ARCHITECTURAL TOPOLOGICAL FORM-FINDING INTEGRATING SOLID AND FLUID STRUCTURAL PERFORMANCES

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Abstract. With the recent developments of digital architecture techniques, performance-based optimisation has been an essential topic in architecture design. Using Finite Element Analysis (FEA) and structural topology optimisation algorithms, designers can easily generate architectural forms with high mechanical performances and unique elegant shapes. Comfortable and pleasant architectural microenvironments can also be designed with Computational Fluid Dynamics (CFD) techniques. However, the architectural form-finding method integrating the above two aspects remains a current research hotspot with room for further exploration. This paper presents an innovative Fluid-Structure-Interaction (FSI) topological optimisation workflow for optimising architectural forms based on both inner solid and surrounding fluid mechanics. This framework consists of three basic parts: (1) fluid-structure interaction (FSI) analysis of buildings and their surroundings, (2) automatic modelling of building forms & surrounding environments, and (3) architectural evolutions referred to gradient-based theory. The research aims to construct an innovative architectural morphological topology optimisation algorithm based on the integration of solid and fluid structural performances. The method also shares the potential to coordinate the diverse architectural physical requirements in the form-finding process for complex building contexts, which holds significant practical potential in architectural and urban design.

Keywords. Topology Optimisation, Solid Structural Performance, Fluid Structural Performance, Fluid-structure Interaction, Form-finding.

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1. Introduction

The advancement of computational technology has provided architects and engineers with numerous digital performance analysis tools. However, normal architectural designs usually require analysis and simulation based on existing architectural form drafts. Given correct decisions during the early stages of design significantly impact future energy consumption and construction costs, the simulation should shift from "posterior" analytical tools to "anterior" generative tools (Lin, 2019).

Currently, significant advancements in computational capabilities have led to substantial developments in performance-based architecture form generation. But most of them are always developed for several specific issues based on some certain digital platforms, rather than the synchronous comprehensive considerations of the diverse complex physical architectural form requirements. As a complex project, architectural forms should be a negotiated result that is generated with the comprehensive consideration of multi-physical fields and these fields can always be divided into building inner solid field and surrounding fluid field. Thus, the classical working flows with diverse professional analysis platforms fail to effectively achieve accurate form-finding results with synchronous and collaborative analysis of multi-fields.

As the two famous general numerical analysis techniques for static solid objects and dynamic fluid fields respectively, Finite Element Analysis (FEA) and Computational Fluid Dynamics (CFD) are simultaneously introduced into an architectural topological form-finding method using the Fluid Structure Interaction (FSI) method in this paper. This innovative automatic digital architectural topological form-finding method can effectively perform fluid-structure coupling operation, analyse the reciprocal influences between a building and its environment. This research bridges the gap that has historically existed in architectural form-finding methods, which were constrained to single building and solid structural performance. The profound significance of this study is evident in its capacity to analyse and optimize the intricate interactions not only among building clusters but also between architectural entities and their environments within urban contexts.

2. Literature Review

2.1. ARCHITECTURAL TOPOLOGY OPTIMISATION

Based on FEA platforms, structural topology optimisation algorithms recently gain widespread attention due to their abilities to effortlessly generate architectural forms characterized by both high mechanical performance and distinctive elegant shapes. The overarching objective of structural topology optimisation is to determine an optimal primary structural layout while adhering to constraints on material consumption, leveraging principles from computational mechanics. There have been several notable methods applied in architecture design. (Yan et al., 2022; Yan, Bao, Xiong, et al., 2023) propose several detail control strategies to pre-design architectural forms in topology optimisation. (Li & Xie, 2021) introduces multi-material constraint into BESO method to separate tension and compression structures in architecture design. The works of (Ohmori, 2011) and (Sasaki et al., 2007) have been instrumental in assisting numerous Japanese architects in designing various building forms through their extended evolutionary structural optimisation (EESO) method. Other notable contributions include the introduction of the BESO method in (Bao et al., 2022; Duan et al., 2023; Ma et al., 2023; Yan et al., 2019; Yan, Bao, et al., 2023), aimed at achieving diverse building structures and fabrications. (Xie, 2022) has also proposed generalized versatile multi-directional control approaches for architectural design.

However, most of the above researchers aim to find the optimal architectural form design with high solid mechanical performance using unchangeable mesh models and static mechanical analysis only referred to the physical building bodies. This limitation significantly impacts the applicability in collaborative research involving architectural and environmental considerations.

