Research on the Influence of Linear Stiffness Design on Human-Induced Vibration Comfort of Steel Box Girder Footbridge

Liang Zeng, Xilong Chen, Fucheng Wu and Huimin Chen*

Guangzhou Guangjian Construction Engineering Testing Center Co., Ltd., Guangzhou 510405, China

*Corresponding email: 13330128087@163.com

Abstract. This study investigates and analyzes the sensitive parameters affecting the comfort of simply-supported steel box girder pedestrian bridges. In response to human-induced vibrations, this study explores the relationship between structural bending stiffness, span length, and peak acceleration. The concept of linear stiffness is introduced, and employing the dynamic response limitation method, the threshold values for linear stiffness required to fulfill the comfort criteria for simply supported steel box girder pedestrian bridges across diverse spans are established. From a design perspective, this study proposes recommended values for bending stiffness that ensure adherence to comfort standards, accompanied by a methodology for evaluating the comfort levels of pedestrian bridges subjected to human-induced vibrations. The results demonstrate that for steel box girder bridges with spans up to 20m, the natural frequency of the structure typically exceeds 3 Hz, thereby enabling the fulfillment of comfort requirements through the avoidance of resonance with critical frequencies. However, for spans exceeding 20m, where the natural frequency typically falls below 3 Hz, adherence to the linear stiffness criteria presented in this study is essential, as determined by the dynamic response limitation method. The initial assessment of comfort should be based on the natural frequency method; if the natural frequency criteria are not met, a subsequent analysis should be conducted using the dynamic response limitation method.

Keywords: Slow traffic system; Footbridge; Vibration comfort; Steel box girder; Peak acceleration; Linear stiffness

1 Introduction

With the increasing focus on both aesthetics and functionality in pedestrian bridge design, there has been a noticeable shift towards larger spans and slender, lightweight structures. Steel box-section bridges, recognized for their high flexural and torsional rigidity, have emerged as a preferred structural solution. However, as spans lengthen and structural stiffness decreases, the natural frequency of these lightweight steel box girder bridges drops, increasing the potential for human-induced resonance. This

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resonance, triggered when the bridge's natural frequency matches pedestrian footfall frequency, can generate significant vibrations that negatively impact pedestrian comfort.

Historical events such as the 1850 Angers Bridge disaster, which resulted in 200 fatalities, and the 2000 Millennium Bridge incident, where lateral vibrations caused widespread panic[1], highlight the critical importance of addressing human-induced vibrations. In response, extensive research has been conducted to understand the relationship between bridge dynamics and comfort. Bachmann[2] identified a quantitative relationship between bridge span and inherent frequency across various pedestrian bridges. Moser[3] examined human-induced vibrations on the Dowling Hall pedestrian bridge, summarizing the relationship between inherent frequency and vibration parameters. Focusing on steel box girder pedestrian bridges, Qin Ling[4] developed a model linking span-to-height ratios with peak acceleration, which is critical for assessing comfort levels. Chen Zhou[5] further explored the vibration response when a single pedestrian crosses the bridge, identifying key factors such as mass per unit length, stiffness, pacing frequency, and speed that influence pedestrian comfort. Yang Yi[6] analyzed human-induced vibrations on a large-span steel box girder pedestrian bridge, developing a tuned mass damper (TMD) system to enhance comfort. Rao Binbin[7] applied a BP neural network algorithm to model comfort, considering parameters like bending stiffness, pacing frequency, and walking speed.

Despite these studies, most efforts have focused on evaluating existing bridges or developing mitigation strategies for excessive vibrations, with limited attention to optimizing structural design parameters to enhance pedestrian comfort. This study aims to address this gap by focusing on steel box girder pedestrian bridges, analyzing the key structural and pedestrian parameters that influence comfort. By establishing quantitative relationships between factors such as bending stiffness and span, and their impact on vibrations, this study provides practical design recommendations that enhance pedestrian comfort in steel box girder pedestrian bridges.

2 Statistics and Analysis of Cross-Section Characteristics

Steel box girder pedestrian bridge is a type of girder bridge characterized by a thin-walled closed-section main girder, comprising a top plate, bottom plate, web, and stiffening ribs, as shown in Fig. 1.

