

Research on Topology Optimization Design of Truss Structure

Shaowei Xu *

Chang' an Dublin International School of Transportation, Chang' an University, Xi'an, China

* Corresponding author: 2021903634@chd.edu.cn

Abstract. Due to continuous advances in engineering technology and architecture, the use of truss structures is expanding. The design method of ideal truss structure is the main research topic of this paper. The topology optimization method is applied to a bridge design case study. The load and total material utilization ratio of each rod of triangular truss, arch truss and Pratt truss were determined by using structural mechanics solver. By comparing the stress and material consumption of the truss structure, it shows that the truss structure has advantages in stress and can be used in the truss construction of short-distance arch bridge. Truss is the basic unit of the topology optimization method of truss structure proposed in this study. By optimizing the topological shape of the truss, the ideal design of the whole structure is realized. While maintaining structural stiffness and stability, the technology can significantly reduce the weight and cost of the structure.

Keywords: Truss structure, Topology optimization, Triangular truss, Pratt truss, Arch truss.

1. Introduction

Truss structure is a kind of structure form composed of straight rods and joints, which has the advantages of small weight, high strength and good rigidity. Therefore, it is widely used in construction, Bridges, towers and other fields. The research of truss structure is very necessary, because it promotes the creation of new materials, strengthens the theory in the field, and improves the efficiency and level of engineering and architectural design. The optimal design of truss structure can be used to study the optimization of truss structure. The main goal of this research area is to optimize the design of truss structures to maximize their economy and performance. It also studies optimal design techniques and algorithms for truss structures in order to provide technical assistance for real-world engineering applications.

This paper is devoted to the foundation of truss structures. In order to explore the best design method of truss structure, this paper starts with three basic structural forms: triangle, space and arch. Triangular truss beam structure is a typical outlet structure in substation frame due to its superior mechanical properties, and has been widely used in recent years [1]. In addition, the space truss has the advantages of low machining and manufacturing complexity, high stiffness, flexible assembly, light volume and so on. In recent years, it has been widely used in the field of architecture and space design, and is often used as a support structure for payloads [2, 3]. Arch trusses are often used in Bridges, arch buildings and other structures because of their convenient construction and good force [4]. Using the optimization method, the strength, stiffness and weight loss of the trusses of these three structures have been significantly improved [5]. This optimization technology has a wide range of practical applications in engineering. The optimization of these three basic truss structures can be achieved by topological optimization. Topological optimization optimizes the stress and stiffness distribution of the structure and improves the performance and reliability of the structure by changing the material distribution and structure shape without increasing the weight. Topological optimization method provides higher design freedom for structural design and more opportunities for application in the field of architecture, helping structural designers to strike a balance between structural efficiency and architectural aesthetics [6]. In addition, topological optimization method has gained certain traction in the field of architectural engineering, which can optimize the spatial form, ensure the convenience of construction, improve structural efficiency, and save money and materials [7].

However, in reality many bridges are currently serving a higher load than expected [8, 9]. Therefore, this paper takes truss bridge design as a model, and proposes Triangle structure, Pratt

structure and Arch connection respectively to overcome this challenge. Through the comparison of the three basic structures and the change of the internal rod of the truss, the optimal optimization strategy of the bridge truss is determined. In this scheme, topological optimization method and structural mechanics solver are used to calculate the force and volume of the truss.

2. Truss Structure

2.1. Truss Classification

Truss structures are primarily classified into triangular, arch, parallel chord, space, and other shapes based on their truss shapes.

2.1.1. Triangular truss

Triangular truss is one of the simplest truss structures, consisting of triangles continuously interconnected as shown in Fig 1. It exhibits high stability and strength to bear large loads and is easy to assemble during construction.

