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Evaluation of optimal lateral resisting systems for tall buildings subject to horizontal loads

Giulia Angelucci[a]*, Fabrizio Mollaioli[a], Omar AlShawa[a]

[a] *Department of Structural and Geotechnical Engineering (DISG), Sapienza University of Rome, via Gramsci 53, 00197, Rome, Italy*

Abstract

The tendency of modern designs towards optimal structures often leads to the lightest and best performing choice among a large set of design alternatives. In a similar scenario, the introduction of automated tools to further guide designers in achieving efficient solutions has been a recurrent topic for mechanical and structural engineers, over the past decades. Nowadays, topology optimization is considered a powerful preliminary design tool to determine the optimal material distribution in a design domain, i.e. the most effective configuration that satisfies a given set of prescribed constraints while reducing the consumption of structural material. Among different applications in the field of Civil Engineering, this work focuses on the definition of optimal layouts of lateral resisting systems for multi-storey steel building frameworks subject to lateral loads using topology optimization techniques. The objective of the research is to illustrate the benefits deriving from the introduction of automated routines within the preliminary design stage and establish reliable guidelines for performing accurate and objective optimization procedures. Since the optimal material distribution follows the load flow within the structure, optimal topologies are especially sensitive to the alteration of support and loading conditions: different loading scenarios naturally lead to distinct optimal layouts. In order to avoid the loss of objectivity and preserve the optimality of the results, the effects that preliminary modelling and loading assumptions produce on final layouts are investigated. Numerical applications to high-rise building models are presented and discussed.

Keywords: Topology optimization; tall buildings; adaptive multi-mode load; loading profiles; minimum volume.

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* Corresponding author. Tel.: +39-06 49919186; fax: +39-06-49919183
E-mail address: giulia.angelucci@uniroma1.it

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1. Introduction

Making an efficient use of material, i.e. designing lightweight structures yet able to exhibit high mechanical performance, is a recurrent topic for mechanical and structural engineers. This naturally leads to the search of optimal designs, where the term "optimum" stands for that solution which minimizes a structural objective function while satisfying a certain number of designer-imposed constraints. The improvement of computational tools has allowed, in the last decades, the possibility to extend optimization techniques to large-scale structures with affordable time consumption. Due to its ability in finding innovative and high-performing designs, topology optimization has been, in the last decades, widely investigated as a preliminary design tool to minimize the material consumption in a structure while satisfying specific behavioural constraints. Because of the need to combine aesthetic criteria with efficient structural systems, the design of tall buildings represents a fertile field of implementation to demonstrate the usefulness of automated optimization techniques. The design of lateral bracing systems, required to stiffen steel frameworks of high-rise buildings and restrain lateral drifts within acceptable limits, commonly involves trial and error procedures to identify alternative arrangements for the diagonals. In this context, the definition of an efficient topology optimization methodology may help designers in selecting the best design strategy that meets the least structural weight requirement with the highest mechanical performances.

In the state of the art, topology optimization procedures have been traditionally framed in a static and deterministic setting [1] with uniform distribution of loads, limiting their applicability in achieving adequate solutions for structural systems subject to uncertain loads. In order to overcome this limitation, a new generation of probabilistic frameworks based on the concept of structural reliability has been developed by researchers to seek optimal topologies under uncertainty, which is often termed as Reliability Based Topology Optimization (RBTO) [2]–[4]. The main objective of integrating reliability analysis with optimization techniques is to define optimal designs that take into account the dynamic nature of lateral loads (e.g. earthquake and wind) acting on the buildings. This implies a dynamic setting for the general problem, which is an actual topic in the literature. However, a dynamic framework further complicates topology optimization, which, being primarily defined as a preliminary design tool, is required to be reasonably practical and quick in achieving optimal material distributions for large-scale problems, as the case of high-rise buildings. Therefore, a balance between realistic and simplified assumptions is needed to meet engineering and architectural criteria while maintaining computational costs low. In order to overcome the challenges related to the correct setting of the topology optimization problem for tall buildings, this paper demonstrates how preliminary assumptions, i.e. the idealization of the design domain and the representation of external actions, impact on the objectivity and reliability of final layouts. In particular, topology optimization is performed on two-dimensional models to define general guidelines effective to assess realistic procedures and preserve the optimality of results. The influence of preliminary modelling assumptions on final topologies is investigated, also by retracing design strategies already proposed by other authors.

