TOPOLOGY OPTIMISATION STUDY FOR THE DESIGN OF LATTICE TOWERS

Andreas Nicolaou
MEng in Civil/Structural Engineering
School of Civil Engineering
University of Leeds
Woodhoouse Lane, LS2 9JT, Leeds, UK
e-mail: nicolaou.andreas92@gmail.com

Konstantinos Daniel Tsavdaridis
Associate Professor of Structural Engineering
School of Civil Engineering
University of Leeds
Woodhoouse Lane, LS2 9JT, Leeds, UK
e-mail: k.tsavdaridis@leeds.ac.uk

Evangelos Efthymiou
Assistant Professor
Institute of Metal Structures
Department of Civil Engineering
Aristotle University of Thessaloniki, Greece
e-mail: vefth@civil.auth.gr

ABSTRACT

Recent developments in Civil Engineering proposed the application of structural topology optimisation to buildings and civil engineering structures. Aerospace and automotive engineers routinely employ topology optimisation and have reported significant structural performance gains as a result. Recently designers of buildings and structures have also started investigating the use of topology optimisation, for the design of efficient and aesthetically pleasing developments. This paper exploits computational structural topology optimisation (STO) to deliver a novel exoskeleton for lattice self-supporting telecommunication towers. Topology optimisation (TO) employs intelligent mathematical algorithms to generate 2D layouts or fine 3D models representing structural skeletons, suitable to prescribed forms, with intriguing architectural features and improved weight-to-stiffness ratio. The present study investigates the potentials on delivering a lattice novel tower morphology through both 2D. In particular, 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 rationale. Conclusions are drawn with respect to the optimisation analyses (OA) major observations and the potential advantages of STO to the design of lattice telecommunication towers or other similar exoskeleton structures.

Keywords: Lattice telecommunication towers, Structural topology optimisation, High-waisted bracing type, Altair Engineering.

1 INTRODUCTION

As the telecommunication industry growth remains fed by the public constant demand for more and better services as well as new infrastructure and 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 on tall lattice broadcasting telecommunication structures. It involves antennas and dish-reflectors of different size, shape and weight in comparison to these currently utilized. Currently, new technologies are mounted on existing towers at different heights than the previous, resulting in the alteration of the design load-carrying scenarios and thus capabilities of the individual structural components with sometimes current asymmetric distribution of forces within the structures' skeleton [1]. In addition, new equipment increase the solidity and surface area of the towers, consequently, the wind drag becomes more intense. However, it is worth to note that existing telecommunication towers have not been designed to that extent to cope with such additional gravitational and lateral forces. Hence, it is possible that existing towers, with newly attached equipment, will get damaged or even collapse due to their inability to carry the new additional forces. 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. Therefore, under the conditions of improvement and upgrade of the current broadcasting services, establishment of new towers, and rehabilitation or complete replacement of the old lattice towers is deemed in many cases necessary [3].

Furthermore, due to the fact that these tall and flexible 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].

Generally, the worldwide demand for installing tall lattice telecommunication towers and masts has increased. 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 if the aesthetic value of the concerned structure is not adequate [6]. In addition, the increasing number of masts and towers can cause visual intrusion to the landscape which makes the process of achieving building permit even more difficult [7, 8]. With that in mind, it is unfortunate that towers with increased solidity are even more noticeable, a distinct disadvantage in aesthetic terms. Therefore, what springs from this situation is the requirement to develop lattice telecommunication towers with improved architectural appearance and reduced solidity while also being able to fulfil all structural capability and functional utility demands. The authors of this research attempt to develop a lattice telecommunication tower topology that fulfils the aforementioned requirements through an intriguing computational STO approach.

2 CONCEPTUAL DESIGNS ON BUILDINGS

The up to date literature shows no sign of the use of computational STO techniques for the production of steel lattice telecommunication exoskeleton structures. Nevertheless, 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 or for the production of complete building skeletons driven by architects [9,10,11] as well as for the design of novel non-standard lightweight and stiff structural elements [12]. Typical examples of the applications mentioned are depicted in Fig.1.