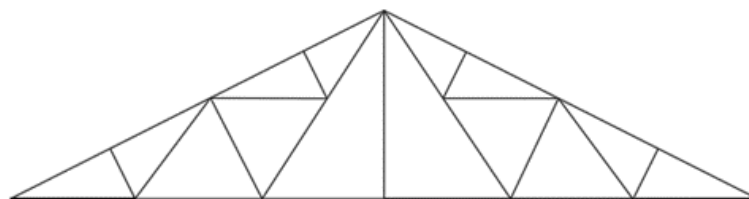


Figure 1. Triangle truss structure diagram

2.1.2. Arch truss

An arch truss is an arch bridge with a solid web section in the middle and arch truss pieces on both sides. It has strong stress capacity. Arch truss has good bearing performance, which can effectively bear horizontal and vertical loads to ensure the stability and safety of the building. The design of arch truss usually adopts curved form, which can present a beautiful arc. This makes the building look more beautiful. Arch truss is suitable for many kinds of building structures, such as arched roof, arched porch and so on, which can meet the needs of different architectural styles. The structure of arch truss is shown in Fig. 2.

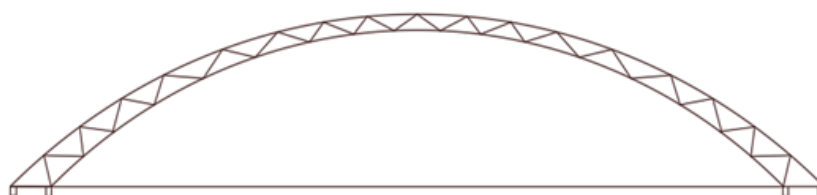


Figure 2. Schematic diagram of the arch truss structure

2.1.3. Space truss

Space trusses are three-dimensional structures that typically consist of several triangles or quadrilaterals. They are known for their excellent load-bearing capacity and seismic performance, and are often used for constructing large buildings and stadiums. There are various types of space trusses, including X-brace truss, Pratt truss, and Warren truss, each with its unique characteristics. X-brace truss, named after its X-shaped diagonal web, consists of several rigid members and is commonly used as the supporting structure for large-span buildings. Pratt truss was invented by an American engineer named Charles Pratt in 1884 and is another common space truss structure often used as the supporting structure for large-span buildings like airport terminals, exhibition halls, and stadiums. Warren truss, invented by American engineer John Roebling in 1853, is also a common space truss structure commonly used as a support structure for large-span buildings like bridges, towers, dams, and so on, as shown in Fig. 3.

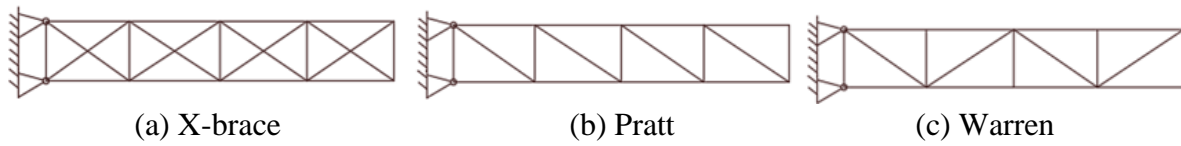


Figure 3. Schematic diagram of the space truss structure

2.2. Topological Optimization Methods

Topology optimization is a structural optimization method used to optimize the performance of a structure by changing its topological form. The structure is viewed as consisting of basic units, and the connectivity between these units constitutes the topological form of the structure. The basic idea of topology optimization is to change the mechanical properties of a structure by changing its topological form. The mechanical properties of a structure are usually measured by indexes such as strength, stiffness, stability, and vibration characteristics, which are used as optimization objectives in topology optimization. This method enables the optimization of both the structural mechanical properties and material usage, making it more scientific and reasonable. In this case study, the multi-objective optimization-based approach was used, which considers multiple optimization objectives such as structural strength, stiffness, and stability, and searches for the optimal topological form of the structure by considering these objectives as optimization targets.