This work aims to establish a compromise between caution in defining a simplified model, accuracy in describing external actions and practicality in adopting a classic form for the problem. In fact, without adding further complexity, a static and deterministic approach is implemented, which allows the possibility of solving the optimization procedure using classical gradient-based algorithms. Typical actions for tall buildings are applied to the design domain in order to identify simplified load profiles capable of capturing the complexity of natural events while preserving the simplicity of a static setting for the analysis. The effects on final topologies of different load patterns, representative of wind and earthquake actions, are investigated by adopting an explicit standard framework with a displacement-constrained formulation for minimum volume.

2. Topology optimization problem for tall buildings

Under the action of wind loads, a regular tall building is generally considered to be composed of two web panels (parallel to the wind load) primary resisting bending action and two flange panels (orthogonal to the wind load) enduring shear forces [5]. Since the in-plane stiffness of the floor slabs is generally intended to be sufficiently high to restrict any tendency for the panels to deform out-of-plane, it is reasonably assumed that the out-of-plane actions are irrelevant compared to the primary in-plane actions and can be neglected. The external skin of the tall building is split into four panels, modelled to behave as equivalent orthotropic membranes, such that each façade can be analyzed as a continuous design domain for the topology optimization procedure. In addition, given the aleatory nature of the wind direction, in the preliminary design of the lateral bracing system, it is opportune that the optimization process produces the worst situation for each façade, which corresponds to the condition of the web panels. Therefore, without adding further complexity to the procedure, two-dimensional case studies are considered sufficiently accurate to capture the main peculiarities of the general problem. In the literature, the topology optimization problem is generally framed using an "academic" formulation, commonly referred to as the design for minimum compliance. However, a compliance measure of the mechanical performances of the system can barely be interpreted by engineers in common practice. In the design of tall buildings, good indicators of the adequate stiffness in the structure, for both serviceability and safety, are the top-story drift and the inter-story drift ratio. Therefore, the topology optimization problem is formulated here in order to minimize the amount of structural material in the design domain while satisfying displacement constraints at certain points of interest:

$$\begin{cases} \min\limits_{\boldsymbol{\rho}} \; V(\boldsymbol{\rho}) = \sum\limits_{e=1}^{n} \int_{\Omega_e} \rho_e \mathrm{d}\Omega \\ \text{s.t.} \;\; C_j(\boldsymbol{\rho}) = \boldsymbol{\Lambda}_j^{\,T} \mathbf{u}(\boldsymbol{\rho}) \le \bar{u}_j, \;\; j = 1,\dots,N \\ \qquad \mathbf{K}(\boldsymbol{\rho})\, \mathbf{u}(\boldsymbol{\rho}) = \mathbf{f} \\ \qquad 0 \le \rho_e \le 1, \;\; e = 1,\dots,n \end{cases} \tag{1}$$

where $\boldsymbol{\rho}(\mathbf{x})$ is the filtered element-wise material density vector; $V(\boldsymbol{\rho})$ is the volume of material in the design domain Ω of the structure; $C_j(\boldsymbol{\rho})$ is the j-th constraint and N is the number of constraints; $\boldsymbol{\Lambda}_j$ is a vector of constants (independent from $\boldsymbol{\rho}$) extracting the displacements to be restricted; $\bar{u}_j$ are the displacement targets prescribed by design codes; $\mathbf{K}(\boldsymbol{\rho})$ is the stiffness matrix; **u** and **f** are the nodal displacement and force vectors, respectively. It is worth noticing that in the case where the compliance measure is constrained, the academic and the minimum volume formulations are equivalent. In this work, the problem is settled using (1) with points of interest taken at the same location of the loading points, in order to compare the material distribution results with those achieved in the literature using the minimum compliance framework. Since topology optimization problems are prone to numerical instabilities, a regularized scheme [6] is adopted to ensure the existence of a solution and avoid computational anomalies, e.g. checkboard patterns. The physical densities $\boldsymbol{\rho}$ are computed by modifying the initial design variables through explicit application of the following density filter in the neighborhood N_e of the element e (i.e. $\rho_e(x_{k\in Ne})$):

