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Research on comfort analysis method and optimization design of pedestrian bridge

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Abstract. In this paper, the characteristics and modes of pedestrian load are summarized, and the norms of pedestrian load in different countries are compared. At the same time, the pedestrian excitation load is briefly introduced .Then, combining the three conditions of single, double and three-person pedestrian load with the above four common pedestrian load conditions, 12 groups of different load conditions are formed, and the case study is carried out, and the conclusion is drawn as follows: Under the condition of slow walking, the vertical peak acceleration response of the structure under inconsistent stride length slightly increases, but the impact on the pedestrian comfort of the bridge is not significant. When walking slowly and at the same pace, the vertical peak acceleration of the structure increases significantly, which has a significant impact on the pedestrian comfort of the bridge. The common vibration control measures are also introduced. Through the comparison of relevant regulations, combined with case studies and common vibration control measures, it is hoped that it will be helpful to improve the comfort of pedestrian Bridges in the future, and the relevant regulations in China will be revised.

Keywords: pedestrian load, comfort analysis method, national norms, control measures.

1. Introduction

Pedestrian bridge is one of the important municipal facilities. Compared with the traditional concrete pedestrian bridge, steel structure pedestrian bridge has the advantages of high strength, light weight, fast construction speed, good seismic performance. And pedestrian bridge is increasingly used in engineering [1]. However, due to the large span of the steel structure pedestrian bridge and the concentration of people, in addition to verifying the strength and deformation index of the structure itself, the comfort problem caused by the rhythmic walking of pedestrians and the resonance of the structure during use should also be considered. Under the situation of rapid development of urban transportation in China, the construction of urban pedestrian bridges has also developed rapidly. With the adoption of high-strength materials, novel structural systems, new construction techniques and modern structural analysis methods, pedestrian bridges are developing in the direction of lightweight, large span and delicate, which will cause vibration problems of pedestrian bridges.

For long-span gentle pedestrian bridges, the structure has a low self-resonating frequency. Under the stimulation of external loads such as pedestrians and ground cars, it is easy to cause large vibrations. These vibration responses, while not sufficient to create safety issues with the structure, can cause discomfort to pedestrians. Pedestrians will be nervous or even panicked during walking, which directly leads to the reduction of the applicability of the pedestrian bridge structure. In this paper, the scheme of optimizing the pedestrian bridge is first proposed, and then the optimal solution is obtained by comparing the schemes. Then, the normative standards of frequency control in various countries are analyzed, and the specific requirements for the comfort optimization of pedestrian bridges in China are finally obtained.

2. Introducing pedestrian load

In recent years, more and more attention has been paid to the excessive vibration of long-span footbridge and long-span floor caused by human-induced vibration. Extensive research has been carried out. Scholars have shown, through a large number of statistical data and research results, that the step frequency of human is between 1.5 Hz~3 Hz, and the step frequency of normal walking is between 1.7 Hz~2.3 Hz. Step frequency during running or jumping is generally greater than 3 Hz [2].

Chinese scholars have carried out some fruitful researches and explorations on the walking characteristics of Chinese people. For example, in 2005, Dong and Chen [3] measured a total of 4016 pedestrian samples of different ages and genders in Shanghai and concluded that the step frequency of young boys and girls obeyed the normal distribution law of N (1.96, 0.24) and N (2.01, 0.23), respectively. These results are reliable, but due to insufficient sample size, if the design value is adopted, the reliability of the bridge will inevitably be low.

2.1. Characteristics of pedestrian load

In order to verify the limit state of structural availability and comfort in relation to pedestrian induced vibration, it is necessary to define dynamic pedestrian loads. Many studies involve the determination of human walking, running, or jumping forces over the years. For example, possible loading scenarios can be divided into five categories, shown as Table 1.

Table 1. Load the model summary.

Model 1	Model 2	Model 3	Model 4	Model 5
A single load	Normal traffic	The crowd load	Group load	Saboteur load

Supplementary note: For model two, everyone can move freely without having to change the way of walking in order to avoid contact with others. For Model 3, everyone's walking is restricted due to the limited space [4]. For model four, many people walk closely together. For model five, a person or group of people try to excite the structure by moving in a relevant harmonic manner in a responsive area [4].

