UHP-FRC for Architectural Structural Columns with Non-Euclidean Geometries

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Abstract: Columns articulated by non-Euclidean geometries offer a new type of architecture with formal and structural possibilities. Specifically, branching concrete columnar structures offer a unique opportunity to merge biomimetic structural geometry with new computationally controlled performance criteria. Typical plain concrete does not willingly lend itself to these types of geometries due to its brittle nature and sensitivity to stress concentration. The non-Euclidean geometries also make the conventional reinforcing methodology difficult to be practically implemented. In the work shown in this research, the introduction of ultra-high-performance fiber reinforced concrete (UHP-FRC) allows for a new way of advancing beyond some of the limitations of conventional construction methods which use reinforced concrete. UHP-FRC provides very high compressive and tensile strengths and ductility against compressive forces; moreover, with these mechanical properties, conventional reinforcement can be nearly eliminated. In addition, UHP-FRC's high flowability allows it to easily satisfy the challenging geometry requirements. The formwork used for these columns presents a unique solution for assembling 2D materials in complex 3D forms. In this research, the two-legged and three-legged branching and twisting scaled columns all rely upon developable geometry that has been cut via a CNC machine out of 1/16th inch polypropylene. The parts are seamed together by hand via a 'zipper' connection that is the result of running an algorithmic script on the edge geometry of each edge of adjoining parts. The control of this script is performed through the computational software that facilities to development of the hexagonal cross-section. The alternating tabs lock into place the adjacent edges into place to ensure that no moisture or concrete mix can escape through the formwork seams. This paper discusses the progress of this novel UHP-FRC application and the experimental testing results of these columns designed with non-Euclidean geometries.

Keywords: Columnar Branching, Biomimicry, Semi-rigid Formwork, Ultra-high-performance Fiber-Reinforced Concrete

1. Introduction

The past 125-year history of architectural structural concrete systems has introduced a range of explorations into non-Euclidean geometries. This exploration is a result of both stylistic design choices as well as structural optimization investigation. From architects like Antonio Gaudi to Miguel Fisac and from Felix Candela to Pier Luigi Nervi, modern architecture pioneers have laid the foundation for the current context of structural innovation (Ceccato, 2012). One of the earliest pioneers, such as Antonio Guadi, worked with analog methods of testing and predicting eccentric loading outcomes of non-Euclidean geometries by using weighted string and chain models (**Fig. 1**). This approach allowed for 3D analysis to lead to maquettes (models built to scale) used to illustrate design intention to masons and fabricators.


(a)

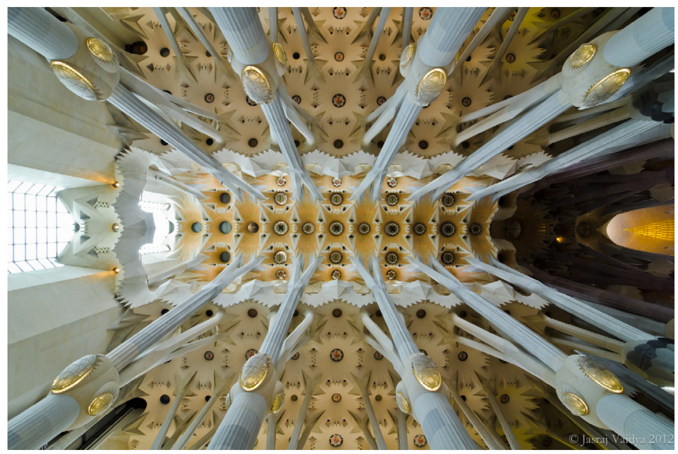
(b)

Figure 1. (a) String model of Sagrada Familia Cathedral by Antonio Guadi; (b) Interior ceiling showing branching columns of Sagrada Familia Cathedral

With the more recent introduction of computational toolsets, the increased capacity to quantitatively control and precisely optimize the performance of structural systems is now providing a very important area of research and exploration. As this relates to non-Euclidean geometry, there is an interest in exploring forms that may have a greater capacity of strength and efficiency as a result of modeling from biological references. As Branko Kolarevic has succinctly summarized, the history of architecture is a record of building what we could draw and with the introduction of new digital tools, we are now able to draw, analyze, and build much more complex geometry (Koleravic, 2003). One outcome, for a particular subset of designers within the field of architecture, is what is being termed biomimetic design or biomimicry (Benyus, 1997). Architects, engineers, and designers recognize the potential of the natural systems at work around them and have implemented design strategies to pursue performance driven outcomes that lead to new geometric possibilities. In this regard aesthetic and formal outcomes are not a stylistic agenda but rather are a byproduct of criteria linked to the rules governing biological form generation and structuring.