$$\rho_e = \frac{\sum_{k\in N_e} H_{ek} x_k}{\sum_{k\in N_e} H_{ek}} \tag{2}$$

where H_{ek} are the weighting functions, which are defined through a linearly decaying function of fixed radius $r_{\min}$ measured from the centroid of the element under examination. The topology optimization problem is settled here using the density-based approach with SIMP (Solid Isotropic Material with Penalization) interpolation, in which the artificial elastic modulus for each element e is computed as:

$$E_e(\rho_e) = E_{\min} + \rho_e^p (E_0 - E_{\min}), \quad 0 \le \rho_e \le 1 \tag{3}$$

where E_0 is the Young's modulus of the base material; $E_{\min}$ represents a non-zero elastic modulus for the void material to avoid any singularity of the stiffness matrix; p represents a penalization factor greater than zero. Given its desirable rapid convergence rate, the Method of Moving Asymptotes (MMA) [7] is used to update the design variables and solve the topology optimization problem in (1). Convergence is checked at each iteration until the difference between two consecutive optimal designs is less than 0.5%.

3. Influence of preliminary modelling assumptions on optimal topologies

A regular multi-story building with a height of 80 meters, a width of 20 meters (resulting discretization of 1,600 finite elements for the continuum domain) is investigated. The external skin of the building is adopted as the design domain Ω of the material distribution problem, discretized using 4-node quadrilateral Lagrangian (Q4) elements with a thickness of 0.15 m and dimensions 1 m x 1 m. Support conditions are assumed to be fixed. The continuum domain is modelled using the properties of steel, with E_0 =210 GPa. The algorithm is run with a constant penalization factor of p =3 and a projection radius of $r_{\min}$ =1.5 m. By retracing the strategies already proposed by other researchers, the effects of preliminary modelling assumptions are investigated here in order to define reliable guidelines useful in performing accurate and realistic topology optimization procedures for tall buildings. A unit lateral distributed load is enforced on the left edge of the design domain. The asymmetric application of the lateral load naturally produces a correspondent non-symmetric layout, as it emerges in Fig. 1 (a). In the design of tall buildings, a symmetry constraint with respect to the centerline of the model is highly desirable in order to generate a pattern repetition along the elevation of the building and minimize the construction costs. Different approaches have been proposed in the literature to force this geometrical configuration. The simplest procedure consists in adopting additional symmetrical load cases, facing towards the same direction. In the present study, symmetry is directly imposed in the problem formulation. The topology optimization problem is settled in order to account for elements lying in the first half part of the domain only, significantly reducing the number of design variables to be updated. The optimal layout is subsequently mirrored with respect to the centerline. In other words, the lateral load acting on the left side of the building implicitly holds a symmetrical counterpart on the right edge of the domain and, as it can be observed in Fig. 1 (b), when symmetry is forced, a pattern repetition arises. One of the major drawbacks in performing topology optimization using a continuum approach is that a direct application of lateral forces at the nodes of the domain may affect the objectivity of the results. For this purpose, recent works have considered the possibility of introducing additional discrete elements to bound the continuum domain [8]–[10]. In order to prevent the formation of multiple small horizontal members, connecting the diagonal braces with the vertical columns, a complete framework composed of columns and beams, so-called secondary system, is considered in Fig. 1 (c), which mimics the presence of floor beams needed to carry gravity loads. The presence of both vertical and horizontal members in the optimizable domain returns the real distribution of load paths within the structure. The adoption of combined continuum and discrete elements presents two main advantages. Firstly, it allows for a uniform distribution of the lateral forces along the column height, making topology results independent from the direct application of loads. Secondly, the presence of vertical members helps reducing the concentration of structural material at the bottom edges of the domain, which impedes a correct identification of the working points between the frame and the braces.

