*Proceedings of the IASS 2024 Symposium*
*Redefining the Art of Structural Design*
August 26-30, 2024, Zurich Switzerland
Philippe Block, Giulia Boller, Catherine DeWolf,
Jacqueline Pauli, Walter Kaufmann (eds.)

# Exploring Innovative Spatial Structures through Topological Optimization and Snow Material Integration in Cold Climate Construction

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## Abstract

This research delves into advancements in structural design and construction by employing the generative design technique Bi-directional Evolutionary Structural Optimization (BESO) and natural materials in cold climates. The study specifically focuses on harnessing snow materials to create spatial structures that are not only efficient but also elegant. Snow and ice, occurring naturally in cold climates, particularly in the Polar and Northern Hemisphere, present a unique opportunity for integration into the construction process within specified parameters. Given its crystal structure, snow is well-suited for compressive structures in sub-zero temperatures, with a density ranging between 400 and 820 kg/m3. The selection of material property values for designing snow structures is contingent upon factors such as temperature, quality, and load, necessitating a case-by-case approach. The distinctive properties of snow and ice materials can be factored into calculations and construction considerations. The research incorporates topological optimization techniques, widely employed in structural engineering and architectural form-finding, to present an innovative pavilion. This pavilion serves as a tangible outcome, illustrating collaborative efforts between architecture and engineering research groups. The central focus revolves around the application of BESO technology to generate the structure. The design features branches of varying sizes, drawing inspiration from iconic structures such as the interior of Sagrada Familia Basilica by Antoni Gaudi and Shanghai Himalaya Centre by Arata Isozaki. The authors' team manually sculpted the full-scale model of the pavilion at a challenging temperature of minus 25 degrees Celsius, utilizing minimal materials. This meticulous process resulted in a remarkable and innovative structure that captures the essence of nature within the frozen landscape. The key advantages of this novel design and construction methodology lie in the efficient utilization of natural materials and the creation of elegant structural forms.

**Keywords**: Snow Structure; Topology Optimisation; Bi-directional Evolutionary Structural Optimization (BESO); Natural Materials; Innovative Pavilion; Form-finding

## 1. Introduction

Topology optimization has increasingly captured the attention of architectural design for its capacity to yield elegant and lightweight structures with superior structural performance. Over the past two decades, numerous classical topology optimization methods have emerged and found widespread adoption. These include the Homogenization method [1, 2], the solid isotropic material with penalization

(SIMP) method [3, 4], evolutionary structural optimization (ESO) [5, 6], Bi-directional evolutionary structural optimization (BESO) [7, 8], and the level-set method (LSM) [9, 10]. Notably, ESO and BESO have gained prominence in architectural practice, serving as both conceptual design tools and analysis aids. This is evident in practical projects like the Akutagawa River Side in Takatsuki City [11], the Qatar National Convention Centre & Shanghai Zendai Himalayan Art Centre [12, 13], as well as research projects such as the Sagrada Familia [14], the Palazzeto Dellospori of Rome [15], and Chinese rainbow bridges [16]. While these projects predominantly employ traditional architectural materials such as timber, concrete, stone, steel, and composite materials in normal temperatures, there remains a paucity of research and projects that explore topologically optimized designs utilizing snow and ice in cold climates.

Furthermore, while classical topology optimization methods excel in identifying globally optimized solutions across the entire design domain, they frequently encounter objective constraints or subjective preferences that significantly shape architectural form-finding. In response to these non-structural requirements, researchers have devised various modified topology optimization methods tailored to specific objectives. These adaptations encompass introducing detailed constraints for concept design [17], eliminating enclosed voids [18], achieving self-supporting optimized models [19], generating diverse truss structures [20], and simulating leaf morphogenesis [21]. In this snow project, the spatial structures pose distinctive challenges for topologically optimized layouts, necessitating modified BESO algorithms with specialized input parameters for material properties. The unique characteristics of snow and ice materials are carefully considered in both calculations and construction planning. This pavilion stands as a tangible manifestation, showcasing the collaborative endeavors between architecture and engineering research groups. At its core, the project centers on the application of the modified BESO technology, known as the Multi-Volume constraint BESO (MV-BESO) method [22]. This method has been successfully implemented in previous projects such as the X-Form 3.0 timber pavilion [23], as well as the X-Form 1.0 & 2.0 3d plastic printed pavilions [24, 25].