In addition to these five groups, three different types of human movement are generally considered to simulate the dynamic loads imposed by pedestrians, namely walking, running, and rhythmic jumping. All these load models can usually be classified as deterministic models and probabilistic models. This paper only considers the deterministic model of individual pedestrian, group and crowd load [5].

At present, pedestrian load is mostly simulated as deterministic periodic load in the evaluation of structural vibration comfort level. However, pedestrian walking has strong randomness, so there is still a lack of relevant studies on the evaluation of the comfort level of structure induced by human vibration. Considering the randomness of pedestrian walking gait and not considering the relative structural dynamic response are quite different, which is worthy of further study. In the actual process, walking is a random process, and the stride length and frequency of pedestrian load both change with time. Therefore, pedestrian load can be studied from the perspective of probability or statistics [5].

2.2. Mode of human load

Study pedestrian load from probability or statistics. Pedestrian load can be divided into several models:

(1) Equivalent synchronous number load mode

When walking, the step distance, step frequency, starting time and phase of different pedestrians are all random. Due to the inconsistency of pedestrian steps, some steps can cancel each other. This makes the effect of N times the number of pedestrians not N times the effect of the one-person model. Therefore, correction and reduction should be carried out under the original load effect. The formula is as follows:

$$N_P = \sqrt{n} \quad (1)$$

where Np is the effective number of people after deduction, and n is n pedestrians.

(2) Fixed multi-person harmonic load model

When the crowd forms a stable flow, it can be regarded as the crowd is evenly distributed on the structure. In a certain period of time, the number of people is stable, so it can be equated with the fixed load in place. Usually, Fourier series sine load is used. This model is too idealistic in a sense, because it is impossible to form a stable flow of people in the actual structure, which is generally used for the preliminary estimation of load.

(3) Mobile multiplayer random walking load model

Different gait parameters of pedestrians have different random distribution characteristics. The crowd load probability distribution model can be built according to the different distribution characteristics of the parameters. This model assumes the real foot trajectory of pedestrians on the structure, and each pedestrian on the structure is regarded as a moving load. The time history of pedestrian load acting on different positions of the structure at different times was calculated. The load time history of different pedestrians is superimposed together to obtain the total continuous load time history of different landing points, which is applied to the structure as an excitation effect to calculate the dynamic response of the structure. The random loading model of pedestrian is shown in Figure 1.

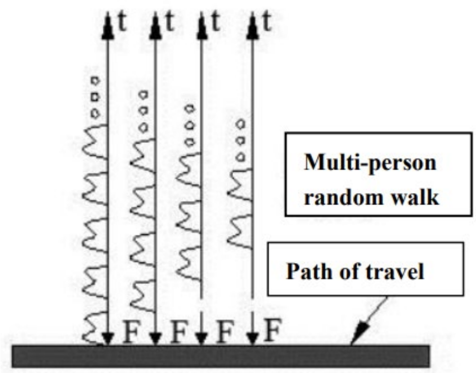

Figure 1 Pedestrian random loading model [5].

(4) Population concentration load model

Based on the equivalent load model and the assumption of ideal mathematical model condition, two kinds of crowd load models are established and improved, and can be well applied to long-span floor structures. Based on the random probability distribution crowd load model, the latest research achievements in the field of traffic science and biology were introduced. By considering the relationship between the crowd concentration, step frequency and walking speed, the multi-person load model was constructed. The model can predict the different operating conditions of the structure, which is also referred to as the crowd concentration load model. The construction idea of this model is shown in Figure 2.