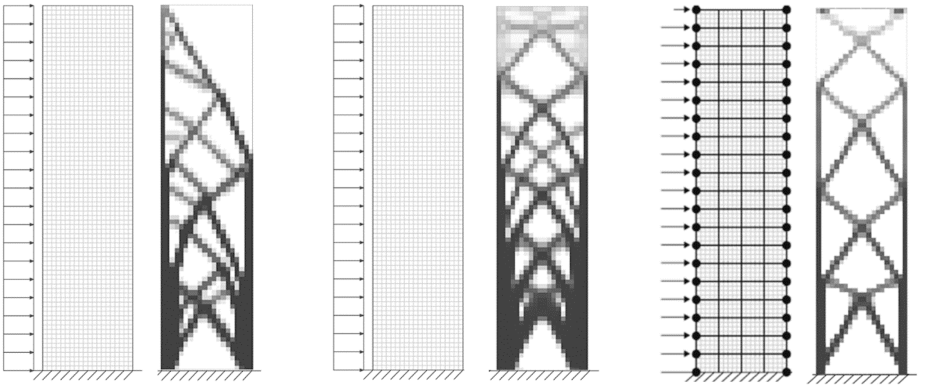

Fig. 1. Topology optimization of an 80x20 m design domain under uniformly distributed load: (a) domain and optimal layout without symmetry constraint; (b) domain and optimal layout with symmetry constraint. (c) Topology optimization under concentrated lateral forces: design domain with secondary system and optimal layout.

Because in the design of tall buildings, wind loads are often reduced to point loads acting on the perimeter of each floor, when a complete framework is introduced in the topology optimization problem, the uniformly distributed load can be converted into concentrated forces by simply multiplying the wind pressure with the influence area of each application point [11]. Fig. 1 (c) confirms that the introduction of a secondary system, bracing the domain, positively contributes in reducing the material demand at the base, providing a clearer identification of the working points and a better diagonalization at the top. In this work, uniform cross-sections are adopted for all the discrete members, sized under gravity loads according to strength requirements. However, when lateral forces are applied, a demand for additional material at the base of the domain results in the final layout. It follows that, once the optimal layout of the bracing system is defined and before performing conclusive analyses, it is necessary to re-size the cross sections of the vertical members so that they gradually increase along the height and exhibit adequate flexural rigidity against lateral loads. As it can be easily noted from the first outcomes of the optimization procedure, the material distribution assumes a specific arrangement composed of lateral columns and full-width diagonal braces. According to the literature, the location of the diagonal working point within each module varies along the height of the building. In particular, the arrangement of braces oscillates between two outer bounds: the high-waisted configuration (lower bound) and the standard cross configuration (upper bound).

4. Influence of loading profiles on optimal topologies

The optimal distribution of structural material in the domain follows the load flow within the structure, from the points of the applied load to the foundations; consequently, optimal topologies are especially sensitive to loading conditions: different loading scenarios naturally lead to different optimal layouts. The reference building is 208 x 36 x 36 m; modelling strategies already investigated in the previous section are adopted here. The topology optimization framework is defined based on the minimum volume formulation in (1). Three load patterns are defined to investigate the influence of typical lateral actions for high-rise buildings on final topologies. In particular, Fig. 2 (a) and Fig. 2(b) simulate the design domain subject to wind action, while Fig. 2 (c) reproduces the load profile in the case of seismic events. In order to achieve comparable results, the load distributions are arbitrary normalized with respect to the maximum concentrated force obtained from the three scenarios.

Topology optimization of structures subject to wind action is frequently performed by assuming a uniform load profile over the height of the building with concentrated forces applied at the nodes, lying on the perimeter of each floor, as illustrated in Fig. 2 (a). In reality, this is not the case for tall buildings.

