



Chapter 32

An Automated Topology Optimization Platform Through a Collaborative Project Between Academia and Industry

Karolina Ohstrom, Seth Law, Alec Maxwell, Zhaoshuo Jiang, Juan Caicedo, Haley Sims, Nick Sherrow-Groves, and Nate Warner

Abstract The gap between research in academia and industry is narrowing as collaboration between the two becomes critical. Topology optimization has the potential to reduce the carbon footprint by minimizing material usage within the design space based on given loading conditions. While being a useful tool in the design phase of the engineering process, its complexity has hindered its progression and integration in actual design. As a result, the advantages of topology optimization have yet to be implemented into common engineering practice. To facilitate the implementation and promote the usage of topology optimization, San Francisco State University and the University of South Carolina collaborated with ARUP, a world leader in structural designs, to develop an Automated Topology Optimization Platform (ATOP) to synchronize commonly used industry software programs and provide a user-friendly and automated solution to perform topology optimization. ATOP allows for users to form a conceptual understanding of a structure's ideal shape and design in terms of ideal material placement by iterating various parameters such as volume fraction, and minimum and maximum member size at the start of a project. With developed platform, a high-rise building design from the literature was first adopted to validate the results from ATOP, after which an actual design project from ARUP was utilized to fully explore its functionality and versatility. Results show that ATOP has the potential to create aesthetic and structurally sound designs through an automated and intelligent process.

Keywords Topology optimization · Automated process · Academia-industry collaboration · Rhinoceros 3D · Altair

32.1 Introduction

Structural optimization has been attracting increasing attention in the design of structures to achieve efficient, lightweight, and thus economical designs [1]. Generally, structural optimization is classified into three categories, 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 to satisfy the desired objectives. Topology optimization aims to find the optimal perimeter layout of a structure within a defined design domain [2]. In the design industry, the shape of the building is often pre-defined to achieve a desired aesthetic. The optimization of the structural member sizes could be done at a later stage after the determination of the structural system without changing much of the global behavior of the

K. Ohstrom
Cornell University, Ithaca, NY, USA
e-mail: ako24@cornell.edu

S. Law
University of Kansas, Lawrence, KS, USA

A. Maxwell · Z. Jiang (✉)
San Francisco State University, San Francisco, CA, USA
e-mail: awm@mail.sfsu.edu; zsjiang@sfsu.edu

J. Caicedo
University of South Carolina, Columbia, SC, USA
e-mail: CAICEDO@cec.sc.edu

H. Sims · N. Sherrow-Groves · N. Warner
Arup North America Limited, San Francisco, CA, USA
e-mail: Haley.Sims@arup.com; nick.sherrow-groves@arup.com; Nate.Warner@arup.com

structure. In contrast, the choice of the topology of a structure in the conceptual phase is generally the most decisive factor for the efficiency of a novel design [3]. Therefore, the focus of the optimization of structures in practice is typically placed on topology optimization.

Topology optimization is an important tool for designing an economical structure by allocating the materials to places that can efficiently transfer the loading acting on the structure. Beginning with Bendsøe and Kikuchi [4], the most common methods for topology optimization involve finite element analysis (FEA). Through FEA, the design space is divided into a series of small elements and each element is determined to either be part of the design or can be removed from the design. Topology optimization is useful for a wide range of fields, as techniques can be applied to large-scale structures as well as at micro- and nano-levels [5]. There is a significant gap between the engineering science with fundamental research in academia and engineering practice with potential implementation in the industry. Extensive research on topology optimization has been performed in academia [4, 6–17]. Although topology optimization techniques have been implemented in structural design in industry, it is not universally applied by all designers mainly due to the lack of integration with current design software and the tedious iteration process.

32.2 Proposed Solution

Through the opportunity provided by an NSF funded Research Experience for Undergraduates (REU) program established by San Francisco State University and the University of South Carolina, the REU participants were working together with faculty advisors in academia and industrial mentors in Arup North America LTD, an industrial leader in structural design, to develop an automated topology optimization platform (ATOP). The platform leverages the advantages of several commercial software platforms, including Rhinoceros 3D [18] and Altair HyperMesh/OptiStruct [19], to provide a user-friendly and automated process for topology optimization. Rhinoceros is a commonly used 3D modeling software which offers high accuracy, great compatibility with other software, and is highly accessible. Altair HyperMesh is a multi-disciplinary finite element pre-processor with advanced meshing capabilities. OptiStruct is an accurate and comprehensive structural solver that also provides innovative optimization technology. Figure 32.1 details the processes behind ATOP. The topology optimization process in ATOP is comprised of three main phases: modeling, pre-processing, and optimization. ATOP uses two programming languages, Python and tool command language (Tcl), to facilitate communication between Rhino and HyperMesh/OptiStruct. Python is a commonly used and highly versatile programming language and is used to communicate between the different components. Tcl is a high-level general-purpose programming language and is the default application program interface (API) for HyperMesh and OptiStruct. In the modeling phase, users will create geometry through the user-