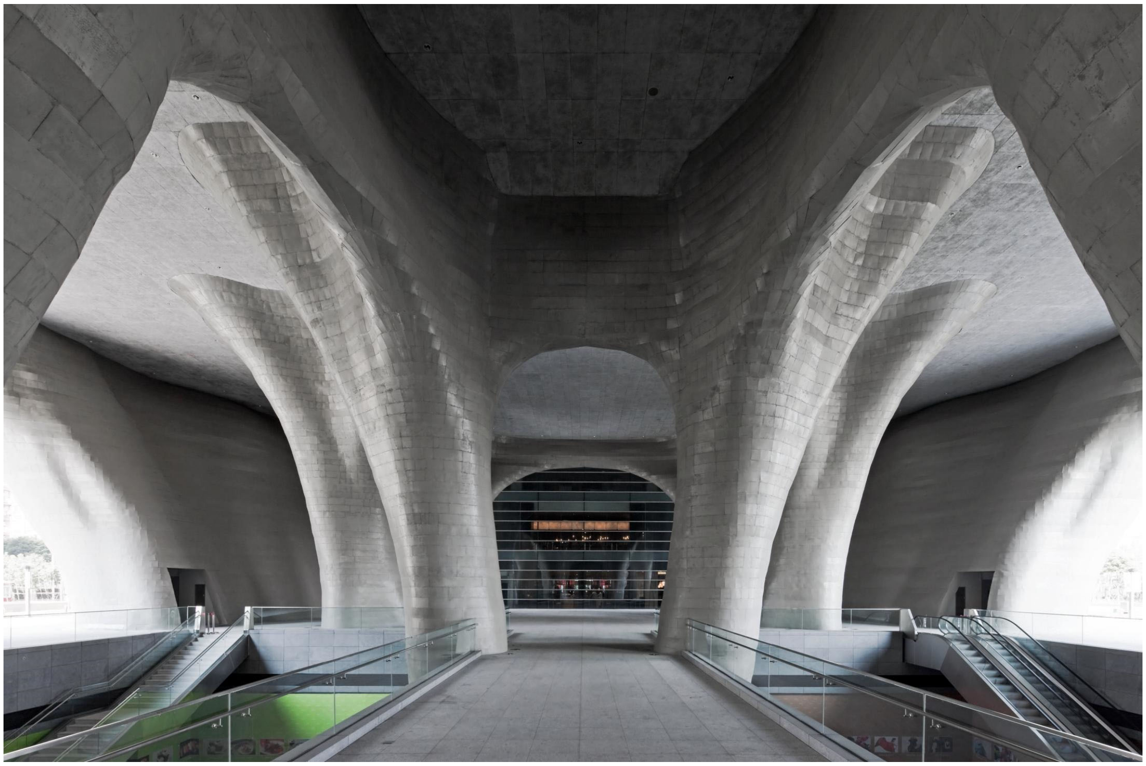

Figure 1: Interior view of Arata Isozaki's Shanghai Himalaya Centre

Drawing inspiration from iconic structures like the interior of Antoni Gaudi's Sagrada Familia Basilica and Arata Isozaki's Shanghai Himalaya Centre, the pavilion design features branches of varying sizes (see Figure 1). To realize this vision, the paper proposes the creation of a new full-scale model of the pavilion under challenging conditions, with temperatures dipping as low as minus 25 degrees Celsius.

This endeavor involves the utilization of the MV-BESO algorithm in conjunction with manual sculpting techniques. The meticulous process yields a remarkable and innovative structure that harmonizes with the frozen landscape, capturing the essence of nature. The key advantages of this novel design and construction methodology lie in its efficient utilization of natural materials and its ability to create elegant structural forms.

## 2. Structural form-finding

### 2.1. Multi-volume constraint BESO method (MV-BESO)

Most conventional topology optimization methods are aimed at achieving the solution which maximizes the structural performance under a certain global volume fraction constraint and always result in continuum solid parts rather than discrete structures. However, in this project, the pavilion form is required to be designed with separated parts to disperse the gravity of the snow. Thus, the Multi-volume BESO method [22] is introduced to optimize the structures with several local volume fraction constraints. The mathematic descriptions of MV-BESO can be written as :

$$min\ \ C(\boldsymbol{X})=\frac{1}{2}\boldsymbol{U}^T\boldsymbol{K}\boldsymbol{U}=\frac{1}{2}\sum_{i=1}^{N}x_i^p\boldsymbol{u}_i^T\boldsymbol{k}_i\boldsymbol{u}_i \tag{1}$$