Su and Tang [9] investigated the wood truss structure and found that the initial shape of the studied bridge was a parallel chord truss, as depicted in Fig. 4. The loads only acted on the lower chord nodes, vertically downward, with equal magnitude, and the truss's lateral stability was not considered. The test was a short-term static test, and the effects of long-term loads and dynamic actions were not considered. The modulus of elasticity of timber and the acting load were considered uncertain variables, and multi-objective topology optimization design was performed using Pareto's method and multi-objective parallelized differential evolution algorithm. The optimal shape and topological layout of the truss bridge were obtained as shown in Fig. 5.

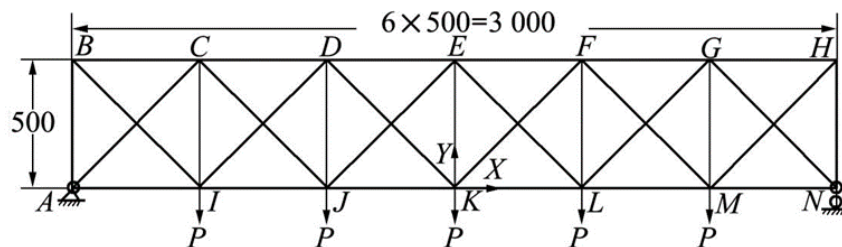


Figure 4. Calculation diagram of wooden truss bridge [9]

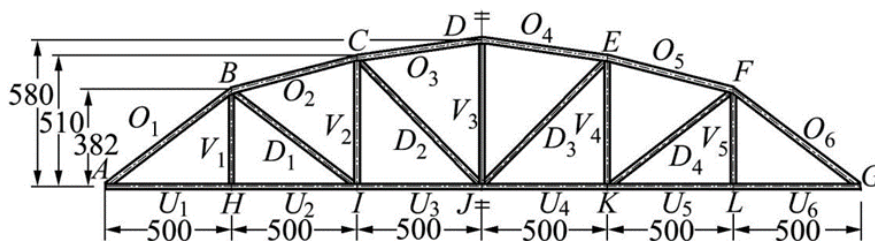


Figure 5. Optimal shape and topology layout of the truss [9]

The research shows that utilizing topology optimization in truss optimization can increase structural safety reserve and improve stability by combining continuum topology optimization method and parameter optimization method. Moreover, topology optimization can avoid specific problems related to non-regular structural requirements and transformation into actual structures [10, 11]. The research highlights that while topology optimization can increase structural safety reserve and stability, and it can also produce regular and restrictive designs that limit design diversity and innovation. Topology optimization designs produced by topology optimization often exhibit regular

and restrictive characteristics, limiting design diversity and innovation. Topology optimization can increase structural safety reserve but practical engineering factors must be considered, such as bar force probability and reliability. Selecting the maximum cross-sectional area that satisfies tensile/compressive stresses and ensuring its consistency for each bar can improve the reliability and safety reserve of the bars. In conclusion, practical engineering factors must be considered to further enhance the structural safety reserve.

3. Case Analysis

3.1. Case Background

This project required the design of a truss bridge with a span of 85 meters and a height of up to 10 meters. It is required that a complete space of 10 meters in height and 50 meters in width be retained under the bridge. The truss is not more than 10 meters above the horizon as shown in Fig. 6. The stability of the compression bars is also considered under a load of 150 KN/m. The allowable strength of the material is 10 0MPa in tension and 30 MPa in compression, and the optimization objective is to minimize the material consumption of the truss while meeting the above requirements.

In this paper, topology optimization is used to find the optimal topology of the truss to minimize the material consumption of the truss. Meanwhile, according to the optimization result, the specific design of the truss is adjusted to get the optimal truss structure.