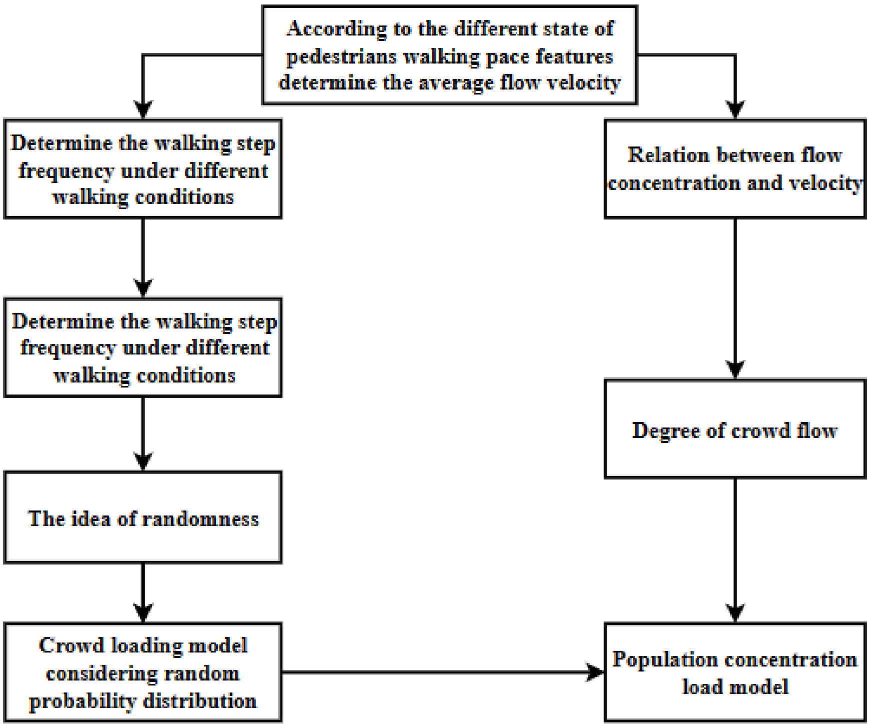

Figure 2. Schematic diagram [5].

3. Understanding of the corresponding national norms

3.1. The comparison of different evaluation norms

The current provisions for pedestrian loads in the various national codes are not uniform, they are studied with different emphases, and there is a certain amount of variability. There is no comprehensive comparative study of the dynamic response of pedestrian bridges under different codes for pedestrian loads [6].

A large span steel box girder bridge with a frequency within the range of pedestrian step frequencies was used as an example to compare the dynamic response of five different code pedestrian load patterns, including the ISO10137 code and the German EN03 code. The results show that under continuous walking conditions, the vertical acceleration produced by different loading modes on the footbridge varies along the span with the same trend. Both increasing first and then decreasing. In general, the acceleration and displacement response of the pedestrian load mode given by IS010137 code is larger than other codes. The dynamic response from the German EN03 code load pattern is more sensitive to the discount factor, especially when the external load is at 2.3-2.5 Hz. The discount factor is zero and the code is no longer applicable; the dynamic response of the pedestrian bridge is relatively small under the load pattern excitation of the other three codes [7].

The following are some conclusions for different codes for pedestrian loads, which have certain limitations and are not general:

(1) Under continuous walking conditions, the vertical acceleration of the pedestrian bridge produced by different codes of pedestrian load loading patterns varies along the span in the same form. They increase first and then decrease in a convex shape, and the vertical acceleration at the mid-span node is the largest.

(2) The dynamic response in the span of a footbridge may be smaller than the dynamic response of the surrounding nodes under the action of the group side-by-side conditions. Therefore, the variation in the dynamic response of the full span of the bridge should be fully considered when designing the bridge for comfort.

(3) The accelerations and displacements produced by the pedestrian load patterns given in the ISO code for pedestrian bridges are generally greater than those of other codes. They are recommended for some practical projects with more stringent vibration comfort requirements when carrying out dynamic response analysis.

(4) The main difference between the pedestrian load pattern given in the German Code and the other codes is that the load reduction factor. The calculation formula is related to the pedestrian step frequency, results in a different pattern of vertical dynamic response to the pedestrian bridge than the other codes. The German Code is second only to the ISO code in terms of vibration comfort requirements for pedestrian bridges.

(5) Relatively speaking, the loading patterns specified in the opinion paper, literature and the Swedish.