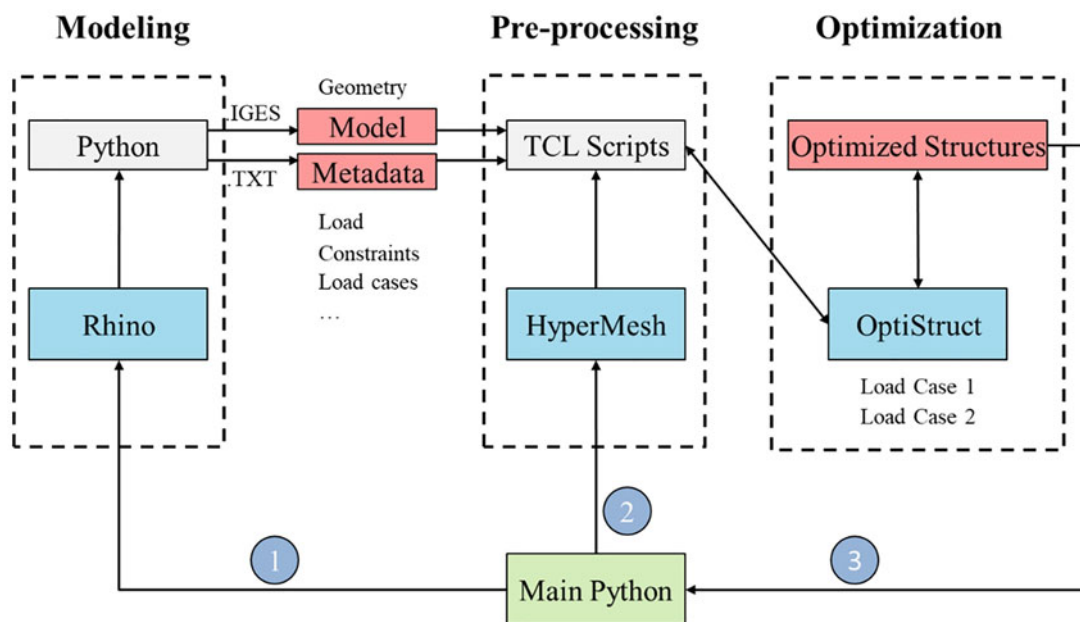
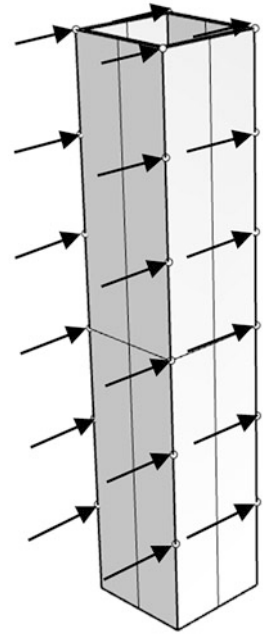


Fig. 32.1 Flowchart outlining ATOP process

Fig. 32.2 Model of high-rise structure case study with loading



friendly interface in Rhino and assign metadata (e.g., material properties, loading, and restraints conditions) to the model. During the pre-processing phase, the Main Python script will drive HyperMesh to import the stored model information and metadata from Rhino and create the corresponding model in HyperMesh. By doing so, the tedious model creating process in HyperMesh is avoided. In the optimization phase, Tcl scripts call the OptiStruct solver to perform topology optimization on the HyperMesh model that was set up in the pre-processing phase. Once that particular model has been optimized, ATOP returns to the pre-processing phase to set up a new load case, or optimization constraint. OptiStruct is then called again to carry out optimization on the next iteration HyperMesh model. This iterative process continues until all user specified combinations of load cases and optimization constraints have been achieved. Results of all user-specified combinations are then exported back to Rhino so that they may be easily viewed and compared.

32.3 Platform Validation

To validate the developed platform, a case study of a high-rise structure from literature [20] was adopted and the effects of several parameters, including volume fraction, and minimum and maximum member sizes were investigated. In the case study, Beghini et al. proposed a topology optimization framework to bridge the gap between architectural and structural engineering communities and performed topology optimization to maximize the stiffness of a tall high-rise building in Australia to serve as an example. In this particular example, the authors demonstrated the results without disclosing much detail on the parameters selection of the topology optimization, as it was not the focus of the study. With that, it is almost impossible to duplicate the results for the given design space without an automatic platform, as it might need an unlimited number of trials to find the unique combination of the parameters to produce the same results. Through the proposed ATOP platform, an attempt was made to iterate on multiple optimization parameters, including volume fraction, and maximum and minimum member size to obtain the same topology optimization results. A high-rise building model with a shell as shown in Fig. 32.2 was set up in this study. The model is constrained at the base both laterally and rotationally (in the x , y , and z directions). As was done in the literature, point loads P spanning multiple floors of the building with $P/2$ acting at its top were applied to represent wind loads. The optimization objective for this study is set to minimize the compliance. The compliance is defined as the inverse of stiffness. By default, OptiStruct performs optimization iterations until either the maximum number of 30 iterations is reached, or two consecutive iterations have a change in the objective function below the objective tolerance of 5%, the percent change in the objective function of two iterations. If a minimum member constraint is specified, the maximum number of iterations is increased to 80.

The following section discussed the selection process of the parameters and their effects on the optimization results.

