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Conceptual design of buildings subjected to wind load by using topology optimization

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Abstract. The latest developments in topology optimization are integrated with Computational Fluid Dynamics (CFD) for the conceptual design of building structures. The wind load on a building is simulated using CFD, and the structural response of the building is obtained from finite element analysis under the wind load obtained. Multiple wind directions are simulated within a single fluid domain by simply expanding the simulation domain. The bi-directional evolutionary structural optimization (BESO) algorithm with a scheme of material interpolation is extended for an automatic building topology optimization considering multiple wind loading cases. The proposed approach is demonstrated by a series of examples of optimum topology design of perimeter bracing systems of high-rise building structures.

Keywords: topology optimization; conceptual design; tall buildings; CFD; wind load

1. Introduction

Wind loading competes with seismic loading as the dominant environmental loading for building structures (Holmes 2007), especially for high-rise towers over 30 storeys. The distribution of wind action on buildings can be obtained from wind tunnel tests, wind codes of design standards, and Computational Fluid Dynamics (CFD) simulations. The ever-progressing numerical techniques in computer hardware and software have increased designers' ability to analyse and simulate wind-related processes greatly; CFD technique complements experimental and analytical approaches by providing an alternative cost-effective means of simulating real fluid flows. In some fields such as aeronautical engineering and automotive engineering, CFD substantially reduces the lead time and costs in design and production compared to experimental-based approach and offers the ability to solve a range of complicated flow problems where the analytical approach is lacking (Tu *et al.* 2008). In civil and environmental engineering, CFD is currently in the research phase and not yet fully accepted in practice for the simulation of wind loads on buildings; investigations

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are being made by researchers to improve CFD techniques for reliably predicting wind loads and other wind-induced responses on high-rise buildings.

A structural design is a load bearing system that satisfies the safety and performance requirements. The aim of structural optimization is to find the best possible design of the structure with minimum cost or minimum material consumption. Generally, structural optimization is categorized into three classes, i.e., sizing optimization, shape optimization and topology optimization. Sizing optimization treats the sizes of structural members as the design variables while shape optimization tries to find better shapes with the design variables as those parameters describing the external and internal boundaries of the structure. Topology optimization, on the other hand, is to find the optimal layout of a structure within a defined design domain. The development of the topology optimization theories dates back to Michell's pioneering work (1904) where the conditions for optimality of load-carrying structures were set up. Since then, engineers and mathematicians have been working continuously on refining the theories and developing methods for realizing topological optima. During the late 40's and early 50's, with the advent of modern computers, the development of Mathematical Programming techniques provided further impetus to the application of optimization methods in engineering design. Over the past decades, structural optimization has been exhaustively explored and successfully applied to optimization structures and mechanical elements. Several popular methods for topology optimization have been established such as the homogenization method (Bendsøe and Kikuchi 1988), the solid isotropic material with penalization (SIMP) method (Bendsøe 1989, Bendsøe and Sigmund 2003, Rietz 2001, Rozvany *et al.* 1992) and the level set techniques (Sethian and Wiegmann 2000, Wang *et al.* 2003). Xie and Steven (1993, 1997) proposed the Evolutionary Structural Optimization (ESO) method for topology optimization in the 1990s. This method was originally based on the simple concept that by slowly removing inefficient material from a structure, the residual shape evolves in the direction of making the structure better. Since then, the ESO method has been improved in many aspects and got various applications in architectural and engineering design (Cui *et al.* 2003, Ohmori *et al.* 2005, Sasaki 2005). Xie *et al.* (2005) proposed an ESO algorithm based on the principal stresses to develop conceptual forms of complex structures such as the hanging models used by the renowned architect Antonio Gaudí. The Bi-directional Evolutionary Structural Optimization (BESO) was proposed to improve the ESO methods by allowing material to be removed and added simultaneously (Yang *et al.* 1999, Young *et al.* 1999). The most recent improvement on BESO by Huang and Xie (2009, 2010) makes this method more robust.

Structural optimization techniques have been widely applied to concrete and steel building structures, including some limited research work on the application of topology optimization considering wind load. Kim *et al.* (2011) presented a design method of building form optimization to incorporate CFD in an early design phase with introduction of Genetic Algorithm (GA) and agent point based modelling technique. Felicetti and Xie (2007) proposed the concept of the Integrated Computerized Multi-disciplinary Design Environment (ICMDE) by combining techniques of Finite Element Analysis, Computational Fluid Dynamics and Evolutionary Structural Optimization to explore a design platform to building structures. Lee *et al.* (2011) proposed to develop a practical building design platform to perform the selection of building structural systems while concurrently achieve external sculpting of the building shape that results in the reduction of the aerodynamic loads, while the wind pressure was actually kept constant as demonstrated in their examples. Zakhama *et al.* (2007, 2010) proposed a formulation for the inclusion of wind loading in the minimum compliance topology optimization problem and applied to a windmill structure design, which made improvement to the methods of design-dependent loads or transmissible loads (Sigmund and Clausen 2007, Yang *et al.* 2005). Since the re-distribution of wind pressure with change of topology has been ignored, this method is not suitable to wind-sensitive structures. According to a previous investigation of the authors of this paper a little geometric change of a bluff body could affect the pressure distribution greatly (Tang *et al.* 2010).