2.2. ENVIRONMENTAL PERFORMANCE BASED FORM FINDING

The building's outer environments are intangible and variable fields that require CFD techniques that can effectively deal with fluid analysis and thermal radiation. In these fields, various scholars from architecture-related disciplines have employed diverse techniques for studying different design objects. The wind environment analysis techniques and low-speed wind tunnel experiment platform are considered a crucial tool for analysing architectural wind environments (Yuan et al., 2021). (Song & Yuan, 2021) has integrated CFD technology with parametric modelling tools, machine learning, and other digital techniques to develop architectural design methods focused on wind environments.

However, constrained by specific architectural simulation platforms, existing research predominantly revolves around interconnecting data from various platforms for diverse building performances to establish workflows, which still encounters certain limitations in terms of computational efficiency and diversity of generated solutions. Although (Feng et al., 2022) develops an evolutionary working loop necessitating manual data transfer across various platforms, the manual processes and rudimentary calculation models have proven to be inefficient and imprecise. These inherent limitations have impeded their practical application in real architectural design contexts.

2.3. COMPUTATIONAL GEOMETRIC MODELLING

In this study, a distinctive difference compared to conventional topology optimisation methods is the dynamic adaptation of the FEA mesh of the architectural form during the optimisation process. This adaptation allows the mesh to evolve with the building morphological changes, enabling the synchronous update of the surrounding fluid field at each iteration. Therefore, the additional computational geometric modelling approaches, particularly mesh smoothing and reconstruction, become crucial research directions.

Remeshing involves improving a triangulation from a potentially noisy triangulation or sampled (scanned) data, and this method is useful for polish the surfaces of topologically optimised architecture forms. After FEA and topology optimisation, it is convenient to generate the point cloud on the optimised design, and thus there are mainly four fundamental methods to construct the smooth surface mesh, which are Alpha shapes (Edelsbrunner & Mücke, 1994), Ball pivoting (Bernardini et al., 1999), Poisson surface reconstruction (Kazhdan et al., 2006), and voxel grid (Lorensen & Cline, 1998). The 3D FEA/CFD mesh should be generated based on the 3D mesh filling algorithms (Hang, 2015).

3. FSI based Architectural Form Optimisation Methodology

3.1. ALGORITHM FRAMEWORK

The FSI based Architectural Topology Optimisation (FSI-ATO) method in this paper is composed of three basic parts: (1) FSI analysis of buildings and their surroundings, (2) automatic modelling of building forms & surrounding environments, and (3) topological evolutions referred to gradient-based theory. Fig. 1 illustrates the basic algorithm workflow in this paper. The evolutionary iteration procedure of FSI-ATO is given as follows.

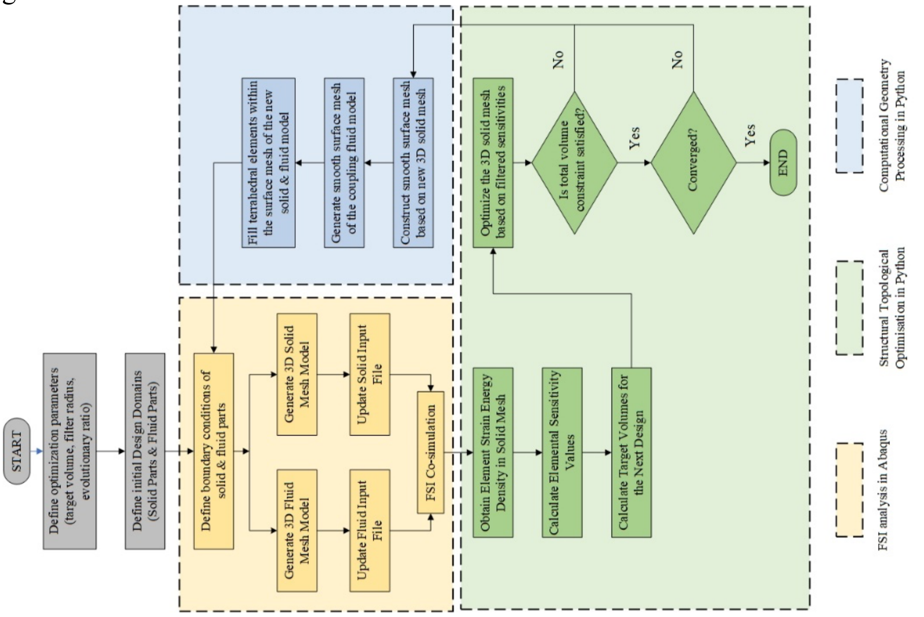


Fig.1 Working flow of FSI-ATO.