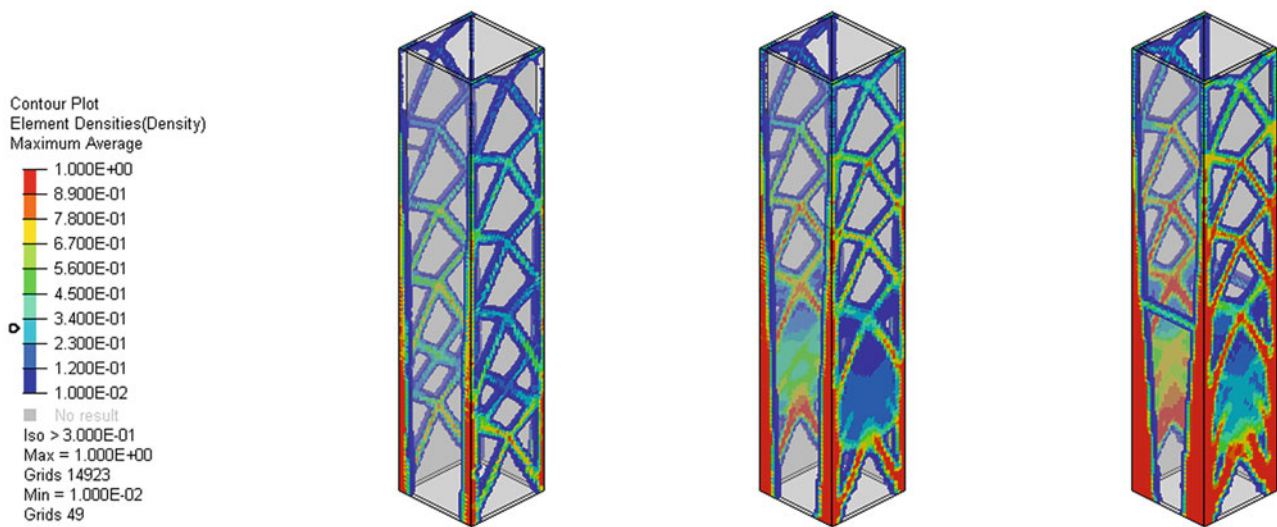


Fig. 32.3 High-rise structure case study showing the effects of different volume fractions: (from left to right) 0.1, 0.2, 0.3

1. Volume fraction is the percentage of the initial design volume that will be maintained in the optimized solid. This parameter guides the amount of material that may be placed within the design space of the final optimized shape. It limits the amount of overall material and is typically within the range of 10–30% of the original design material. Figure 32.3 shows the results of applying a volume fraction of 0.1, 0.2, and 0.3 (10%, 20%, and 30% of the original design volume) to demonstrate the effects that volume fraction has on the optimized results. As volume fraction increases, the amount of material allowed within the optimization continued to increase. The figures include a scale on the left side, which shows the density of material in the design space. The dark blue indicates an element density close to 0, while the red indicates an element density of 100%. Results can be further refined to only show material above a certain density threshold. In the figures of the optimized structures in this paper, a density threshold of 0.3 or 30% is used. This means that any element with a density less than 30% is not shown (becomes transparent) in the design space. Notably, because there are no other constraints on the optimization, as more material was added, a higher concentration was placed towards the bottom corners. This directly coincides with the objective of minimizing the compliance as these locations provide the highest amount of structural stiffness to the model.
2. Minimum Member Size is the lower limit for the diameter of elements in the final optimization. The minimum member size parameter narrows the scope of the topology optimization by assigning a factor that penalizes the formation of members smaller than the minimum member size. It is defined specifically to be a factor times the average element size within the model. An inherent function of the program exists that calculates the average size of the member within the optimization by comparing the sizes of the individually shaped elements that make up the finite element mesh. This parameter helps guide the program by ensuring that members of a reasonable size are created within the optimization. In HyperMesh, by default, the minimum member size must be at least 3 times the average element size but no greater than 12 times the average element size. Figure 32.4 shows the effects of applying a minimum member size of 3, 6, and 9 times the average element size. As the minimum member size increases, so does the size of the members. HyperMesh does take into consideration the necessity for members outside of the specified range. There may exist members whose sizes are smaller than the specific member size if these members are integral to the structural integrity of the model. As the minimum member size increases within the optimization, the number of members typically decreases as it takes more material to create each larger member.
3. Maximum Member Size, as the name indicated, is the opposite to the minimum member size parameter. It is defined as being 2 times the minimum member size within an optimization. While this parameter is not necessarily required in an optimization, it helps to further clean up the results. Figure 32.5 shows the effects of applying the maximum member size with the minimum member size. A small maximum member size creates members that may be deemed intangible. The maximum member size of 24 produced clear and legible members within the optimization which has better constructability in a real-life implementation.

Figure 32.6 provides a summary on the influence trend of the different parameters to the overall structural compliance. Figure 32.6a shows the correlation between volume fraction and compliance. As the volume fraction increases, the

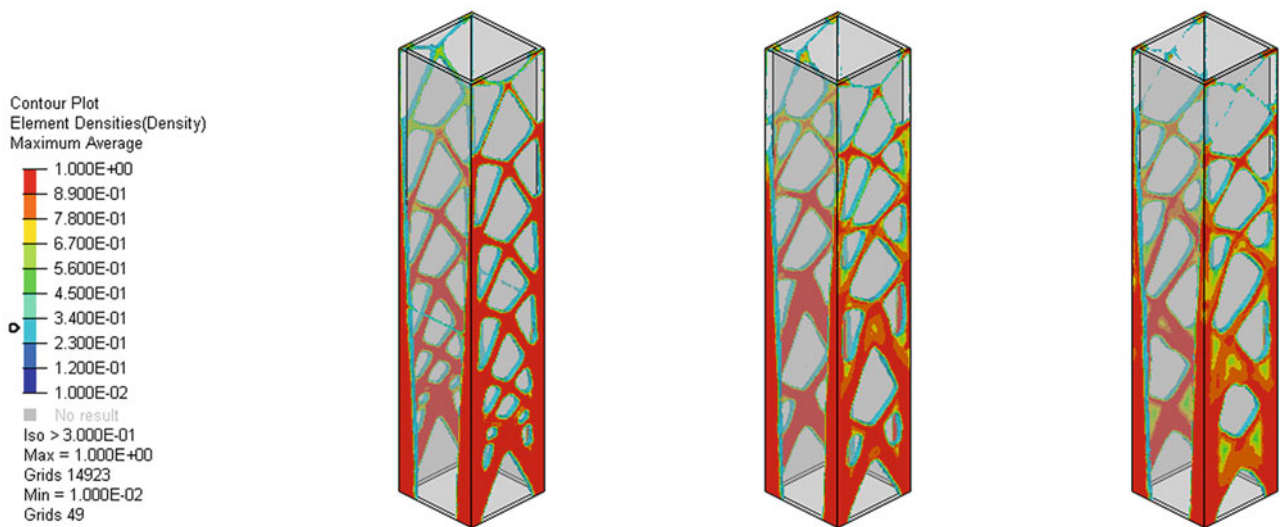


Fig. 32.4 High-rise structure case study showing the effects of different minimum member sizes: (from left to right) 3, 6, 9