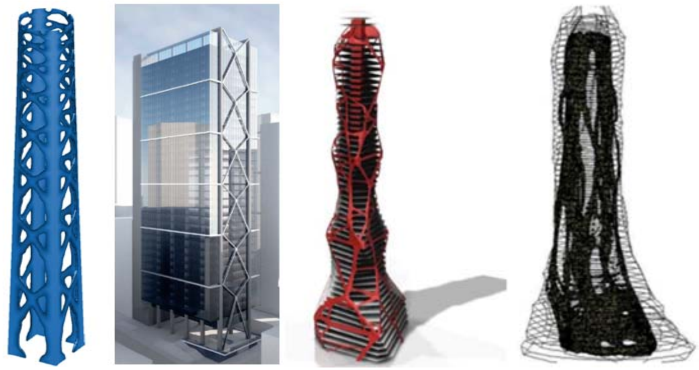

Fig. 1. Structural topology optimisation techniques on buildings [9,10,11].

To interpret the results of this paper, resulting topologies of previous studies will be used. These studies aimed in producing topology layouts, appropriate for high-rise building design, 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] will be mentioned to explain the conceptual layouts obtained herein.

Ultimately, this endeavour aims to investigate STO potentials as a tool when this is employed in the design process of aesthetically pleasing and structurally enhanced lattice telecommunication towers. The overall objectives of this research paper, in the context of fulfilling this aim, are to: (a) produce optimised conceptual layouts through computational STO; (b) compare conceptually the results with existing literature; (c) enhance the structures' aesthetic value; (c) deliver topologies with low number of structural elements to create in the future exoskeletons with reduced solidity and mass in comparison to the existing ones; (d) deliver an easy to assembly topology.

3 CONSTRUCTION OF THE 2D DESIGN DOMAINS

To perform the optimisation analysis (OA) and produce a topology layout for a novel morphology of a new tower, the 2D must be first created. 2D approach is followed to visualize topologies for a single tower's face formed in relation to the domain, loading and boundary conditions and 3D mainly to see if horizontal members are required in between the exoskeleton structure. 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

All the design domains created are based on the geometry of a steel lattice self-supported tower located in Greece while designed to resist wind as well as seismic actions (Fig. 2). The 19 m tall four-legged tower features square on plan configuration, partially tapered vertical profile and triangular shaped tip to allow antenna fitting. Following that, three2D 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 shall be considered in the creation of the novel skeleton.

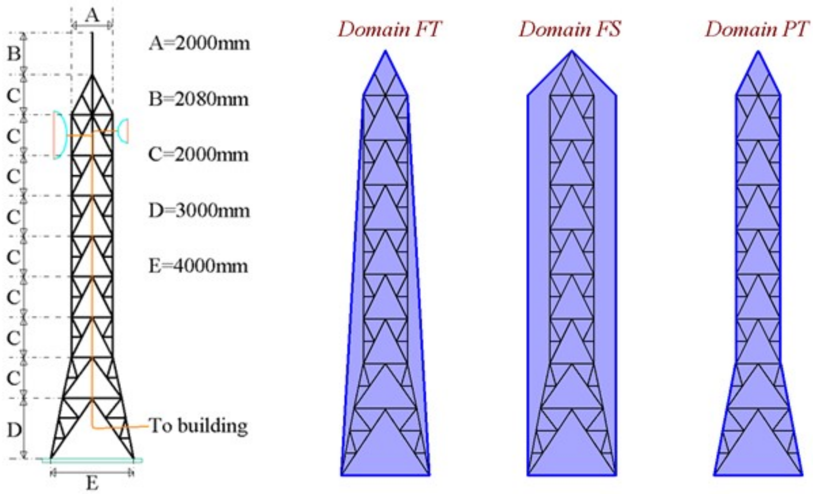

Fig. 2. Developing the 2D domains based on the geometry of the conventional tower(CT).

Moreover, the 2D design domains were formed using the geometry tools of Altair HyperMesh. The domains as shown by HyperMesh and their main characteristics can be visualised in Table 1 respectively.

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

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

3.2 Loads and boundary conditions

Static wind loading will be employed at this initial endeavour in developing designs of lattice towers through computational STO. Guidance for predicting the effect of wind on lattice structures is provided by EC 1 and DIN 4131 in conjunction with EC 3 Part 3-1 and DIN 1991, respectively [2, 14]. Static wind forces are determined herein based on Eurocodes assuming the tower is subjected to the worst wind scenario that takes place in the UK. Both methods rely on the solidity of the tower [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.