3.2. FLUID-STRUCTURE INTERACTION ANALYSIS

Fluid-structure interaction (FSI) refers to the complex interaction between a fluid (liquid or gas) and a structure (solid) that is immersed or interacts with the fluid. It is essential to consider when analysing the behaviour of structures subjected to fluid flow or vice versa. In FSI, the deformation of the structure affects the flow of the surrounding fluid, and, in turn, the fluid exerts forces on the structure. The complexity of these calculations demands a substantial number of simulations and time. For this study, the Abaqus 2016 has been introduced to conduct Fluid-Structure Interaction (FSI) computations effectively.

In Abaqus 2016, the FSI co-simulation is based on two separate modules: the CFD solver and the standard/explicit solver. The computational core will generate two distinct input files for the fluid and solid models respectively, which are also the fundamental data exchange carriers between our python codes and the Abaqus software. The input files contain all the necessary solid/fluid data for FSI, including the mesh information, the boundary conditions, material assumptions, analysis settings, output recording requirements, etc. During the whole evolution process, both the solid and fluid input files update their mesh data and the solid-fluid interface information simultaneously.

3.3. TOPOLOGY OPTIMISATION

Through FSI analysis, the structural mechanical states under the influence of the fluid can be easily analysed. And the structural topology optimisation can be modified according to the multi-volume constraint BESO method (Yan, Xiong, et al., 2023) for optimising multi-building clusters in cities.

According to the BESO theory, the elemental sensitivity numbers α_i, representing how much the element contributes to the structure, can be calculated easily with the FSI output data (e.g., strain energy density, von Mises stress, etc.) as follows,

$$\alpha_i = \sum_{k=1}^{M} w_k^{load} \cdot NS_i^{(k)}$$

$$\sum_{k=1}^{M} w_k^{load} = 1$$

$$NS_i^{(k)} = \frac{S_i^{(k)} - \min(S^{(k)})}{\max(S^{(k)}) - \min(S^{(k)})}$$

where $NS_i^{(k)}$ represent the normalised simulation data of i-th element in k-th loading case, including solid and fluid analysis. And w_k^{load} is the weighting coefficient for k-th load case which is defined according to the project requirements before the evolution and describe how importance the load case is.

Then, the elements with low sensitivity values are removed while the high-sensitivity elements are reserved in the next iteration. Thus, the evolutionary loop stops when the target volume fraction (VF) and following coverage requirements are satisfied,

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

in which k is the current iteration number, τ is an allowable convergence error ($\tau = 0.001$ in this paper), which means stable compliance at least in successive 10 iterations.

One biggest difference between FSI-ATO and classical topology optimsation methods is that the fluid field behaviour can be accurately introduced in optimisation. In conventional topology optimisation like BESO or Ameba software, the only way to simulate the wind load is to simplify the flow pressure with formulas (like uniform distribution or triangular force proportional to the height of the building, etc), which fails to take the eddy current variation and flow interactions between neighbour buildings. However, FSI-ATO method can be used to solve these problems.

3.4. COMPUTATIONAL GEOMETRY PROCESSING

After removing/adding elements, the surface of the solid model tends to exhibit numerous sharp irregularities. These morphological imperfections not only impact the aesthetic appeal and manufacturing complexity but also hinder the flow of surrounding fluids. Therefore, in each optimisation iteration, the optimised architectural mesh needs to undergo a smoothing process.

As shown in Fig. 2(b), topology optimized solid model usually shares sharp angles over the external surface, and thus a Poisson reconstruction smooth method (Kazhdan et al., 2006) is introduced to construct a smooth shell surface for the buildings. After getting the smooth surface mesh of building, its updated surrounding fluid field surface mesh can be easily constructed with the Mesh Boolean Operations. Furthermore, due to both the smooth surface meshes of building and its environment (Fig. 2(c)) only have smooth outer shells without any solid elements inside, a 3D tetrahedral generation method (Hang, 2015) is implemented to fill in the inner space based on the smooth outer surface mesh for the topology optimization evolution in the next step. Subsequently, new tetrahedral computational meshes for both solids and fluids are generated. This ensures the mesh is refined and conducive to fluid flow in the vicinity, contributing to a more visually appealing and manufacturable architectural design.