This paper will focus on the combination and application of CFD simulation and topology optimization techniques for conceptual design of building structures considering multiple wind loads, given that the external shape of a building is already determined by architects. The proposed strategy and method will be applied to the preliminary optimum structural design of high-rise buildings.

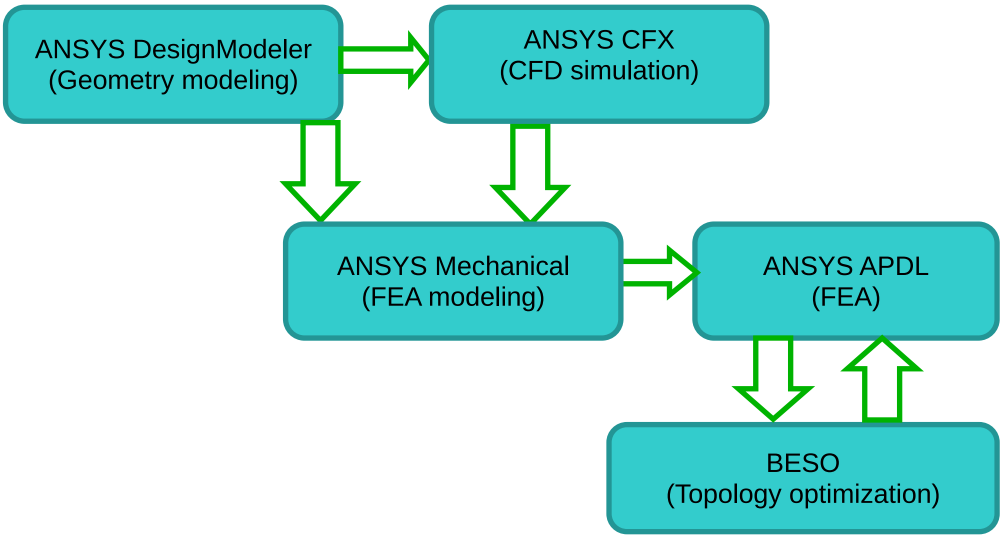

Fig. 1 Outline of ANSYS-based BESO system considering multiple wind loads

2. Overall strategy and general approach

A BESO method will be extended to topology optimization of buildings for minimum structural compliance. In order to avoid removal of wind loading by deleting elements on the building surface a soft-kill method will apply, i.e., inefficient solid elements are replaced with a soft material (comparatively lower Young's modulus) rather than removed completely. The soft material may represent glass curtain walls and should be stiff enough to resist local wind pressure. Soft-kill method can also avoid a possible singularity problem of finite element analysis after a group of elements are removed during optimization.

Both CFD simulation of wind loading and finite element analysis of building structures will be performed in the ANSYS environment, as outlined in Fig. 1. ANSYS provides a comprehensive design and analysis environment covering both solid and fluid fields. ANSYS Parametric Design Language (APDL) is a scripting language that can be used to automate common tasks or to build user's own applications. BESO is integrated with ANSYS to automate the process of topological structural optimization considering wind loads. The functions of modules are summarized as follows:

- Create fluid (wind) and solid (building) geometries in ANSYS DesignModeler;
- Simulate wind effects and obtain wind pressure distribution on the building using ANSYS CFX;
- Create FEA model files of building structure in ANSYS Mechanical, with wind loading imported from ANSYS CFX;
- Finite element analysis of building structure using ANSYS APDL;
- Optimize building structural topology using BESO program.

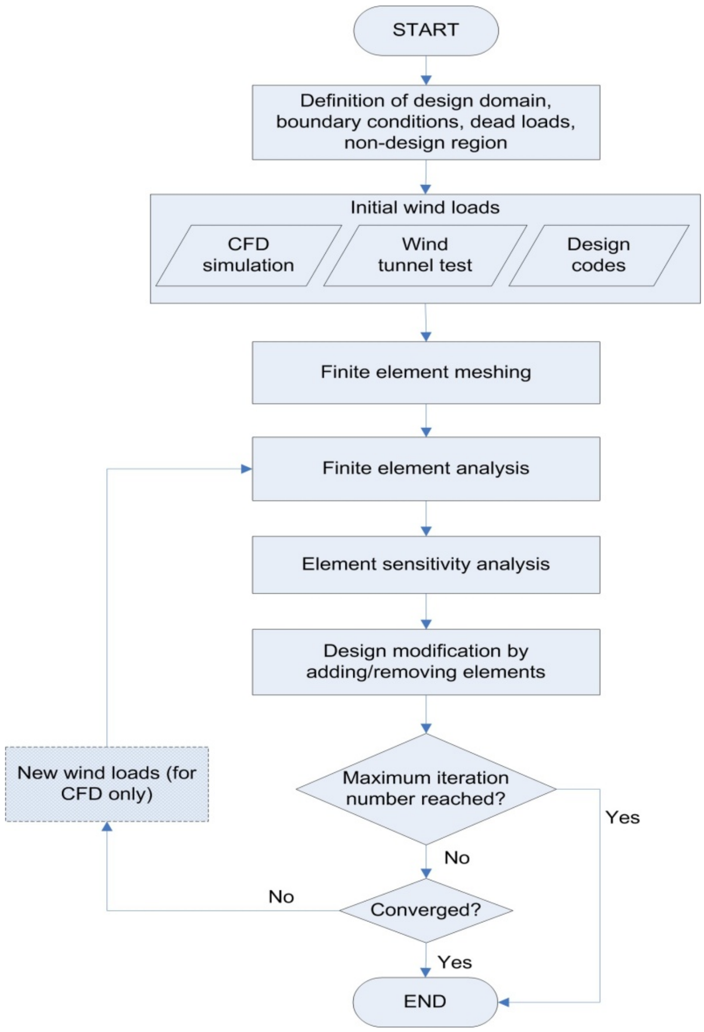

Fig. 2 Flowchart of BESO algorithm for structural optimization considering wind loads. The automatic feedback of wind load modification is not yet available in the current work