4 TOPOLOGY OPTIMISATION STUDY

The resulting topology layouts within a domain are presented within this section. Only the final solutions are presented within this paper. These were progressively developed by mainly changing element thicknesses and introducing manufacturing constraints such as symmetry. In addition, the penalisation factor ‘*p*’ was kept as 1.0 for the analysis. The use of the penalty factor equal to 1.0 will help in identifying whether bigger members are required to the bottom (i.e., by indicating higher density). In general, it was realised that setting the element thickness at 250mm and volume fractions between 0.2 and 0.3 made the output of both types of analyses coherent.

4.1 The application of symmetry

To create a topology able to resist wind in the both directions symmetry constraints were implemented as shown in Fig. 4. Two symmetry axes were introduced in the 2D domain PT to ensure enough material distribution to the bottom where high overturning moments take place.

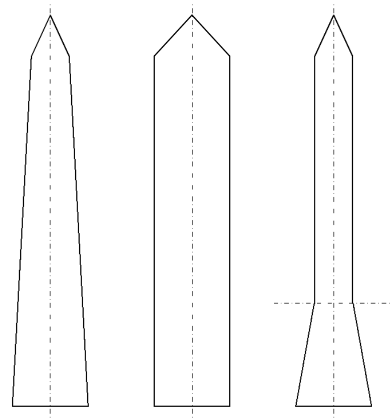

Fig. 4. Symmetries introduced on each domain.

4.2 Optimisation study on 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 for its analysis.

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

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

As it can be observed by the results 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 confirmed 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 less dense 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 tall structures.

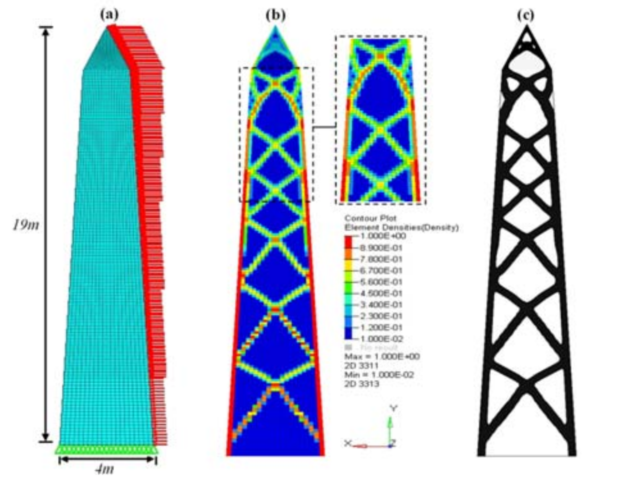

Fig. 5. Fully tapered face optimisation: (a) loading scenario; (b) element-density plot; (c) 2D rendering plot.

Although at the top bracing panel (d) it seems like a ‘shear problem’ is formulated the angles observed again lean towards the optimum angles of a ‘cantilever problem’ bracing. Height *z* indicated that both top panels (e) and (f) look more like high-waisted bracings; good on resisting shear and bending actions. Therefore, the optimisation analysis results of the fully tapered domain indicated the use of high-waisted braces throughout the full height of the structure. It is also noticed that as the height of the taper tower increased, height ‘z’ of each panel decreased - except panel (f).

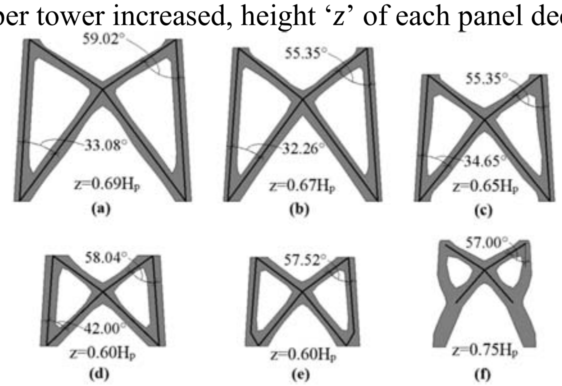

Fig. 6. Interpretation of the optimised topology on the domain FT.