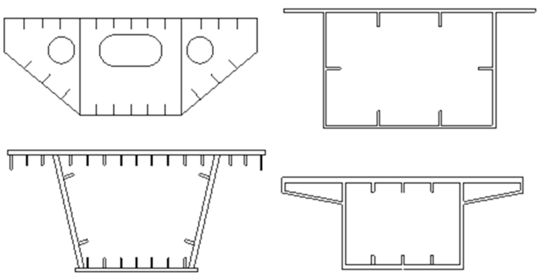

Fig. 1. Section form of steel box girder footbridge

Table 1. Moment of inertia and area of the section of the steel box girder footbridge

NO.	Bridge name	Moment of inertia of section /m^4	Area of section /m^2	NO.	Bridge name	Moment of inertia of section /m^4	Area of section /m^2
1	A long-span footbridge[9]	0.093213	0.195035	20	A footbridge in Beijing[28]	0.071746	0.179748
2	A long-span footbridge in Shen-Yan[10]	0.085157	0.163920	21	A single span simply supported steel box girder structure pedestrian bridge[29]	0.066143	0.153489
3	East of the proud walk across the street sky bridge[11]	0.100890	0.200539	22	Some long-span footbridge[30]	0.074703	0.181997
4	A pedestrian bridge on a main road in Nanjing[12]	0.053943	0.135459	23	A long-span pedestrian steel bridge in a city[31]	0.069867	0.172320
5	A steel structure footbridge in Hefei[13]	0.015561	0.124512	24	Ham Tang Hong Kong people Bridge[32]	0.017245	0.135311
6	Happiness Intersection pedestrian bridge[14]	0.015930	0.140400	25	A steel box girder footbridge in Qingdao[33]	0.056742	0.143341
7	Wuhan University of Technology No.2 pedestrian bridge[15]	0.018112	0.114682	26	A pedestrian bridge crossing a river in a residential area of Nanjing[34]	0.052768	0.170320
8	A pedestrian bridge in Nanjing[16]	0.012949	0.132320	27	A man walks on a bridge in Guang-zhou[35]	0.020467	0.116761
9	Beijing Taipingqiao Street over-pass[17]	0.100854	0.209879	28	Poluo River pedestrian landscape bridg[36]	0.089639	0.194353
10	A pedestrian bridge in Chang-sha[18]	0.022926	0.118630	29	A long-span curved footbridge[37]	0.067546	0.181555
11	A steel box girder footbridge[19]	0.032357	0.123801	30	Suzhou Industrial Park Zhongtang River landscape bridge[38]	0.016784	0.137961
12	A steel structure footbridge[20]	0.019685	0.143167	31	A long-span footbridge[39]	0.047645	0.143424
13	A rigid frame curved continuous beam footbridge with inclined legs[21]	0.080728	0.192577	32	Double river Red star gate landscape bridge[40]	0.087718	0.170892
14	A pedestrian landscape bridge in Beijing[22]	0.025514	0.138598	33	Sanjiang Bridge in Mianyang, Si-chuan [41]	0.023583	0.122130
15	Changzhou BRT Line 2 project Huaide New Bridge[23]	0.013937	0.100796	34	Akagi Yuizumi River footbridge[42]	0.053147	0.166608
16	A simple supported steel box girder footbridge[24]	0.098756	0.211284	35	Guangzhou Fangcun Huafei Road pedestrian bridge[43]	0.023697	0.148217
17	A corrugated web steel bridge[25]	0.054291	0.163477	36	Xiamen University pedestrian bridge[44]	0.061021	0.147594
18	Xiangyang City Yongan Square pedestrian bridge[26]	0.021671	0.116676	37	A steel structure footbridge[45]	0.019547	0.115062
19	A steel structure pedestrian bridge[27]	0.079787	0.190862	38	Star Harbor special shape pedestrian landscape bridge[46]	0.016975	0.143106

The mass per unit length of a bridge is related to its cross-sectional form, which in turn determines the flexural stiffness of the structure. In Table 1, the bending moments of inertia of the cross-sections of 38[8] completed steel box girder pedestrian bridges and their cross-sectional area parameters are counted.

