Research and Application of Topology Optimisation Design of Truss Structures

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Abstract. Truss structure is a common structural form. The optimal design of truss structure has important research significance. The main purpose of this paper is to discuss the method and practice of optimal design of truss structure in order to improve the efficiency and economy of structure. This paper introduces the basic concept of truss structure optimization design, and three types optimization design methods including shape optimization, size optimization and topology optimization. Then the topology optimization design is focused on in this paper. Firstly, the solid isotropic material point method in topology optimization is introduced. Then, combined with a practical engineering case, the application of topology optimization design in truss structure is analyzed and studied. The results show that the optimized truss design has good application effect in practical engineering. By considering the structural performance, cost and environmental impact, a more efficient, economical and environmentally friendly truss structure design can be achieved.

Keywords: Truss structure, optimal design, topology optimization.

1. Introduction

In construction, trusses are used to support floors and roofs to provide a stable structure for buildings. In aerospace, trusses are also used to support aircraft to withstand the external environment, storms, etc. The significance of trusses is that they provide a stable support and profile for structures to withstand the external environment. The significance of this is that it provides a stable support and profile for the structure to withstand the effects of the external environment. The design and optimisation of trusses has long been a focus of research in the field of engineering. The optimal design of a structure is to optimise some broad performance indexes (e.g. cost, weight, stiffness or frequency, etc.) of a structure under the condition of meeting various codes or some specific requirements. The design of trusses can also help to optimise the weight and balance of a structure and improve the efficiency and performance of a building or machine.

With the advancement of technology and the rapid development of computers, advanced computational methods and optimisation algorithms can be utilised to achieve lightweighting and maximise the cost-effectiveness of truss design. Finite Element Analysis (FEA) is a sophisticated computational tool used to simulate and predict the response of structures under various loads and stresses. In truss design, FEA can be used to accurately analyse and adjust the stress distribution of a structure to ensure structural safety and reliability while minimising material usage. Genetic Algorithm (GA), on the other hand, is an optimisation algorithm that mimics the natural evolutionary process and is ideally suited for solving complex design optimisation problems. Whereas genetic algorithms can help find the lowest cost and best performance design solution, they continuously improve the design solution by mimicking the evolutionary process until an optimal solution is found. By combining these methods, the lightweighting of truss design can be effectively achieved while ensuring the structural strength and stability to maximise the cost-effectiveness. Maheri et al. [1] amalgamated genetic algorithms with particle swarm optimisation to conduct topological optimisation of truss structures, yielding substantial enhancements. Concurrently, Zhu et al. [2] devised a quasi-full stress genetic algorithm for a similar endeavour. This method augments the efficacy and quality of solutions by embedding a quasi-full stress operator into the genetic algorithm and implementing improvements such as preserving the optimum individuals, substituting the least effective ones, and managing diversity within the population [3].These innovations not only elevate the efficiency and performance of the design process but also contribute to reducing material utilization and costs, thereby benefiting environmental protection and sustainable development.

The origins of optimal design of truss structures can be traced back centuries and were initially used mainly in the construction of bridges and buildings. These early designs were usually based on intuition and practical experience. With the development of mechanics and structural engineering, especially in the 19th century, truss design began to be based on more precise scientific and mathematical principles. More systematic methods of analysis, such as graphical and analytical methods, emerged during this period. With the development of computer technology, a new era of truss design was introduced in the second half of the 20th century. Computer Aided Design (CAD) and Finite Element Analysis (FEA) enabled designers to perform more complex and accurate structural analyses. In recent decades, the development of topology optimisation techniques has revolutionized truss design. Topology optimisation uses algorithms and simulations to find the most efficient material distribution under specific conditions, making the design more efficient and material-saving. In this paper, the optimisation method of truss structure based on finite element analysis and optimisation algorithm (Genetic Algorithm) is introduced from three aspects, namely, size optimisation, shape optimisation and topology optimisation, respectively. The results of the study can provide an effective reference for the optimal design of truss structure.

