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Vibration response analysis of footbridge based on pedestrian perception

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Abstract

This article aims to study the influence of random crowd loading on the perceived vibration response of pedestrians. Firstly, a vertical vibration response analysis method considering pedestrian perception was established based on the random crowd walking model. Secondly, change rules of maximum vibration response of pedestrians, occurrence time and position interval under different random walk models were compared and analyzed. Finally, the vibration response reduction factor was defined by studying the correlation between the maximum vibration response of pedestrians and the peak acceleration of the structure, and the approximate calculation method of the maximum vibration response of pedestrians was proposed. The results show that the maximum acceleration perceived by pedestrians obeys the normal distribution under the four crowd walking models, the response distribution of ordered arrangement model (OAM) is larger than that of the other three models; The location and occurrence time of the maximum response depend on the distribution of pedestrian locations on the footbridge, and there is no significant change with the increase of population density. In addition, the distribution of OAM and stochastic arrival model (SAM) are consistent, which is concentrated in the middle of the total time-history. In contrast, the distribution of stochastic distribution model (SDM) and dynamic equilibrium model (DEM) are relatively uniform. The maximum error between the calculated acceleration maximum value and the actual acceleration value felt by the pedestrian is less than 5%. These results can provide reference for quantitative evaluation of pedestrian-induced vibration comfort.

Keywords: Footbridge, Stochastic walk model, Pedestrian real sense, Human-induced vibration, Reduction factor of vibration response

1 Introduction

As a carrier of pedestrian traffic, footbridges are also an important part of the urban transportation system. In recent years, with the gradual application of new materials and complex structural forms to footbridges, modern footbridges are developing in the direction of light weight, slender and beautiful, making the footbridge more sensitive to human-induced loads (Ramos M et al. 2020). When the fundamental frequency falls within the pedestrian step frequency range, it is easy to produce large vibration and affect pedestrian comfort (Pedersen L et al. 2010; Dallard P 2005). Therefore, human-induced vibration comfort is a key issue to consider in the design of footbridges. (Zhou et al. 2022a, b; Zhou et al. 2022a, b).

Many scholars have studied the vibration comfort evaluation. Chen et al. (2013) evaluated the vibration comfort of a cable-stayed bridge based on the British standard BS5400 (1979), using the method of finite element analysis and dynamic characteristics measurement. Hui et al. (2020) combined the single-degree-of-freedom human body dynamics model with the Fourier series model to generate a single-person load, and analyzed the acceleration response under three loading forms, the structural peak acceleration was used as an indicator to evaluate the vibration comfort of the steel structure corridor. Ngoan et al. (2018) suggested that the duration of vibration should be included in the evaluation criteria of comfort degree, and proposed a new evaluation framework of vibration comfort degree by combining it with conventional evaluation indexes. The above research has made a lot of contributions to the evaluation of human-induced vibration comfort. It mainly uses a representative value of the structure in the case of vibration as a comfort evaluation index, which indirectly reflects the perception of pedestrians and facilitates practical engineering applications. However, due to the randomness of pedestrian walking parameters and walking modes, the vibration response of the structure under human-induced load excitation is not a single deterministic value (Fu et al. 2022, Chen et al. 2021). At the same time, pedestrians as the most direct perceiver of vibration, it is necessary to use the actual maximum vibration response perceived by pedestrians as a reference basis for comfort evaluation. However, the maximum vibration response perceived by each pedestrian in the same operating condition is not exactly the same as the peak acceleration generated at a specific location of the structure. Therefore, taking full account of the vibration perception of all pedestrians, the comfort evaluation results should be displayed by the maximum vibration response probability actually perceived by pedestrians under random conditions.

Vibration response analysis is the key means of comfort evaluation (Liu et al. 2022; Zhou et al. 2021). Jia et al. (2020) established a vibration response calculation method based on dynamic reliability with a simply supported beam as the research object, and the response probability of the structure at any time can be obtained by probability density evolution. Caprani et al. (2012) studied the correlation curves of crowd density, synergy and amplification factor, and obtained the vibration response of footbridges under human-induced loads using probability density prediction. Cao et al. (2020) considered the human-bridge coupling effect and analyzed the effect of different crowd synergy on structural dynamic parameters by dividing the area. Zhou (2016) used the Monte Carlo method to fit the random walking load curve, and established a standard response spectrum curve model based on the vibration response simulation analysis. Wang et al. (2020) proposed a cross-power spectrum model considering pedestrian coherence by combining the coherence function between pedestrians and the single-person load power spectrum model. Chen et al. (2020) used Hilbert-Huang transform to study the vibration response of footbridge under different environmental excitations, and introduced energy entropy to describe the variation of power spectrum and energy distribution. Zhang et al. (2017) established a random load model of crowd-structure coupling based on the social force model, and analyzed the influence of pedestrian number on the modal characteristics of the coupling system. Wang et al. (2017) established four random walk models considering time–space multi-scale, and compared the variation of peak acceleration response under each model. These studies have usefully investigated the acceleration response generated by the structure under random pedestrian load excitation from different perspectives, but none of them have considered the response of the perceiver, and relevant studies on vibration response analysis for pedestrian perception are very rare.

In view of the existing problems, firstly, considering the randomness of pedestrian distribution and walking parameters, this paper studies the distribution, occurrence time and distribution position of the maximum vibration response felt by pedestrians, and compares the calculation results of different walking models. Meanwhile, the comfort probability evaluation method based on pedestrian perception is proposed. Finally, the vibration response reduction coefficient is defined by analyzing the correlation between the mid-span peak acceleration distribution and the maximum vibration response of pedestrians.

1.1 Random walk model

1.1.1 Ordered arrangement model

The ordered arrangement model (OAM) is a walking mode considering the most unfavorable situation of human-induced footbridge vibration. The crowd crosses the bridge according to a specific walking mode, as shown in Fig. 1. The model constrains the position coordinates of the pedestrians at the initial moment, the arrangement of the crowd, and the location of the walking load with time-varying effects. In the process of passing, the front row of pedestrians can adjust their pace according to their own factors and environmental conditions, and the rest of the pedestrians are constrained by the front row of pedestrians and will not overtake, and keep the same pace with the row of pedestrians, which can better reflect the crowd synergy situation.