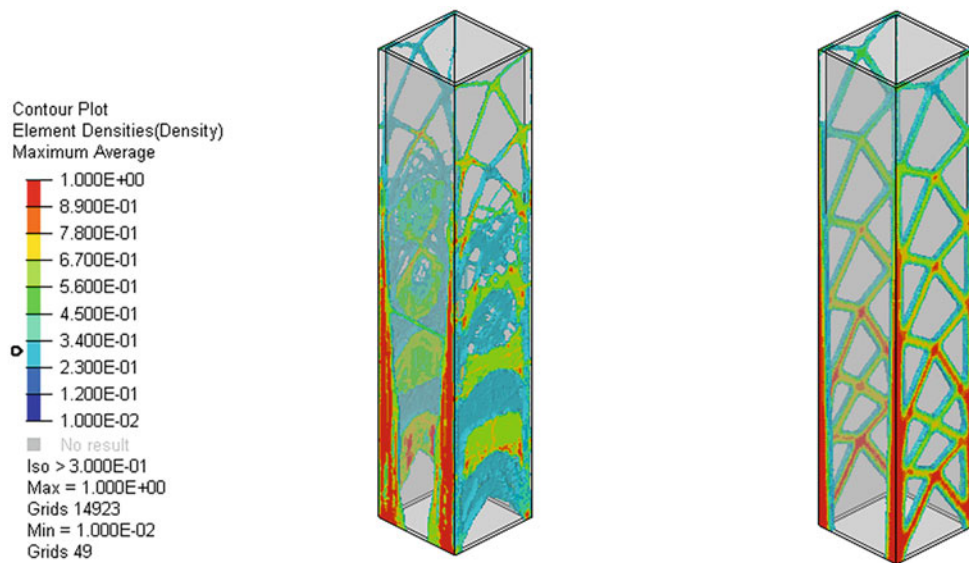


Fig. 32.5 High-rise structure case study showing the effects of different maximum member sizes: (from left to right) 6, 24

compliance decreases. The more material that may be used within the structure, the more it can be placed in various areas to increase stiffness. Figure 32.6b shows that an increase in minimum member size causes an increase in compliance because the larger members would find themselves more spaced out within the design field, which limits the area that the model may use to transfer the applied loads. The increase in compliance provides a tradeoff in the design aspect as members that are too small may not be realistically manufacturable. As shown in Fig. 32.6c, the maximum member size shares a similar correlation with compliance to that of the minimum member. As it increases, so does the compliance.

Through the 80 automated iterations using the ATOP platform to vary the parameters mentioned above, a result very similar to the design in Beghini et al. was achieved as shown in Fig. 32.7, which provided a validation and demonstrated the functionality of the platform. Without the use of the automated platform, each combination of parameters would have to be applied individually, which is a tedious and nearly impossible task to accomplish.

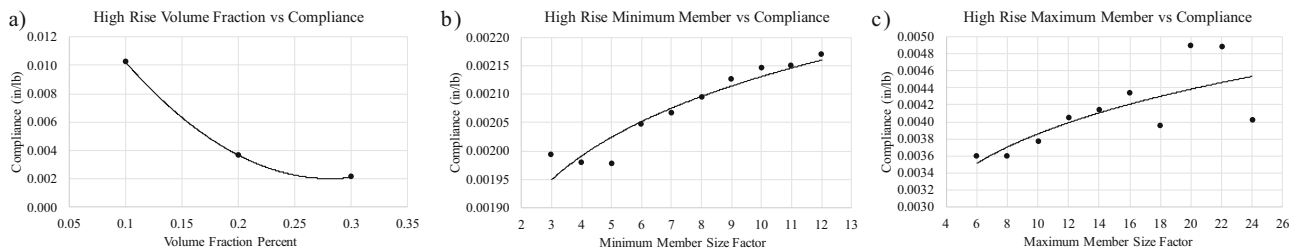
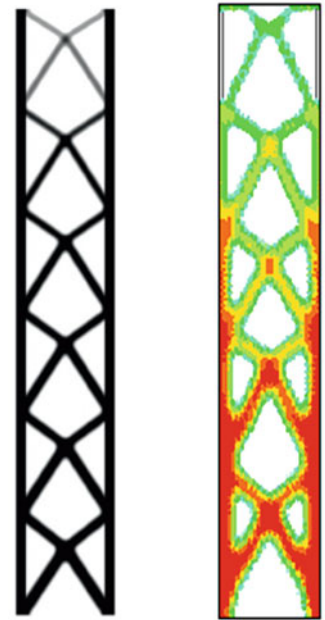


Fig. 32.6 High-rise Structure – (a) volume fraction (b) minimum member size (c) maximum member size

Fig. 32.7 High-rise structure case study results - design from Beghini et al. (left) vs ATOP results (right)



32.4 Case Study

After the validation of ATOP, the platform was used to perform topology optimization on an actual design project from Arup to fully explore its functionality and versatility. The design project is known as the Cosmos Sculpture, and its function is an artistic shade canopy. The cosmos sculpture has a skewed funnel shaped design space as can be seen in Fig. 32.8, with a height of 24.5 ft. and a 3-inch thick shell throughout the height of the sculpture. The top of the sculpture is an ellipse with a dimension of 30.5 ft. by 23.9 ft., and the bottom of the structure is circular with a diameter of 6.8 ft. Similar to the high-rise structure case study, the optimization results for the Cosmos Sculpture were created by iterating over volume fraction, minimum member sizes, and maximum member sizes. The loading for the Cosmos Sculpture is also shown in Fig. 32.8. In this study, only wind loads with a magnitude of 30psf were considered. The optimization objective and convergence criteria were the same as the high-rise case study.