Besides, as it was expected, the optimisation of the domain FS in Fig. 7 provided X bracing systems arrangement throughout. The resulting topology consisted of four bracing panels in total where: (a) and (b) are high-waisted bracings. In addition, panel (c) (Fig. 8) seems to compose a topology of a ‘shear problem’. 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., [9,13] the angles must be equal to 45^{o}).

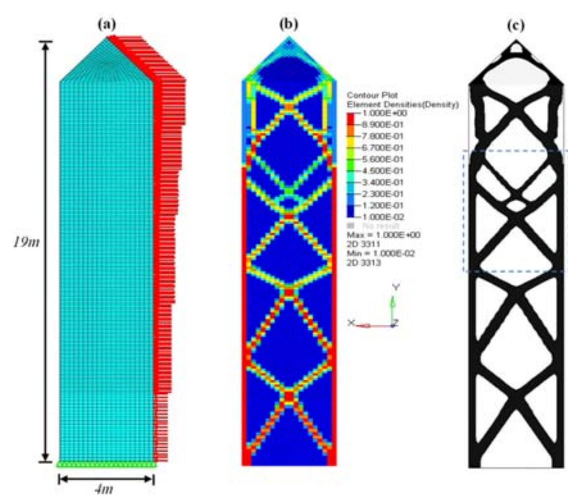

Fig. 7. Fully straight face optimisation: (a) loading scenario; (b) element-density plot; (c) 2D rendering plot.

The additional smaller bracing system formed at the top of bracing (c) was possibly the best way to stiffen the resulting topology using the available material volume and to satisfy the weighted compliance objective function. The angles observed to for 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.

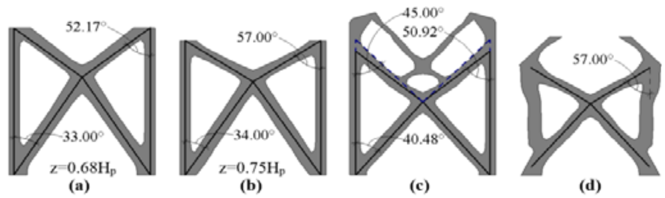

Fig. 8. Interpretation of the optimised topology on the domain FS.

Optimising domain PT available in Fig. 9, it is observed that the bracing pattern produced above the tapered section is irregular. High-waisted and optimal shear bracings are not found at the expected locations. This is because of the current location of the horizontal axis of symmetry.

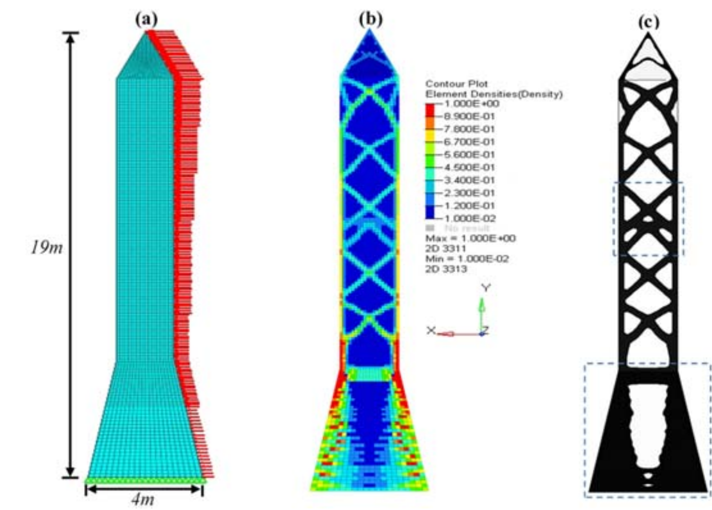

Fig. 9. Partially tapered face optimisation: (a) loading scenario; (b) element-density plot; (c) 2D rendering plot.

In the analysis of this domain, it seems that OptiStruct splits the given volume equally about each axis of symmetry. Therefore, it can be argued that symmetry constraints are used to obtain symmetrical distribution of material rather than geometries.