Specifically, branching concrete columnar structures offer a unique opportunity to merge biomimetic form with structural geometry by implementing computationally controlled performance criteria. Because of advancements in the software used in the design and development process, precision of geometry or the ability to understand forces associated with asymmetrical loading, are no longer limited. Architects and engineers are now able to create digital models that will simulate loading patterns, material properties, and apply a physics engine calculation in order to derive optimized structural performance. In the case of columnar design, the geometric outcomes are now a byproduct of a range of parametric factors. What continues to make construction and fabrication challenging is not the formal generation or the analytical calculation, but rather the reinforcement fabrication when pursuing a standardized construction process. Typical reinforced concrete methodology does not easily lend itself to these types of geometries. Certainly it is possible to bend rebar into position, however, the pursuit of very precise bending along spline curves and the desire for a minimal cross section in the columnar pieces makes any rebar adjustments very challenging As a result, one must either change the material composition or the standard reinforcing methods. In the work shown in this research, the introduction of UHP-FRC allows for new ways to advance beyond some of the limitations of conventional construction methods which use reinforced concrete. The uniform qualities of the UHP-FRC provide very high strength against compressive forces – to the extent that no additional reinforcements are needed.

2. Column Specimen Fabrication and Experimental Program

2.1. Column Fabrication

This research illustrates the use of non-traditional fabrication techniques implementing UHP-FRC to produce non-Euclidean branching columnar structures. The formwork was developed by the Yogiaman Tracy (YO-CY) Design Team from the Singapore University of Technology and Design in collaboration with the Digital Architecture Research Consortium (DARC) at the University of Texas at Arlington. This formwork presents a unique solution for assembling 2D materials in complex 3D forms. In this instance, the two-legged and three legged branching and twisting columns all rely upon developable geometry that has been cut via a CNC machine out of 1/16th inch polypropylene. The parts are seamed together by hand via a ‘zipper’ connection that is the result of running a programming script on the edge geometry of each edge of the adjoining parts. The control of this script is performed through the computational software that helps to develop the hexagonal cross-section. The alternating tabs lock into place at the adjacent edges to ensure that no concrete mix can escape through the formwork seams. Both the edge connection detail and the hexagonal cross section ensure that accurate and developable geometry can be produced. The only additional component necessary is a wooden box scaffolding which, serving as a temporary exoskeleton, braces the semi-rigid plastic formwork during the casting process; this exoskeleton is removed within the first 20 hours after the cast is completed (**Fig. 2**).

(a) (b) (c)

Figure 2. (a) CNC cut 2D polypropylene parts ready for assembly; (b) Assembly detail of hexagonal cross-section; (c) Bifurcated column inside of wood box scaffolding

This fabrication methodology was first developed and tested by the YO-CY & DARC teams on a previous full-scale piece done in 2014. The results of this initial prototyping provided the groundwork to understand both the possibilities of the formwork and the inherent complexities and challenges presented in the internal reinforcement. For the 2014 prototype, laser-cut steel provided the structural reinforcement. The centerline geometry of the entire piece was processed as a tensile network of lines. These lines were translated into laser cut steel profiles that could interlock and provide exact 3D branching configurations able to be wrapped by the assembled polypropylene molds (Tracy et al., 2014) (**Fig. 3**).

(a) (b)

Figure 3. (a) Formwork during assembly; (b) Final prototype after formwork was removed

2.2. UHP-FRC

As a means to examine the potential of implementing UHP-FRC into the formwork methodology and thereby eliminating the need for the internal reinforcement, a series of cross sectional profiles were produced to so that a testing and production sequence could be evaluated. The five casts (**Fig. 4**) have a range of X/Y configurations; yet, all employed the same hexagonal branching cross section and all maintained a height of three feet. The casts simplify the bifurcation and twisting that were found in the larger piece as shown in **Fig. 3**. The cast also allowed structural testing of the material strengths relative to the geometry to be more precisely isolated. The columns were made at a scale of approximately 1/4~1/5 the size of the actual columns. The UHP-FRC used in this research was developed based on the dense particle packing concept at the University of Texas at Arlington. It had 3% by volume straight steel fibers (12.5 mm long and 0.175 mm dia.) and a tensile strength of 2200 MPa). The UHP-FRC also had a compressive strength of about 22 ksi [150 MPa]) with excellent flowability.