A general flowchart of the BESO program for wind loading problems is illustrated in Fig. 2. It is noted that the automatic feedback of wind load modification has not been included in the current work yet. The BESO method will be applied step by step as follows:

(1) Discretise the structure with finite elements and apply support conditions and dead loads to the model;

(2) Define the non-design domain properly and apply wind loads to the model from the results of wind tunnel test, wind design codes or CFD simulations;

(3) Structure analysis with finite element method;

(4) Element sensitivity analysis according to a design criterion;

(5) Modify the topology of the structure by removing less efficient elements and adding more efficient ones according to their sensitivity numbers;

(6) Evaluate the design criterion and repeat steps (3)-(5) until the maximum iteration number or a convergence criterion is reached.

The sensitivity analysis and convergence criterion of the extended BESO method will be detailed in Section 4.

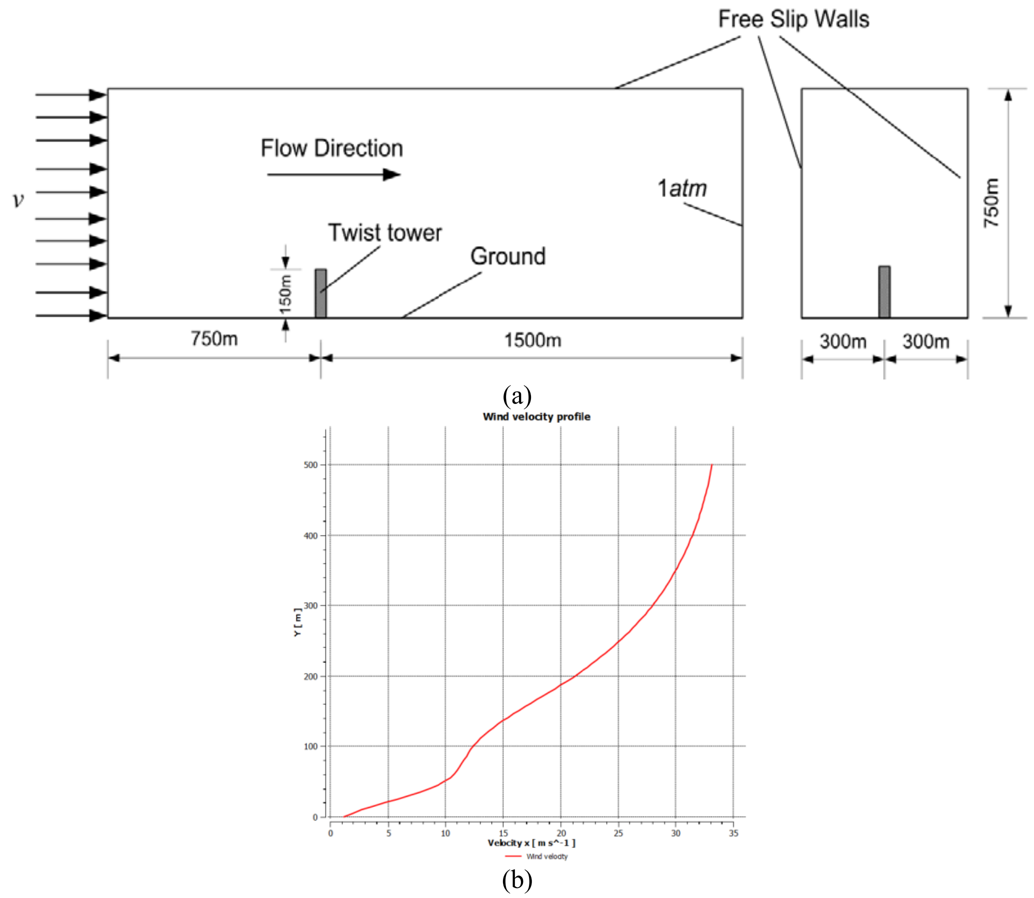

Fig. 3 Three-dimensional CFD model of a tower considering a single wind direction: (a) definition of simulation domain and (b) wind velocity profile in front of the building