2. Theory of Optimal Design of Truss Structures

Most of the structural optimisation projects involve geometrical changes in the structure. As shown in Fig. 1, optimisation designs can be classified into three categories based on the characteristics of the geometrical variations of the structure: size optimisation, shape optimisation and topology optimisation [4]. In size optimisation, the design variables are usually parameters that control the internal and external contours or surface morphology of the structure. If these parameters are discrete, theoretical dimensional parameters of the structure boundaries can be set. Changes in the overall or local cross-sectional shape of the structure are usually caused by changes in these dimensional parameters, but such changes are usually not too far from the original basic shape. Shape and size optimisation are usually necessary in the optimisation process, and size optimisation is usually performed after shape optimisation to ensure that the optimised structure is more rational. Topology optimisation, on the other hand, involves the creation of new holes and connections that alter the original continuum, and it provides the greatest degree of optimisation freedom. Topological optimisation is less dependent on the original design configuration than size and shape optimisation and is therefore more advantageous in the early theoretical design stages of a structure [5]. The actual engineering structural design process usually combines all three methods, and it is advisable to start with topology optimisation at the initial stage of optimal design, followed by further optimisation of the details of the structure through shape optimisation and size optimisation.

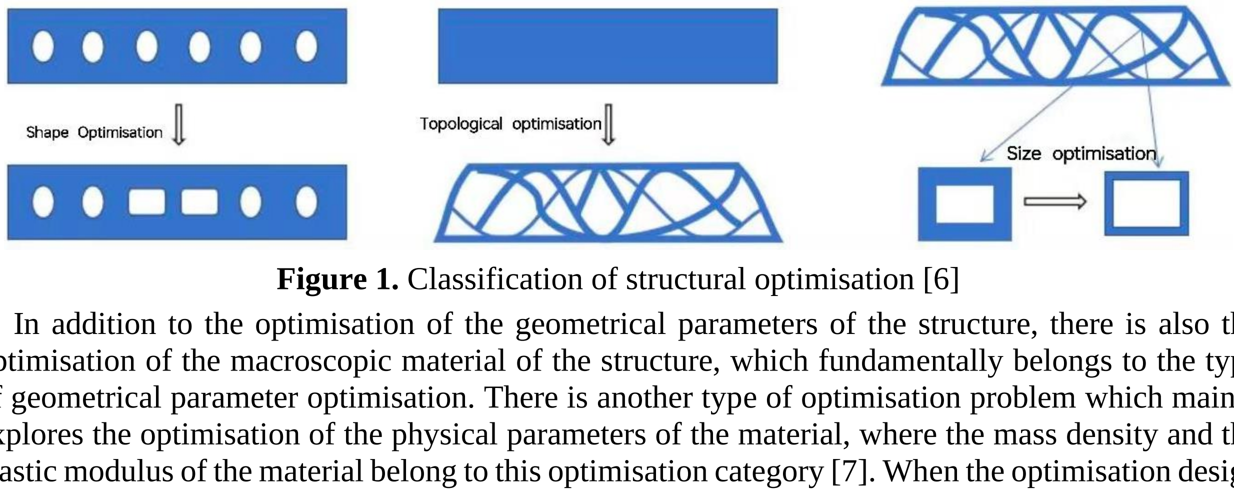


Figure 1. Classification of structural optimisation [6]

In addition to the optimisation of the geometrical parameters of the structure, there is also the optimisation of the macroscopic material of the structure, which fundamentally belongs to the type of geometrical parameter optimisation. There is another type of optimisation problem which mainly explores the optimisation of the physical parameters of the material, where the mass density and the elastic modulus of the material belong to this optimisation category [7]. When the optimisation design process adopts a material free approach, with no restriction on the type or dosage, such optimisation results will only have theoretical significance, and it will be difficult to be applied in practical engineering. In order to achieve the purpose of combining theory and practice, the optimisation process must include restrictions on factors such as manufacturability [8]. This can make the optimisation results have practical significance, of course, after the operation, whether it is a physical model or mathematical model will be more complex, how to control the balance between the two is an important factor in solving engineering optimisation problems.

3. Topology Optimisation

Research work on structural size optimisation has been relatively mature therefore researchers have adopted the research idea of topology optimisation based on size optimisation, i.e., the cross-sectional area of the bars is taken as the design variable, and the topological change of the structure is achieved by taking zero value for the area of the bars. The design variables of this model can be divided into two types: continuous (i.e., it can be changed continuously within the specified range and take any value) and discrete (i.e., it can take a certain discrete value within the specified discrete domain), and the objective function is generally taken as the structure with the lightest weight or the smallest volume. The flow chart of topology optimisation of truss structure is shown in Fig. 2.