Figure 4. Five different columns with various non-Euclidean geometries and UHP-FRC

2.3. Finite Element Analysis

A finite element study using ABAQUS Software was carried out to determine the potential failure locations. The model used a conventional plain concrete without reinforcing bars. A concrete compressive strength of about 8000 psi (55 MPa) was used, and the concrete section was assumed to be homogeneous with a Poisson ratio of 0.18. A 3-D nonlinear analysis was used in the model to consider the material nonlinearity of concrete. The mesh size was 1.0-in. (25.4 mm) with tetrahedral elements. Due to irregularity in the geometry, the free-mesh technique was used. The damage plasticity of concrete in compression and tension was also considered. The loading was applied by using the displacement-control technique, which is more stable for the analysis compared to the load-control technique. **Fig. 5** shows that the initial concrete cracking, starting at a very low load of 2.2 kips (9.8 kN), at the locations near the junction of the three legs. On the other hand, the top of the three legs and the narrow region of the upper column are subject to the largest compressive stresses. While reinforcing bars are needed in the plain concrete column, no reinforcing bars were used in the UHP-FRC column specimens to investigate UHP-FRC's load-carrying capacity.

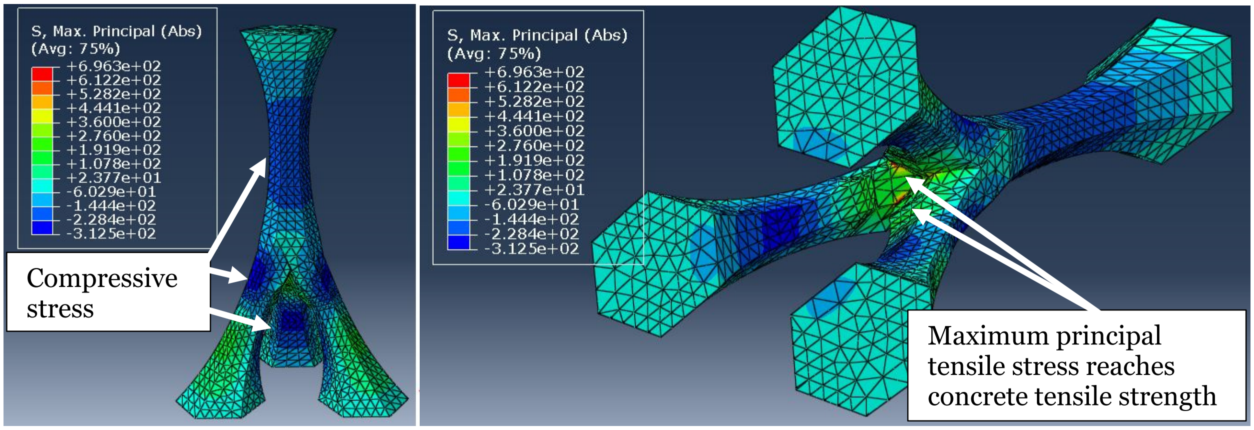

Figure 5. Finite element model and analysis result of three-legged columns

All columns were tested monotonically by a hydraulic cylinder up to failure. The full field strains of the column specimens were measured by a digital image correlation (DIC) system (**Fig. 6**).