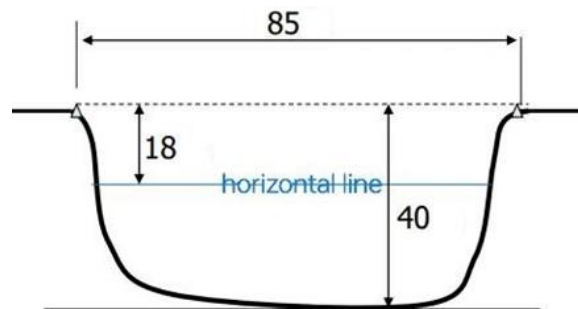


Figure 6. Engineering Design Background (Unit: m)

3.2. Selection of Truss Structure

This study analyzes the triangular truss, arch truss, and Pratt truss under the condition of topology optimization analysis. The force conditions and material usage of the three truss structures are evaluated under a loading of 150 KN/m, and the optimal truss structure is determined based on material consumption and volume comparison. HRB400 hot rolled ribbed steel bar is used in the first test truss structure design, with a cross sectional area of 113.1 mm². The study aims to minimize material consumption while meeting engineering requirements, and the results are used to determine the optimal truss structure.

3.2.1. Triangular truss

The first test of the triangular truss was conducted. The design of the triangular truss bridge was based on the design background of the actual project. The bridge deck was connected by six bars of length 14.167 m, and eight bars of length 10.812 m were chosen for the diagonal bars. For the web bars, several different lengths of bars were selected to meet the design requirements, which included 16.27 m, 14.168 m, 8.132 m, and 4.068 m. The design height of the entire bridge was set to 8m, and the 150 KN/m load was applied to the bridge deck according to the project requirements. Fig. 7 shows the design of the triangular truss bridge. The forces and used volumes of the triangular trusses were calculated by the structural mechanics solver as shown in Table 1.

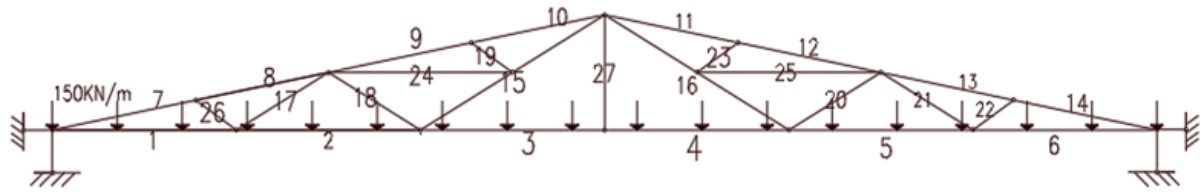


Figure 7. Design drawing of triangular truss bridge

Table 1. Force situation of triangular truss and use volume of rod

Serial Number	Axial force (KN)	Tensile strength/pressure (Mpa)	Sectional area (mm ²)	Length (m)	Volume (m ³)	Total Volume (m ³)
1	5017.4	44.36	113.1	14.167	0.0016	0.033
2	1254.5	11.09	113.1	14.167	0.0016	
3	-6271.9	-55.45	113.1	14.167	0.0016	
4	-6271.9	-55.45	113.1	14.167	0.0016	
5	1253.7	11.08	113.1	14.167	0.0016	
6	5015.8	44.35	113.1	14.167	0.0016	
7	-28718.6	-253.92	113.1	10.812	0.0012	
8	-28718.6	-253.92	113.1	10.812	0.0012	
9	-22976	-203.15	113.1	10.812	0.0012	
10	-22976	-203.15	113.1	10.812	0.0012	
11	-22971.9	-203.11	113.1	10.812	0.0012	
12	-22971.9	-203.11	113.1	10.812	0.0012	
13	-28717	-252.92	113.1	10.812	0.0012	
14	-28717	-252.92	113.1	10.812	0.0012	
15	6483.5	57.33	113.1	16.27	0.0018	
16	6480	57.29	113.1	16.27	0.0018	
17	-2162.8	-19.12	113.1	8.132	0.00092	
18	4321	38.21	113.1	8.134	0.00092	
19	0	0	113.1	4.068	0.00046	
20	-2159.9	-19.1	113.1	8.132	0.00092	
21	4321.4	38.21	113.1	8.134	0.00092	
22	0	0	113.1	4.068	0.00046	
23	0	0	113.1	4.068	0.00046	
24	0	0	113.1	14.168	0.0016	
25	0	0	113.1	4.068	0.00046	
26	0	0	113.1	14.168	0.0016	
27	2124.7	18.79	113.1	8	0.0009	

In order to meet the actual engineering requirements, the cross-sectional area of the bars of the triangular truss structure was adjusted with the allowable strength of the material being 100 MPa in tension and 30 MPa in compression. The cross-sectional area of the diagonal bar was replaced with 1018 mm² of reinforcement, and the calculation and analysis of the bar force and the used volume were re-calculated. The results are shown in Table 2.

