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APPLICATION OF STRUCTURAL TOPOLOGY OPTIMIZATION TO SLENDER TELECOMMUNICATION LATTICE TOWERS

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Abstract

Recent developments in civil engineering proposed the application of structural topology optimisation to buildings and infrastructure projects. Architects and engineers have also started investigating the use of topology optimisation, for the design of efficient, functional, and aesthetically pleasing structures. Topology optimisation (TO) employs intelligent mathematical algorithms to generate 2D layouts or fine 3D models representing structural frames, suitable for prescribed forms, with intriguing architectural features and improved weight-to-stiffness ratio. This paper applies structural topology optimisation (STO) techniques to create a radical design for a slender lattice self-supporting telecommunication tower. The study investigates novel lattice tower morphology through both 2D and 3D approaches. A new topology representing a single face of a lattice self-supported tower composed of 'high-waisted' bracing type was created using 2D STO with a sequential refining rationale. Conclusions are drawn with respect to the optimisation analyses (OA), observations, and the potential advantages of STO to the design such slender space frames but also other similar exoskeleton structures.

1 Introduction

As the telecommunication industry growth remains fed by the public constant demand for more and better services, replacements, modernizations and necessary upgrades of the existing ones continue to take place. This calls for the creation of new competent technology that will be attached to tall lattice broadcasting telecommunication structures to support antennas and dish-reflectors of different size, shape, and weight in comparison to these currently utilized. More and more equipment is usually mounted on existing towers at various heights, creating rather complex design load-carrying scenarios and asymmetric distribution of forces within the structural frame [1]. New equipment increase the solidity and surface area of the towers, consequently, the wind drag becomes more intense. However, on certain occasions existing telecommunication towers have not been designed to carry such loads and the additional gravitational and lateral forces, thus they required meticulous checking and strengthening before get damaged or even collapse. Efthymiou et al. [2] stated that the consequences to the social and economic domain resulting from the collapse of such structures can be regarded as equally damaging to the consequences caused by the collapse of a bridge or other similar infrastructure. The human loss is directly related to the damage of such a tower but the loss of communication for a period of time through damaging equipment may be catastrophic. Therefore, to meet the requirements for the upgrade of the current broadcasting services, development of new towers and the rehabilitation existing ones is deemed in many cases [3].

Furthermore, due to the fact that these tall and flexible (slender) structures are repeatedly subjected to fluctuating stresses induced by dynamic wind effects, it is very likely that they will undergo fatigue damage. Old telecommunication masts and towers that suffer fatigue damage may need to be replaced [4].

The rapid growth of mobile telecommunication industry ushered in a bright new era for the lattice self-supported towers and guyed masts. Just to get a feeling of the telecom industry's effect in the installation of new towers or masts, Støttrup-Andersen [5] mentions that 800 of a specific type of towers were created for Connect-Austria in a short period of time.

This great demand for the installation of new towers requires building permits which are very difficult to acquire especially when the aesthetic value of the structure is not adequate [6]. In addition, the increasing number of masts and towers can cause visual interruption landscapes which makes the process of achieving building permit even more difficult [7,8]. Consequently, what stems is the need to develop lattice telecommunication towers with improved architectural appearance and reduced solidity while also being able to meet the structural capacity and functional utility demands. This paper attempts to develop a lattice telecommunication tower topology that fulfills the aforementioned requirements employing an STO technique.

2 Conceptual designs on buildings

The up-to-date literature covers various applications of computational STO techniques but there is limited work on slender space frames such as the lattice telecommunication exoskeleton towers. However, there is a current trend in research and practice to employ computational STO techniques for the design of optimal lateral support systems of high-rise buildings and building skeletons driven by architects [9,10,11] and for the design of non-standard lightweight and stiff structural elements [12]. Typical examples of the applications mentioned are depicted in Fig.1.

Fig. 1. Structural topology optimisation techniques on buildings [9,10,11].

To interpret the results of this paper, resulting topologies of previous studies will be also employed. These studies aimed at producing topology layouts, appropriate for high-rise buildings, using manufacturing constraints such as symmetry and pattern gradation [9]. Topologies such as the optimum cantilever and shear bracing presented within Stromberg et al. [13] are also studied to explain the conceptual layouts obtained in this particular study.