1. Volume Fractions of 0.1, 0.2 and 0.3 were investigated for the Cosmos Sculpture. Results from iterating over volume fractions are shown in Fig. 32.9. It can be observed that, as the volume fraction increases, the amount of material was placed throughout the original design space with the concentration at the base of the sculpture. With only applying a volume fraction constraint, the optimized results did not display an aesthetic shape, nor any bracing pattern.
2. Same as the high-rise case study, the allowable minimum member sizes equal to 3–12 times the average element size were investigated. Results from applying minimum member size constraints of 3, 8, and 12 are shown in Fig. 32.10. In these results, the volume fraction remained consistently at 0.3. From Fig. 32.10, as minimum member size increases, the bracing pattern becomes clearer, and denser material is placed throughout the optimized result. For the Cosmos Sculpture, increasing minimum member size leads to a clearer conceptual starting point in the design phase. This information may be hidden without the automated process to explore a large variation of this parameter.

Fig. 32.8 Model of Cosmos Sculpture case study showing loading

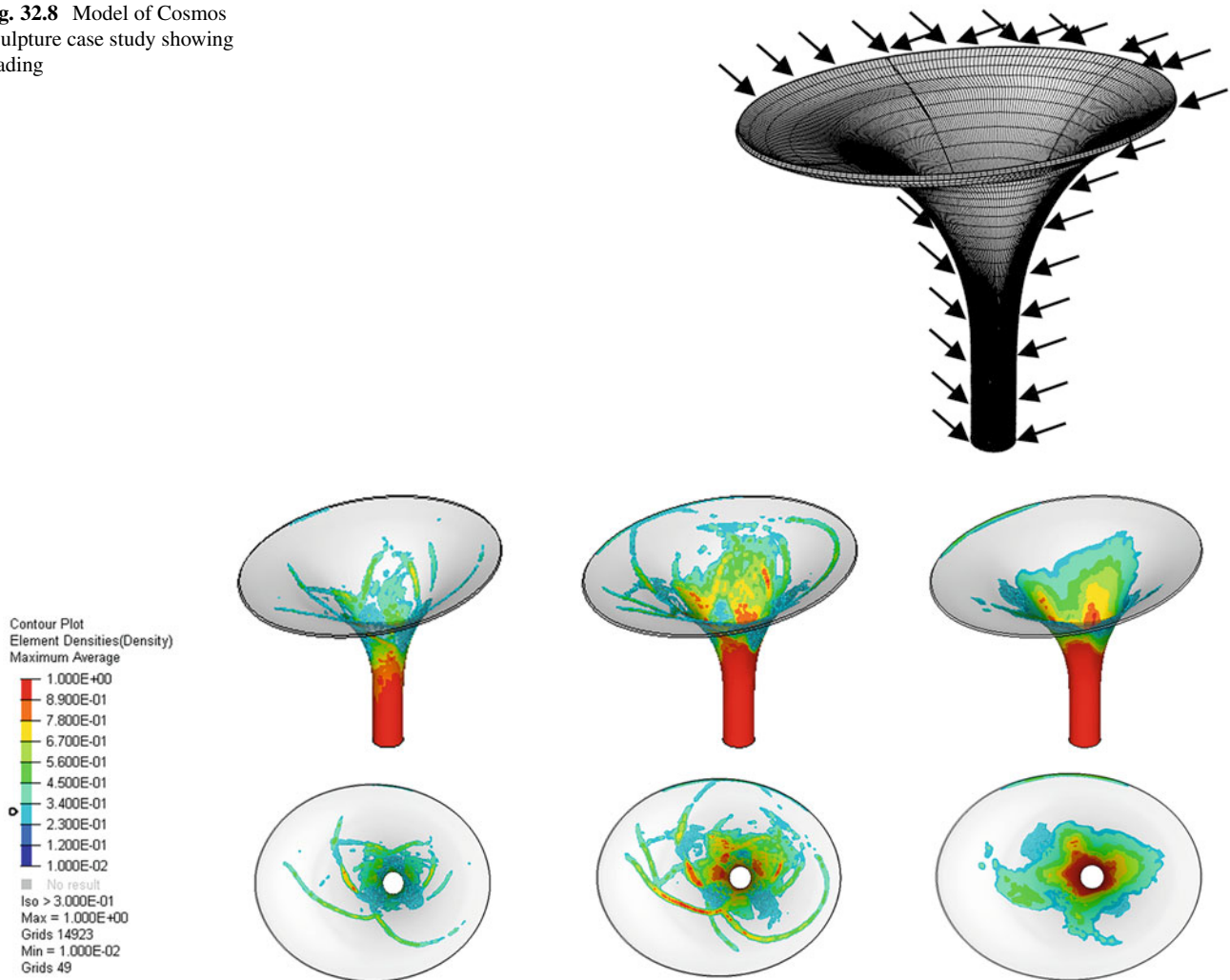


Fig. 32.9 Cosmos Sculpture case study (side and top view) showing the effects of three different volume fractions: (from left to right) 0.1, 0.2, 0.3

- The maximum member sizes were investigated in the range of 6–24 times the average element size of the finite element model. As maximum member size increases, the size of the members in the optimized shape increases while less dense material is available to be placed at the base of the structure to balance the increase of material placed at the top. For the Cosmos Sculpture, a maximum member size within the range of 12–16 times the average element size produces the best results since the design provides a more constructible brace pattern that covers more of the original design space (Fig. 32.11).