Table 2. Force situation of triangular truss and use volume of rod after replacing rod

Serial Number	Axial force (KN)	Tensile strength/pressure (Mpa)	Sectional area (mm ²)	Length (m)	Volume (m ³)	Total Volume (m ³)
1	5017.4	44.36	113.1	14.167	0.0016	0.111
2	1254.5	11.09	113.1	14.167	0.0016	
3	-6271.9	-55.45	113.1	14.167	0.0016	
4	-6271.9	-55.45	113.1	14.167	0.0016	
5	1253.7	11.08	113.1	14.167	0.0016	
6	5015.8	44.35	113.1	14.167	0.0016	
7	-28718.6	-28.21	1018	10.812	0.011	
8	-28718.6	-28.21	1018	10.812	0.011	
9	-22976	-22.57	1018	10.812	0.011	
10	-22976	-22.57	1018	10.812	0.011	
11	-22971.9	-22.56	1018	10.812	0.011	
12	-22971.9	-22.56	1018	10.812	0.011	
13	-28717	-28.21	1018	10.812	0.011	
14	-28717	-28.21	1018	10.812	0.011	
15	6483.5	57.33	113.1	16.27	0.0018	
16	6480	57.29	113.1	16.27	0.0018	
17	-2162.8	-19.12	113.1	8.132	0.00092	
18	4321	38.21	113.1	8.134	0.00092	
19	0	0	113.1	4.068	0.00046	
20	-2159.9	-19.1	113.1	8.132	0.00092	
21	4321.4	38.21	113.1	8.134	0.00092	
22	0	0	113.1	4.068	0.00046	
23	0	0	113.1	4.068	0.00046	
24	0	0	113.1	14.168	0.0016	
25	0	0	113.1	4.068	0.00046	
26	0	0	113.1	14.168	0.0016	
27	2124.7	18.79	113.1	8	0.0009	

3.2.2. Pratt truss

The second test of the Pratt truss was conducted, and the Pratt truss bridge was designed based on the design requirements of the actual project. The bridge deck and top were connected by 10 bars with a length of 14.167 m, while the web was connected by 6 bars with a length of 16.2866 m. Vertical bars were connected by 5 bars with a length of 8 m, and the design height of the entire bridge was chosen to be 8m. The action load of 150 KN/m was applied on the bridge deck according to the project requirements, as shown in Fig. 8.

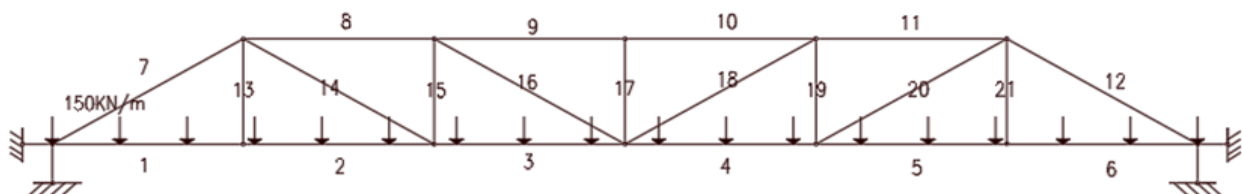


Figure 8. Design drawing of the Pratt Truss Bridge

The force situation and use volume of the Pratt truss are calculated by the structural mechanics solver, as shown in Table 3.