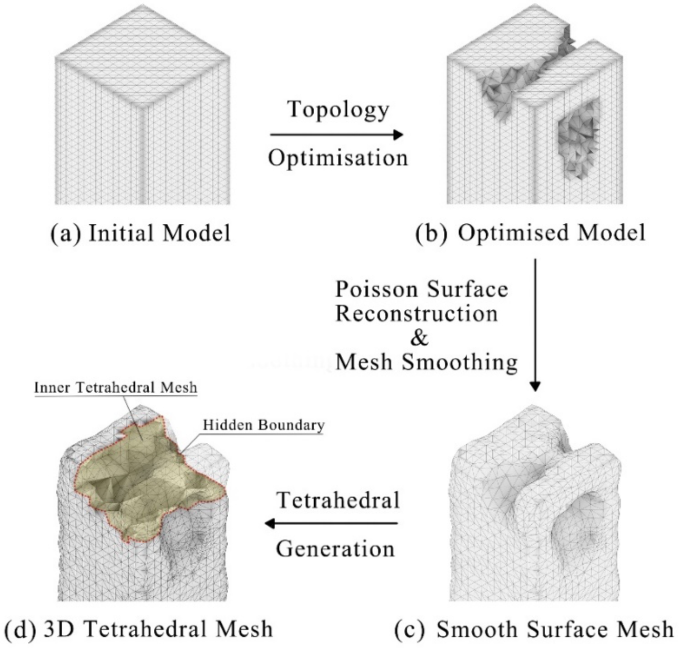
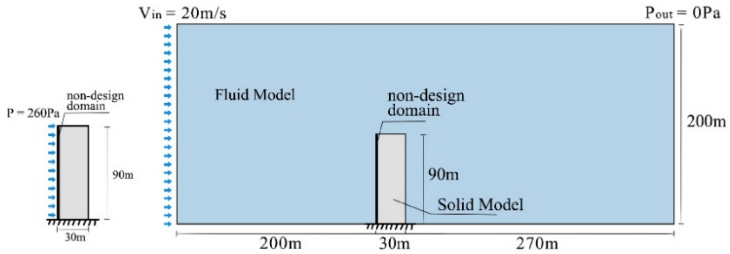


Fig.2 Computational geometric modelling in FSI-ATO.

4. Numerical examples

4.1. FAÇADE OPTIMISATION OF SINGLE BUILDING

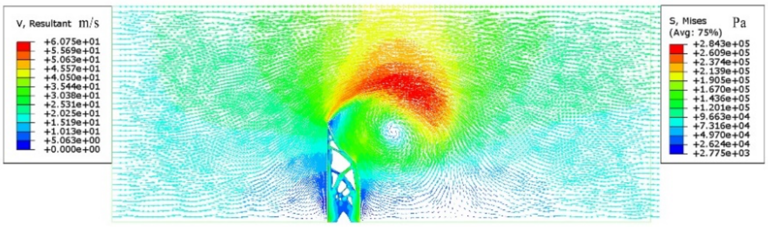
In this part, a traditional 2D high-rise building with horizontal wind load is introduced. The initial architectural form domain is assumed as a long rectangle with width of 30m and height of 90m. The solid material is set as steel with density of $7800\ \mathrm{kg/m^3}$, Young's modulus of $210\ \mathrm{GPa}$ and Poisson ratio of 0.3. The values of target volume fraction, filter radius and evolutionary ratio are 50%, 2m and 5%, respectively. The bottom boundary is fixed in three directions.



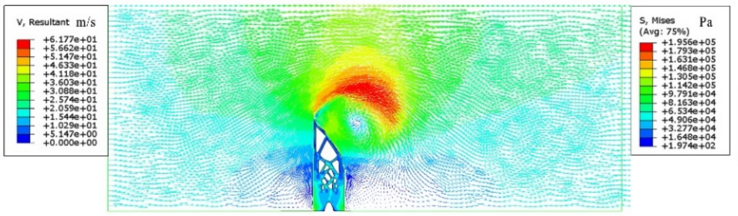
(a) BESO method (b) FSI-ATO method

Fig.3 Boundary conditions of BESO and FSI-ATO methods.