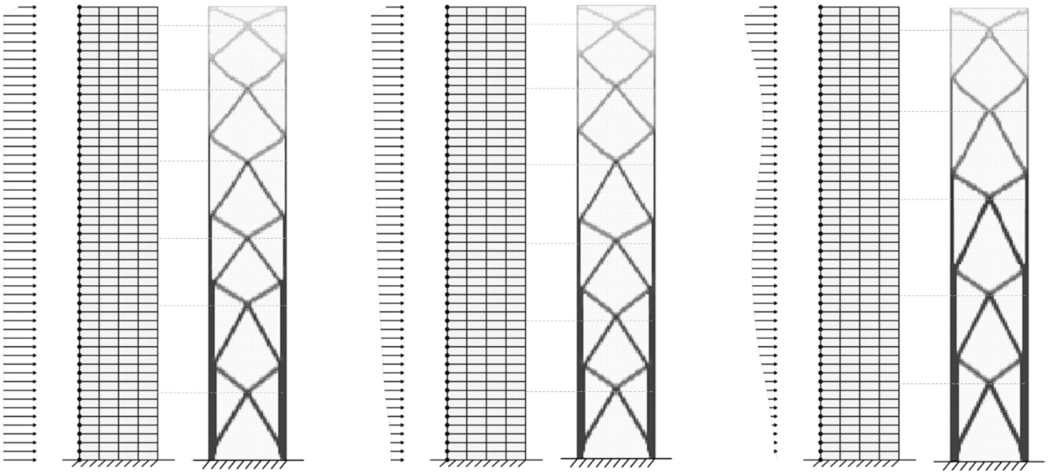

Fig. 2. Design domain and topology optimization of a 208x36 m building under (a) uniform distribution of the lateral load, (b) logarithmic load distribution (Eurocode4) and (c) adaptive multi-mode load profile.

According to Eurocode [12], the wind profiles are represented by power laws with exponent depending on the exposures. Thus, the wind increases with height, until reaching a boundary layer where it becomes uniform. This generates a logarithmic wind profile with larger wind forces at the top than at ground level, as illustrated in Fig. 2 (b).

It is well known that lateral resisting systems designed for wind actions naturally yield poor performance when subjected to seismic actions. In fact, the mechanical response of the structure under wind loads is mainly governed by the first mode while higher modes can significantly affect the global seismic response of the tall building. Moreover, current building codes generally refer only to the seismic behaviour of conventional low- or medium-rise buildings. This is mainly due to the fact that, as the height of the building increases, its flexibility increases accordingly, and the acceleration of the structure is expected to be smaller than in low-or-mid-rise buildings. However, the response of a tall building is strongly influenced by its complex dynamic behaviour in which higher modes can produce non-negligible accelerations, inevitably leading to a significantly higher response. In regions with high seismicity it is therefore essential to ensure adequate mechanical performance for tall buildings to withstand seismic action. According to these preliminary considerations and in order to satisfy a static and deterministic setting for the topology optimization problem, a multi-mode distribution is considered in Fig. 2 (c). In the topology optimization procedure, the dynamic properties of the design domain, i.e. mass and stiffness matrices, are updated iteratively. Therefore, at each step of the routine, mode shapes, mass participation factors and periods of the modes of interest are evaluated and different modal patterns are defined. A number of three higher modes is considered sufficient to excite a mass participation factor of 90%. In order to evaluate the seismic response, Eurocode [13] recommends using the Complete Quadratic Combination (CQC) if the modes cannot be considered independent. Therefore, the profiles associated to each higher mode are combined using the CQC method and the correlation among the modes is addressed explicitly by introducing the coefficients ρ_{ij} [14]:

$$\rho_{ij} = \frac{8\sqrt{\xi_i \xi_j (\xi_i + r\xi_j) r^{3/2}}}{(1-r^2)^2 + 4\xi_i \xi_j r(1+r^2) + 4(\xi_i^2 + \xi_j^2) r^2} \tag{4}$$

where $r = \omega_j / \omega_i$ and ξ_i, ξ_j are the damping ratios for modes i and j, respectively. Finally, the maximum forces acting at each floor are obtained through the envelope of the effects of higher modes using:

$$f_k = \sqrt{\sum_{i=1}^{N} \sum_{j=1}^{N} f_{i,k} \rho_{ij} f_{j,k}} \tag{5}$$

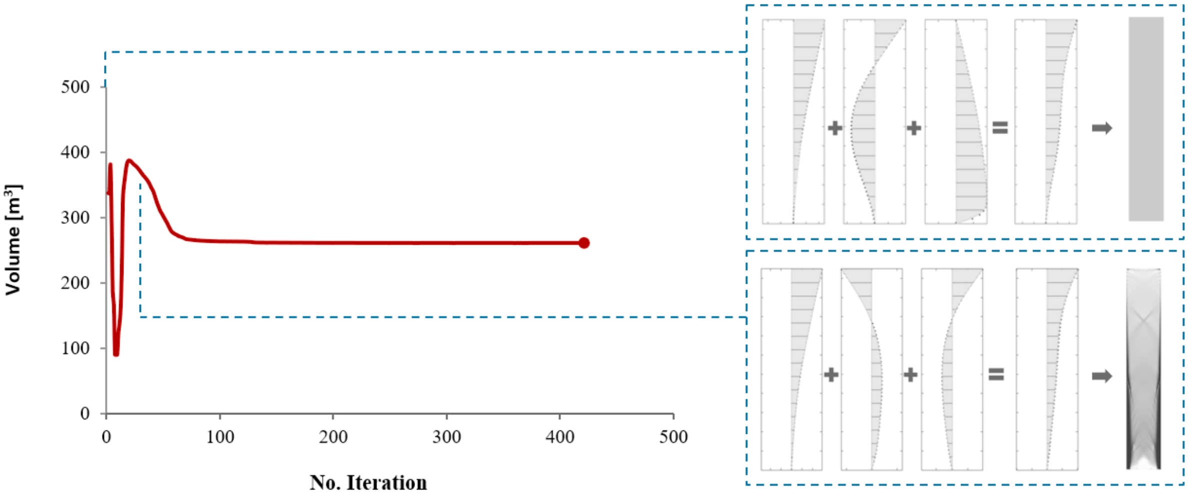

Fig. 3. Schematic of the adaptive multi-modal process at two representative steps of the topology optimization procedure.

where $f_{i,k}$ and $f_{j,k}$ are the maximum seismic forces of the modes i and j, respectively, acting at each floor k, and N is the number of modes of interest. Fig. 3 shows the calculations for the load patterns of the reference building at two representative steps of the topology optimization procedure. Within each panel, the mode shapes for the first three modes of interest at the corresponding iteration are illustrated and the resulting combined load pattern is provided, which represents the load forces statically applied to the domain during the next iteration. This naturally leads to an adaptive multi-mode distribution, which means that loading profile adapts to the updated dynamic properties of the optimizable domain. The final topologies related to the different loading scenarios are shown in Fig. 2. As expected, the arrangement of the lateral bracing system varies along the height of the building, with a high-waisted configuration of the diagonals at the base of the building and a gradually reducing slope towards the top. In particular, the uniform profile in Fig. 2 (a) and the logarithmic profile in Fig. 2 (b) produce very close optimal layouts with only a divergency on the location of the working points at the first and the second modules. This discrepancy between the layouts is reasonably attributable to the reduction of the lateral forces at the base of the building when approaching the boundary layer provided in Fig. 2 (b). Further information on the optimization procedures performed adopting different load profiles can be assessed by comparing the iteration histories of the objective function (structural volume), as provided in Fig. 4. The chart demonstrates that the uniform pattern and the logarithmic distribution lead to very close results for the structural volume (246.9 m^3 and 241.4 m^3, respectively) with a slightly different number of iterations required to achieve a convergence of 0.5% (389 and 698 iterations, respectively). In other words, the uniform wind distribution produces analogous layouts and comparable values of volume demand with a drastically reduced time consumption with respect to a logarithmic distribution. This result is particularly significant in the case of topology optimization, since it demonstrates that a simplified uniform scenario produces to the most conservative result with the lowest number of iterations. By comparing the three topologies, the adaptive multi-mode profile in Fig. 2 (c) produces a qualitatively different layout with the loss of a bracing module and a sharper high-waisted X-bracing scheme. This confirms that lateral resisting systems designed for wind actions generally exhibit inadequate mechanical performance in regions of high seismicity. Furthermore, it can be observed that the multi-mode scenario leads to an optimal structural volume (261.1 m^3) and a number of required iterations (421 iterations) comparable to those obtained using the uniform pattern. To this end, it can be concluded that an adaptive multi-mode procedure represents a sufficiently accurate and rapid strategy to incorporate seismic actions within a classic topology optimization framework for the preliminary design of tall buildings.