$$subject\ to\ SUBV_k(\boldsymbol{X}_k)=\sum_{i=1}^{N_k}x_iv_i\le SUBV_k^* \tag{2}$$

in which $C$ , $\boldsymbol{X}$ , $\boldsymbol{U}$ , $\boldsymbol{K}$ are the compliance, matrixes of design varible, displacement, and global stiffness respectively. And $SUBV_k^*$ , $\boldsymbol{X}_k$ and $N_k$ are the local target volume, local design vairable matrix and local element number of *k*-th sub-domain. $v_i$, $x_i$ , $k_i$ and $\boldsymbol{u}_i$ are the volume, design variable, stiffness matrix and nodal displacement matrix for *i*-th element.

For structural stiffness optimization, the *i*-th element sensitivity value $\alpha_i$ can be calculated as the gradient of compliance with respect to the design variable $x_i$ [26],

$$\frac{\partial C(\boldsymbol{X})}{\partial x_i}=-\frac{1}{2}p\boldsymbol{x}_i^{p-1}\boldsymbol{u}_i^T\boldsymbol{k}_i\boldsymbol{u}_i \tag{3}$$

$$\alpha_i=-\frac{1}{p}\frac{\partial C}{\partial x_i}=\begin{cases}\frac{1}{2}\boldsymbol{u}_i^T\boldsymbol{k}_i\boldsymbol{u}_i & \text{when } x_i=1\\ 0 & \text{when } x_i=x_{min}=0\end{cases} \tag{4}$$

The above sensitivity is typically modified to address the mesh-dependency issue [26], employing a filtering scheme:

$$\tilde{\alpha}_i=\frac{\sum_{j=1}^{N}w_{ij}\alpha_j}{\sum_{j=1}^{N}w_{ij}} \tag{5}$$

$$w_{ij}=\max(0,R_{min}-d_{ij}) \tag{6}$$

in which $d_{ij}$ is the distance between *j*-th and the *i*-th element centers. $R_{min}$ and $\alpha_i$ are the filter radius and the original sensitivity of the *j*-th element. To ensure a convergent solution, an additional historical average of in different iterations is introduced [27]:

$$\bar{\alpha}_i=\frac{\tilde{\alpha}_i^{(n)}+\tilde{\alpha}_i^{(n-1)}}{2} \tag{7}$$

In MV-BESO method, for *k*-th sub-domain, the element sensitivities are ranked in each iteration to determine a threshold with local target volumes of next iteration, $SUBV_k^{(n)}$ , which is defined based on the current volume $SUBV_k^{(n-1)}$ and the evolutionary ratio $\delta$ .

$$SUBV_k^{(n)} = SUBV_k^{(n-1)}(1-\delta) \tag{8}$$

The threshold can be used to evaluate if the element shall be changed in a such way that if one solid element's sensitivity is lower than the threshold, its design variable will be switch from 1 to $x_{min}$ , and the design variable of a void element will be changed from $x_{min}$ to 1 as well if its sensitivity is higher than the threshold.

The process of evolution persists until the convergence criterion, which is established based on the changes in the objective functions, is met[27]:

$$\frac{\left|\sum_{i=1}^{N}\left(C_{k-i+1}-C_{k-N-i+1}\right)\right|}{\sum_{i=1}^{N}C_{k-i+1}} \le \tau \tag{9}$$

where $\tau$ (set to 0.001 in this paper) is an allowable convergence error, signifies stable compliance for at least the subsequent 10 iterations.

## 2.2. Topology optimization applied on pavilion design

The pavilion in this project features a centrally symmetric free-form roof with dimensions of approximately 3000mm x 3000mm x 3000mm (width x length x height). Figure 2 illustrates various stages of the MV-BESO stiffness optimization process, ranging from iteration 1 to iteration 80. The Finite Element Analysis (FEA) model comprises 200,000 shell elements, each with a thickness of 10 mm. The snow/ice material properties are assumed to be a Young's Modulus of 830 MPa and a Poisson ratio of 0.35 (at -25 degrees). MV-BESO parameters include an Rmin of 20 mm and an ER of 2%. Local volume fraction constraints are set at 50%. Following 80 iterations, the final optimized structural layout is generated in Figure 1.