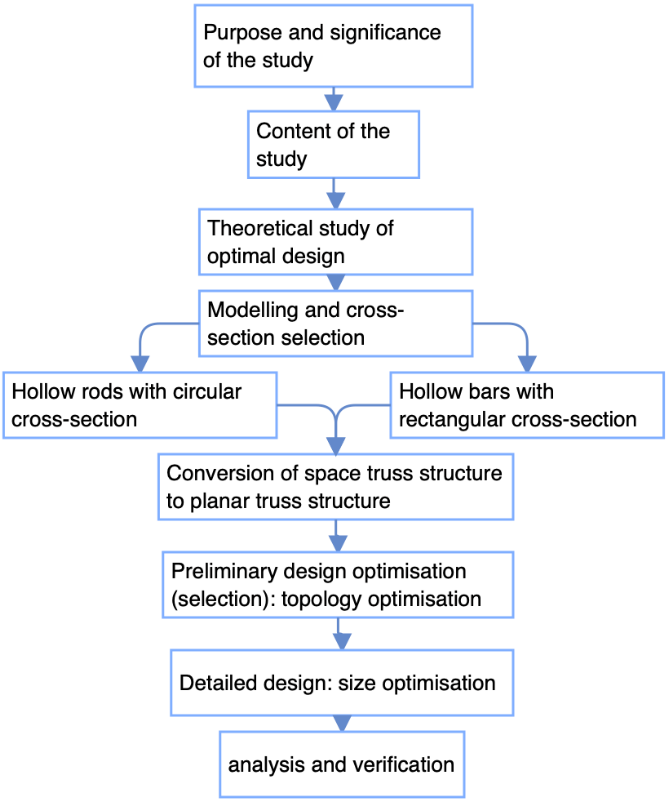


Figure 2. Flowchart of topology optimisation of truss structure [9]

3.1. Solid Isotropic Material Point Method

One of the best-known topology optimisation methods is the Solid Isotropic Material with Penalization (SIMP). This method is widely used in the field of optimal structural design and is particularly good at dealing with material distribution problems.

The core idea of the SIMP method is to quantify the allocation of material as a continuous variable so that the material can be freely allocated within the design space. In practice, the design area is divided into a finite element mesh and the material density of each element can vary between completely blank (i.e. no material) to completely solid (i.e. completely filled by material.) The SIMP method controls the validity of the intermediate density values by introducing a penalty parameter that tends to generate density values close to 0 or 1 in the final design, resulting in a clearer and more practical structural design. This approach has the advantage of automatically generating innovative design solutions and is particularly suited to applications where material usage and distribution are critical, such as aerospace, automotive and biomedical engineering. The SIMP approach not only improves structural performance and efficiency, but also contributes to weight reduction and material usage, in line with the concept of sustainability. The application and development of the SIMP approach has driven the field of structural optimisation and design forward, particularly in the area of complex structural design. The application and development of SIMP methods have pushed forward the progress in the field of structural optimisation, especially in the optimal design of complex structures and materials, which shows great potential.

3.2. A Case Study on the Optimal Design of Truss Structures

The height of the project's podium is approximately 22 metres, which is below the 24-metre standard, while the height of the tower is approximately 83 metres. The structure of the podium is made of reinforced concrete frame while the tower is made of reinforced concrete frame-core structure. These three parts of the podium are connected by three steel connecting corridors which are about 28 metres in length, 22 metres in width and about 5.5 metres in height at one end and 11 metres in height at the other end to form a kind of large-span steel connecting corridor, the appearance of which is shown in Fig. 3. The optimisation objective of the project is to find a reasonable and efficient arrangement of the truss structure by means of topology optimisation.

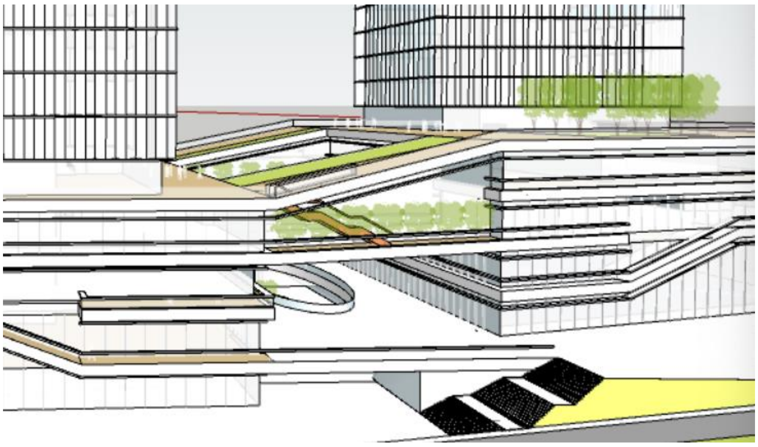


Figure 3. Podium corridor building programme [10]