As illustrated in Fig. 3, in the traditional BESO method, the Class 8 horizontal wind load (with wind speed of 20 m/s) has to be represented by a uniform wind pressure of $260\ \mathrm{N/m^2}$ due to there is not surrounding fluid model. Meanwhile, the left boundary must be set as non-design domain to resist the pressure, which limits the scopes of architectural form-finding. However, with FSI-ATO method, the additional fluid model can be defined as incompressible navier stokes with the air density of $1.29\ \mathrm{kg/m^3}$. Thus, the initial wind velocity can be directly defined on the left inlet boundary. Fig. 4 lists the two results of BESO and FSI-ATO method respectively. It is obvious that the BESO optimised design holds more structural Mises stress and lower wind speed than FSI-ATO design. This means that FSI-ATO can generate more accurate and reasonable architecture forms in real wind fluid environment to reduce its own inner stress level and make the surrounding air easier to circulate at the same time. It is noted that although Fig. 4(b) shows an example of FSI-ATO with fixed left boundary, FSI-ATO has advantage of defining non-design domains freely, as shown in Fig. 5(b).



(a) BESO optimised design



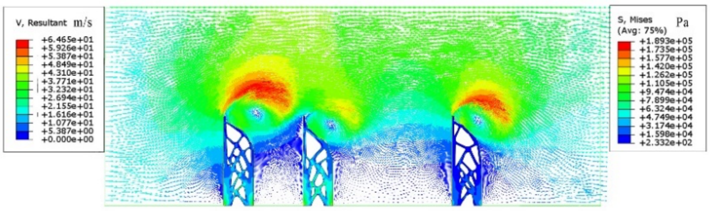
(b) FSI-ATO optimised design

Fig.4 Wind speed and Mises stress analysis of BESO and FSI-ATO structures.

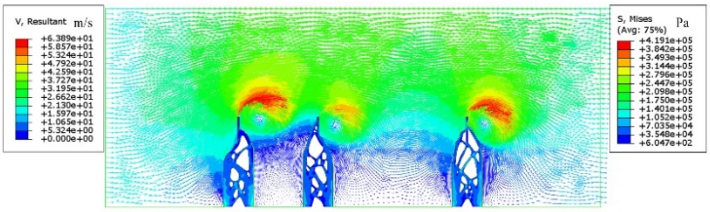
4.2. INTERACTIVE OPTIMISATION AMONG BUILDING CLUSTERS

With modelling the fluid model, FSI-ATO shares the advantage of optimising the buildings clusters due to its ability to deal with the complex fluid interactive behaviours among different buildings. Fig. 5 shows two examples about three buildings under similar settings in Section 4.1. The only difference between these two examples is the non-design domain, which locates at left boundary in Fig. 5 (a) and the top middle parts in Fig. 5 (b).

The optimised designs of the three buildings are totally different in both Fig. 5. It indicates that although with the same macroscopical conditions (wind speed, material assumptions, boundary conditions, etc), the complex air flow among buildings place a huge impact on the architecture forms.



(a) Left boundaries as non-design domains.



(b) Middel top parts as non-design domains.

Fig.5 Wind speed and Mises stress analysis of FSI-ATO structures.

5. Conclusion

This work develops an innovative architectural topological form-finding method integrating CFD with FEA using the FSI technique. This method can effectively balance the influences of the building inner structural performance and the outer fluid field performance. Architects can use it to obtain diverse optimal individual building or building cluster form drafts in 2D/3D. Several numerical examples about single high-rise building, and urban building clusters are also implemented to demonstrate the effectiveness of the method in optimising structure design and building environment. The approach aims to harmonize various physical requirements in the form-finding process within intricate architectural contexts. This innovation holds substantial practical promise for applications in architectural and urban design.

From these examples, it is obvious that FSI-ATO method has many advantages than the previous methods:

(1) FSI-ATO can balance the influence of inner solid mechanics and surrounding fluid environments and generate innovative forms with high performances.

(2) There are less constraints about non-design domains in FSI-ATO method, which means that architects have more freedom in optimising and designing building forms with FSI-ATO.

(3) Benefit from additional CFD model meshes in FSI-ATO, the interactive influences among building clusters can be incorporated into optimization considerations, and as a result, the urban building clusters can be simultaneously optimised.

(4) With more material settings and constraints, FSI-ATO shares the potential of automatically generating other form designs besides the high-rise building facades, such as Taihu stone-like porous structures in water flows.

Due to FSI requires more computing power than the conventional methods, it is essential to researching large scale high-performance computing methods in the future work.

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Author 1 and author 2 contributed equally to this work.

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