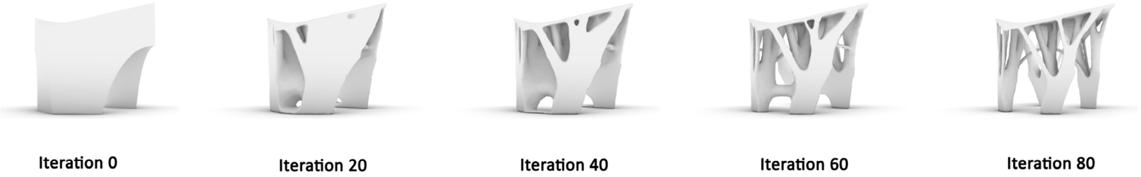

Figure 2: MV-BESO evolutionary history of snow pavilion

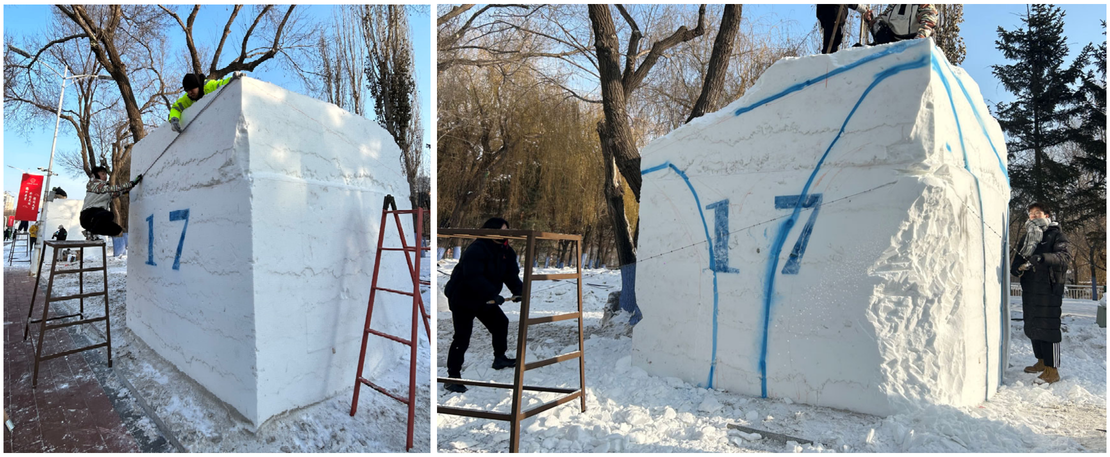

Figure 2: The 3m x 3m x 3m snow cube on the site (left) & trimming roof (right)

## 3. Manual Sculpting for Fabrication

As shown in Fig. 2, the original snow cube boasts dimensions of 3m x 3m x 3m. The initial phase of fabrication commences with the delicate trimming of the roof, a meticulous task accomplished using a specialized snow shovel tool. With a hands-on approach, the authors ascend the snow cube, meticulously crafting the sloped roof to mirror the vision outlined in Iteration 0, as showcased in Figure 1.

Following this shaping, the next step entails delineating the approximate outline of the pavilion. This is achieved through the careful application of blue spray paint, outlining the envisioned shape with precision.

Transitioning to the third phase, the focus shifts to the core structure. A central hole is excavated from the heart of the snow cube, marking the inception of the main supporting columns. These foundational elements are meticulously crafted, laying the groundwork for the framework of the pavilion, while simultaneously refining the rough outline envisioned for the project as shown in Figure 3.