3.2.1. Optimised design methods

In the optimisation process, the design space and boundary conditions are firstly determined, and different topology optimisation results can be obtained through different optimisation objectives and control requirements on the morphology. As shown in Fig. 4, during the optimisation process, the design space and boundary conditions are firstly determined, as shown in Fig. 4(a). Different topology optimisation results can be obtained through different optimisation objectives and control requirements on the morphology, and the typical results are shown in Fig. 4(b) and Fig. 4(c).

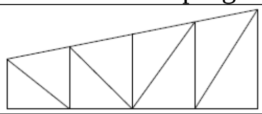
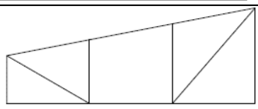
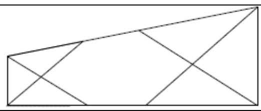
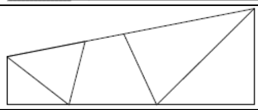
(a) Design space model (b) Topology optimisation I (c) topology optimisation II

Figure 4. Schematic representation of the topology optimisation process in the cases [10]

3.2.2. Results of the Optimised Design of the Joist

In this project, based on the results of the topology optimisation and in conjunction with the actual engineering requirements, the optimised completed structure was adapted to fit the structural support rods at the corresponding locations. Four different truss structure schemes were designed, as shown in Table 1. These scenarios include: scenario 1, with a four-span structure; scenario 2, with three spans and two diagonal struts; scenario 3, featuring staggered diagonal struts; and scenario 4, equipping the three-span structure with all diagonal struts. Among these scenarios, Scenario I serve as the baseline scenario and its virtual work value is set to 1 to facilitate comparison with the other scenarios. The graphs created by the graphical static method and the corresponding virtual work values were used to compare these scenarios, as shown in Table 1. According to the data in Table 1, although Option 3 has the highest structural efficiency, Option 4 was finally chosen as the structural layout option for the connecting trusses, taking into account the architectural aesthetics. Compared with the conventional Option I, Option IV selected through topology optimisation has about 20% improvement in structural efficiency.

Table 1. Comparison of different truss options [10]

Truss programme	Illustration of truss programme	Relative value of the virtual work representative value
Option 1: Four-span option		1
Option 2: Three-span, two diagonal web bar solution		0.83
Option 3: Crossed diagonal web bar option		0.71
Option 4: Three-span full diagonal web bar option		0.79

4. Conclusion

This paper focuses on topology optimisation methods in the optimal design of truss structures, and the following main conclusions are obtained:

(1) The topological optimisation approach has a higher degree of design freedom for structural design, which makes it easier for structural designers to balance the relationship between structural efficiency and building aesthetics, and has a greater application prospect in the field of architecture. Moreover, topological optimisation has a large number of design variables, large computational scale, and the objective function and constraint function are generally non-linear, non-monotonic implicit functions of the design variables. Thus, not all common mathematical planning algorithms are suitable for solving topology optimisation problems. The MMA algorithm proposed by Svanberg et al is one of the most widely used algorithms, which is suitable for solving structural optimisation problems with complex objective functions and many constraints.

(2) The case study analyses the construction of the podium, in which the project team applied topology optimisation techniques on a large scale, thus effectively enhancing the efficiency of the layout design of the truss structure. Through this optimisation method, a variety of optimal layout solutions for truss rods were derived. Using graphical static analysis and comparison of the total value of virtual work, the final solution identified was approximately 20% more structurally efficient than the traditional design method.

(3) In the future, it is expected to provide a more efficient, economical and environmentally friendly truss design method for the engineering design field. Meanwhile, it can provide scientific basis and methodological guidance for the design of similar structures in the future. In addition, the

environmental impacts of truss design can be evaluated to promote the development of engineering design field towards a more sustainable and environmentally friendly direction.

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