete slab at the bottom and the “spoke” points. Stresses should tend to concentrate in the depressions and protrusions as well, which is what is observed. All of these observations point to shrinkage cracking as the main culprit in this typology. These cracks did not significantly worsen from the first trip to the second, as well, indicating that most of this type of damage was already completed within the first year, and corresponding to shrinkage processes.

The macrocracking that appears in the mesh subdivision typology, however, is more likely due to freezing. As seen in Fig. 1, there is not an exaggerated exterior shell diameter, so shrinkage stresses are lower compared to the trigonometric typology, and overall these columns are in quite good condition from a macrocracking standpoint. The cracks in the top of the column appear only where water can pool at the top, are only evident in columns with poor coverage of the top bituminous layer, and worsened from one year to the next, indicating a repeated damage process such as freezing and thawing. As a final point on the macrocracking issue, it should be stated that water pooling and freezing at the bottom of the trigonometric typological columns could also be a contributor to the cracking on those columns.

The granular disintegration can possibly be caused by either crystallization of salts, or freeze-thaw damage, but more likely from the latter. Another study has shown that a similar printed mixture to the one of these columns starts showing superficial granular disintegration after about 150 freeze-thaw cycles [5]. With five months where the average low temperature dips below zero in Riom, this amount of cycles can certainly be reached within a year or two. It is also worth noting that this damage was observed to have worsened from one year to the next, indicating a continual degradation from freeze-thaw cycles. Localization of this damage, especially to certain layers, could also indicate a certain dependence of the material properties to susceptibility of this type of damage.

It is possible that certain layers where the production process was not consistent, for example with either too much or too little fluidity, allow for locally susceptible points for damage, as seen in Fig. 4.

The efflorescence indicative of salt crystallization did show some interesting aspects related to moisture transport. The near global presence of efflorescence on all columns indicated that the general movement of moisture out from the core, and localized efflorescence tended to come from areas where moisture accumulated as well, further highlighting the need to understand how design and moisture transport could be inter-linked. Finally, while damage from freezing seems to be the source of the disintegration observed, salt crystallization cannot be completely ruled out as a reason.

5 Conclusion

Overall, the main conclusions that can be drawn from this study are that for printed formwork columns, the design plays an enormous role in durability. Obvious design rules such as minimizing zones of moisture accumulation should be taken into account, but it should also be noted that if printable concrete is acting as formwork, the tendency to shrink on the cast concrete core should be taken into account by proper material matching, or adequate mitigating measures. The connection between processing and durability must also be investigated more thoroughly, especially as tight process requirements tend to limit certain fixes, such as adding an admixture.

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