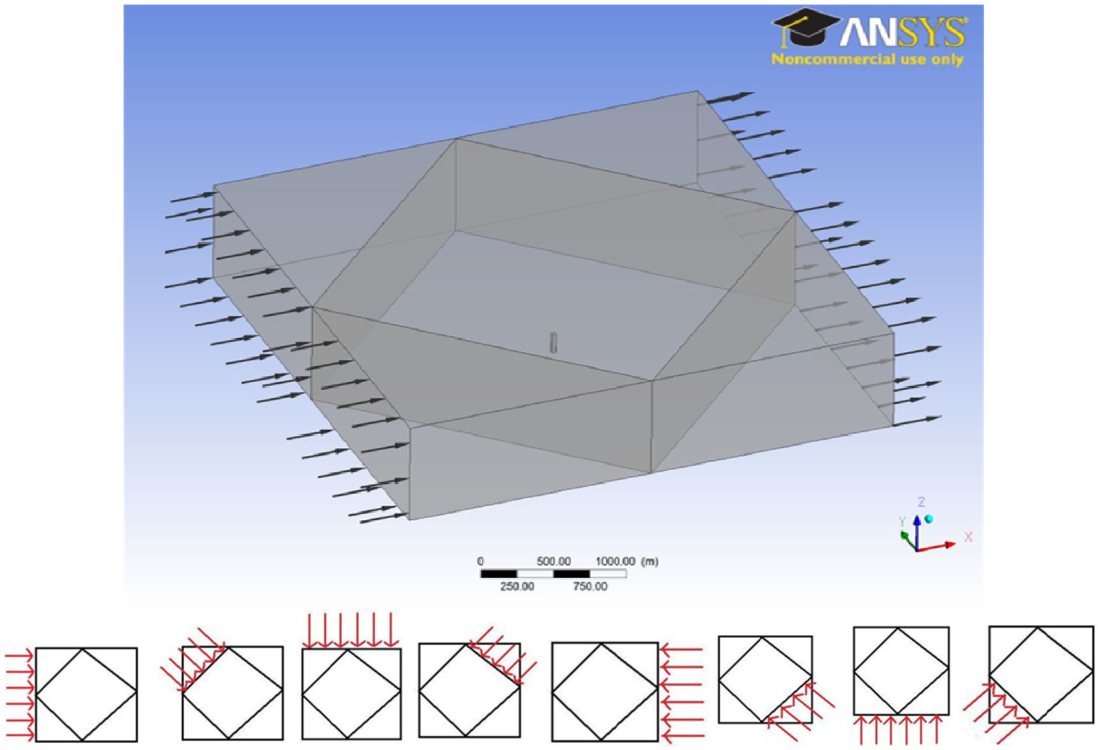

Fig. 4 Three-dimensional CFD model of a tower considering multiple (up to 8) wind directions

3. CFD simulation of wind loading

A steady-state CFD simulation will be applied to get the distribution of wind pressure on a building. The domain of the CFD simulation is set as incompressible air flow at 25°C with SST (Shear Stress Transport) turbulence model. A uniform normal velocity (v=35 m/s) is applied at the inlet far away from the building, and 1atm average static pressure at the outlet (Fig. 3(a)). The ground and building walls are defined as *No Slip Walls*. The fluid immediately next to a no slip wall is assumed to have the velocity of the wall, which is zero by default. When the wind approaches the building, a non-uniform velocity profile is developed, as shown in Fig. 3(b). The CFD simulations have been tested with various mesh patterns and grid densities in order to produce reliable and mesh-independent results for all cases. However, this definition of CFD domain is only suitable to a single wind direction. In practical, wind comes from various directions with different velocity through time. Usually, several CFD models must be created to simulate multiple wind directions, but this will result in several different finite element models for the same building. In order to apply the results of CFD simulation as multiple load cases for structural optimization of a building, the building structure must have the same finite element model with exactly the same definition of elements and nodes. One possible solution is to perform a coordinate transformation after a finite element model file is exported, but it is not convenient to control all the models at various wind directions to be meshed with the same number and the same sequence of elements and grids. Alternatively, it is convenient to perform CFD simulation and FE analysis using the same fluid and solid model for different wind directions by simply adopting a larger simulation domain.

This alternative CFD domain has been proposed to meet the requirement of multiple wind directions for a unique model. It features a larger square fluid domain for CFD simulation of multiple wind directions, rather than a narrow one for one wind case. In addition, the fluid domain is cut to five parts so that the 45° wind directions (e.g., northwest and northeast) can also be considered with the same model (Fig. 4).

The extension of CFD domain will definitely increase the model scale for numerical simulation; however the increase of elements and nodes is actually not very much, since fine meshes are only concentrated close to the building while regions away from the building are in coarse mesh. In case that the domain becomes too large using this method the domain size can be reduced to some extent without losing much accuracy. It was found that for the steady-state CFD modelling of a tall building a domain of approximately 10% the volume of that suggested by the existing guidelines could be used with a loss in accuracy of less than 10% (Revuz *et al.* 2012).

4. BESO method with material interpolation

The BESO method with a material interpolation scheme proposed by Huang and Xie (2009) is extended and applied to topology optimization of building structures in this paper. Two materials are modelled in the interpolation scheme. The hard material represents solid elements of structural components while the soft one represents 'void' elements of non-structural components which resist local wind pressure only and do not contribute to global load-bearing.

4.1 Problem description

The objective of topology optimization is to maximize the stiffness of a structure, or to minimize the mean compliance for a given volume of material. The topology optimization problem is stated as

$$\begin{aligned} &\text{Minimize: } C = \frac{1}{2}\mathbf{u}^{\mathrm{T}}\mathbf{K}\mathbf{u} \\ &\text{Subject to: } V^{*} - \sum_{i=1}^{N} V_i x_i = 0 \\ &x_i = x_{\min} \text{ or } 1 \end{aligned} \tag{1}$$

where C is the mean compliance of the structure. In finite element analysis, the static equilibrium equation of a structure is expressed as **Ku**=**f**, where **f** is the force vector, **u** is the displacement vector and **K** is the global stiffness matrix. N denotes the total number of finite elements. Vi is the volume of the ith element. V^* is the prescribed total structural volume. The binary design variable x_i denotes the relative density of the ith element with a small value of x_{min} as its lower bound.