Table 3. Force situation of Pratt truss and use volume of rod

Serial Number	Axial force (KN)	Tensile strength/pressure (Mpa)	Sectional area (mm ²)	Length (m)	Volume (m ³)	Total Volume (m ³)
1	-1881.8	-16.64	113.1	14.167	0.0016	0.032
2	-1882	-16.64	113.1	14.167	0.0016	
3	3761.6	33.26	113.1	14.167	0.0016	
4	3764.2	33.28	113.1	14.167	0.0016	
5	-1880.3	-16.63	113.1	14.167	0.0016	
6	-1880.3	-16.63	113.1	14.167	0.0016	
7	-1080.4	-9.55	113.1	16.2688	0.00184	
8	-15051.2	-133.08	113.1	14.167	0.0016	
9	-16933.6	-149.72	113.1	14.167	0.0016	
10	-16933.6	-149.72	113.1	14.167	0.0016	
11	-15053.9	-133.1	113.1	14.167	0.0016	
12	-10805.3	-95.54	113.1	16.2688	0.00184	
13	2124.8	18.79	113.1	8	0.0009	
14	6481.7	57.31	113.1	16.2688	0.00184	
15	-1062.8	-9.4	113.1	8	0.0009	
16	2161.7	19.11	113.1	16.2688	0.00184	
17	0	0	113.1	8	0.0009	
18	2159	19.09	113.1	16.2688	0.00184	
19	-1062	-9.4	113.1	8	0.0009	
20	6482	57.31	113.1	16.2688	0.00184	
21	2125.5	18.79	113.1	8	0.0009	

To meet the requirements of the actual project, the cross-sectional area of the rods in the Pratt truss structure was adjusted based on an allowable strength of 100 MPa in tension and 30 MPa in compression. The cross-sectional area of four crossbars on the upper side of the truss was replaced with 615.8 mm² bars, while the rightmost diagonal bar was also replaced with a 615.8mm² bar. The calculation and analysis of the force conditions and the volume of the bars used were then recalculated. The results are shown in Table 4.

Table 4. Force situation of Pratt truss and use volume of rod after replacing rod

Serial Number	Axial force (KN)	Tensile strength/pressure (Mpa)	Sectional area (mm ²)	Length (m)	Volume (m ³)	Total Volume (m ³)
1	-1881.8	-16.64	113.1	14.167	0.0016	0.058
2	-1882	-16.64	113.1	14.167	0.0016	
3	3761.6	33.26	113.1	14.167	0.0016	
4	3764.2	33.28	113.1	14.167	0.0016	
5	-1880.3	-16.63	113.1	14.167	0.0016	
6	-1880.3	-16.63	113.1	14.167	0.0016	
7	-1080.4	-9.55	113.1	16.2688	0.00184	
8	-15051.2	-24.44	615.8	14.167	0.0872	
9	-16933.6	-27.5	615.8	14.167	0.0872	
10	-16933.6	-27.5	615.8	14.167	0.0872	
11	-15053.9	-24.45	615.8	14.167	0.0872	
12	-10805.3	-17.55	615.8	16.2688	0.10	
13	2124.8	18.79	113.1	8	0.0009	
14	6481.7	57.31	113.1	16.2688	0.00184	
15	-1062.8	-9.4	113.1	8	0.0009	
16	2161.7	19.11	113.1	16.2688	0.00184	
17	0	0	113.1	8	0.0009	
18	2159	19.09	113.1	16.2688	0.00184	
19	-1062	-9.4	113.1	8	0.0009	
20	6482	57.31	113.1	16.2688	0.00184	
21	2125.5	18.79	113.1	8	0.0009	

The Pratt truss is more common and uses less material than the triangle truss. Moreover, the material usage rate of Pratt joist is significantly higher than that of triangle joist. However, the structure of space truss is more complicated and needs to consider many factors, such as the position of support, node structure, etc., which makes the construction more difficult.