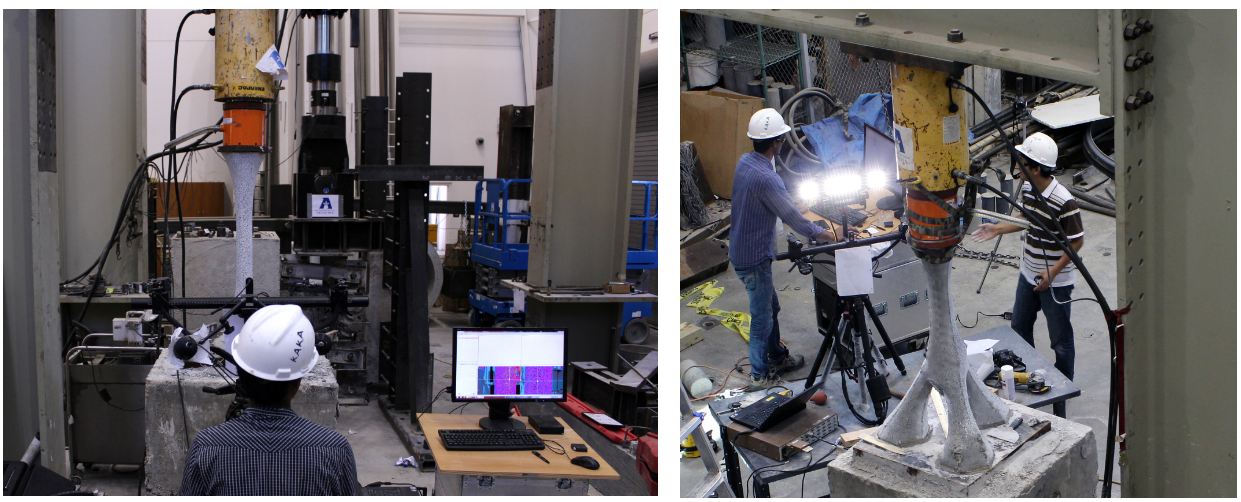

Figure 6. Load testing at UTA CELB: Column #1 (left) and Column #3 (right)

3. Experimental Results

Test results of Column #1 and Column #3 are summarized in this paper.

The detailed dimensions and measured strains of Column#1 are shown in **Fig. 7**. This column has a varying cross section with the narrowest section near the mid-height of the column. This column was able to carry an ultimate load of 160 kips (710 kN). This load is corresponding to a compressive stress of about 22 ksi (150 MPa). **Fig. 7** also shows that the column had a greater stiffness than that measured from cubes. Failure was due to the concrete crushing at the mid-height (**Fig. 9a**) where had the maximum compressive strains were measured by the DIC (**Fig. 7**). After crushing the fibers could still kept the fractured pieces together.