Each pedestrian starts from the bridge end and passes the footbridge in a specific order. According to the distribution characteristics of orderly arranged crowds, it is assumed that the total number of people crossing the bridge is m, and the position of pedestrians on the bridge at time t is:

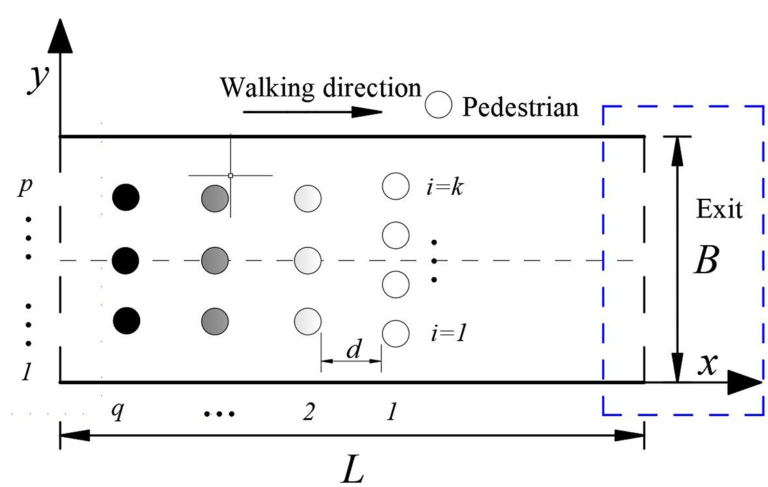

Fig. 1 Ordered arrangement model

$$\begin{cases} q = \lceil m/p \rceil \\ k = m - \lfloor m/p \rfloor p \\ x_{qi} = v_i t - (i-1)d \\ y_i = \begin{cases} Bn/(k+1)(n = 1, 2, K, k), k = 1, 2, K, P - 1 \\ \begin{cases} 0, n = 1 \\ B(n-1)/(k-1) \end{cases} \end{cases} \end{cases} \tag{1}$$

where: B is the width of footbridge; p is the total number of columns, and the value is determined by the transverse width of the bridge deck, which is taken as 3 in this paper; q is the total number of rows, when the total number of pedestrians is determined, considering the pedestrian spacing d and the number of pedestrian columns to determine the value of q; k is the number of people in the front row; x_i is the walking speed of the i-th row; y_i is the ordinate of pedestrian i at time t; x_{qi} is the position along the footbridge at time t of Row i.

1.2 Stochastic distribution model

The orderly arrangement model is a specific way of walking organized by the crowd. The pace of pedestrians is limited to a certain extent by adjacent people, and it is difficult to achieve free walking. Unlike the ordered arrangement model, the stochastic distribution mode (SDM) takes into account the differences between individual pedestrians and the uncertainty of their distribution on the bridge deck. The walking mode is unconstrained and allows free walking, which is more realistic, as shown in Fig. 2.

In order to reflect the randomness and variability of pedestrian walking parameters (Ding et al. 2012), the whole movement process of pedestrian is decomposed into finite segment superposition of each step length based on the step length superposition method (Cao et al. 2018), and the step length is randomly assigned according to the statistical law of walking parameters. The relationship between pedestrian speed and step frequency established by Reference (Fiammetta V et al. 2007) can be obtained:

$$v_{ij} = 0.175 - 0.057 f_{pij} + 0.349 f_{pij}^2 \tag{2}$$

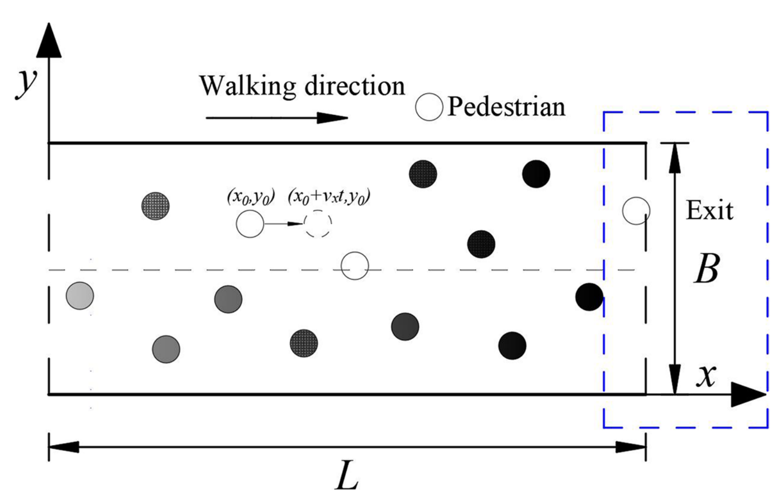

Fig. 2 Stochastic distribution model

$$t_{ij} = \frac{l_{ij}}{v_{ij}} \tag{3}$$

where: v_{ij} is the step speed of the jth step of pedestrian i; f_{pij} is the step frequency of the j-th step of pedestrian i; t_{ij} is the time required for the jth step of pedestrian i; l_{ij} is the step length of the jth step of pedestrian i. Assuming that the position of the pedestrian is constant in the y-direction during the movement, the displacement of pedestrian i on the bridge at time t is:

$$x_{ij} = \begin{cases} x_{i0} + v_{i1}t, t \le t_{i1}; \\ x_{i0} + \sum_{k=1}^{j-1} l_{ij} + v_{ij}\left(t - \sum_{k=1}^{j-1} t_{ij}\right), \sum_{k=1}^{j-1} t_{ij} < t \le \sum_{k=1}^{j} t_{ij}; \\ x_{i0} + \sum_{k=1}^{N_i} l_{ij} + v_{iN_i}\left(t - \sum_{k=1}^{N_i} t_{ij}\right), \sum_{k=1}^{N_i-1} t_{ij} < t \le \sum_{k=1}^{N_i} t_{ij}; \end{cases} \tag{4}$$

where: x_{i0} is the initial position of pedestrian i; N_i is the number of steps required for pedestrian i to travel the full distance.