3 2D & 3D design domains

2D domains are initially developed to visualize topologies for a plane frame with respect to the loading and boundary condition, followed by 3D domains to investigate the distribution of horizontal forces and the need for members. The following sections briefly describe the idea and process for the construction of the domains and establishment of loads and boundary conditions.

3.1 Domains computational design and geometrical characteristics

Design domains are based on the geometry of a steel lattice self-supported tower located in Greece and designed to resist wind as well as seismic actions (Fig. 2). The 19m tall four-legged tower with a square plan, partially tapered vertically, and with a triangular shaped tip to allow antenna fitting. Following that, three 2D distinct geometries were formed, all based on the perimeter lines of the tower CT: (i) a fully tapered (FT), (ii) a fully straight (FS), and (iii) a partially tapered (PT) (Fig. 2). The analysis of the domain to produce the most consistent and realistic outcomes gas been considered for the creation of the novel skeleton.

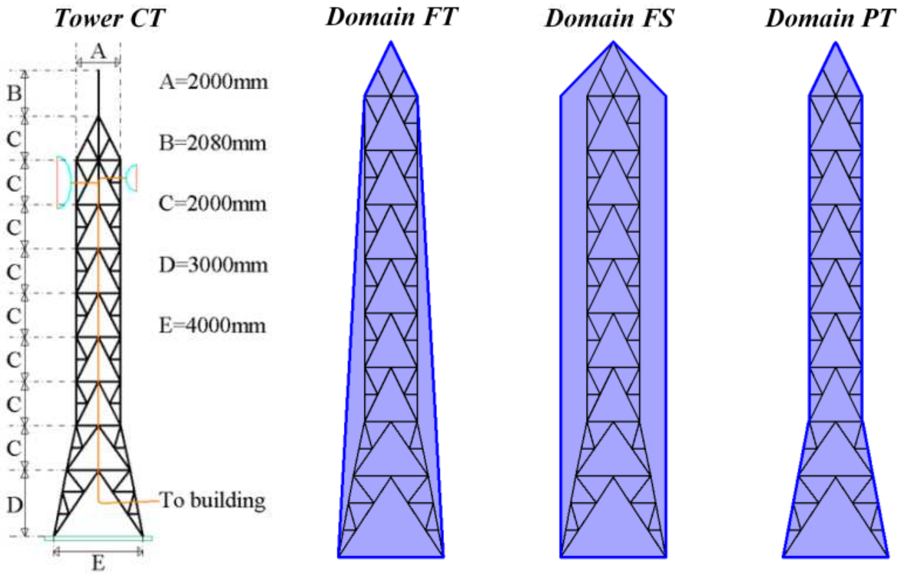

Fig. 2. 2D domains based on the geometry of the conventional tower (CT).

The design of the FT3D domain involved the creation of three intermediate 2D sheet panels for the horizontal bracing and a 3D exterior solid for the exoskeleton (Fig. 3). It is worth mentioning that the panels have been distributed vertically at an equal distance from each other. All 2D and 3D design domains were formed using the geometry tools of Altair HyperWorks. The domains as shown by HyperMesh and their main characteristics can be visualised in Fig. 3 and Table 1 respectively.

Table 1. Basic characteristics and dimensions of the final designed domains.

Domain	Characteristics			Dimensions [m]				
	Type	Cap	Taper	Base grid W	Cap width W_c	Cap height H_c	Taper height H_t	Total height H
FT	2D	Yes	Yes	4	2	2	17	19
PT	2D	Yes	Yes	4	2	2	5	19
FS	2D	Yes	No	4	4	2	---	19
FT$_{3D}$	3D	No	Yes	4	---	---	17	17