For multiple load cases, the optimization problem is formulated as one of minimizing a weighted average of the mean compliances of all load cases. Therefore, the topology optimization problem for multiple load cases is stated as

$$\text{Minimize: } f(x) = \sum_{k=1}^{M} w_k C_k$$
$$\text{Subject to: } V^* - \sum_{i=1}^{N} V_i x_i = 0 \tag{2}$$
$$x_i = x_{\min} \text{ or } 1$$

where M is the total number of load cases, w_k is the prescribed weighting factor for the kth load case, C_k is the mean compliance of the kth load case, and $\sum_{k=1}^{M} w_k = 1$.

4.2 Material interpolation

Material interpolation schemes with penalization have been widely used in the SIMP method to achieve nearly solid-void design solutions (Bendsøe 1989, Bendsøe and Sigmund 1999, Rietz 2001). Young's modulus of intermediate material is interpolated as a function of the element density variable as

$$E(x_i) = E_1 x_i^p \tag{3}$$

where E_1 denotes the Young's modulus for solid material, p is the penalty exponent.

In the two non-zero materials case, the Young's modulus of two materials are E_1 and E_2 where $E_1 > E_2 \neq 0$. The material interpolation scheme is expressed as

$$E(x_i) = E_1 x_i^p + E_2 (1 - x_i^p) \tag{4}$$

4.3 Sensitivity analysis

For a single load case the gradient of the objective function with respect to individual element density can be derived from Eq. (1). For solid-void designs, the sensitivity of ith element is expressed by

$$\frac{\partial C}{\partial x_i} = -\frac{p x_i^{p-1}}{2} \mathbf{u}_i^{\mathrm{T}} \mathbf{K}_i \mathbf{u}_i \tag{5}$$

where $\mathbf{K}_i$ is the elemental stiffness matrix and $\mathbf{u}_i$ is the elemental displacement vector.

In the evolutionary structural optimization method, a structure is optimized using discrete design variables, and the sensitivity number represents the relative ranking of the sensitivity of an individual element (Huang and Xie 2010). The sensitivity number is defined as

$$\alpha_i = -\frac{1}{p} \frac{\partial C}{\partial x_i} = \frac{x_i^{p-1}}{2} \mathbf{u}_i^{\mathrm{T}} \mathbf{K}_i \mathbf{u}_i = \begin{cases} \frac{1}{2} \mathbf{u}_i^{\mathrm{T}} \mathbf{K}_i \mathbf{u}_i & \text{when } x_i = 1 \\ \frac{x_{\min}^{p-1}}{2} \mathbf{u}_i^{\mathrm{T}} \mathbf{K}_i \mathbf{u}_i & \text{when } x_i = x_{\min} \end{cases} \tag{6}$$

If the design is composed of two non-zero materials, as the cases in this paper, the elemental sensitivity number is determined through sensitivity analysis (Bendsøe and Sigmund 1999) as

$$\alpha_i = -\frac{1}{p}\frac{\partial C}{\partial x_i} = \frac{1}{2}x_i^{p-1}(\mathbf{u}_i^{\mathrm{T}}\mathbf{K}_i^1\mathbf{u}_i - \mathbf{u}_i^{\mathrm{T}}\mathbf{K}_i^2\mathbf{u}_i) \tag{7}$$

where K_i^1 and K_i^2 denote the elemental stiffness matrix calculated with mechanical properties of material 1 and 2, respectively. If we assume both materials have the same Poisson's ratio, the sensitivity number for the two materials can be expressed explicitly as

$$\alpha_i = \begin{cases} \dfrac{1}{2}\left[1 - \dfrac{E_2}{E_1}\right]\mathbf{u}_i^{\mathrm{T}}\mathbf{K}_i^1\mathbf{u}_i & \text{for material 1} \\ \dfrac{1}{2}\dfrac{x_{\min}^{p-1}(E_1 - E_2)}{x_{\min}^p E_1 + (1 - x_{\min}^p)E_2}\mathbf{u}_i^{\mathrm{T}}\mathbf{K}_i^2\mathbf{u}_i & \text{for material 2} \end{cases} \tag{8}$$

The above sensitivity analysis is derived for the problem of one load case. For the problem of multiple load cases defined in Eq. (2), as the displacement field of one load case is independent of that of another load case, the sensitivity of the weighted objective function is simply given as

$$\alpha_i = \sum_{k=1}^{M} w_k \alpha_i^k \tag{9}$$

where M is the total number of load cases, w_k is the prescribed weighting factor for the kth load case, α_i^k is the sensitivity number of the ith element for the kth load case defined by Eqs. (6)-(8).