1.2.1 Stochastic arrival model

The stochastic arrival model (SAM) considers the variability of pedestrians among individuals and treats footbridge crossings as Poisson events, as shown in Fig. 3. The time series of different individuals on the bridge are random variables with the same expectation and independent of each other, and the spatial location of pedestrians can be determined according to the randomly generated time variables. SAM is in a no-load state at $t=0$, and the pedestrians get on the bridge sequentially according to the randomly generated time interval, and the crowd density on the bridge gradually increases with time, which is the same as OAM.

Based on the characteristics of SAM, $x_{j,t}$ can be expressed as:

$$x_{i,t} = \begin{cases} l_{i,1}f_{pi,1}t, \tau_i \le t_{i,1} + \tau_i \\ \sum_{j=1}^{k-1} l_{i,j} + l_{j,k}f_{pi,k}\left(\sum_{j=1}^{k-1} t_{i,j}\right), \sum_{j=1}^{k-1} t_{i,j} + \tau_i < t \le \sum_{j=1}^{k} t_{i,j} + \tau_i, 1 < k \le a \\ 0,\ t > \sum_{j=1}^{a} t_{i,j} + \tau_i \end{cases} \tag{5}$$

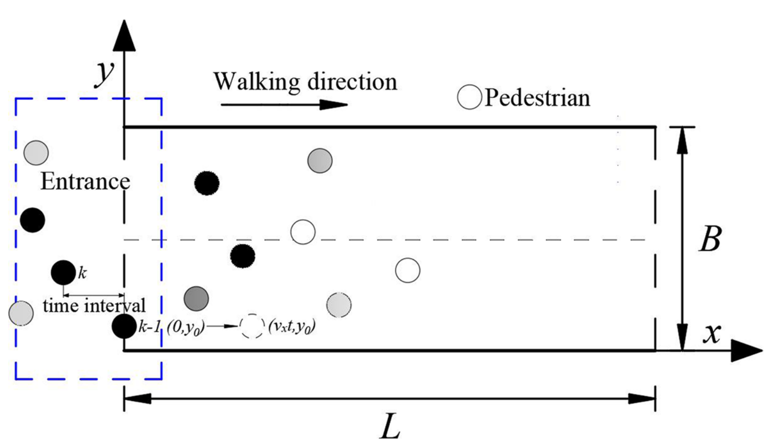

Fig. 3 Stochastic arrival model

where: τ_i is the time of the ith pedestrian on the bridge, $\tau_j = \sum_{k=1}^{j} \tau_{\Delta k}$. $\tau_{\Delta k}$ is the time interval between the k-1st person and the kth person arriving at the boundary of the bridge; $\tau_{\Delta k}$ is a random variable with mean recurrence period $\overline{\tau_\Delta} = \overline{T}/(m-1)$ and follows an exponential distribution, and $\overline{T}$ is the average time required for pedestrians to cross the bridge.

1.2.2 Dynamic equilibrium model

The dynamic equilibrium model (DEM) considers the footbridge based on SDM where the pedestrian input and output basically reach equilibrium in a specific period of time, as shown in Fig. 4. When the pedestrians reach the boundary of the lower bridge, the DEM generates a random single person load at the upper bridge at the same time to achieve a stable dynamic equilibrium process of pedestrian flow. DEM is established on the basis of SDM. The same point is that the two models have the same initial position of the crowd, that is, they are randomly distributed on the two-dimensional bridge deck; the difference is that when the pedestrian reaches the lower bridge boundary, SDM will not make corresponding feedback until the last pedestrian on the bridge reaches the lower bridge boundary, and the calculation stops.

Since the DEM and SDM initially distribute pedestrians in the same way, the position of pedestrians on the bridge at moment t can be calculated according to Eq. (4) at this time.

2 Analysis of vibration response felt by pedestrians based on random walk model

A simple-supported steel-composite footbridge was studied and modeled using ANSYS finite element software, as shown in Fig. 5. The footbridge span L = 32 m, width B = 3 m, linear density $\overline{m} = 1 \times 10^3 kg/m$, vertical no-load frequency is 2.3 Hz, and the first-order vibration type is vertical bending (Xia et al. 2022).

Based on the above four random walking models, the variation law of pedestrian vibration response under different walking modes is analyzed. The analysis process is shown in Fig. 6. Among them, the pedestrian vertical vibration response analysis method is as follows:

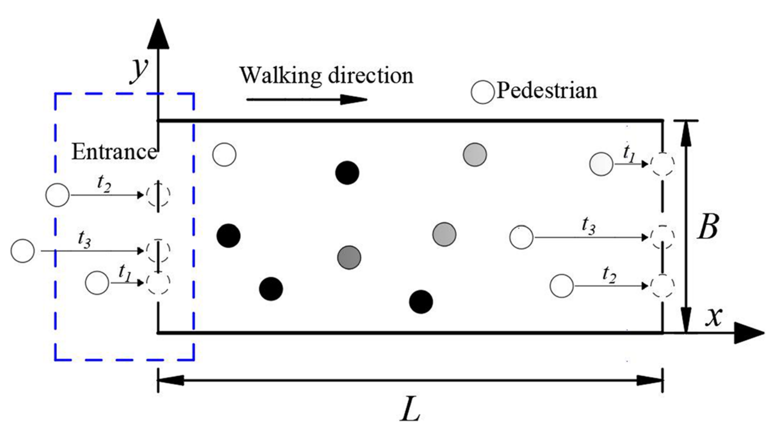

Fig. 4 Dynamic equilibrium model

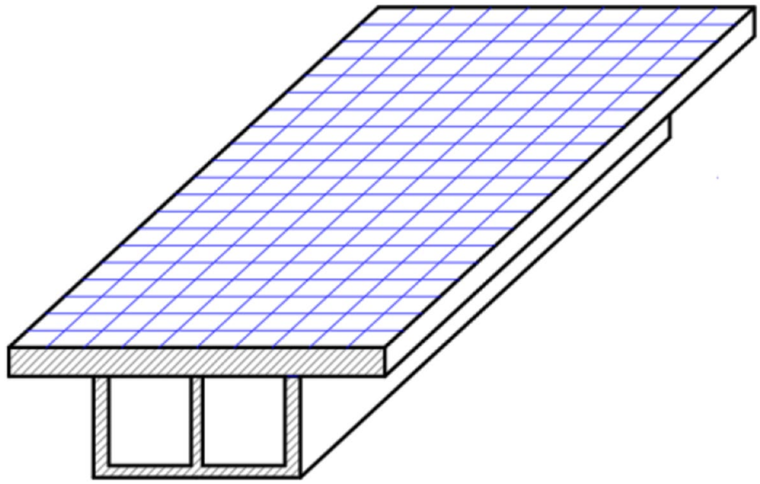

Fig. 5 Footbridge model

1) Determine the total number of people m. The value of m needs to be changed during the analysis to study the variation pattern of vibration response felt by pedestrians at different crowd densities.
2) Add the load. Pedestrian loads are generated on the bridge deck according to the random walk model characteristics, and the pedestrian walking parameters are taken as follows.
3) pedestrian step frequency. According to the analysis of a large amount of data collected in the literature (Chen et al. 2009), the pedestrian step frequency satisfies the normal distribution N (1.825,0.221).
4) Initial phase. Fully consider the randomness of pedestrian walking, no constraint is placed on the pedestrian movement on the bridge, and the initial phase is reasonably assumed to be uniformly distributed within $[0, 2\pi]$.
5) Human body weight. The human body mass obeys a normal distribution N (64.6,7.99);
6) Update the calculation time. The action points of the pedestrian walk are continuously updated as they move in time, increasing the total duration by Δt.
7) Complete the calculation. Based on the input pedestrian load parameters, the maximum acceleration at each point of the structure is calculated using ANSYS software, and the calculation stops when the last pedestrian reaches the lower bridge boundary. The time-history response curve is established by extracting the acceleration at the location of the pedestrian at moment t and processed accordingly for subsequent analysis.

2.1 OAM-based analysis of the perceived vibration response of pedestrians

In view of the walking characteristics of the OAM crowd, it is stipulated that the phase and step frequency of the same row of people are the same, and the spacing of the rows of people in the same group of working conditions is kept consistent. In order to

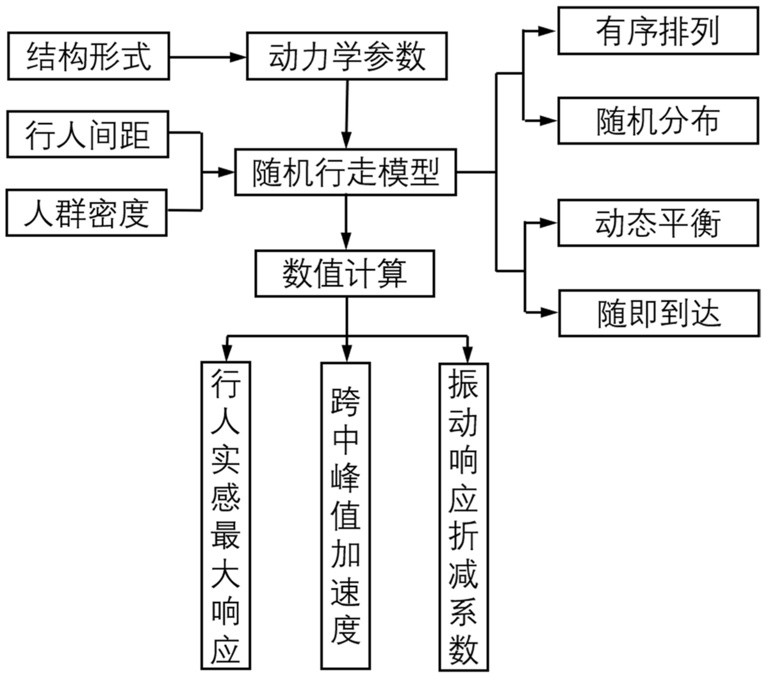

Fig. 6 Flow of analysis of vibration response felt by pedestrians

compare the maximum vibration response felt by pedestrians with the peak acceleration within the span of the structure, 100 groups of random population loads were calculated, each with a population size of m = 18 and a row spacing of [L/32, L/8], and the probability distribution of the maximum vibration response felt by pedestrians with the peak acceleration within the span of the structure was obtained, as shown in Fig. 7.

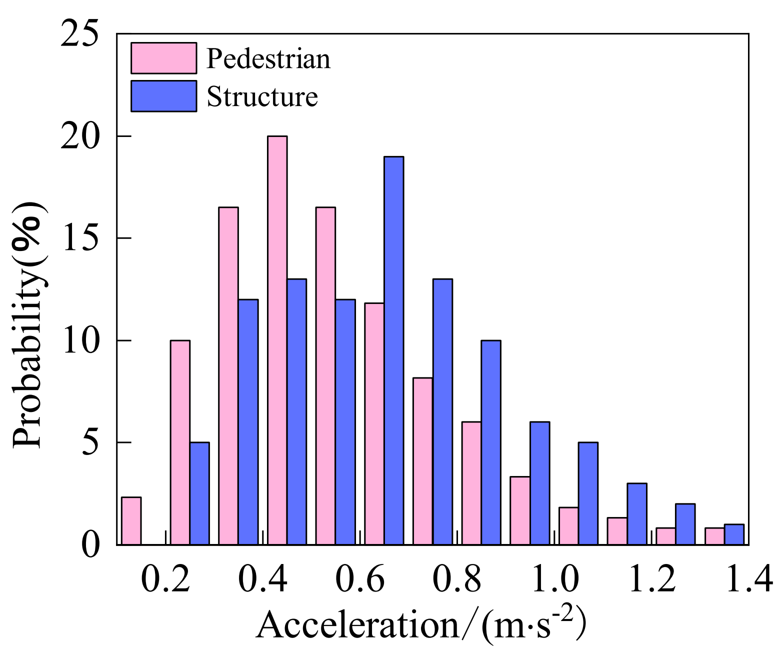

Fig. 7 Acceleration probability distribution of pedestrian real sense and Structure

From Fig. 7, it can be seen that the maximum vibration response felt by pedestrians follows a normal distribution N (0.540,0.2392) with a value range of [0.1,1.4], which is overall smaller than the peak acceleration in the span of the structure.