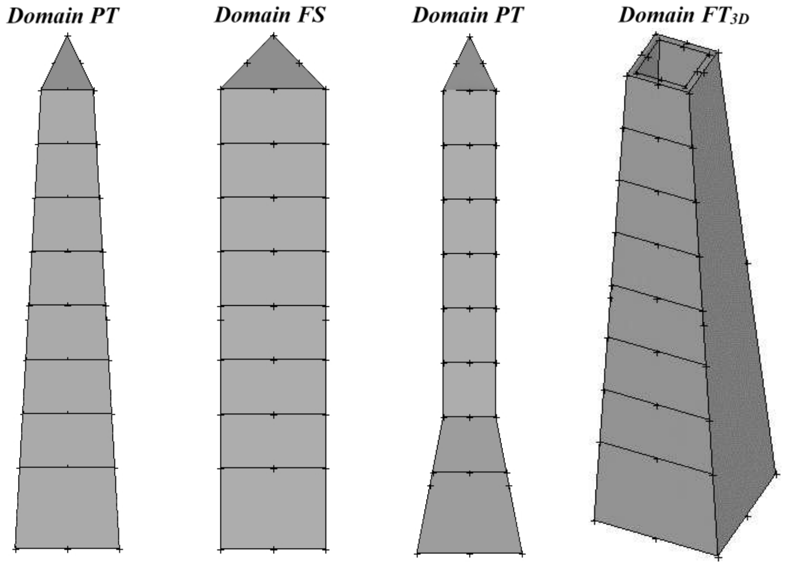

Fig. 3. 2D and 3D design domains in HyperMesh.

3.2 Loads and boundary conditions

Static wind loading was used to develop new designs of lattice telecommunication towers through computational optimisation. Guidance for predicting the effect of wind on lattice structures is currently provided by Eurocode 1 and German codes DIN 4131 in conjunction with Eurocode 3 Part 3-1 and DIN 1991, respectively [2,14]. Static wind forces are determined based on Eurocode 1 assuming the tower is subjected to the worst wind loading scenario that can possibly take place in the UK. Both methods rely on the solidity of the structure [15-17]. At this stage, the optimised steel lattice towers topology has not been developed yet and therefore, the wind forces were calculated based on the arrangement of tower CT.

In particular, the initial analyses were performed considering point loads applied only at the top and at the locations of secondary horizontal bracing members as currently used in the topology of CT model. Nevertheless, it was noticed that by altering the loading scenario to a higher magnitude distributed load, the outcome of the analyses is also improved by providing coherent and ideal topology layouts. Thus, this practice was adopted for the analyses of all the domains.

4 Topology optimisation study

The final resulting topology layouts within a domain are presented in this section. These were progressively developed by mainly changing element thicknesses and introducing symmetry manufacturing constraints. The penalisation factor ‘p’ was kept as 1.0 for the analysis of 2D domains as it helps in identifying whether bigger members are required towards the bottom of the structure (i.e., by indicating higher density). Regarding the 3D domain, in order to obtain a rational and easy to interpret topology, a penalisation factor of 3.0 was used. In addition, it was observed that a penalisation factor of 3.0 also helps to achieve members with constant thicknesses and widths along their length [18]. In general, it was observed that setting the element thickness at 250mm and the volume fraction between 0.2 and 0.3, the output of both types of analyses were more coherent.

4.1 The application of symmetry

To create a topology able to resist wind actions in the leeward and windward directions, symmetry constraints were employed on the design variables of each domain as it is shown in Fig. 4. Two symmetry axes were introduced in the 2D domain PT to ensure enough material distribution to the bottom section where high overturning moments take place.

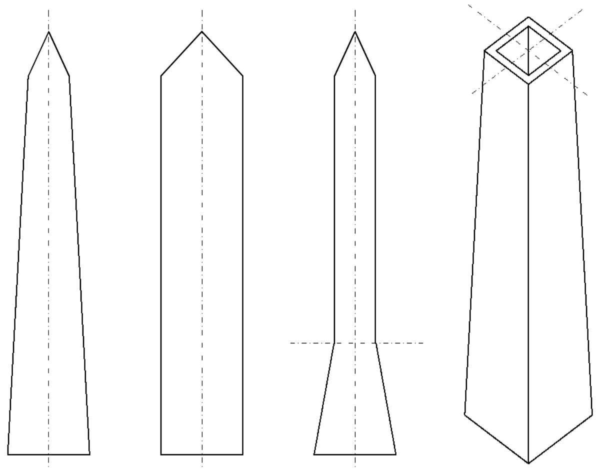

Fig. 4. Symmetries introduced on each domain.