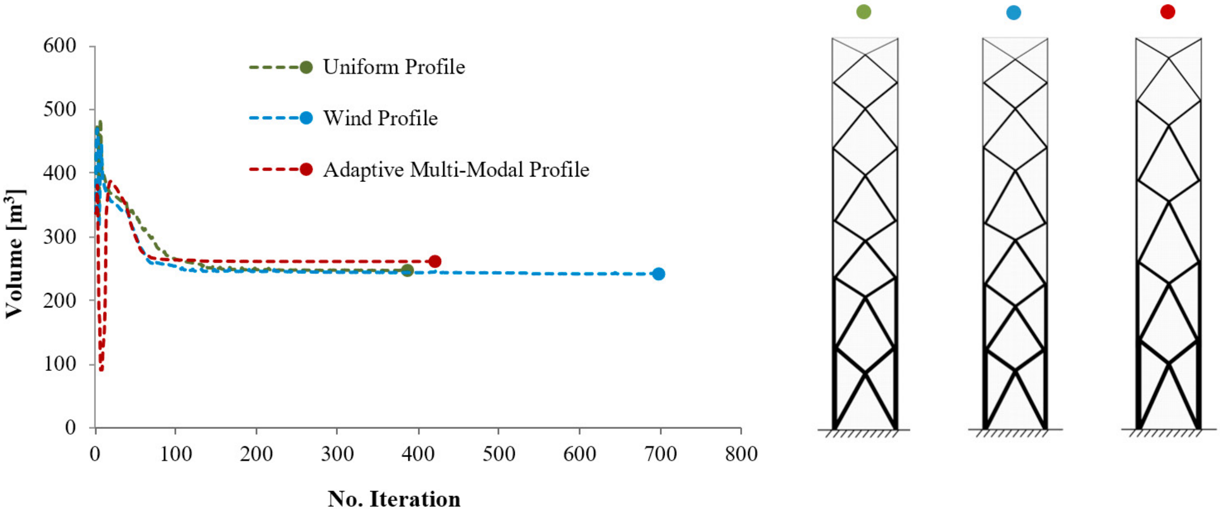

Fig. 4. Iteration histories of the topology optimization procedures using different lateral load distributions.

5. Conclusive remarks

This paper provides modelling and loading strategies to incorporate topology optimization routines in the definition of lateral resisting systems for tall buildings. By revising existing approaches already proposed by other authors, the influence of modelling assumptions on optimal topologies is investigated, in the first part of this work, to preserve the objectivity of the final results. A symmetry constraint is enforced along the vertical centerline of the building and a complete steel framework is introduced, in order to convert the distributed lateral load, directly acting on the domain, into point loads applied at the master nodes. Because the optimal layout of the lateral resisting system is strictly dependent on the load distribution adopted, in the remaining part of the paper, a deep investigation is provided to correctly simulate wind and seismic actions within a static and deterministic topology optimization framework. A uniform profile and a more realistic logarithmic profile (according to Eurocode 4) are modelled to reproduce the wind action on the tall building. The seismic action is simulated using an adaptive multi-mode pattern, which adapts to the updated dynamic properties of the design domain at each iteration of the topology optimization procedure. The results demonstrate that a simplified scenario with uniform distribution of the lateral load captures the fundamental aspects of the problem in the case of wind action. This avoids adding further complexity to the optimization routines and ensures a limited number of iterations needed to achieve convergence. On the other hand, for tall buildings located in regions of high seismicity, it is demonstrated the need to include seismic actions into the topology optimization process. The adaptive multi-mode profile, proposed in this work, represents a valid strategy to accurately model the seismic load while preserving the advantages of a preliminary design procedure under static forces. The findings presented here can also be included within more sophisticated performance-based topology optimization frameworks for the identification of optimal lateral resisting systems for tall buildings accounting for multi-hazard wind and seismic conditions.

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