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Discussion on Human-induced Vibration of Glulam Pedestrian Arch Bridge

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Abstract: In the process of urban modernization, with the wide application of lightweight and high-strength structural materials and the constant pursuit of structural aesthetics, footbridges tend to develop in the direction of long span, slender and gentle. However, the problem of human-induced vibration comfort caused by such bridges is becoming increasingly prominent. Especially the wooden footbridge, although its static performance (such as bearing capacity and deflection) can well meet the structural design and use standards, its dynamic performance, especially the excessive vibration under the excitation of crowds, has become the core consideration to control the design of modern wooden footbridges.

Keywords: Pedestrian bridge; Human-induced vibration response; Comfort evaluation.

1. Introduction

Nowadays, the relationship between human beings and nature has undergone a fundamental reshaping. Faced with the uncontrolled consumption of resources and serious pollution to the environment in the process of human survival and development, human beings re-examine and adjust their past survival mode and development path. It is against this background that sustainable development has become a global consensus. Wood structure is regarded as the preferred structure of green building because of its advantages of renewable utilization, cost competitiveness, light weight and high strength, and short construction period. Wood-structure buildings are closely linked to the national double-carbon policy, which not only has remarkable carbon sequestration capacity, but also has far lower carbon emissions than the traditional reinforced concrete building system in the whole production and use cycle of the building. Therefore, it has become a universal trend in the world to vigorously develop low-carbon and environmentally-friendly modern wooden buildings. In addition, promoting the development of modern wood structure is one of the key ways for China to move towards green, ecologically livable and socioeconomic sustainable development. At present, wood structure engineering materials have become one of the most potential green building materials in the world. With the progress of modern wood structure engineering technology and the improvement of processing methods, the manufacture of wood structure is becoming increasingly industrialized and widely used in the construction field. Wooden bridge combines the essence of modern engineering technology and traditional culture, which not only represents an environment-friendly architectural concept, but also attracts extensive attention in the field of contemporary bridge engineering because of its advantages of beauty and sustainability [1-3].

With the widespread application of lightweight and high-strength structural materials and the continuous improvement of the pursuit of architectural aesthetics, the span of footbridge shows an expanding trend, and at the same time, its structural fundamental frequency is gradually reduced. This change leads to the problem of comfort caused by excessive vibration when pedestrians cross the bridge becoming increasingly prominent. The current national standards mainly adopt two strategies: avoiding sensitive frequency bands and limiting human-induced vibration response to control excessive vibration caused by crowd load (especially resonance phenomenon), so as to ensure that pedestrian comfort is not negatively affected during bridge use. As a passive control technology, external dampers have been widely used in civil engineering practice in recent years. For example, on Solferino Bridge in Paris and Millennium Bridge in London, tuned mass dampers (TMD) were added to effectively reduce the vibration caused by pedestrian activities[4-5].Similarly, on the footbridge in Toda Park, Japan, remarkable vibration reduction effect has been achieved by combining the use of tuned liquid dampers (TLD) and the arrangement of deck flower beds. Although increasing damping can significantly improve the safety of bridge structure, this method also has some shortcomings, such as the maintenance and replacement costs of damping equipment. When the damper is used for more than a certain period of time, the damping device may fail and lose its damping effect, and it needs to be inspected and replaced regularly, which undoubtedly increases the maintenance cost and workload. In order to reduce the project investment, it is necessary to consider how to apply some simple and effective technologies to practical projects.

Avoiding sensitive frequency band method, a technology applied in the design stage, aims to ensure that the natural frequency of the structure avoids overlapping with the resonance frequency caused by pedestrian load. This method is especially suitable for the design of wooden footbridges. As a prior control strategy, it can effectively prevent resonance. This method is not only easy to operate and can ensure safety and comfort, but also gives designers more flexibility and encourages the exploration of more innovative design schemes. As a preventive measure, this strategy effectively reduces the complexity and cost of subsequent vibration problems by avoiding possible resonance problems in advance, so it becomes a key means to improve the design quality of footbridges and ensure the safety and comfort in use.

2. Development Status of Wooden Bridge

On a global scale, especially in Europe, America, Japan and Australia, the development of wooden bridges presents unique regional characteristics and diversified interactive influences. In contrast, the bridge construction in China tends to the overall unified development model [6-8].

During the Middle Ages to the 17th century, many wooden bridges, as well as various arch bridges and frame structures, were built. In the 16th century, unique bridges with roofs appeared in America and Europe. In Central Europe, especially in Switzerland, it is an ancient and protected tradition to build and maintain wooden bridges. Switzerland has preserved more than 200 wooden bridges in good condition, many of which were built in the Middle Ages. The capel covered bridge in Lucerne is one of the most famous examples. However, by the end of 17th century, with the development of technology and the increase of traffic demand, the use of wood in bridge construction gradually decreased, and it was mainly replaced by steel bars and concrete structures. Nevertheless, the wooden bridge structure is still used in many countries, which bears witness to the lasting charm and historical value of the wooden bridge technology. Since the 20th century, countries in developed areas such as Europe and America have carried out comprehensive and in-depth scientific research and exploration in the field of wooden bridges, especially in the aspects of anti-corrosion, fine processing, efficient connection and innovative construction technology. According to the bridge survey data recently released by the Federal Highway Administration, there are about 75,000 wooden bridges in the United States, accounting for 15% of the total number of highway bridges, and this proportion is on the rise, and the demand for this type of bridges in the United States is increasing. It is worth noting that the service life of most bridges built by wooden structures has exceeded 50 years. In addition, various construction projects of wooden structures are started one after another every year. The double-deck wooden arch bridge in the United States is a typical example. The history of this building can be traced back to 1968, and it has been standing since then. This unique bridge structure skillfully combines two independent elements, the upper layer presents a delicate arch bridge design, while the lower layer adopts a unique transverse curved beam slab bridge, and its exquisite construction skills are amazing. These developments and examples fully demonstrate the innovation and development of wooden bridge in technology, design and construction, and prove that wooden bridge, as an ancient architectural form, still has its unique value and development potential in modern times [9-12].