5 CONCLUSIONS AND REMARKS

The most consistent, realistic and optimal topology obtained was on the 2D domain FT and, therefore, it will be studied in the future further to be employed for the design of novel telecommunication towers. The aim to create an aesthetically pleasing lattice telecommunication tower layout with the potential of creating an exoskeleton with significantly low solidity and mass is fulfilled. The new topology comprises a contemporary and intriguing design for this industry. Following that, optimised tower skeleton is not yet created and therefore the topology and its overall design can be improved under a future development process towards the construction of the final novel tower (i.e., research, analysis, observe, optimise). Regarding the topologies obtained on the rest 2D domains, it seemed somewhat complex to interpret. Other important findings in relation to the optimisation studies performed include the following:

- In the vicinity of FT domains, the height z decreases with the increase of the domain height. Values of z ranged from $0.60H_p$ to $0.75H_p$.
- Although further investigation is required, by investigating 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 of the bottom width of the domain results in 2% reduction of height z.
- Through the analysis of PT domain, it was realised that reaching the optimal solution might mean that it is necessary to combine optimal layouts resulting from different analyses.
- Angles of high-waisted bracings observed in the analysis 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 to the loading scenario and support conditions. The optimisation techniques used indicated one reasonable and consistent conceptual layout. Not all studies indicated the same consistency in understanding the arrangement of voids and material. Therefore, a detailed parametric optimisation study is further required for developing the optimal layouts.
- By inspection it can be said that the numbers of individual structural components for a single tower's face are much lower on the optimum layouts in comparison to this of model CT. Consequently, the optimised tower will be significantly lighter and potentially have much lower solidity than the conventional structures.
- Finally, the application of manufacturing constraints enabled this study to create a symmetrical and easy to construct tower topology.

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] Pospíšil, 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.

ΜΕΛΕΤΗ ΤΟΠΟΛΟΓΙΚΗΣ ΒΕΛΤΙΣΤΟΠΟΙΗΣΗΣ ΧΑΛΥΒΔΙΝΩΝ ΔΙΚΤΥΩΤΩΝ ΠΥΡΓΩΝ

Ανδρέας Νικολάου
Απόφοιτος Τμήματος Πολτικών Μηχανικών
Σχολή Πολιτικών Μηχανικών,
Πανεπιστήμιου του Λίντς,
Woodhoouse Lane, LS2 9JT, Leeds, UK
e-mail: nicolaou.andreas92@gmail.com

Κωνσταντίνος Δανιήλ Τσαβδαρίδης
Αναπληρωτής Καθηγητής
Σχολή Πολιτικών Μηχανικών,
Πανεπιστήμιου του Λίντς,
Woodhoouse Lane, LS2 9JT, Leeds, UK
e-mail: k.tsavdaridis@leeds.ac.uk

Ευάγγελος Ευθυμίου
Επίκουρος Καθηγητής
Εργαστήριο Μεταλλικών Κατασκευών,
Τμήμα Πολιτικών Μηχανικών,
Αριστοτέλειο Πανεπιστήμιο Θεσσαλονίκης, Ελλάδα
e-mail: vefth@civil.auth.gr

ΠΕΡΙΛΗΨΗ

Στο πλαίσιο της ανάπτυξης νέων μεθόδων σχεδιασμού των κατασκευών αρμοδιότητας Πολιτικού Μηχανικού, η τοπολογική βελτιστοποίηση αποκτά ολοένα και αυξανόμενο ενδιαφέρον, καθώς μέσω μαθηματικών εργαλείων επιτυγχάνεται καλύτερη κατανομή υλικού που μπορεί να επιφέρει σημαντική βελτίωση της αναλογίας βάρους-δυσκαμψίας σε δομικά στοιχεία εξασφαλίζοντας ισορροπημένη εξοικονόμηση κόστους-απόδοσης, ενώ μπορεί να επιτευχθεί αναβαθμισμένο αισθητικό αποτέλεσμα αρχιτεκτονικής μορφής. Η παρούσα εργασία επιχειρεί να διαμορφώσει μία νέα πρόταση φορέα αναφορικά με την περίπτωση των χαλύβδινων δικτυωτών πύργων τηλεπικοινωνίας, εφαρμόζοντας την τοπολογική βελτιστοποίηση. Μέσω της χρήσης «έξυπνων» μαθηματικών αλγορίθμων και της υιοθέτησης δισδιάστατων διαδοχικών προσεγγίσεων, αναπτύχθηκε μία νέα τοπολογία δικτυωτού πύργου (high-waisted bracing type), του οποίου η δομική συμπεριφορά ελέγχθηκε μέσω κατάλληλων υπολογιστικών εργαλείων.