Through the statistics and analysis of the cross-sectional dimensions of the 38 completed steel box girder pedestrian bridges in Table 1, it is found that there exists a more typical linear relationship between the cross-sectional bending moment of inertia and cross-sectional area. Based on the algorithm of linear regression method, the Origin software was used to carry out linear regression on the above statistics, and the results are shown in Fig. 2.

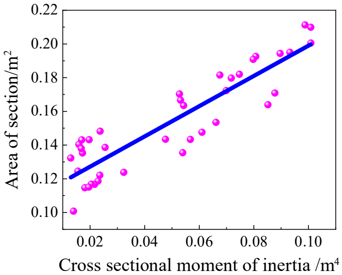

Fig. 2. Linear fitting diagram of section moment of inertia and section area

Fig. 2 reveals that, after excluding the outliers represented by bridges No. 7 and No. 15, the cross-sectional moment of inertia and cross-sectional area of the remaining bridges demonstrate a nearly linear distribution. The linear relationship between the cross-sectional area A and the cross-sectional bending moment of inertia $I_z$is represented in Equation (1).

$$A=0.89747*I_z+0.10923 \quad (1)$$

Through the statistical analysis of the design parameters of constructed steel box girder pedestrian bridges, a relationship equation between mass per unit length and flexural stiffness has been established. This equation aims to mitigate the influence of mass per unit length-identified as a sensitive parameter-on human-induced vibration comfort during the study.

3 Analysis of Anthropogenic Vibration Response of Lower Bridges

3.1 Peak Acceleration Response Analysis

According to the specification[47], the width of the footbridge should be more than 3m, with existing footbridges typically ranging from 3 to 5 meters in width. Therefore, this paper adopts a compromise by selecting 4m for analysis. The mass per unit length is expressed by the bending moment of inertia of the cross-section in Equation (1). The pedestrian pacing frequency is taken to be calculated as 1.0ω. Considering that the damping ratio of actual steel structures exhibits minimal variation, a damping ratio of

1% is used for calculations in this study. The mass of the pedestrians and the length of the pedestrian step are referred to the experimental conclusion of Chen Zhenqing[48], 65kg and 0.715m are taken to be calculated respectively. The pedestrian mass and the pedestrian step length are calculated by taking 65kg and 0.715m respectively, and the corresponding values of the test parameters are shown in Table 2.

Table 2. Parameter values

Parameter	Pedestrian frequency /Hz	Span/m	Damping ratio	Pedestrian quality /kg	Walking step length /m	Deck width /m
Value	$\frac{1.0}{2\pi}\omega_n$	20-60	0.010	65	0.715	4

Table 3. Peak acceleration response values for different spans and flexural stiffness

Test NO.	Span L /m	EI /N · m^2	Mass per square meter M/kg	Equivalent row number n	Peak Acceleration m/s²	Test NO.	Span L /m	EI /N · m^2	Mass per square meter M/kg	Equivalent row number n	Peak Acceleration m/s²
20-1	20	1.78×10^9	913	6	0.570	45-1	45	3.08×10^9	957	9	0.613
20-2		2.14×10^9	925	6	0.551	45-2		3.69×10^9	978	9	0.586
20-3		2.57×10^9	939	6	0.535	45-3		4.43×10^9	1003	9	0.554
20-4		3.08×10^9	957	6	0.518	45-4		5.32×10^9	1033	9	0.529
20-5		3.69×10^9	978	6	0.499	45-5		6.38×10^9	1069	9	0.497
20-6		4.43×10^9	1003	6	0.476	45-6		7.66×10^9	1112	9	0.475
20-7		5.32×10^9	1033	6	0.458	45-7		9.19×10^9	1164	9	0.451
20-8		6.38×10^9	1069	6	0.442	45-8		11.0×109	1227	9	0.429
35-1	35	2.57×10^9	939	8	0.596	55-1	55	4.43×10^9	1003	10	0.598
35-2		3.08×10^9	957	8	0.571	55-2		5.32×10^9	1033	10	0.560
35-3		3.69×10^9	978	8	0.543	55-3		6.38×10^9	1069	10	0.531
35-4		4.43×10^9	1003	8	0.517	55-4		7.66×10^9	1112	10	0.509
35-5		5.32×10^9	1033	8	0.488	55-5		9.19×10^9	1164	10	0.477
35-6		6.38×10^9	1069	8	0.462	55-6		11.0×10^9	1227	10	0.461
35-7		7.66×10^9	1112	8	0.447	55-7		13.2×10^9	1302	10	0.440
35-8		9.19×10^9	1164	8	0.430	55-8		15.9×10^9	1392	10	0.421