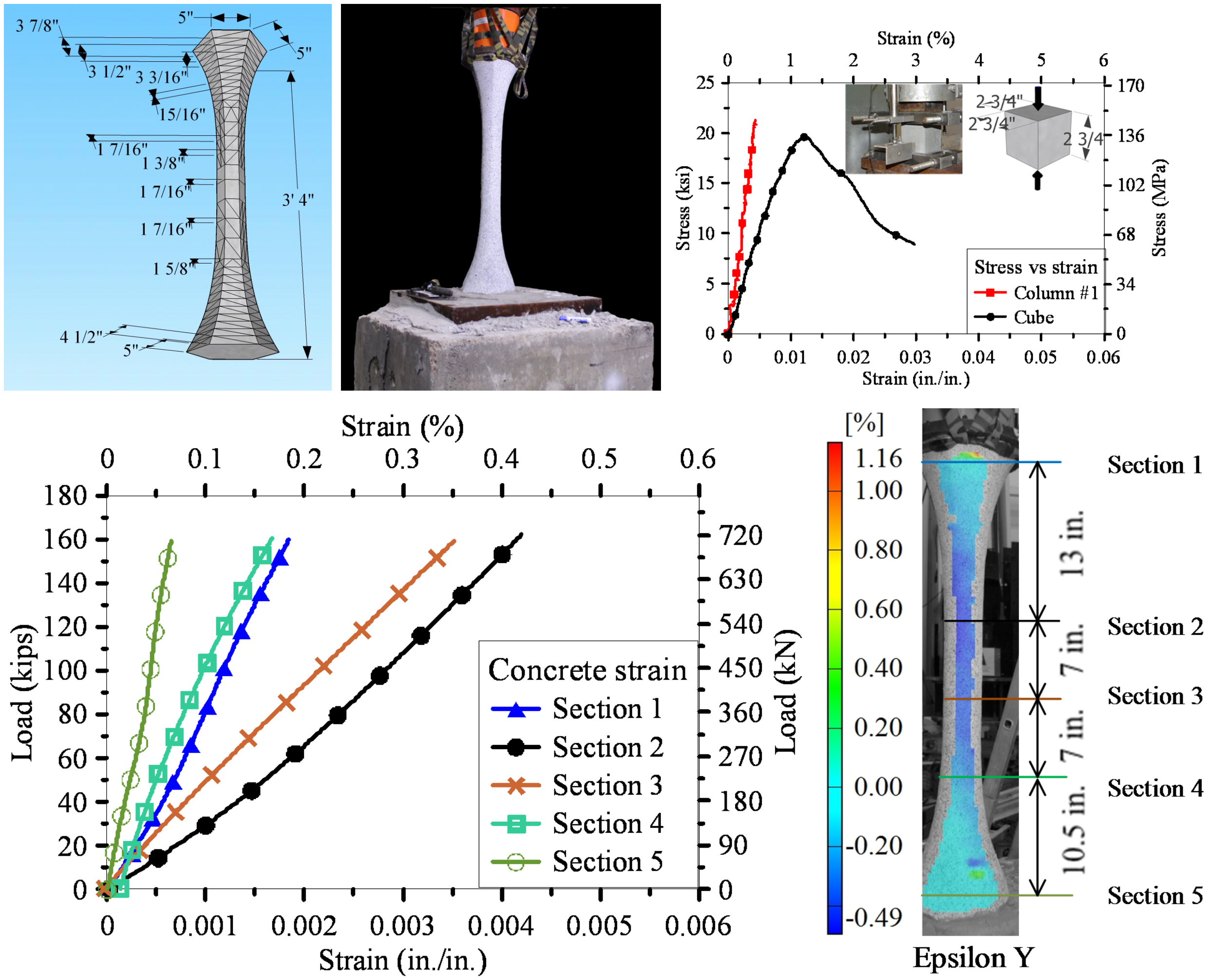

Figure 7. Summary of experimental results: Column #1

The detailed dimensions and measured strains of Column#3 are shown in **Fig. 8**. This column has a varying cross section at the top portion, with the narrowest section measured at about 20-in. (508 mm) from the top surface. The lower part of the column consisted of three inclined legs having varying cross sections. This column carried an ultimate load of 260 kips (1156 kN). This load corresponds to a compressive stress of about 23 ksi (158 MPa). This column had a greater stiffness than that measured from cubes (**Fig. 8**). Unlike the results at the locations predicated by finite element analysis for normal strength plain concrete, failure was due to the concrete crushing at the narrowest portion of the top column (**Fig. 9b**) which had the maximum compressive strains as measured by the DIC (Section 2 in **Fig. 8**). After crushing the fibers could still keep the fractured pieces together.