The previous results showed a lack of symmetry in the optimized results, evident by the lack of material in the lower left quadrant of the original design space. This is due to the fact that the loading is only applied at one side of the structure. To investigate the effects of possible loading from the other direction on the optimized shape, the Cosmos Sculpture was loaded with equivalent wind loads on the opposing sides, as seen in the bottom right of Fig. 32.12. When comparing results from the one side loading conditions, the full design space is used in this loading condition and the overall design is much more symmetrical.

Figure 32.13 shows the influence of optimization parameters on the structural compliance of the Cosmos Sculpture. Figure 32.13a demonstrates the effect of volume fraction on compliance. As volume fraction increases, the compliance decreases. By allowing more material to be placed throughout the design space, especially in critical areas, the optimized structure becomes stiffer. Figure 32.13b shows the effect of minimum member size on compliance. As minimum member size increases, compliance increases. As members are forced to become larger, it reduces the amount of area that the loads can be transferred over. The increase in compliance comes with the tradeoff of more manufacturable and aesthetic designs that

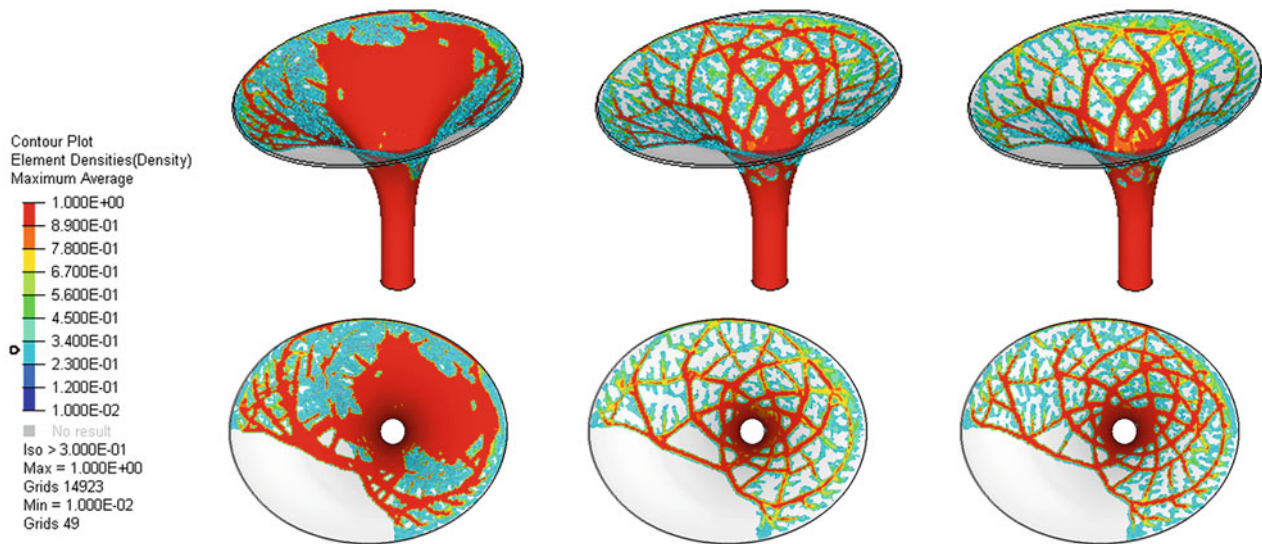


Fig. 32.10 Cosmos Sculpture case study (side and top views) showing the effects of applying different minimum member sizes: (from left to right) 3, 8, 12