The optimal span length for simply supported steel box girders ranges from 40 m to 60 m. This study focuses on the comfort of pedestrian steel box girder bridges subjected to human-induced vibrations, specifically examining spans from 20 m to 60 m, with increments of 5 m, resulting in a total of 9 spans. For each span, 8 corresponding cross-sectional stiffness gradients were designed. To facilitate the analysis of the relationship between flexural stiffness and peak acceleration, the structural response for each span and stiffness combination was controlled to approximately 0.5 m/s². A calculation program written in Matlab was utilized to pre-calculate all test groups, with the peak acceleration responses corresponding to each sample point presented in Table 3. Due to space constraints, only the calculation results for spans of 20 m, 35 m, 45 m, and 55 m are provided.

3.2 Acceleration Response Time-Course Curve Analysis

Plotting the response time curve for all 8 bending stiffness groups within each span would result in reduced graphical clarity, making it difficult to identify trends. Therefore, in the test group, spans of 20 m, 35 m, 45 m, and 55 m were selected, and only the 1st, 4th, and 7th bending stiffness groups were analyzed for their acceleration response time curves. These are depicted in Fig. 3, where the carmine, green, and blue lines represent the 1st, 4th, and 7th bending stiffness groups, respectively, for each span.

The human bridge resonance frequency f can be calculated from Eq. (2):

$$f = \frac{L}{t \times l} \tag{2}$$

Where: L is the bridge span, t is the bridge crossing time, l is the length of the pedestrian step, which is taken as 0.715m in this study.

As can be seen from Fig. 3, when the span L=20m, the complete crossing time t of each test group is within 7 seconds, so the resonance frequency f of the bridge is ≥4.0Hz, which is much larger than the normal pedestrian pacing frequency of 3Hz. therefore, the small-span bridges of 20m and less can easily satisfy the relevant regulations of comfort.

For the bridge with span L=25~60m, it can be seen from Eq. (2) that the resonance frequency f of the bridge is 1.05Hz~2.69Hz, which is within 3Hz of the normal pedestrian pacing frequency, and it is difficult to satisfy the relevant provisions of comfort, and vibration response analysis is required.

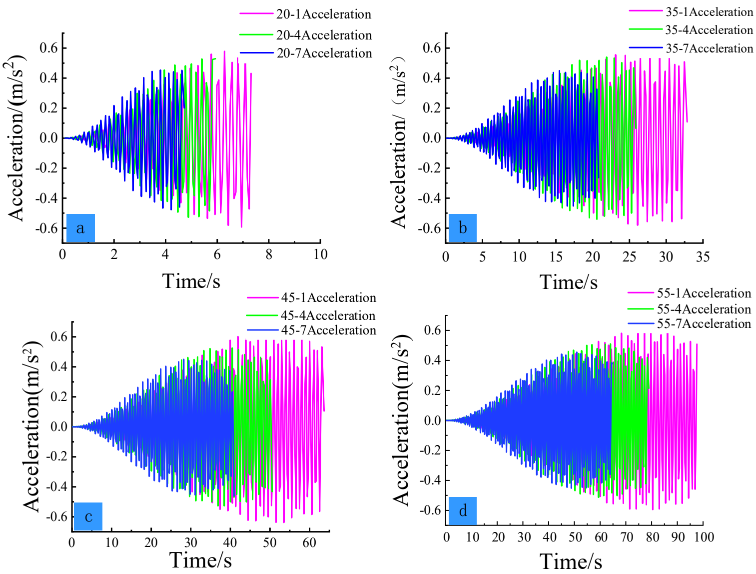

Fig. 3. Acceleration response time history curve with different spans (a) L=20m (b) L=35m (c) L=45m (d) L=55m