3.2. Pedestrian excitation loads

Code is conservative in their calculation of the dynamic response generated by footbridges. In general, pedestrian movement is haphazard, but the superposition of a large number of pedestrian movements can produce regular periodic features in the vertical and lateral directions of a structure. According to the code IS010137 "Structural Design Fundamentals Building Vibration Resistant Usability", getting the vertical load model for a single person walking. with periodic superposition of a single footfall and taking into account a certain overlap time. They use first order load harmonics to simulate pedestrian excitation loads in order to simplify the model. The German EN03 code modelled the pedestrian excitation as a uniform harmonic load, using the self-oscillation frequency of the structure in the range of the pedestrian step frequency as the pedestrian excitation frequency.

The first- and second-order harmonic frequencies of the vertical load are 1.25-4.6 Hz, and the first-order harmonic frequency of the lateral load is basically 0.5-1.2 Hz. The codes of various countries specify the range of sensitive frequencies, which are considered to be in a certain range to cause structural resonance and pedestrian discomfort.

The main codes of each country also provide for vertical sensitive frequencies, but there are fewer provisions for lateral sensitive frequencies. However, the fact that humans are more uncomfortable with lateral resonance than vertical resonance due to their habits should be a concern for designers. The the German code makes clear provisions for this. The torsion of a double main beam structure can be broken down into two main beam structures vibrating in a regular vertical direction [8].

3.3. Case study

Chen et al. [9] conducted research on a cantilever light steel truss structure (as shown in Figure 3) as the engineering background. The main span of the bridge (length of the walkway platform) is 11.2 m, with a width of 1.4m. The handrail truss and walkway platform are made of thin-walled cold-formed steel materials, and each member is tightly connected by high-strength bolts. 8 rotating pile flange support feet and 4 connection supports are arranged at the middle position of each span and the connection between the two spans of the pedestrian bridge.

Figure 3. A light steel pedestrian bridge [9].

The case study is based on four common pedestrian load conditions: fast running, slow running, fast walking, and slow walking. A combination of three scenarios, single person, double person, and three persons, and the four common pedestrian load cases mentioned above, formed 12 different load case types to fully consider the most unfavourable load excitation of multi person loads on pedestrian bridges. The case study used accelerometer to record the vertical acceleration values of each measurement point under the above 12 working conditions, took the average value of the peak acceleration value of the symmetrical measurement point, and conducted field tests according to EN03 and ISO2631 to evaluate the comfort of the vertical peak acceleration measured under each working condition in the field test. The results are shown in Table 2. The following points can be seen from Table 2. At the same walking speed, the effect of more pedestrians on the bridge response acceleration is not significant. At the same time, the overall response acceleration increases slightly. The walking speed of pedestrians has a greater influence on the response acceleration.

Table 2. Comfort ratings based on EN03 and ISO2631 [9].

Number of people	Walking conditions	Peak acceleration ($m \cdot s^{-2}$)	Rating specifications	Comfort rating
Single	Slow walking	0.28	EN 03	1
			ISO 2631	1
	Fast walking	0.89	EN 03	2
			ISO 2631	2-3
	Jogging	1.59	EN 03	3
			ISO 2631	4-5
	Fast running	3.02	EN 03	4
			ISO 2631	6
Double	Slow walking	0.37	EN 03	1
			ISO 2631	2
	Fast walking	0.93	EN 03	2
			ISO 2631	3-4
	Jogging	1.87	EN 03	3
			ISO 2631	5
	Fast running	3.43	EN 03	4
			ISO 2631	6
Triple	Slow walking	0.43	EN 03	1
			ISO 2631	2
	Fast walking	1.01	EN 03	3
			ISO 2631	4
	Jogging	2.14	EN 03	3
			ISO 2631	5-6
	Fast running	3.73	EN 03	4
			ISO 2631	6

Chen et al. [9] used Midas Civil software to establish a finite element model of the bridge. The simulated data in the model were compared with the measured data. The maximum vertical acceleration values under each working condition were plotted as shown in Figure 4.