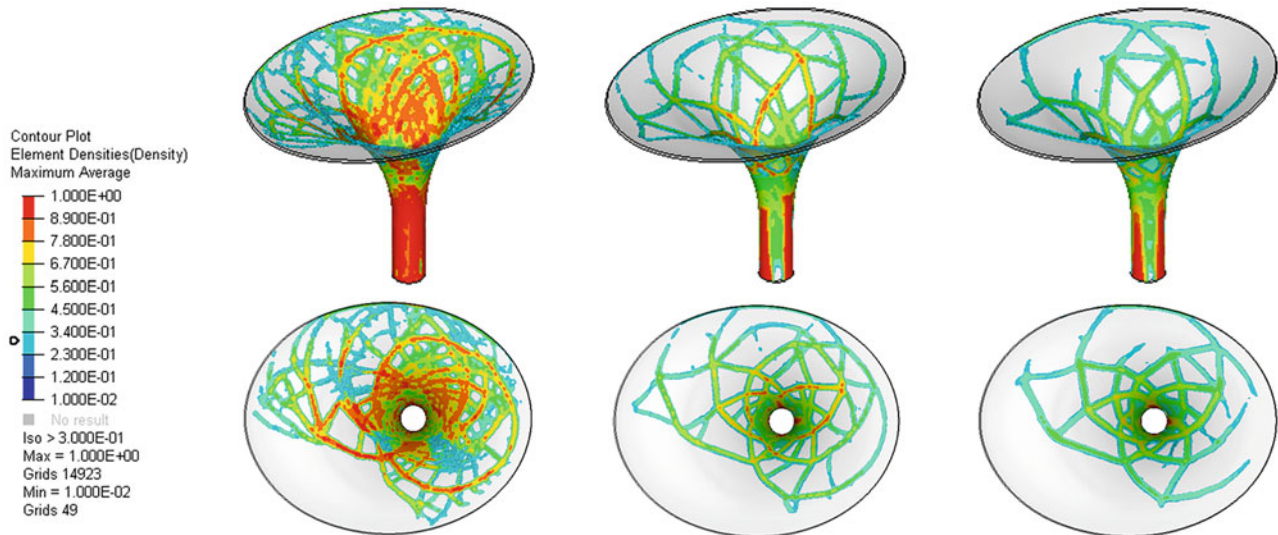


Fig. 32.11 Cosmos Sculpture case study (side and top views) showing the effects of different maximum member sizes: (from left to right) 6, 16, 24

could prove to be a more meaningful conceptual design. Figure 32.13c shows the relationship between maximum member size and compliance, which is similar to the relationship between minimum member size and compliance.

32.5 Conclusion

Structural optimization has been attracting increasing attention in the design of structures to achieve efficient, lightweight, and thus economical designs. Topology optimization has shown to have large effects on the global behavior of structures during the conceptual phase and have been intensively studied in academic world. Techniques on Topology optimization have been applied to structural design in industry, however, it is not universally applied by all designers mainly due to the lack of integration with current design software and the tedious iteration process. To bridge the gap between the fundamental research in academia and engineering practice in the industry, an NSF funded Research Experience for Undergraduates (REU)

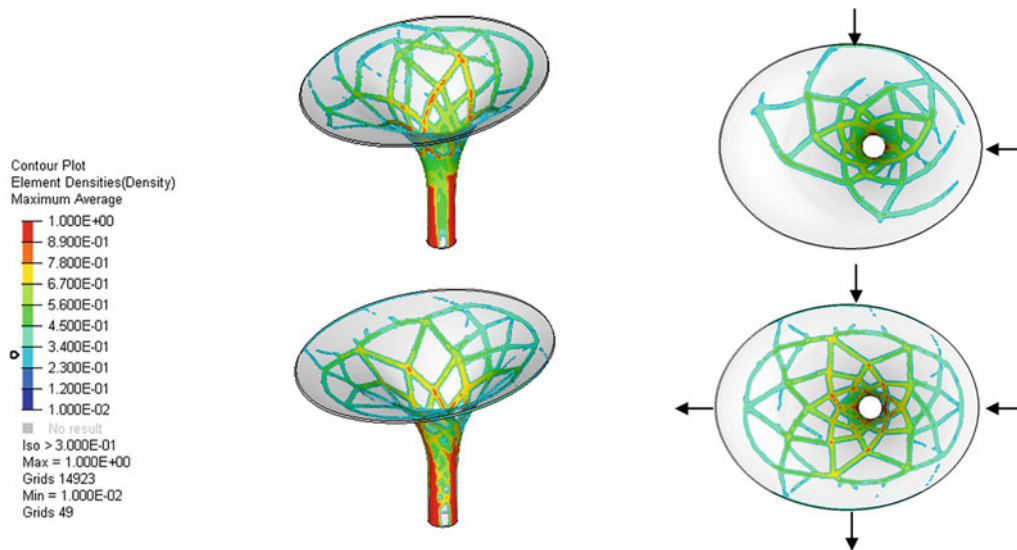


Fig. 32.12 Cosmos sculpture case study showing results from asymmetric loading (top) and symmetric loading (bottom)

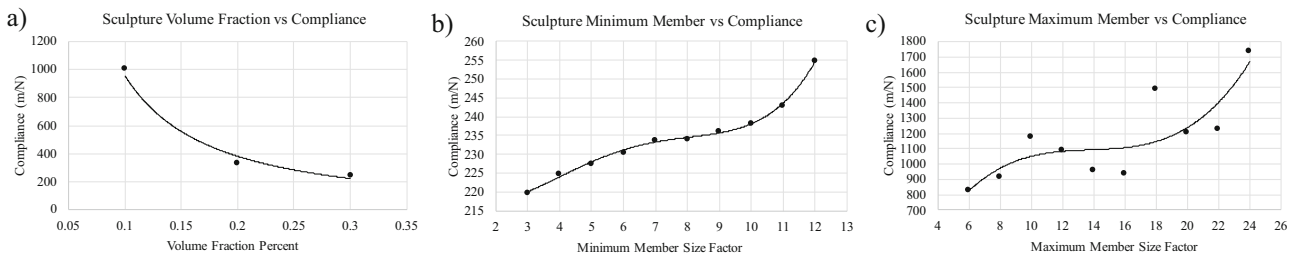


Fig. 32.13 Sculpture Structure – (a) volume fraction (b) minimum member size (c) maximum member size