To study the changes in the number of pedestrians and row spacing on the distribution of pedestrians' standing position when they feel the maximum vibration response, the bridge span is subdivided into 7 areas by equal distance, and the number of crowd m is 9 and 18, while the row spacing is L/32, L/16, L/12 and L/8 for 100 groups of working conditions, and the human-induced vibration is calculated. The stationing distribution of pedestrians when they feel the maximum vibration response is shown in Fig. 8. From Fig. 8, it can be seen that the pedestrian stationing positions are distributed on intervals 4, 5, and 6 for different pedestrian numbers and row spacing, with interval 5 accounting for the largest percentage and the percentage of the number of people staying in the other intervals tending to be close to 0. In addition, the distribution pattern of pedestrians in different row spacing is basically the same for the same number of pedestrians, but as the number of pedestrians increases, the percentage of interval 5 decreases and shifts to both sides. The distribution pattern of pedestrians in different row spacing with the same number of pedestrians is basically the same.

Due to the random nature of the pedestrian distribution method, the total analysis time T is not the same for different working conditions, and it is not comparable to describe when the pedestrian feels the maximum vibration response using the physical quantity of the moment of emergence. To facilitate the comparison between the results, the moment when the pedestrian feels the maximum vibration response is transformed into the proportion of that moment to the total duration by normalization. The emergence moment of the maximum acceleration felt by the pedestrians is recorded as t_{amax}, and the distribution of the emergence moments of the maximum response of pedestrian perception under different row spacing is shown in Fig. 9. From Fig. 9, it can be seen that the moments of maximum response are mainly distributed in the interval of [0.4 T,0.8 T], and the moments are concentrated in the middle region as the row spacing decreases. The main reason is that all rows of pedestrians in the OAM have the same pace and better synergy, and the spacing is small enough to be considered as a single load (Yuan 2006), while the middle of the bridge is the most unfavorable location for the load, and the vibration response felt by the pedestrians is the largest when they reach this location.

Figure 10 shows the comparison of the occurrence moments of structure and pedestrian perceived maximum acceleration. It can be observed that 25% ~ 75% of the data volume is mostly distributed below "1", and the mean and median are less than "1". This indicates that the moment of maximum vibration response perceived by pedestrians mostly occurs before the peak acceleration is generated in the span, and the maximum response perceived by some pedestrians is "synchronized" with the time of peak acceleration generated by the structure. As the distance and number of pedestrians increase, the maximum and minimum limits expand and the volume of the box tends to increase towards the lower part of "1", which is due to the gradual dispersion of the pedestrian distribution on the bridge, resulting in a decrease in the number of "synchronized" responses and an advance in the moment when the maximum response is perceived by the pedestrians in the front row.

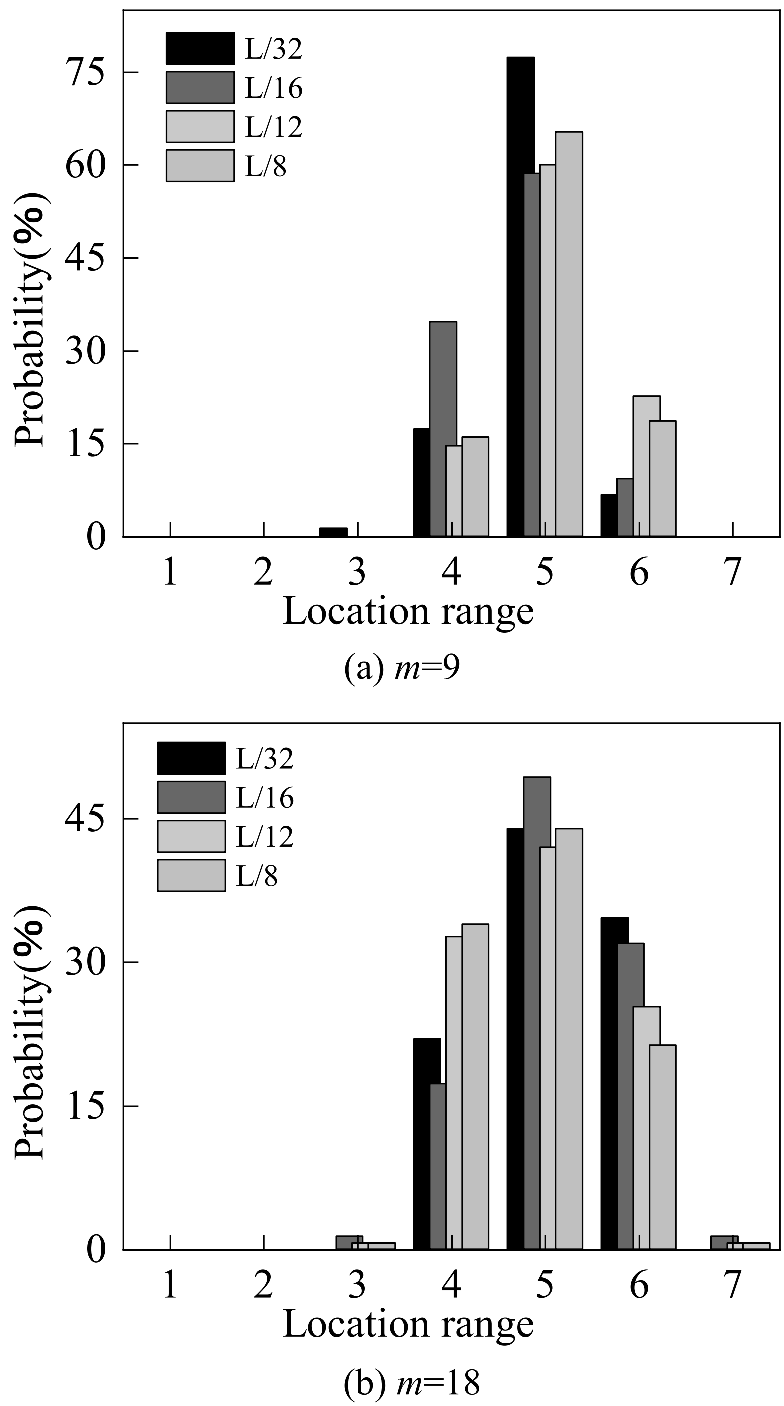

Fig. 8 Location interval distribution of the maximum response felt by pedestrians