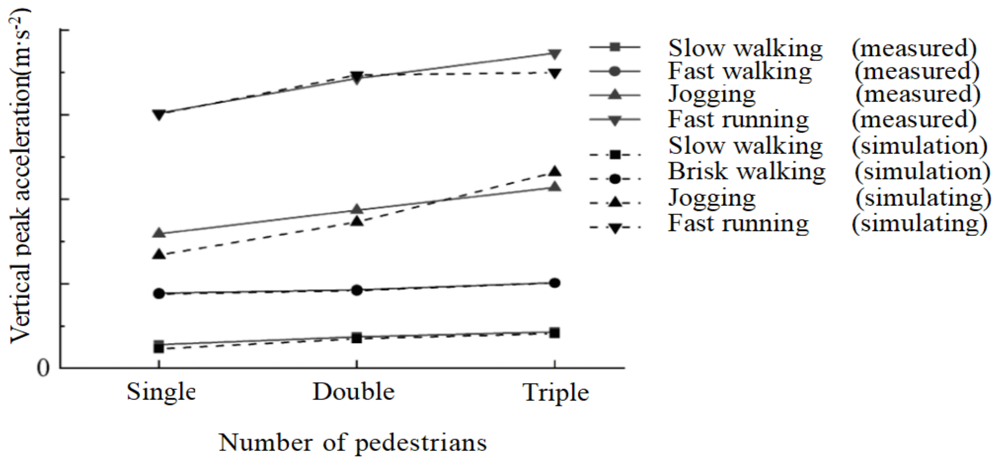

Figure 4. Actual and simulated maximum vertical acceleration under operating conditions [9].

From Figure 4, it can be seen that for the working conditions of single person, double person, and three persons walking slowly, the vertical peak acceleration response of the structure under the walking condition of the crowd with inconsistent steps slightly increases but has little effect on the pedestrian comfort of the bridge. When the pace of the crowd is consistent, the peak of the periodic load of the crowd walking appears at the same time. Therefore, there is a significant increase in the vertical peak acceleration of the structure under the slow walking condition of the crowd with consistent steps, which has a significant impact on the pedestrian comfort of the bridge. Compared with the traditional reinforced concrete bridge, the dead weight of the pedestrian bridge is light, and the external load has obvious influence on the natural frequency and response acceleration of the structure.

4. Commonly used vibration control measures

The adaptation and tolerance of footbridge vibration is a complex process, so vibration control measures need to consider many factors. Not only the size of the motion itself and the duration of the motion should be considered, but also the mechanism of human-induced vibration and its influence should be considered. The ultimate purpose of vibration control is to obtain effective vibration reduction control.

The method of increasing the damping ratio of the pedestrian bridge structure without changing the structure and appearance of the pedestrian bridge by installing damping Settings on the pedestrian bridge is called damping adjustment method. Viscous Damper (VD), Tuned Liquid Damper (TLD) and Tuned Mass Damper (TMD) are commonly used in pedestrian Bridges. VD and TLD are usually used to control the lateral vibration of pedestrian Bridges, and TMD is usually used to control the lateral and vertical vibration of pedestrian Bridges [10]. TMD is installed the cross section of the bridge diagram as shown in Figure 5and TMD model under moving concentrated load is shown in Figure 6 [11-12]. However, in the VD and TLD damping control, the liquid evaporation and loss will reduce or even lose the damping effect. Therefore, TMD is widely used in controlling the vibration of pedestrian Bridges.

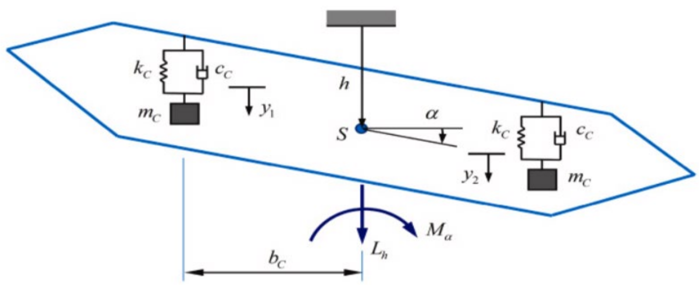

Figure 5. Cross section of bridge with TMD installation [11].

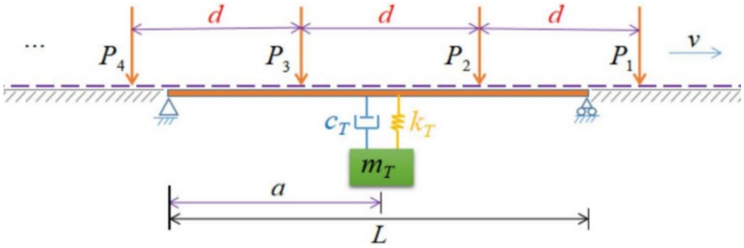

Figure 6. TMD model of bridge under moving concentrated load [12].