4.2 Optimisation study of the 2D domains

The characteristics of each optimisation analysis are summarised in Table 2. As it can be observed, the analysis of domain PT required more iterations to determine the optimal distribution of material. This is mainly because of the two symmetry axes used during the analysis.

Table 2. Characteristics of the optimisation analyses performed on the 2D domains.

Domain	Boundary conditions	Iterations number	Elements thickness t_e [mm]	Volume fraction V_f [%]
FT	Full base fixed	59	215	0.25
FS	Full base fixed	52	215	0.25
PT	Full base fixed	74	215	0.25

As it is depicted in Fig. 5, the topology of the domain FT comprises of three consecutive 'high-waisted' bracings closer to the bottom of the tower's face due to the coupling effect of bending and shear actions. This is established by investigating the angles as well as the distance z of the braces (a), (b), and (c) available on Fig. 6. Both measurements lean towards the angles and z height of the optimum cantilever bracing illustrated by Stromberg et al. [9,13]. In addition, the material of the columns is of lower density at the top indicating the change in the cross-section size from the bottom to the top of the tower; a concept already applied in the design of conventional lattice telecommunication towers and in general tall slender structures.

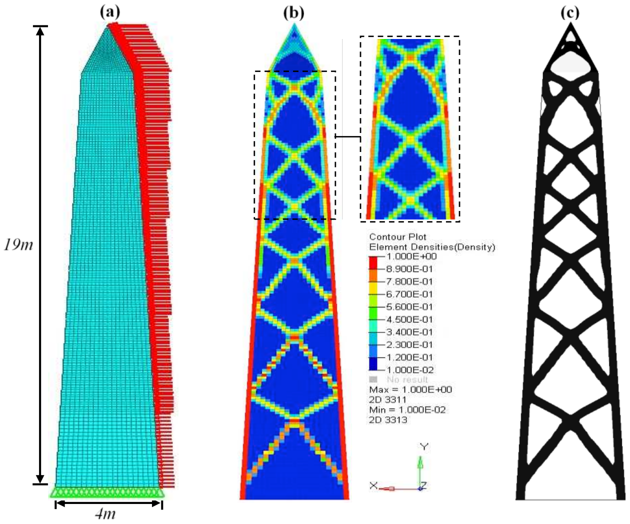

Fig. 5. Fully tapered face optimisation: (a) loading scenario; (b) element-density plot; (c) 2D rendering plot.

Although at the top bracing panel (d) a ‘shear problem’ is formulated from the topology optimization study, the angles observed lean towards the optimum angles of a ‘cantilever problem’ bracing. Panels (e) and (f) are more complex to interpret due to the numerous intermediate lines required to simplify their current shapes and sequentially measure the angles. However, height z indicated that both top panels tend to be characterised as high-waisted bracings having the capacity to resist shear and bending actions. Overall, the optimisation analysis results of the fully tapered domain suggested the use of high-waisted braces throughout the full height of the structure. It is also noticed that as the height of the tapered tower increased, the distance ‘z' of each panel decreased - excluding panel (f).

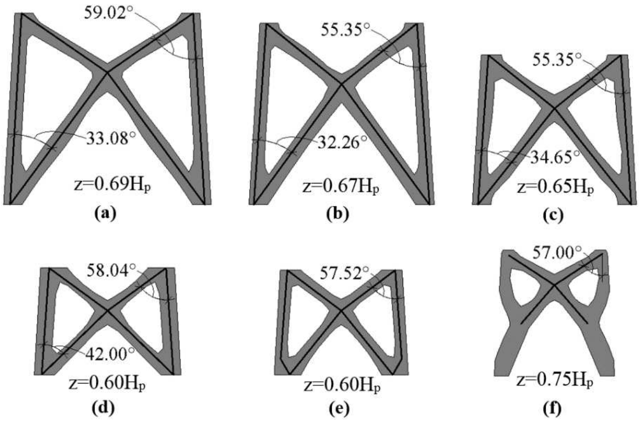

Fig. 6. Interpretation of the optimised topology on the domain FT.