3.3 Analysis of Flexural Stiffness, Span and Peak Acceleration Response

The German guideline "Human Induced Vibrations of Steel Structures: Design of Footbridges - Guideline EN03"[49](referred to as EN03) specifies that a structure satisfies comfort requirements at CL1 level when its peak acceleration is below 0.5 m/s². To assess the impact of various span lengths and flexural stiffness on vibration comfort, a three-dimensional surface diagram of peak acceleration response was generated based on the calculation results from each test group in Table 3, as shown in Fig. 4.

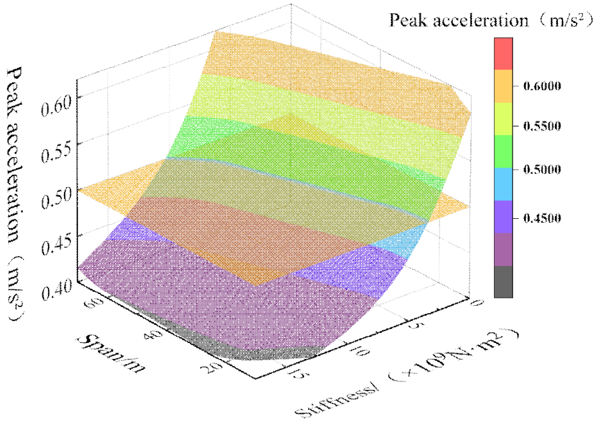

Fig. 4. 3D fitted surfaces

Fig. 4 shows that when the structural span and flexural stiffness values fall below the plane$a = a_{lim}$=0.5 m/s^2, the human-induced vibration comfort requirements are satisfied. Conversely, when these values exceed the plane $a = a_{lim}$=0.5 m/s^2, the structure fails to meet the comfort standards.

In bridge design, the span is typically considered a fixed parameter, and the bridge is designed to satisfy both load-bearing and comfort requirements by adjusting the cross-sectional size and type. The stiffness-to-span ratio, also referred to as linear stiffness iii, represents the ratio of a structure's flexural stiffness to its span, reflecting the relationship between flexural stiffness and span length. Once the linear stiffness is defined, each span corresponds to a specific flexural stiffness value. Thus, the relationship between linear stiffness and vibration comfort can be more effectively evaluated during the design stage for ensuring ergonomic comfort.

By dividing the flexural stiffness of each test group by the span length, the linear stiffness for each group is obtained. These values are then categorized into four span ranges: 20~30 m, 30~40 m, 40~50 m, and 50~60 m. Analyzing the results, the relationship between the peak acceleration response and the stiffness-to-span ratio (linear stiffness i) for simply-supported steel box girder pedestrian bridges is fitted for each span range. The resulting peak acceleration versus linear stiffness (a~i) curves are shown in Fig. 5 and Fig. 6.