Recently, the application of Eddy Current Damper (ECD) becomes increasingly prevalent. Compared with traditional viscous damper, which has low sensitivity and low durability, ECD is more reliable and sensitive. Meanwhile, the Eddy Current Tuned Mass Damper (EC-TMD) developed on the basis of ECD and TMD can greatly increase the efficiency of eddy current damper and has a higher application prospect. TMDS can also be divided into two forms: Single Tuned Mass Dampers (STMD) and Multiple Tuned Mass Dampers (MTMD) [13]. The research shows that MTMD system can control a larger frequency bandwidth than STMD system. The effectiveness of STMD system is comparable to that of MTMD system under normal deviation, but STMD system is superior to MTMD system under the most unfavorable condition. Increasing the number of sub-TMDs of STMD system can improve the reliability of vibration reduction. The MTMD system has the opposite effect [14]. Domaneschi et al. explored the optimal installation position of the damper as shown in Figure 7 [15].

Theoretically, the damping effect of TMD system is positively correlated with its mass. However, the excessive mass of TMD system is more difficult for construction and affects its original load. Therefore, the mass ratio of TMD system is usually between 0.01 and 0.05, and the damping ratio added to the main structure is usually several times of the original structure, and the damping effect is better.

Because the number of moving loads and the distribution of moving loads will affect the optimization of TMD parameters, the damping ratio of Bridges will affect the optimal parameters of TMD. Therefore, the vibration is also related to the number distribution of moving loads and the damping ratio of Bridges. At the same time, different types of pedestrian Bridges have different vibration and damage due to different materials used, and also related to regular maintenance.

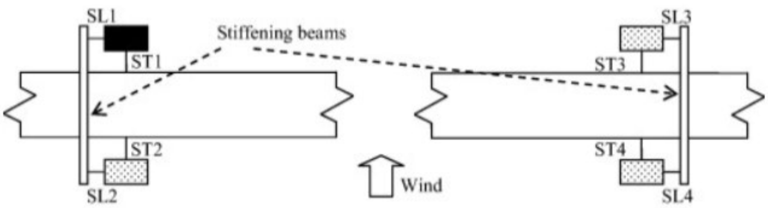

Figure 7. Installation position of damper [15].

5. Conclusion

This paper draws a conclusion based on the understanding of pedestrian load, national norms, analysis of various cases and the common vibration measures of pedestrian Bridges.

(1) Each figure should have a brief caption describing it and, if necessary, a key to interpret the various lines and symbols on the figure. The pedestrian load mode given by the ISO specification is generally larger than other specifications for the acceleration and displacement of the pedestrian bridge, and it is recommended to be the first choice for dynamic response analysis for some actual projects with strict vibration comfort requirements.

(2) The main difference between the pedestrian load mode given by the German code and other specifications is that in the load reduction coefficient, the code has the requirements for the vibration comfort of the pedestrian bridge second only to the ISO specification. Relatively speaking, the calculation of the dynamic response generated by pedestrian bridges as stipulated in the draft opinion, literature and Swedish specifications is conservative. The time history curve of pedestrian load given in

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standard ISO 10137 is close to the actual pedestrian load. When designing lightweight bridges, consideration should be given to the impact of the possible fastest pedestrian walking speed on the comfort of the bridge.

(3) The installation of TMD has a good effect on the dynamic response under the suppression of pedestrian loads, plays a major role, and can also meet the comfort level. The control of vibration is also related to the number of moving loads, the damping ratio of the bridge, and the pedestrian bridge's own materials, maintenance intervals and other related factors.

By comparing relevant specifications, combined with case studies and analysis of common vibration control measures, it is hoped that it will help to improve the comfort of pedestrian bridges in the future and revise relevant domestic regulations.

Authors contribution

All the authors contributed equally and their names were listed in alphabetical order.

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