The optimisation of domain FS as shown in Fig. 7, resulted in X bracing systems arrangement throughout the height of the tower. The resulting topology consisted of four bracing panels where: (a) and (b) are high-waisted bracings, panel (c) as shown in Fig. 8 composes a topology usually presented in ‘shear problems’. This inference is based on the fact that the top angle of 50.92^{o} approaches the optimal angle resulting from a ‘shear problem’ (i.e., approximately 45^{o} [9,13]).

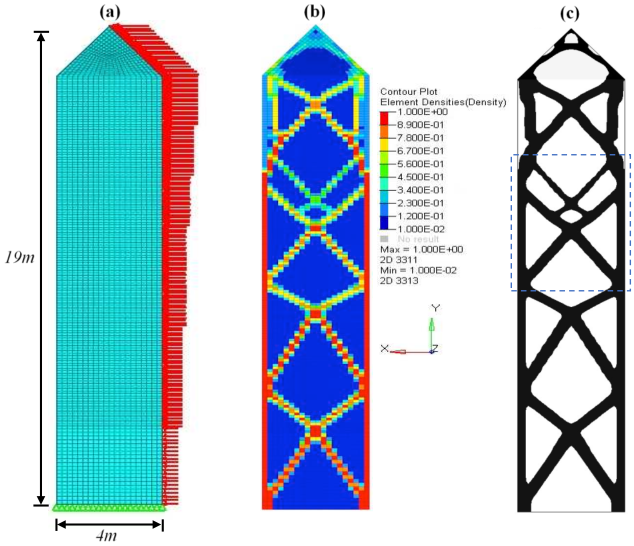

Fig. 7. Fully straight face optimisation: (a) loading scenario; (b) element-density plot; (c) 2D rendering plot.

The additional smaller bracing system formed at the top of bracing (c) was possibly the most optimum way to stiffen the resulting topology using the available material volume and to satisfy the weighted compliance objective function. The angles observed for the panel (d) indicate a ‘cantilever problem’ topology system. It is worth noting that OptiStruct significantly reduced the number of structural elements required for this structure.

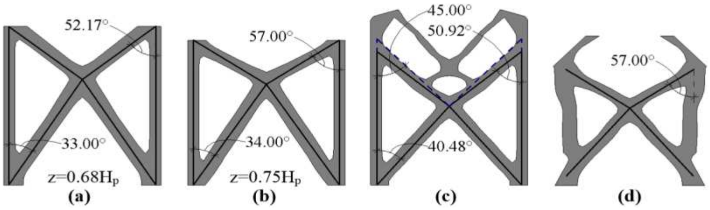

Fig. 8. Interpretation of the optimised topology on the domain FS.

Optimising domain PT as shown in Fig. 9, the bracing pattern resulted above the tapered section is rather irregular. High-waisted and optimal shear bracings are not found at the expected locations. This is mainly due to the current location of the horizontal axis of symmetry.