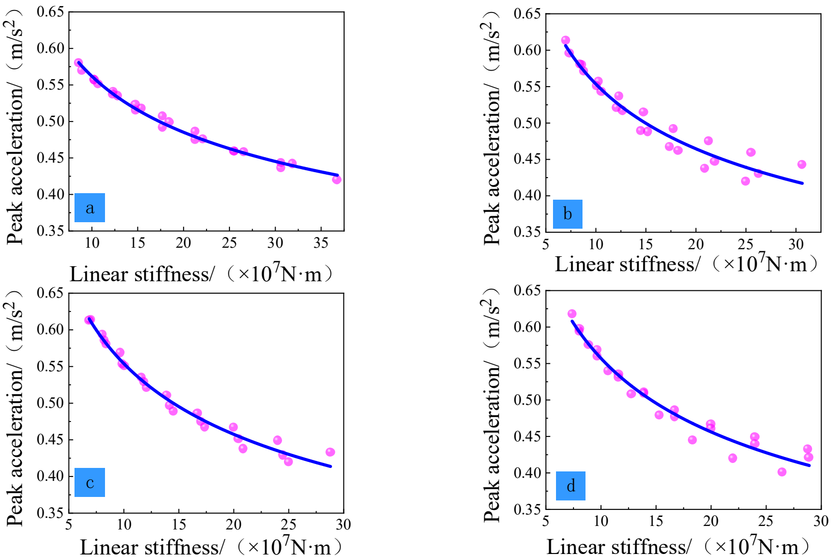

Fig. 5. Fitting curves of peak acceleration and linear stiffness under each span (a) L=20m~30m (b) L=30m~40m (c) L=40m~50m (d) L=50m~60m

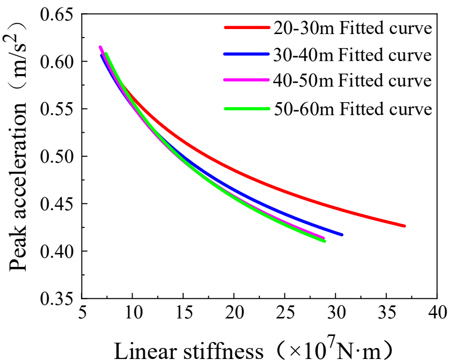

Fig. 6. Fitting curve of peak acceleration and linear stiffness

From Fig. 5 and Fig. 6, it can be observed that the *a~i* curves for the four span ranges exhibit a negative correlation between line stiffness and peak acceleration response. As the line stiffness increases, the peak acceleration response induced by vibrations decreases. This trend becomes more pronounced as the span length L increases. In general, for a simply supported steel box girder pedestrian bridge with a span length of *L*=20~60m, when the line stiffness exceeds $15\times10^7 N\cdot m^2$, the peak acceleration due to vibration remains below 0.5 m/s^2, thus satisfying the comfort requirements.

Consequently, when the bridge span *L* is fixed, the structural bending stiffness must comply with the requirements outlined in Table 4 to ensure that pedestrian bridge comfort is maintained in response to human-induced vibrations. These results provide a useful reference for the future design and assessment of comfort in pedestrian bridges.

Table 4. Value table of structural flexural stiffness

Span /m	20~30	30~40	40~50	50~60
Flexural Rigidity /$\times 10^7 \mathrm{N \cdot m^2}$	$>17.3L$	$>14.9L$	$>14.5L$	$>14.4L$

4 Proposed Methodology for Evaluating the Comfort of Pedestrian Bridges

This study proposes a method to meet the comfort requirements of human-caused vibration from the design point of view, i.e., evaluating and analyzing the structure by avoiding the sensitive frequency method and restricting the dynamic response method in turn. The method of avoiding sensitive frequency refers to limiting the inherent frequency of the bridge structure so that it falls outside the pacing frequency of pedestrians, thus avoiding resonance and meeting the comfort requirements. The method of limiting dynamic response refers to limiting the maximum vibration response of the structure by calculating its range when the inherent frequency of the structure falls within the range of the sensitive frequency, so that the structure meets the comfort requirements.

(1) The requirement that the vertical inherent frequency of the structure is greater than 3Hz put forward by our specification takes full account of the characteristics of bridge construction in the past, such as moderate span diameter and self-importance, and this requirement is widely used in the construction of bridges in China[50]. Therefore, the structural anthropogenic vibration comfort evaluation method is: first analyze the inherent frequency of the bridge structure, if the inherent frequency is greater than 3Hz, the bridge is considered to meet the comfort requirements; if the inherent frequency is less than 3Hz, and then carry out the structural vibration response analysis, and evaluate the design structure by limiting the dynamic response method, so as to make it meet the comfort requirements.

(2) For the inherent frequency is less than 3Hz need to carry out vibration response analysis of the structure, when the bridge span is determined, the structural bending stiffness to meet the structural bending stiffness table (Table 4) requirements.

(3) If the inherent frequency is less than 3Hz and the bending stiffness does not meet the requirements, the use of performance damping technology can be considered for vibration reduction design.