2.2 SDM-based realistic vibration response analysis of pedestrians

Based on the SDM, taking $m = 18$, the probability distribution of the maximum vibration response of pedestrian and the mid-span peak acceleration of the structure is shown in Fig. 11. It can be seen that the maximum response of pedestrian in SDM obeys normal distribution N $(0.305,0.132^2)$, and the range of value is wider than that

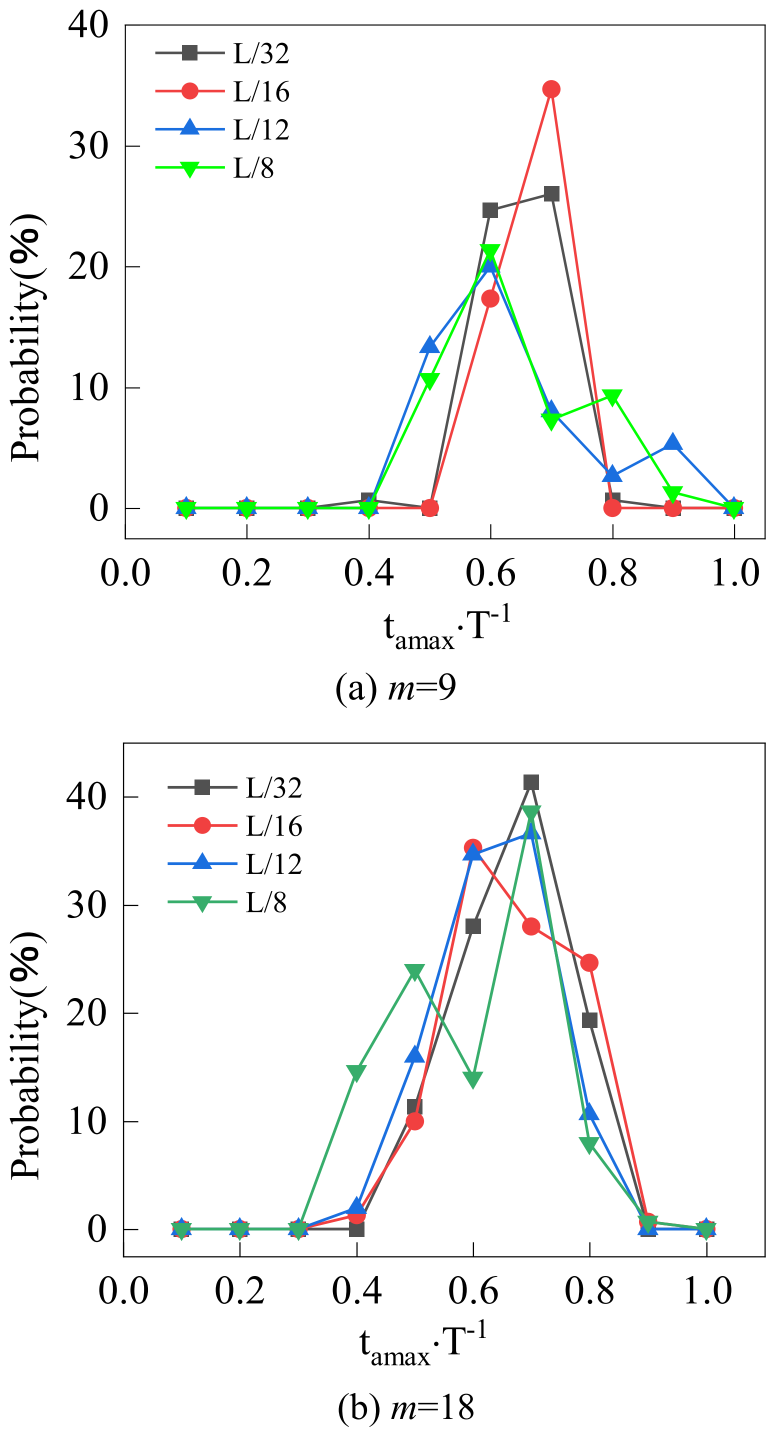

Fig. 9 Distribution of the emergence moments of the maximum response of pedestrian perception

of mid-span peak acceleration, but the mean value is still smaller than that of mid-span peak acceleration.

The location distribution of the perceived maximum acceleration of pedestrians in SDM for different crowd density cases is shown in Fig. 12. As can be seen from Fig. 12,