4.4 Convergence criterion

The cycle of finite element analysis and element removal/addition continues until the objective volume (V^*) is reached and the change in the objective function is within an acceptable tolerance, i.e., $\tau \le \tau^*$ where τ is the variation of the objective function and τ^* is its allowable convergence tolerance. Considering numerical instability, τ is evaluated as an average change of the objective function (mean compliance) over several successive iterations

$$\tau = \frac{\left|\frac{1}{n}\sum_{i=1}^{n} C_{k-i+1} - \frac{1}{n}\sum_{i=1}^{n} C_{k-n-i+1}\right|}{\frac{1}{n}\sum_{i=1}^{n} C_{k-i+1}} \tag{10}$$

where k is the current iteration number and n is an integer number controlling the number of iterations with a numerically steady solution. The convergence criterion is therefore defined as

$$\tau = \frac{\left|\sum_{i=1}^{n} C_{k-i+1} - \sum_{i=1}^{n} C_{k-n-i+1}\right|}{\sum_{i=1}^{n} C_{k-i+1}} \le \tau^* \tag{11}$$

Normally, n is selected to be 5, which implies that the change in the mean compliance over the last 10 iterations is acceptably small. For example, if the current iteration number is 20 and n is taken as 5, then, τ is a relative variation of average mean compliance over iterations from 16 to 20 and that over iterations from 11 to 15.

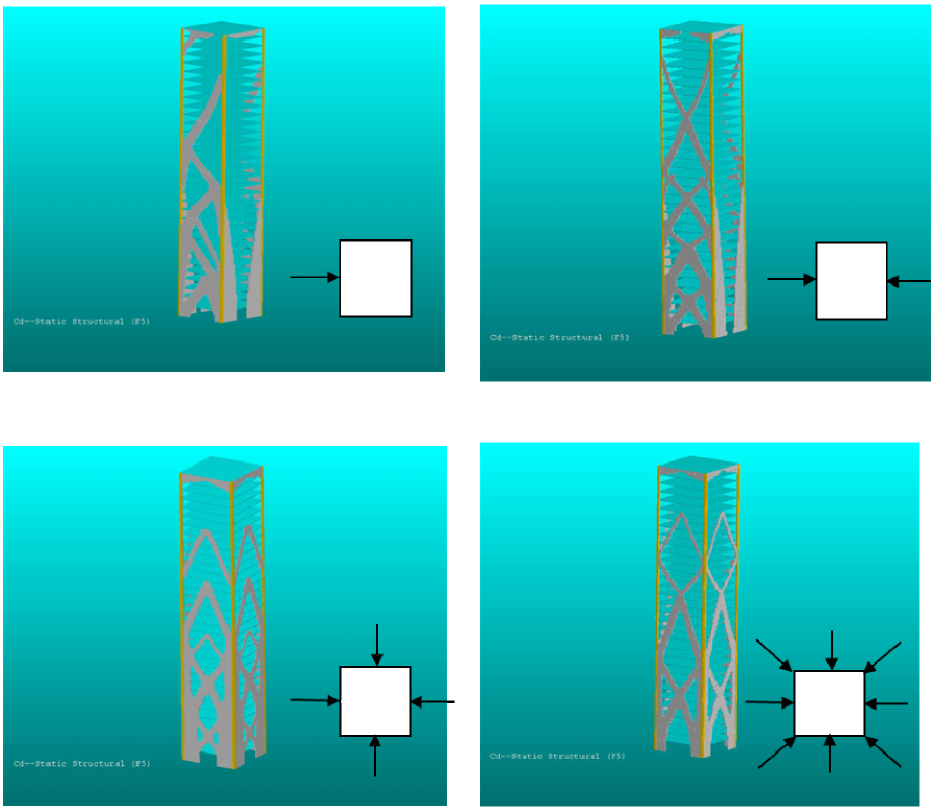

Fig. 5 Optimum bracing topologies of a straight tower with square floor plan. Four cases of wind combination are considered

5. Illustrative examples

The proposed method is applied to high-rise buildings with various floor plans for an optimum design of the bracing system. As a preliminary study, only the wind load is considered in the following examples. It is also assumed that the probability of wind occurrence is the same for all directions, and that the importance of all wind directions is the same as well; therefore, the weighting factors w_k in Eq. (9) are equal for all load cases.

5.1 A straight tower with square floor plan

This example is a high-rise building with a square floor plan of 30 m × 30 m. The height of the tower is 150 m, with 50 storeys. All the floor slabs are constructed of concrete with Young's modulus of 30 GPa and Poisson's ratio of 0.18, while the walls are made of steel with Young's modulus of 210 GPa and Poisson's ratio of 0.3. It is assumed that all columns and floor slabs are non-designable, and only the four walls are designable to produce the bracing system. The thickness of walls is 300 mm. It is assumed that wind blows randomly from all directions with velocity 35 m/s.

By considering various combinations of wind directions, the building structures are optimized under different load cases (Fig. 5). The target volume is set as 30% of the initial design (full designable domain).

(a) One load case. Wind blows from west. Most elements on west and east walls are removed (replaced by soft material to resist local wind pressure only), while braces are formed on the other two walls. The topology of bracing system features a pattern of ‘W’ or ‘V’-shape.

(b) Two load cases. In addition to the load case considered above, the second load case is applied as a symmetric one to the first load case, representing the wind from an opposite direction - east. Using the same BESO procedure the initial model evolves gradually to a symmetric pattern, an ‘X’-like bracing system on the north and south walls.