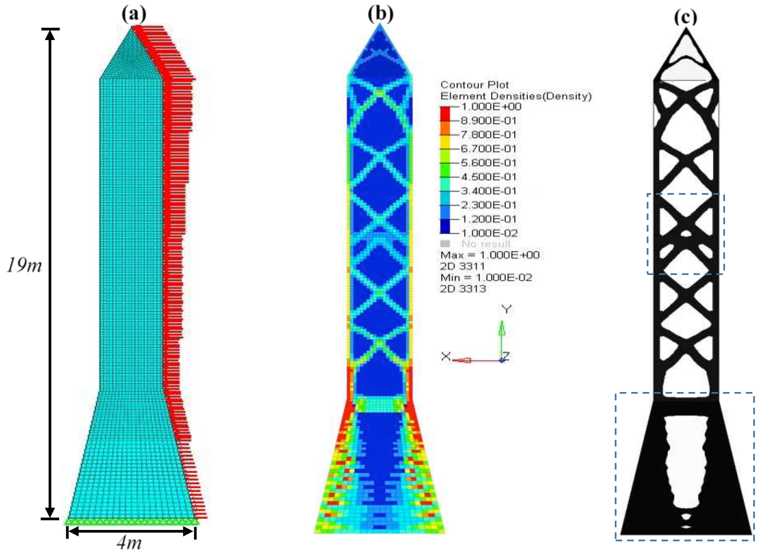

Fig. 9. Partially tapered face optimisation: (a) loading scenario; (b) element-density plot; (c) 2D rendering plot.

During the analysis of domain PT, OptiStruct split the given volume equally about each axis of symmetry. Therefore, it can be argued that symmetry constraints are used to obtain the symmetrical distribution of material only, rather than the geometries.

4.3 Optimisation study of the 3D domain

The resulting 3D topology clearly demonstrated that the solution is heavily dependent on the location of the support conditions and the direction of the applied forces. Unlike 2D domain analyses, although axes of symmetry were used in two directions, the topology generated is only able to resist the loading scenario shown in Fig. 10.

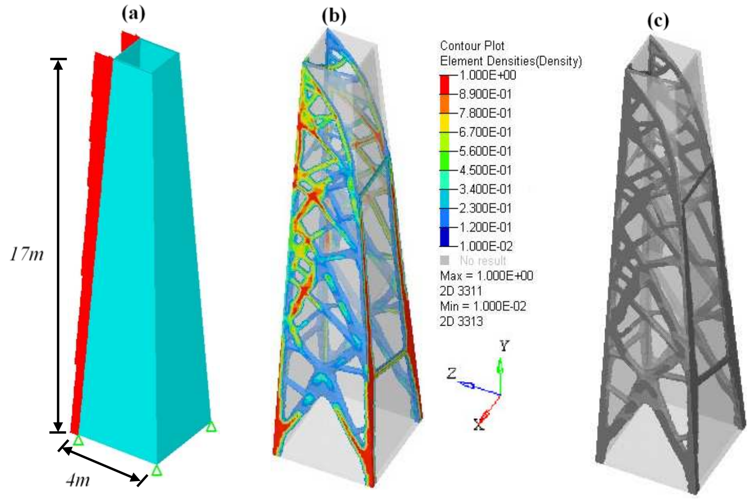

Fig. 10. Fully tapered optimised tower: (a) loading scenario; (b) element-density plot; (c) 3D rendering plot.

Horizontal bracings increase the bending stiffness of the structure and thus they were included in the analysis to resist the torsional effects. This caused very little material to be distributed on the panels transverse to the loading direction during the 3D optimisation analysis and no twisting effect on the domain FT3D was obtained.

5 Concluding remarks

All analyses produced reasonable results with the most realistic being the one from 2D domain FT. Important findings in relation to the optimisation studies performed are such as:

- In the vicinity of FT domains, the height z decreases with the increase of the domain height. Values of z ranged from 0.60Hp to 0.75Hp.
- Assessing bracing panels (a), (b) and (c) of the domain FT, it can be argued that 20% reduction of the top width of each panel in relation to its bottom width, results in 2% reduction of height z.
- Examining PT domain, it was revealed that reaching the optimal solution requires combining optimal layouts resulting from different analyses.
- The angles of high-waisted bracings observed in the analyses of FT and FS domains were similar to the optimum angles of high-waisted bracings demonstrated by Stromberg et al. [9,13].
- The material distribution is heavily dependent on stress paths trajectories generated within the domain in accordance with the loading scenario and support conditions. The optimisation techniques used indicated one reasonable and consistent conceptual layout.
- The application of manufacturing constraints enabled the development of symmetricalinterpet topology.

In conclusion, fewer individual structural components are obtained as a result of this structural topology optimisation study when compared with model CT. Consequently, the optimised tower is significantly lighter and less visually intrusive. The authors suggest the dynamic identification of the characteristics of the optimised spatial frames and exoskeletons through a time-history analysis with a wind velocity which is usually represented by a broad-band power spectrum as the next important stage in order to understand and further improve the proposed morphology.