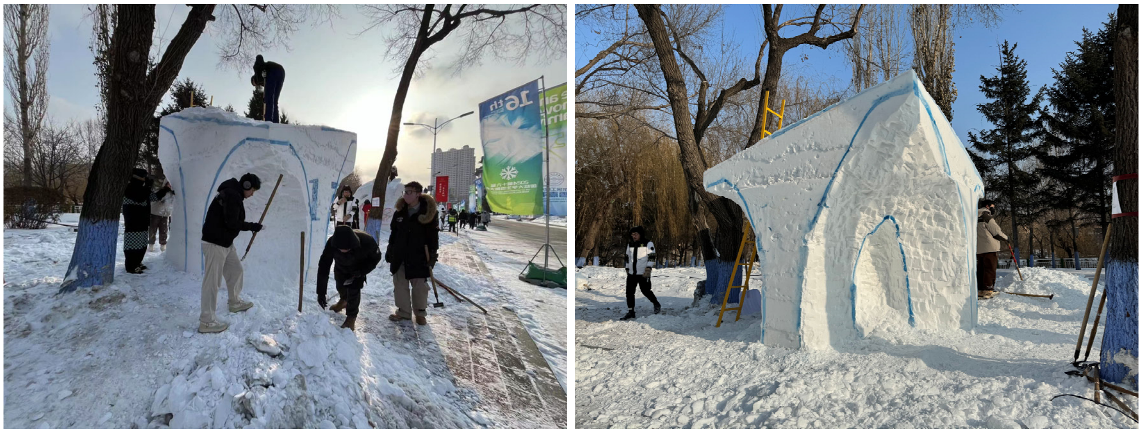

Figure 3: Early stage of sculpting process for creating the basic branch columns

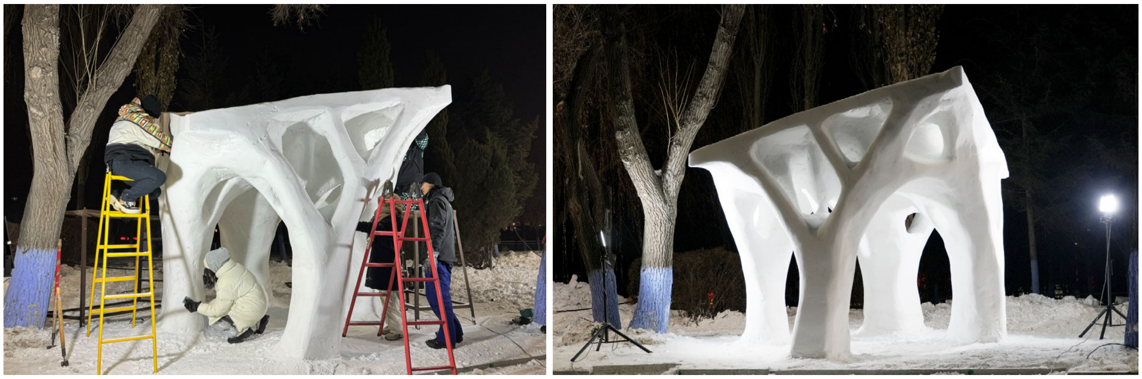

Figure 4: Polishing Process on the left and completed project on the right.

The subsequent phase encompasses meticulous sculpting, a procedure analogous to the iterative topology optimization process, which progresses from the formation of substantial pillars to the generation of intricate bifurcations. Attention to detail is imperative during the sculpting endeavor, given the considerable difficulty associated with rectifying fractures once they manifest. Approximately by the 70th iteration of optimization, the author embarked upon the endeavor of refining the surface through the application of snow polishing tools.