5 Case Study

The Beijing People's Walking Bridge[51] is a bridge over a river (Fig. 7). The bridge is a simply-supported steel box girder structure with a span of 48 m and an effective width of the bridge deck of B=4 m. The cross-section form is a single box with two chambers, with longitudinal and vertical stiffening ribs, and the material is Q235B steel. The substructure is pile-jointed single-column abutment, and the bearing is plate rubber. The mass per unit length of the pedestrian bridge is M=1145kg/m, the flexural rigidity is EI=1.33×1010 N·m2, and the specific dimensions of the cross-section are shown in Fig. 8.

Fig. 7. KY Footbridge

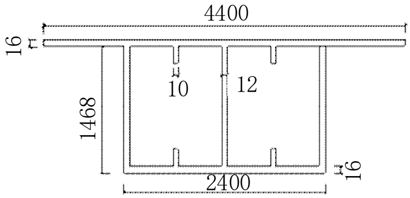

Fig. 8 Cross section of KY Footbridge (L/mm)

5.1 The Comfort Evaluation Methodology in This Study Evaluates the Comfort Level of This Bridge

(1) The inherent frequency of the bridge is f=2.32Hz, which is less than 3Hz, and structural vibration response analysis is required, which is evaluated by limiting dynamic response method.

(2) The middle span of the bridge is 48m, for 40m~50m span bridges, the bending stiffness is more than $14.5L\times10^7$ N·m^2, i.e., the bending stiffness needs to be more than 6.99×109 N·m^2. The bending stiffness of this bridge is 13.3×109 N·m^2, which is more than the recommended value, so it is judged that this bridge meets the requirements of the comfort level.

5.2 Measured Values to Evaluate the Comfort Level of This Bridge

Based on the analysis of human-induced vibrations and the corresponding measured data of the bridge as conducted by Cai-Feng Wang, it is evident that Condition 8 in the referenced literature represents the scenario in which the bridge experiences an equivalent pedestrian density of d=1.0P/m^2. Under this condition, the peak acceleration within the span is observed to be 0.44 m/s^2, which meets the established comfort level criteria.

In conclusion, the empirical data obtained from the comfort level assessment of the bridge exhibit a strong correlation with the final evaluation outcomes of this study. This consistency reinforces the validity and robustness of the proposed comfort evaluation methodology.

In contrast, the stiffness of the bridge line is calculated as $i=27.7\times10^7$ N·m. By utilizing the fitting curve between the peak acceleration and line stiffness (Fig. 6), the corresponding peak acceleration response is determined to be 0.42m/s^2. This value is lower than the threshold of0.50m/s^2 for high comfort standards and closely aligns with the measured data. This consistency further substantiates the validity of the comfort evaluation method proposed in this study.

6 Conclusion

In this study, the influence of linear stiffness of steel box girder footbridge on human-caused vibration comfort is studied, and the following conclusions are drawn:

(1) The proposed method for evaluating human-induced vibration comfort in pedestrian bridges consists of two parts: the method of avoiding sensitive frequencies and the method of limiting dynamic response. First, the inherent frequency of the bridge structure is analyzed. If the inherent frequency is greater than 3Hz, the bridge is considered to meet comfort requirements. However, if the inherent frequency is less than 3Hz, a structural vibration response analysis is required. The designed structure is then evaluated using the limiting dynamic response method to ensure it meets comfort standards, offering guidance for optimal design.

(2) For small-span bridges within 20m, the structural inherent frequency is generally greater than 3Hz, meaning the comfort requirements can be met using the method of avoiding sensitive frequencies. For steel box girder bridges with spans greater than 20m, where the inherent frequency is typically below 3Hz, the limiting dynamic response method must be applied, and the bending stiffness needs to meet the following criteria: for spans L=20m~30m, the bending stiffness $EI > 17.3L$; when L=30m~40m, $EI > 14.9L$; when L=40m~50m, $EI > 14.5L$; when L=50m~60m, $EI > 14.4L$ ($\times 10^7$N·m). These criteria serve as important reference points for designing pedestrian bridges to meet comfort requirements.

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