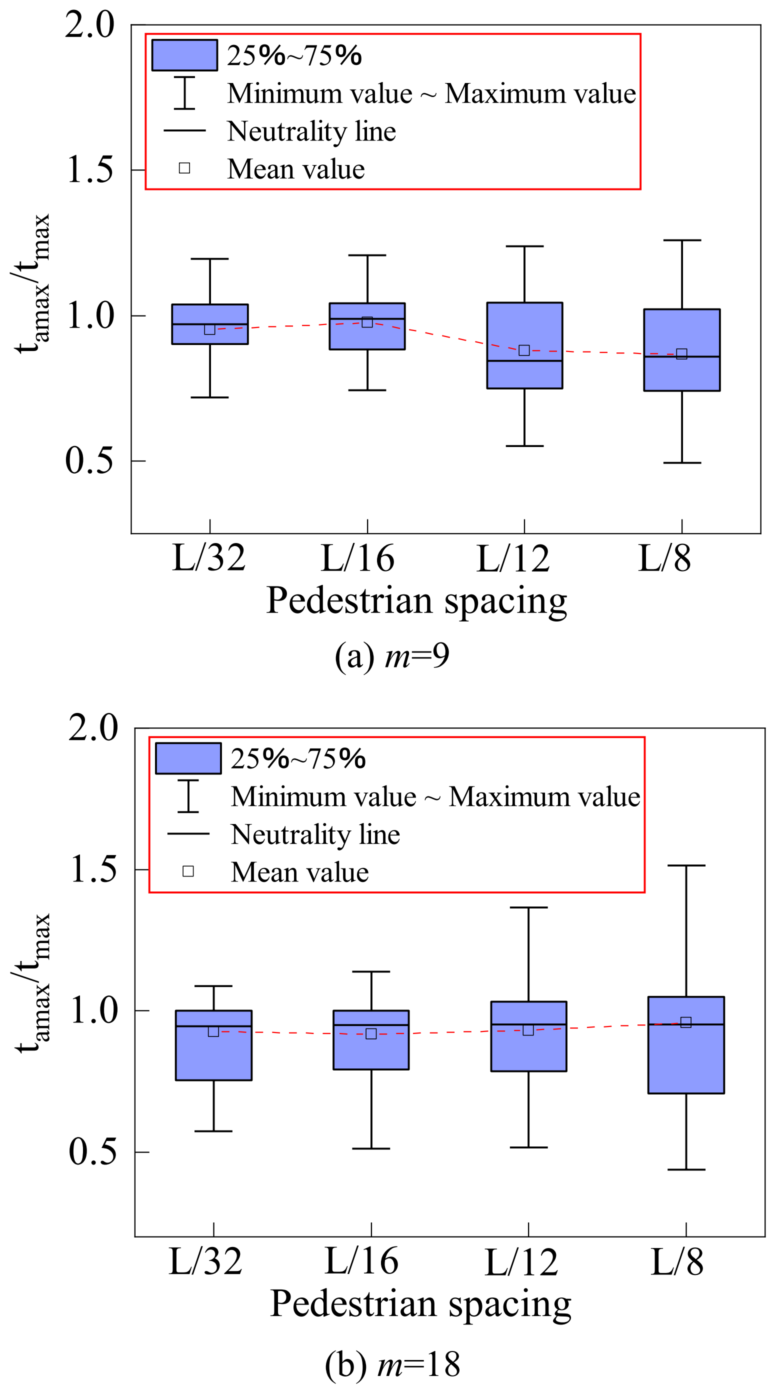

Fig. 10 Comparison of the moments of peak acceleration

the location distribution patterns of the three crowd densities are basically the same, and pedestrians are mainly concentrated in the latter half of the bridge span, accounting for more than 80% of the total number of pedestrians, with the largest percentage of pedestrians in interval 7. Figure 13 shows the distribution of the occurrence time of the maximum response of the pedestrian in SDM. It can be seen from Fig. 13 that the

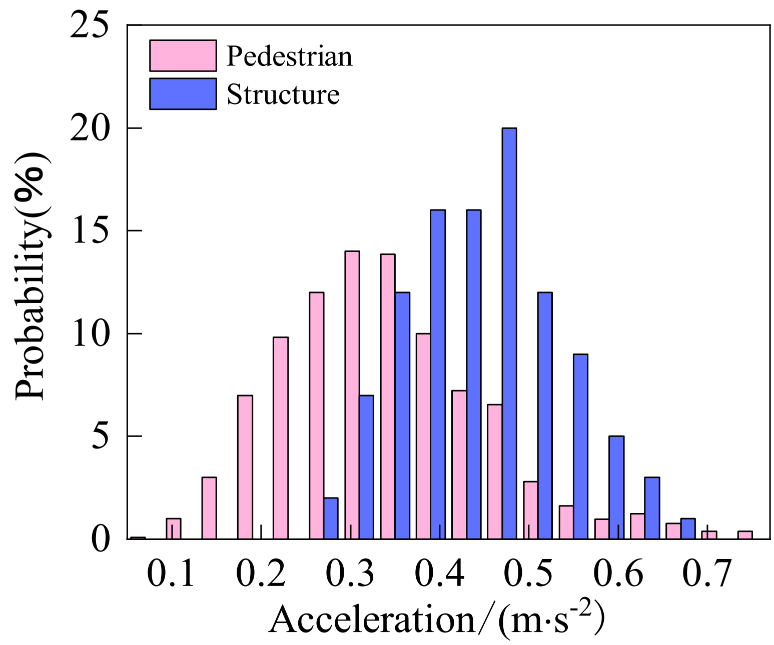

Fig. 11 Probability distribution of pedestrian's maximum vibration response and peak acceleration of structure

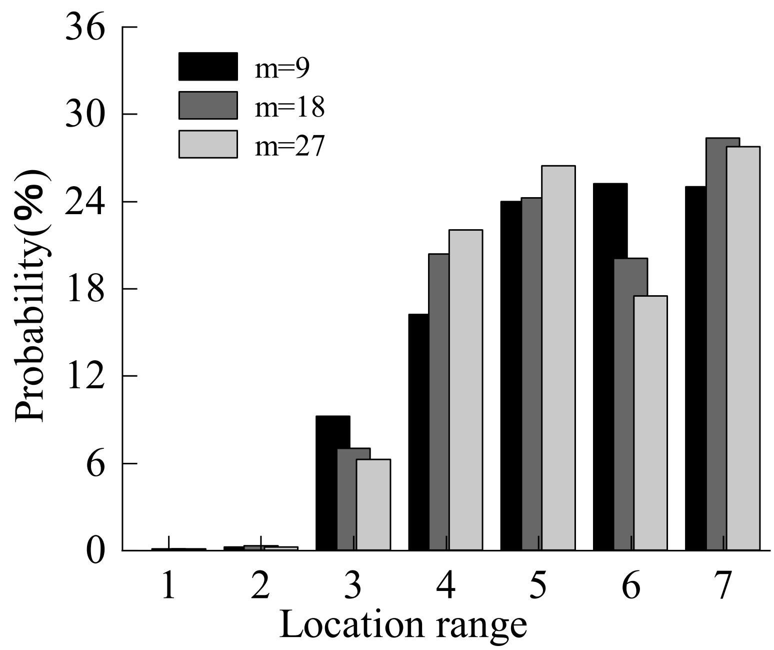

Fig. 12 Interval distribution of pedestrian maximum response position

maximum response corresponding to the three pedestrian numbers has the largest proportion in the [0, 0.1 T] interval, which is 42.1%, 33.6% and 28.9% respectively, indicating that most pedestrians have felt the maximum vibration response at the beginning of the total human-induced vibration time course. The proportion of this interval in the total sample gradually decreases as the maximum response occurrence moment is delayed.