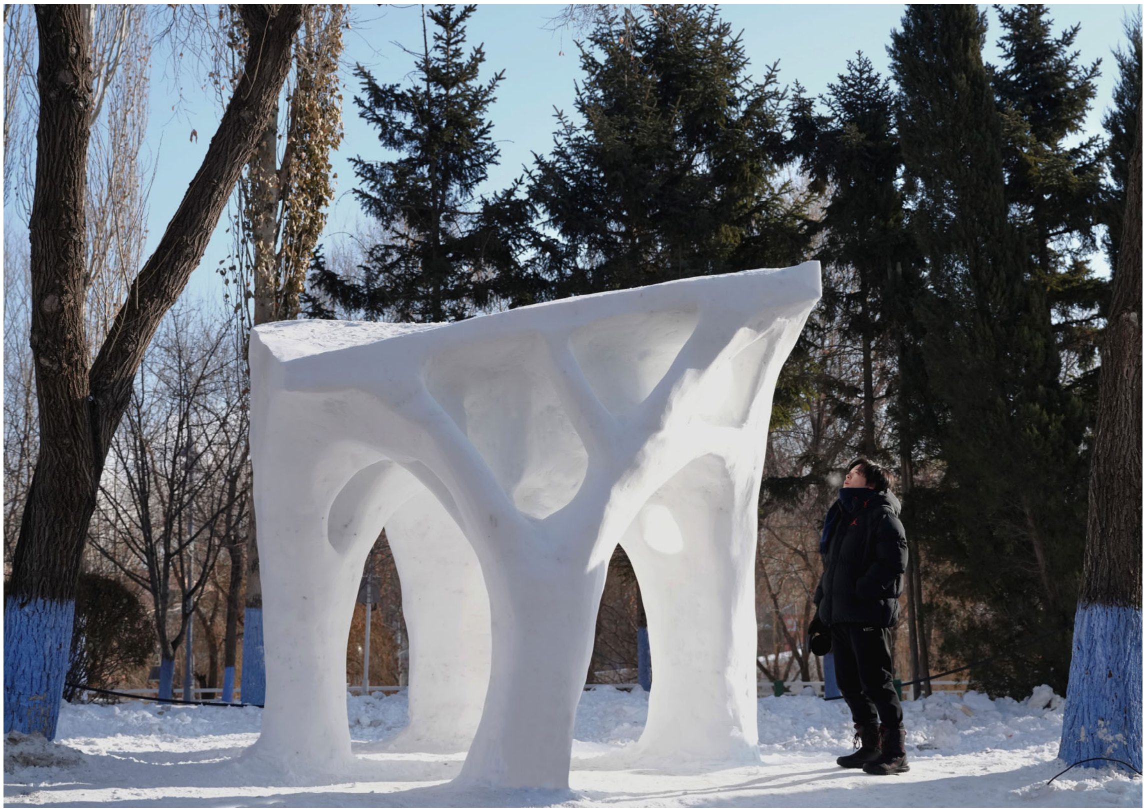

Figure 5: The completed pavilion – The Castle of Snow

## 4. Conclusion

In summary, this research explores the frontier of structural design and construction by leveraging modified Bi-directional Evolutionary Structural Optimization (BESO) alongside natural materials, specifically snow and ice, in cold climates. Through collaborative efforts between architecture and engineering research groups, the study develops an innovative pavilion that embodies efficiency, elegance, and a harmonious blend of natural forms and architectural innovation. By adapting and modifying optimization methods to suit the unique challenges posed by snow and ice, this research not only pushes the boundaries of traditional design methodologies but also underscores the potential for sustainable and aesthetically captivating structures in cold climate regions.

This world's largest topologically optimized snow pavilion serves as a testament to the amalgamation of innovative design and time-honored construction techniques. It elucidates the pavilion's design and construction process by exploring emerging technologies in digital design and subtractive manufacturing. This holds immense significance for architects, engineers, and designers alike, encapsulating a groundbreaking fusion of artistry, engineering, and environmental sustainability.

## Acknowledgements

The authors gratefully acknowledge the financial support provided by the Australian Research Council (IH220100016), the Australian Research Council (FL190100014), and 16th International Snow Festival hosted by Harbin Engineering University in China.

## References

[1] M. P. Bendsøe, "Optimal shape design as a material distribution problem," *Structural optimization,* vol. 1, pp. 193-202, 1989.

[2] M. P. Bendsøe and N. Kikuchi, "Generating optimal topologies in structural design using a homogenization method," *Computer methods in applied mechanics and engineering,* vol. 71, no. 2, pp. 197-224, 1988.

[3] M. P. Bendsøe and O. Sigmund, "Material interpolation schemes in topology optimization," *Archive of applied mechanics,* vol. 69, no. 9, pp. 635-654, 1999.

[4] M. P. Bendsøe and O. Sigmund, *Topology optimization: theory, methods, and applications*. Springer Science & Business Media, 2003.

[5] Y. M. Xie and G. P. Steven, "A simple evolutionary procedure for structural optimization," *Computers & structures,* vol. 49, no. 5, pp. 885-896, 1993.

[6] Y. M. Xie and G. P. Steven, "Optimal design of multiple load case structures using an evolutionary procedure," *Engineering Computations,* vol. 11, no. 4, pp. 295-302, 1994, doi: 10.1108/02644409410799290.

[7] X. Huang, Y. M. Xie, and M. C. Burry, "Advantages of bi-directional evolutionary structural optimization (BESO) over evolutionary structural optimization (ESO)," *Advances in Structural Engineering,* vol. 10, no. 6, pp. 727-737, 2007.

[8] X. Huang and Y. Xie, "A new look at ESO and BESO optimization methods," *Structural and Multidisciplinary Optimization,* vol. 35, no. 1, pp. 89-92, 2008.

[9] M. Yulin and W. Xiaoming, "A level set method for structural topology optimization and its applications," *Advances in Engineering software,* vol. 35, no. 7, pp. 415-441, 2004.

[10] G. Allaire, F. Jouve, and A.-M. Toader, "Structural optimization using sensitivity analysis and a level-set method," *Journal of computational physics,* vol. 194, no. 1, pp. 363-393, 2004.