(c) Four load cases. The four orthogonal wind directions (east, west, south and north) are considered in this model. Due to the symmetry of geometry and load cases consistent pattern of braces are formed on all the four walls.

(d) Eight load cases. In addition to the four main wind directions considered above, four more wind directions from NW, NE, SW and SE are applied. Regular and consistent braces are formed on all four walls, similar to (c), featured with ‘X’-like braces.

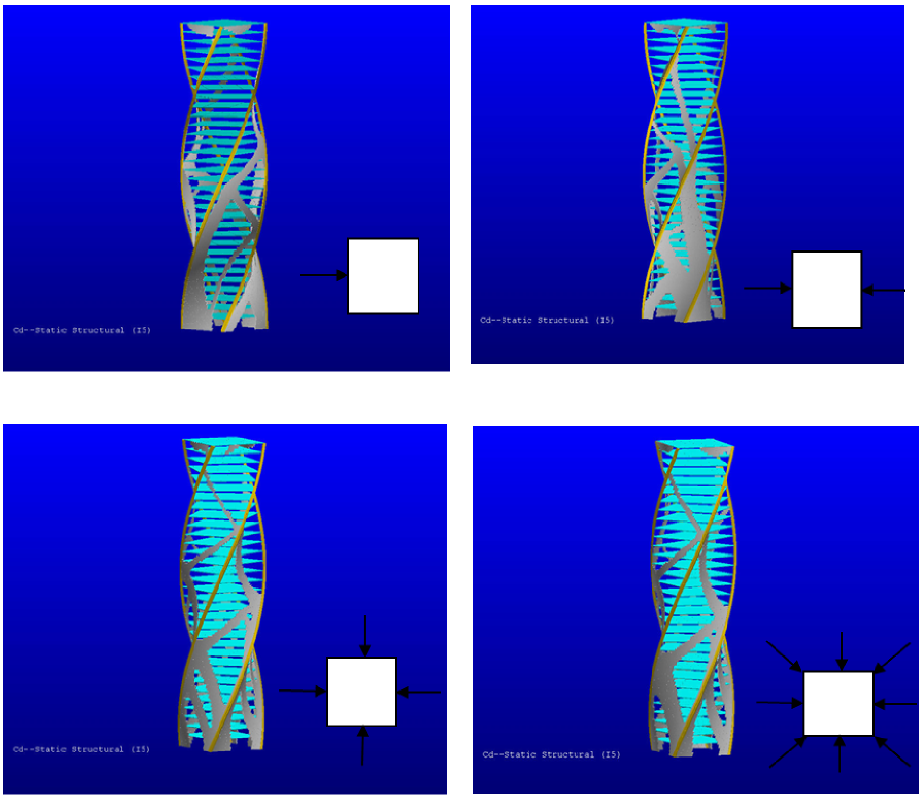

Fig. 6 Optimum bracing topologies of a twist tower with square floor plan. Four cases of wind combination are considered

5.2 A twist tower with square floor plan

In this example, the straight tower in section 5.1 is twisted by 180°evenly through the building height. Due to the curved faces of walls and the redistribution of wind pressure the optimum patterns of braces change a lot for all load conditions. Particularly, the examples with four load cases and that with eight load cases demonstrate very similar topologies (Fig. 6).

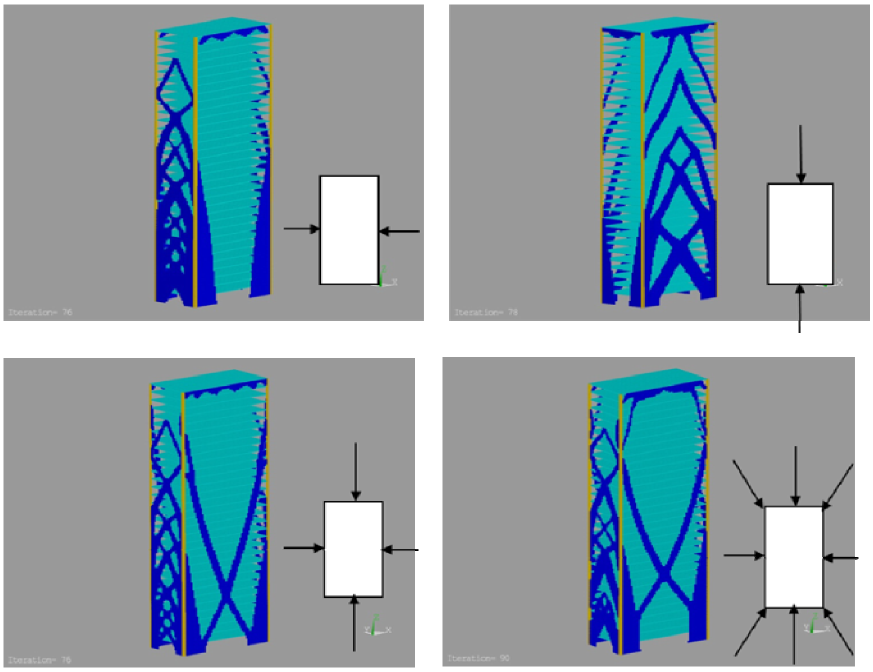

Fig. 7 Optimum bracing topologies of a straight tower with rectangular floor plan. Four cases of wind combination are considered

5.3 A straight tower with rectangular floor plan

This example considers a building with a rectangular cross section. The dimensions of floor plan are 60 m × 30 m. The height of the tower is still 150 m. The wind is assumed to blow equally from all directions with uniform velocity 35 m/s at the inlet far away from the building.