Since 1992, Helsinki University of Technology has started the in-depth research and development of wooden bridges. The initial project was a national project (1992-1994), which laid the foundation for the subsequent Nordic Wooden Bridge projects (carried out in 1994-1996, 1997-1999 and 1999-2001 respectively). These projects have played a decisive role in promoting the development of modern wooden bridges in Finland and other Nordic countries.

During the period from 1994 to 2001, some Nordic countries actively launched a series of in-depth research and innovation projects aimed at modern wooden bridge. Through these intensive scientific research activities, they gradually built a fairly perfect engineering technology system, and won a number of innovative patent achievements in the process. These achievements have been widely and effectively integrated into the design and construction of various large-scale public facilities, such as bridges, stadiums, exhibition centers and various educational institutions. Through these projects and studies, Nordic countries not only demonstrated the feasibility and sustainability of wooden bridges in modern infrastructure, but also emphasized the potential and value of wood as a building material.

With the increasing awareness of social environmental protection, people pay more and more attention to green buildings, especially modern wooden bridges that can effectively save energy and reduce emissions. Northern Europe, thanks to its rich forest resources and profound history of wooden buildings, has made remarkable achievements in the development of wooden bridges. Take Finland as an example, the country's wood structure construction industry is highly mature, and more than 700 wood structure bridges have been successfully built for roads and pedestrians. On a global scale, especially in Europe, America, Japan and Australia, the development of wooden bridges presents unique regional characteristics and diversified interactive influences. In contrast, the bridge construction in China tends to the overall unified development model.

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3. Summary

At present, China's wood structure engineering design standards mainly include Code for Design of Wood Structure (GB50005-2003) and Code for Design of Steel Structure and Wood Structure of Highway Bridges and Culverts (JTJ025-86). Code GB50005-2003 mainly aims at the design of wood structure in building structure, but does not cover the design of highway wooden bridge; Code JTJ025-86 is mainly used for emergency maintenance of wooden bridges and other temporary wood structure design, and the existing technical standards are adequate. However, in terms of detailed design specifications for permanent and semi-permanent wooden bridges, the existing regulations seem to be insufficient. In addition, it is worth noting that at present, most higher education institutions specializing in civil engineering in China have not set up courses related to wood structure, which leads to a gap in the design and construction of wooden bridges for professionals.

Obviously, compared with the international leading level, the research on the basic theory and engineering application of modern wood structure in China still has obvious shortcomings. This significant technical gap leads to the limitation of the design theory and construction practice of modern wooden bridge, which has a negative impact on the overall safety of the bridge and the comfort of human-induced vibration, and invisibly improves the probability of structural safety hazards. In addition, it also limits the popularization and application of modern wood structure in China, and hinders the process of localized production of wood structure materials for heavy engineering.

At present, a detailed technical specification and standardization framework has been established in the world, which comprehensively covers all key links such as production technology, modification method, component design and quality evaluation, structural construction management, acceptance procedures and post-maintenance of glued wood. However, there is still a lack of research on the evaluation of human-induced vibration comfort of wooden footbridges. Remarkable achievements have been made in the construction of wooden bridges abroad, but there are also some problems in human-induced vibration. At present, there is a widespread problem of excessive human-induced vibration in the built wooden footbridges, which seriously affects the comfort of pedestrians on the bridges. It is necessary to pay enough attention to the problem of human-induced vibration of wooden footbridges.

Because the natural frequency of traditional concrete and steel footbridges is easy to avoid the sensitive range of walking frequency, the structural design of footbridges usually regards crowd load as static load, but seldom studies the excessive vibration caused by crowd excitation. With the wide application of lightweight and high-strength structural materials, the fundamental frequency of pedestrian bridge is gradually reduced, which is easy to fall within the walking frequency range, which has a negative impact on pedestrian comfort on the bridge. For a pedestrian bridge with wood structure, if it is difficult to ensure that the fundamental frequency of the structure avoids the walking frequency range, the pedestrian load must be regarded as a dynamic load and dynamically designed. At the beginning of footbridge design, by adjusting its stiffness and mass, its fundamental frequency can avoid the walking frequency range, which can effectively prevent excessive vibration. However, in the design stage of wooden bridge, designers often pay too much attention to the static performance of footbridge and ignore the dynamic response caused by crowd excitation, which leads to the need to take post-event control measures to solve the problem of excessive vibration. Therefore, bridge engineers should fully consider the influence of human-induced vibration when planning the wooden footbridge, and carry out in-depth research to ensure that the human-induced vibration comfort of the wooden footbridge meets the requirements.

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