6 References

[1] Szafran, J. 2015. An experimental investigation into failure mechanism of a full-scale 40m high steel telecommunication tower. Engineering Failure Analysis. 54pp.131-145.
[2] Efthymiou E., Kaziolas, D. N. and Baniotopoulos C. C. 2009. On the response of steel telecommunication masts under environmental actions and seismic loading. In Proc. of 11th Nordic Steel Conference (NSCC2009), Malmo, Sweden, pp. 375-381.
[3] Albermani, F., Mahmendran, M. and Kitipornchai, S. 2004. Upgrading of transmission towers using a diaphragm bracing system. Engineering Structures. 26(6), pp. 735-744.
[4] Pospíšíl, S., Lahodný, J., Janata, V., Urushadze, S., Král, R. and Hračov, S. 2012. Lifetime prediction of wind loaded mast and towers with respect to lateral and longitudinal wind spectrum. In: 18th International Conference Engineering Mechanics, 14/17 May 2012, Svratka, Czech Republic. Czech Republic: 18th International Conference Engineering Mechanics.
[5] Støttrup-Andersen, U. 2014. Masts and Towers. Journal of the international association for shell and spatial structures. 55(2), pp.69-78.
[6] Nielsen, M.G and Støttrup-Andersen, U. 2006. Advantages of using tubular profiles for telecommunication structures. In: Tubular Structures XI Willibald, S. and Packer, J.A., 31 August/2 September, Quebec City. London: Taylor & Francis Group plc, pp. 45-51.
[7] Forest of Dean District Council. No date. Telecommunications. [Online]. [Accessed 29 April 2016]. Available from: http://www.fdean.gov.uk/nqcontent.cfm?a_id=6500
[8] Coventry City Council. 2005. Supplementary guidance note 'telecommunications – a design guide'. UK: Coventry City Council.
[9] Stromberg, L.L., Beghini, A., Baker, W.F. and Paulino, G.H. 2010. Application of layout and topology optimization using pattern gradation for the conceptual design of buildings. Structural and Multidisciplinary Optimization. 43(2), pp. 165-180.
[10] Beghini, L.L., Beghini, A., Katz, N., Baker, F.W. and Paulinho, G.H. 2014. Connecting architecture and engineering through structural topology optimization. Engineering Structures. 59pp. 716-726.
[11] Kingman, J.J., Tsavdaridis, K.D., and Toropov, V.V. Applications of Topology Optimisation in Structural Engineering: High-rise Buildings & Steel Components. Jordan Journal of Civil Engineering, Vol. 9, No. 3, 2015, pp. 335-357.
[12] Tsavdaridis, K.D., Kingman, J.J. and Toropov, V.V. Application of Structural Topology Optimisation to Perforated Steel Beams. Computers and Structures, Vol. 158, 2015, pp. 108-123.
[13] Stromberg, L.L., Beghini, A., Baker, F.W. and Paulinho, G.H. 2012. Design of Structural Braced Frames Using Group Optimization. In: 20th Analysis and Computation Specialty Conference, 29/31 March 2012, Chicago. USA: Structures Congress 2012.
[14] Baniotopoulos, C. and Stathopoulos, T. 2007. Wind effects on buildings and design of wind-sensitive structures. Italy: SpringerWien New York
[15] Nielsen, M.G. 2014. Analysis and design of masts and towers. Journal of the international association of shell and spatial structures. 55(2), pp. 79-88.
[16] Carril Jr., C.F., Isyumov, N. and Reyolando, M.L.R.F. 2003. Experimental study of the wind forces on rectangular latticed communication towers with antennas. Journal of Wind Engineering and Industrial Aerodynamics. 91(8), pp. 1007-1022.
[17] Eurocode 1. 1991. BS EN 1991-1-4:2005. Eurocode1: Actions on Structures – Part 1-4: General actions – Wind actions. UK: BSi.
[18] Olason, A. and Tidman, D. 2011. Methodology for Topology and Shape Optimization in the Design Process. MSc. Thesis, Chalmers University of Technology.