(a) Two load cases. Wind blows from west and east respectively (wide faces).

(b) Two load cases. Wind blows from north and south respectively (narrow faces).

For both (a) and (b) in this model, braces are formed on the 'non-wind' walls to resist transverse shear and over-turning moment.

(c) Four load cases. The four main wind directions (east, west, south and north) are considered in this model.

(d) Eight load cases. In addition to the four wind directions considered above, four more wind directions from NW, NE, SW and SE are applied.

Similar topologies of bracing system are achieved for (c) and (d). It is interesting that much fewer braces are shown on the wide walls (Fig. 7). This phenomenon can be explained in such a way. When a wind blows into a wide face of the building, the along-wind drag on this wall is higher than the case of wind into a narrow face for the same wind velocity, because the value of wind drag is proportional to the frontal area of the bluff body in flow. On the other hand, braces on narrow faces are structurally less efficient. Therefore, the narrow faces are required to be strengthened with more material to resist wind-induced transverse shear and over-turning moment for the same wind velocity.

5.4 A straight tower with L-shaped floor plan

A more complicated building tower is investigated in this example. The floor plan features an L-shaped pattern, which is quite common among existing towers nowadays. Two combinations of wind loadings are considered.

(a) Four load cases. The four main wind directions (east, west, south and north) are considered in this model.

(b) Eight load cases. In addition to the four wind directions considered above, the 45° wind directions from NW, NE, SW and SE and applied.

Both models evolve to interesting symmetric bracing systems that are structurally most efficient (Fig. 8).

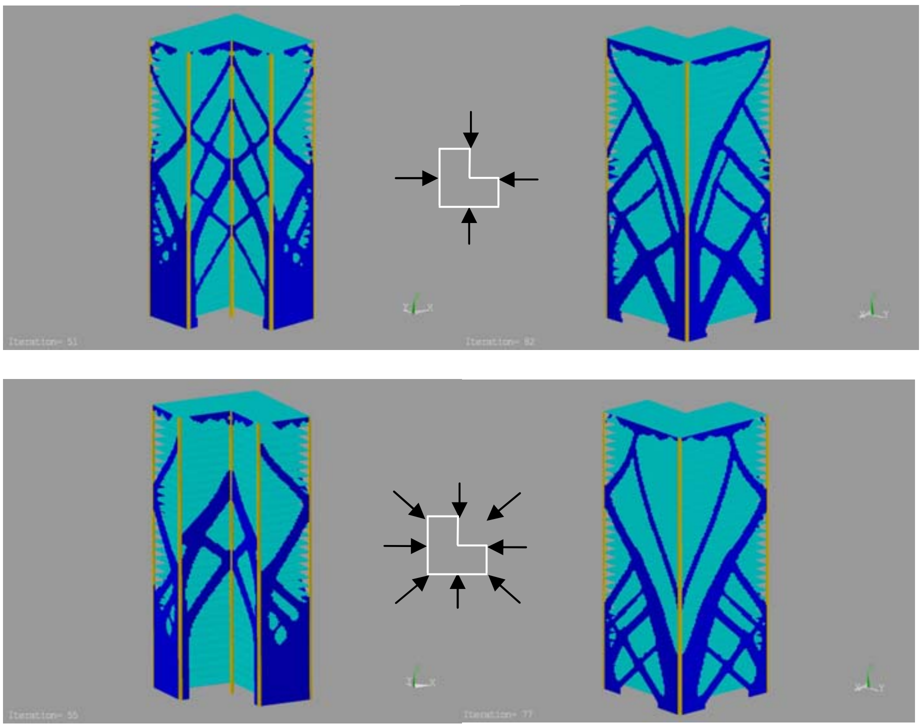

Fig. 8 Optimum bracing topologies of a straight tower with L-shaped floor plan. Two cases of wind combination are considered

6. Conclusions

In this paper the conceptual design of building structures were performed by using topology optimization and computational fluid dynamics techniques. In order to find the optimum design of building structures considering wind load, CFD method was combined with structural finite element analysis and BESO algorithm. Multiple wind directions were considered in CFD modelling and structural optimization. The examples demonstrate the ability of BESO in generating bracing system of high-rise buildings under wind loading. The research demonstrates the benefits of topological optimization in creating innovative and efficient structural systems.

The results of optimization display not only the position of braces but also the relative sizes of bracing members. The examples show that it is not necessary to have bracing system uniformly distributed throughout the height of the building. At the upper floors, fewer braces are needed. This will allow for more transparency for the apartments at upper levels. These apartments with unobstructed views will provide great financial benefits to the building owner.

Putting fewer bracing elements at the upper levels will also provide the additional benefit of lowering the centre of gravity of the whole building. For such a slender structure, considerable costs will be involved in constructing an appropriate anchor system in the foundation. When the centre of gravity is lowered, such costs could be significantly reduced.

In this paper, the overall stiffness of the building is maximized subject to a given structural volume. Other objectives/constraints such as the drift of the building can also be considered similarly.

The dynamic effect of the wind loading on the building topology can be considered by conducting transient CFD analysis. This is part of the current research of the authors.

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