[11] H. Ohmori, "Computational Morphogenesis: Its Current State and Possibility for the Future," *International Journal of Space Structures,* vol. 26, no. 3, pp. 269-276, 2011.

[12] T. Ito, A. Isozaki, and M. Sasaki, "Morphogenesis of Flux Structure," 2007.

[13] C. Cui, H. Ohmori, and M. Sasaki, "Computational morphogenesis of 3D structures by extended ESO method," *Journal of the International Association for Shell and Spatial Structures,* vol. 44, no. 1, pp. 51-61, 2003.

[14] J. Burry, P. Felicetti, J. Tang, M. Burry, and M. Xie, "Dynamical structural modeling: a collaborative design exploration," *International Journal of Architectural Computing,* vol. 3, no. 1, pp. 27-42, 2005.

[15] X. Yan, D. W. Bao, K. Cai, Y. F. Zhou, and Y. M. Xie, "A new form-finding method for shell structures based on BESO algorithm," in *Proceedings of IASS Annual Symposia*, 2019, vol. 2019, no. 17: International Association for Shell and Spatial Structures (IASS), pp. 1-8.

[16] X. Meng, Q. Zhou, W. Shen, and Y. M. Xie, "Structural and architectural evaluation of Chinese rainbow bridge and related bridge types using BESO method," in *Proceedings of IASS Annual Symposia*, 2018, vol. 2018, no. 2: International Association for Shell and Spatial Structures (IASS), pp. 1-8.

[17] X. Yan, D. Bao, Y. Zhou, Y. Xie, and T. Cui, "Detail control strategies for topology optimization in architectural design and development," *Frontiers of Architectural Research,* vol. 11, no. 2, pp. 340-356, 2022.

[18] Y. Xiong, S. Yao, Z.-L. Zhao, and Y. M. Xie, "A new approach to eliminating enclosed voids in topology optimization for additive manufacturing," *Additive Manufacturing,* vol. 32, 2020, doi: 10.1016/j.addma.2019.101006.

[19] M. Bi, P. Tran, and Y. M. Xie, "Topology optimization of 3D continuum structures under geometric self-supporting constraint," *Additive Manufacturing,* vol. 36, 2020, doi: 10.1016/j.addma.2020.101422.

[20] Q. Cai, L. He, Y. Xie, R. Feng, and J. Ma, "Simple and effective strategies to generate diverse designs for truss structures," *Structures,* vol. 32, pp. 268-278, 2021, doi: 10.1016/j.istruc.2021.03.010.

[21] J. Ma, Z.-L. Zhao, S. Lin, and Y. M. Xie, "Topology of leaf veins: Experimental observation and computational morphogenesis," *Journal of the Mechanical Behavior of Biomedical Materials,* vol. 123, p. 104788, 2021.

[22] X. Yan, Y. Xiong, D. W. Bao, Y. M. Xie, and X. Peng, "A Multi-volume constraint approach to diverse form designs from topology optimization," *Engineering Structures,* vol. 279, p. 115525, 2023.

[23] X. Yan, D. W. Bao, C. Ren and Y. M. Xie, "Constructing topologically optimized spatial structure using innovative mortise-and-tenion joints," in *Proceedings of IASS Annual Symposia*, 2023 International Association for Shell and Spatial Structures (IASS), pp. 1-12.

[24] D. W. Bao, X. Yan, R. Snooks, and Y. M. Xie, "Design and construction of an innovative pavilion using topological optimization and robotic fabrication," in *Proceedings of IASS Annual Symposia*, 2019, vol. 2019, no. 5: International Association for Shell and Spatial Structures (IASS), pp. 1-8.

[25] D. W. Bao, X. Yan, and Y. M. Xie, "Fabricating topologically optimized tree-like pavilions using large-scale robotic 3D printing techniques," *Journal of the International Association for Shell and Spatial Structures,* vol. 63, no. 2, pp. 122-131, 2022.

[26] X. Huang and Y. M. Xie, *Evolutionary topology optimization of continuum structures: methods and applications*. John Wiley & Sons, 2010.

[27] X. Huang and Y. M. Xie, "Convergent and mesh-independent solutions for the bi-directional evolutionary structural optimization method," *Finite Elements in Analysis and Design,* vol. 43, no. 14, pp. 1039-1049, 2007, doi: 10.1016/j.finel.2007.06.006.