3.2.3. Arch truss

After adjusting the cross-sectional area of the bars in the arch truss structure to meet the allowable strength of the material, which is 100 MPa in tension and 30 MPa in compression, the testing of the arch truss was conducted. The bridge deck was connected by six bars of length 14.167 m, while the web bars were connected by 15.023 m and 16.27 m long bars. The vertical bars were connected by 5 m, 8 m, and 10 m long bars, respectively, and the diagonal bars were connected by 15.023 m, 14.418 m, and 14.307 m long bars to meet the design requirements. The design height of the entire bridge was chosen as 10m, and the acting load of 150 KN/m was applied on the bridge deck according to the engineering requirements, as shown in Fig. 9.

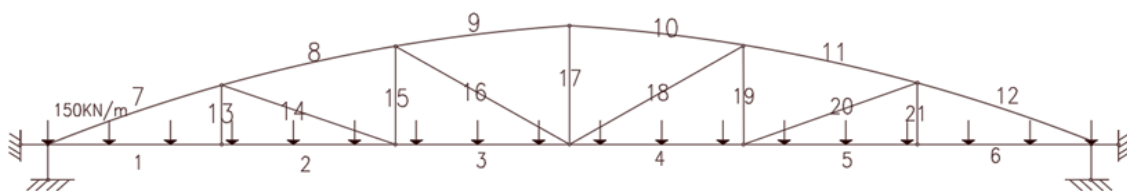


Figure 9. Design drawing of the arch-shaped truss bridge

The force situation and use volume of the arch truss are calculated by the structural mechanics solver, as shown in Table 5.

Table 5. Force situation of arch truss and use volume of rod

Serial Number	Axial force (KN)	Tensile strength/pressure (Mpa)	Sectional area (mm ²)	Length (m)	Volume (m ³)	Total Volume (m ³)
1	-0.691	-0.006	113.1	14.167	0.0016	0.031
2	-1.12	-0.01	113.1	14.167	0.0016	
3	-2.07	-0.018	113.1	14.167	0.0016	
4	0.584	0.0051	113.1	14.167	0.0016	
5	1.647	0.0146	113.1	14.167	0.0016	
6	1.647	0.0146	113.1	14.167	0.0016	
7	-15962.6	-141.14	113.1	15.023	0.0017	
8	-15385.1	-136.03	113.1	14.481	0.00164	
9	-13681.1	-120.96	113.1	14.307	0.0016	
10	-13681.3	-121	113.1	14.307	0.0016	
11	-15387.5	-136.05	113.1	14.481	0.00164	
12	-15964.7	-141.10	113.1	15.023	0.0017	
13	2124.8	18.79	113.1	5	0.00057	
14	-1.014	-0.009	113.1	15.023	0.0017	
15	2125.4	18.79	113.1	8	0.0009	
16	-1727.5	-15.27	113.1	16.27	0.00184	
17	3825.5	33.82	113.1	10	0.00113	
18	-1730.9	-15.3	113.1	16.27	0.00184	
19	2125.1	18.79	113.1	8	0.0009	
20	-1.127	-0.01	113.1	15.023	0.0017	
21	2125.5	18.79	113.1	5	0.00057	

To meet the practical engineering requirements, the cross-sectional area of the bars in the arch truss structure was adjusted based on the allowable strength of the material, which is 100 MPa in tension and 30 MPa in compression. As a result, the cross-sectional area of 6 diagonal rods on the upper side of the truss was reduced from 150 mm² to 490.9 mm², and the calculation and analysis of the force condition were re-calculated using the reinforcement. The results are shown in Table 6.