program, was established by San Francisco State University and the University of South Carolina to provide an opportunity for the REU participants to experience research in both academic and industry settings and facilitate the knowledge exchange. In this study, the REU participants worked together with faculty advisors in academia and industry mentors at Arup North America Limited to develop ATOP, an automated topology optimization platform. The platform leverages the advantages of several commercial software platforms, including Rhinoceros 3D and Altair HyperMesh/OptiStruct, to provide a user-friendly and automated process for topology optimization that will incentivize implementation of topology optimization in structural design. After development, the platform was validated through performing optimizations on a high-rise structure in recent literature that was subjected to static wind loads. Even with limited information on the topology optimization parameters, the platform successfully achieved a similar optimized shape as in the literature case study, an almost impossible task without the help of automation. After the validation, ATOP was used to perform topology optimization on an actual design project from Arup. The design project was an artistic shade canopy subjected to wind loads and required to be aesthetically pleasing and have sufficient structural stiffness. ATOP was able to produce multiple optimized shapes by varying optimization parameters and investigating various loading conditions to provide the design team meaningful options on conceptual design. In these studies, analysis of the optimization parameters, including volume fraction, minimum member size and maximum member size, on the structure's compliance (inverse of stiffness) was investigated. The results of both studies showed similar trends on the effects of the various optimization parameters. When volume fraction is increased, compliance decreases as the increase in the allowable amount of material, especially in critical areas, increases the overall stiffness of the structure. The increase of minimum member size increases the compliance. As members are forced to become larger, it reduces the amount of area that the loads can be transferred over. The increase in compliance comes with a tradeoff of more manufacturable and aesthetic designs that could prove to be a more meaningful conceptual design. With the increase of the maximum member size, the overall compliance also increases. More aesthetically pleasing conceptual designs with well-defined members were produced when introducing some sort of member size constraint. Future work includes increasing

capabilities of the platform by providing more options on optimization objectives and optimization constraints, and to use this platform on different scale design problems to explore the scope of the platform.

Acknowledgements The authors would like to acknowledge the supports from National Science Foundation EEC-1659877/ECC-1659507, the College of Science and Engineering and the School of Engineering at San Francisco State University, and College of Engineering and Computing at the University of South Carolina. Supports from the industrial collaborator, Arup North America Limited, are also appreciated. In addition, the student cohort, Kaitlyn Chin and Alex Donner, who participated in the same NSF REU summer program in 2018 contributed greatly in creating the first version of the ATOP platform. Their efforts are also acknowledged and highly appreciated.

References

1. Beghini, A., Shook, D., Mazurek, A.: Material optimization for tall buildings. In: AEI, vol. 2015, pp. 567–580 (2015)
2. Tang, J., Xie, Y.M.: Conceptual design of buildings subjected to wind load by using topology optimization. *Wind Struct.* **18**(1), 021–035 (2014)
3. Eschenauer, H.A., Olhoff, N.: Topology optimization of continuum structures: a review. *Appl. Mech. Rev.* **54**(4), 331–390 (2001)
4. Bendsoe, M.P.: Optimal shape design as a material distribution problem. *Struct. Multidiscip. Optim.* **1**(4), 193–202 (1989)
5. Huang, X., Xie, M.: *Evolutionary Topology Optimization of Continuum Structures: Methods and Applications*. Wiley, Chichester (2010)
6. Zhou, M., Rozvany, G.I.N.: The COC algorithm, part II: topological, geometrical and generalized shape optimization. *Comput. Methods Appl. Mech. Eng.* **89**(1–3), 309–336 (1991)
7. Mlejnek, H.P.: Some aspects of the genesis of structures. *Struct. Multidiscip. Optim.* **5**(1), 64–69 (1992)
8. Sokolowski, J., Zochowski, A.: On the topological derivative in shape optimization. *SIAM J. Control. Optim.* **37**(4), 1251–1272 (1999)
9. Allaire, G., Jouve, F., Toader, A.M.: A level-set method for shape optimization. *Comptes Rendus Mathématique.* **334**(12), 1125–1130 (2002)
10. Allaire, G., Jouve, F., Toader, A.M.: Structural optimization using sensitivity analysis and a level-set method. *J. Comput. Phys.* **194**(1), 363–393 (2004)
11. Wang, M.Y., Wang, X., Guo, D.: A level set method for structural topology optimization. *Comput. Methods Appl. Mech. Eng.* **192**(1), 227–246 (2003)
12. Bourdin, B., Chambolle, A.: Design-dependent loads in topology optimization. *ESAIM: Control, Optimisation and Calculus of Variations.* **9**, 19–48 (2003)
13. Xie, Y.M., Steven, G.P.: A simple evolutionary procedure for structural optimization. *Comput. Struct.* **49**(5), 885–896 (1993)
14. Querin, O.M., Steven, G.P., Xie, Y.M.: Evolutionary structural optimisation (ESO) using a bidirectional algorithm. *Eng. Comput.* **15**(8), 1031–1048 (1998)
15. Li, Q., Steven, G.P., Xie, Y.M.: A simple checkerboard suppression algorithm for evolutionary structural optimization. *Struct. Multidiscip. Optim.* **22**(3), 230–239 (2001)
16. Kim, H., Querin, O.M., Steven, G.P., Xie, Y.M.: Improving efficiency of evolutionary structural optimization by implementing fixed grid mesh. *Struct. Multidiscip. Optim.* **24**(6), 441–448 (2002)
17. Yang, X.Y., Xie, Y.M., Liu, J.S., Parks, G.T., Clarkson, P.J.: Perimeter control in the bidirectional evolutionary optimization method. *Struct. Multidiscip. Optim.* **24**(6), 430–440 (2002)
18. Altair Engineering Inc.: Introducing Altair HyperWorks 2019. Retrieved September 28, 2019, from <https://altairhyperworks.com/>. (2019)
19. McNeel, R. & Associates.: Rhino 6 for Windows and Mac. Retrieved September 28, 2019, from <https://www.rhino3d.com/>. (2019)
20. Beghini, L.L., Beghini, A., Katz, N., Baker, W.F., Paulino, G.H.: Connecting architecture and engineering through structural topology optimization. *Eng. Struct.* **59**, 716–726 (2014). <https://doi.org/10.1016/j.engstruct.2013.10.032>