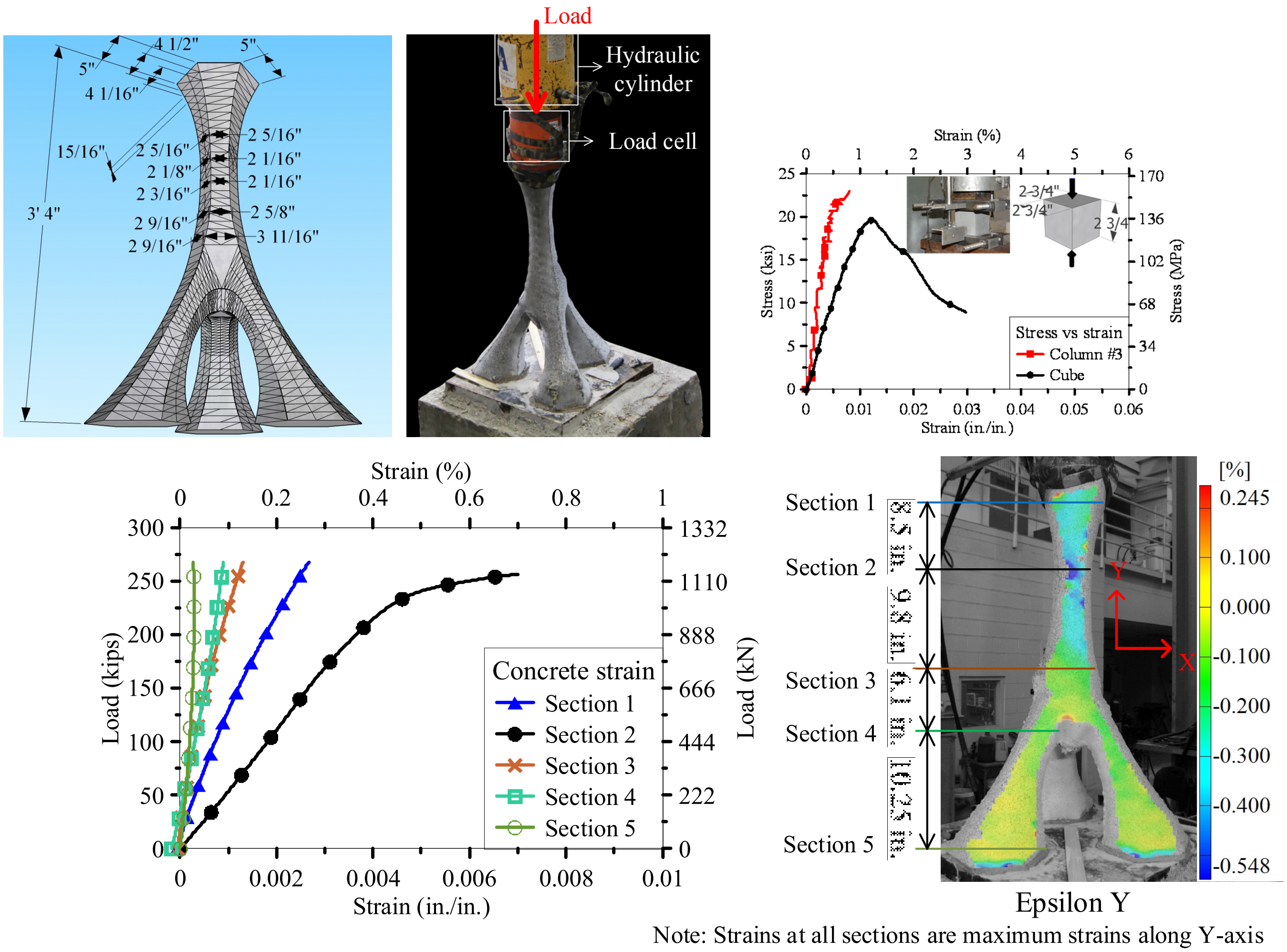

Figure 8. Summary of experimental results: Column #3

(a) (b)

Figure 9. Final failure pattern: (a) Column#1 and (b) Column#3

4. Summary and Conclusions

Columns articulated by non-Euclidean geometries offer a new type of formal and structural possibilities. Specifically, branching concrete columnar structures offer a unique opportunity to merge biomimetic structural geometry with new computationally controlled performance criteria. Typical plain concrete does not willingly lend itself to these types of geometries due to its brittle nature and sensitivity to stress concentration. The non-Euclidean geometries also make the conventional reinforcing methodology difficult to be practically implemented. In the work shown in this research, the introduction of ultra-high-performance fiber reinforced concrete (UHP-FRC) allows for a new way of advancing beyond some of the limitations of conventional construction methods of reinforced concrete. UHP-FRC provides very high compressive and tensile strengths and ductility against compressive forces. With these mechanical properties, conventional reinforcement can be nearly eliminated. In addition, UHP-FRC's high flowability allows it to easily satisfy the challenging geometry requirements.

This research tested five columns with various non-Euclidean geometries. No conventional reinforcement was used in these columns except UHP-FRC. The formwork used for these columns was done by a unique solution for assembling 2D materials in complex 3D forms. A finite element analysis considering plasticity of plain concrete was carried out first to determine the critical locations where the tensile cracks may initiate in the columns. Experimental results indicated that the UHP-FRC did not fail at these critical locations and the failure was all controlled by concrete crushing. This type of failure would fully utilize the ultra-high strength of the UHP-FRC, and thereby considerably increase the load-carrying capacity to five-fold or more compared to columns made of plain concrete. The steel fibers proved capable of keeping the fractured pieces together thereby preventing any possibility of a catastrophic failure.

This preliminary research demonstrated the feasibility of using UHP-FRC in geometrically complex structures, and provides valuable information showing a new proximity toward the realization of biomimetic structural geometry used in actual applications.

5. References

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6. Acknowledgements

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