Table 6. Force situation of arch truss and use volume of rod after replacing rod

Serial Number	Axial force (KN)	Tensile strength/pressure (Mpa)	Sectional area (mm ²)	Length (m)	Volume (m ³)	Total Volume (m ³)
1	-0.691	-0.006	113.1	14.167	0.0016	0.064
2	-1.12	-0.01	113.1	14.167	0.0016	
3	-2.07	-0.018	113.1	14.167	0.0016	
4	0.584	0.0051	113.1	14.167	0.0016	
5	1.647	0.0146	113.1	14.167	0.0016	
6	1.647	0.0146	113.1	14.167	0.0016	
7	-15962.6	-30.5	490.9	15.023	0.0074	
8	-15385.1	-29.3	490.9	14.481	0.0071	
9	-13681.1	-27.9	490.9	14.307	0.0070	
10	-13681.3	-27.8	490.9	14.307	0.0070	
11	-15387.5	-29.4	490.9	14.481	0.0071	
12	-15964.7	-30.8	490.9	15.023	0.0074	
13	2124.8	18.79	113.1	5	0.00057	
14	-1.014	-0.009	113.1	15.023	0.0017	
15	2125.4	18.79	113.1	8	0.0009	
16	-1727.5	-15.27	113.1	16.27	0.00184	
17	3825.5	33.82	113.1	10	0.00113	
18	-1730.9	-15.3	113.1	16.27	0.00184	
19	2125.1	18.79	113.1	8	0.0009	
20	-1.127	-0.01	113.1	15.023	0.0017	
21	2125.5	18.79	113.1	5	0.00057	

Arch trusses are more economical in terms of material usage compared to Pratt truss and Triangle truss. They have fewer members, which results in lower construction costs. Additionally, Arch trusses use the arch bearing method, which makes them more resistant to external forces and deformations. However, the high maintenance cost of Arch trusses requires frequent inspections and maintenance. Constructing Arch trusses in actual projects can be challenging and requires higher technical expertise and experience.

3.3. Discussion

After conducting a structural optimization, the arch truss was selected as the preferred option for the 85m span and to preserve the natural space under the bridge. This choice offers several advantages, including uniformly distributed forces, high material utilization, minimal material volume requirement, and superior force performance. However, the complexity of the arch truss structure also results in higher maintenance costs. Regular inspections and maintenance are necessary to maintain the safety and reliability of the structure.

In general, arch trusses have simpler cross-sectional shapes compared to other types of trusses with complex cross-sections. Arch trusses typically use rectangular or elliptical cross-sections, requiring less material compared to other types of trusses with complex cross-sections. Additionally, the bracing method of arch trusses is simpler, with the arch joist typically supported by simple triangular or flat plate bracing, which uses less material compared to the complex bracing structures of space joist and triangular joist.

The study aimed to identify the optimal design of an arch truss through a comparison of three different truss types. The primary advantage of arch trusses is their clear force transfer path, which enables them to effectively distribute horizontal and vertical loads and maintain the stability and safety of the building. Additionally, the curved form of arch trusses facilitates a straightforward force transmission path, which makes them easier to design and construct. Arch trusses are known for their superior stability and can withstand heavy loads to ensure the safety of the building. They are ideal

for arch building, such as arch bridges, while space trusses are suitable for larger buildings like gymnasiums, and triangle trusses are best suited for smaller structures like small houses.

4. Conclusion

In this paper, the topology optimization design of truss structure is studied, and the main conclusions are as follows:

(1) Topological optimization is a powerful optimization design method that can optimize the material distribution in a structure to achieve optimal structural performance and weight. The case study in this paper shows that by optimizing material distribution, it is possible to reduce the amount of material in the structure, resulting in a lighter and cheaper structure.

(2) Through the force analysis and volume calculation of the three basic truss structures used in the case, it can be seen that the arch truss structure can withstand greater stress. When designing short-distance Bridges, under the same load, arch truss structure requires the least material and the highest material utilization rate.

(3) While this study compares three basic truss structures and calculates the stresses under optimal conditions, it does not take into account more complex realities. In addition, the length design of the trusses in this paper needs to be more realistic to avoid the trusses being too long. With the development and improvement of topology optimization method, its application in arch truss structure design will be more and more extensive. Topological optimization can help designers more accurately determine the structural form and material distribution of arch trusses, thereby improving their load-bearing capacity and stability. The continuous advancement and refinement of artificial intelligence and machine learning techniques will further optimize topology optimization methods.

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