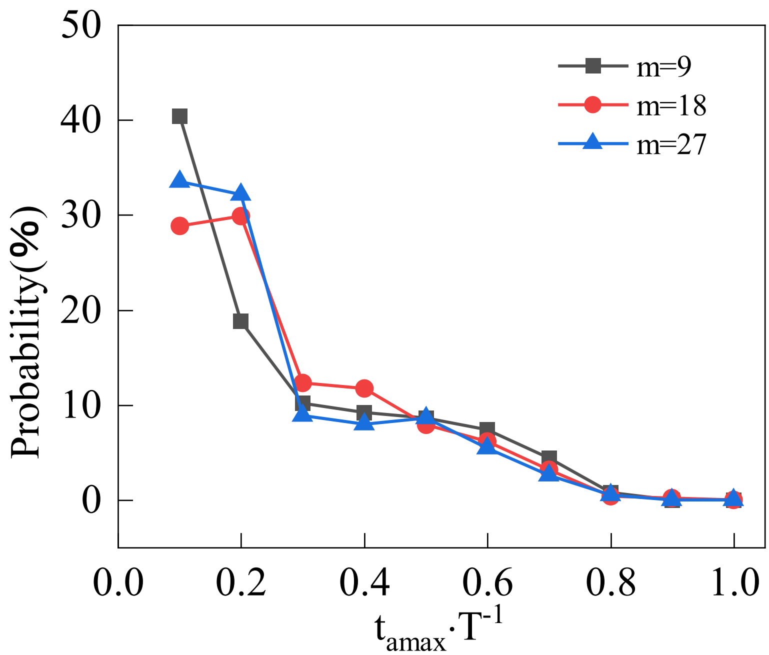

Fig. 13 Time distribution of pedestrian maximum response

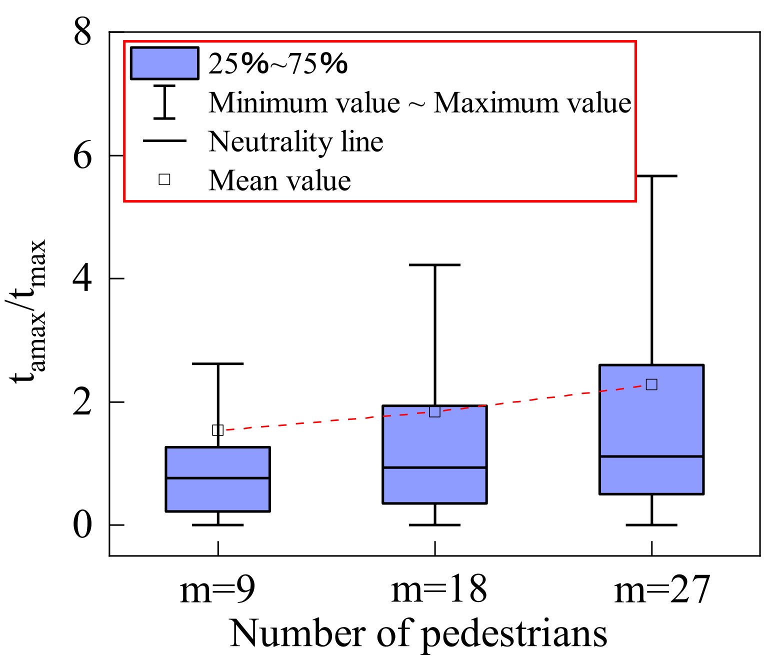

Fig. 14 Comparison of pedestrian reality and mid-span peak time of structure

The comparison of the occurrence times of the peak acceleration of pedestrians and structures is shown in Fig. 14. It can be seen that the average value of the time comparison in the three cases is greater than "1". As the number of pedestrians increases, the maximum, mean, and median lines show an increasing trend, and the number of pedestrians who perceive the maximum vibration response after the structure generates peak acceleration increases, which is contrary to the OAM situation.

2.3 SAM-based realistic vibration response analysis of pedestrians

Based on SAM, the pedestrian on the bridge is regarded as a Poisson event. The acceleration probability distribution is shown in the Fig. when the number of pedestrians $m = 18$. It can be seen from Fig. 15 that the maximum response of the pedestrian is approximately subject to the normal distribution N (0.271, 0.118^2). The range interval is [0.05,0.68], which is 0.121 m/s^2 different from the average peak acceleration of the structure.

Correspondingly, the location distribution of pedestrian perceived maximum vibration response of SAM is shown in Fig. 16. The distribution of the number of people is similar to that of OAM. Under the three population densities, the number of pedestrians staying in interval 5 is the most, accounting for 43.1%, 46.3% and 39.3% of the total number of people respectively.

Figure 17 shows the distribution of the appearance time of the maximum acceleration response of the SAM. It can be seen from the diagram that compared with OAM and SDM, the distribution of the appearance time of the maximum response of SAM is relatively uniform, mainly distributed in [0.4 T, 0.8 T]. The reason can be combined with the position distribution of pedestrians at the maximum response time. Under SAM, the crowd enters from the upper bridge end, and most pedestrians feel the maximum acceleration in the middle section of the bridge span, that is, the middle period of the total time history.

The comparison of peak acceleration between pedestrian and structure is shown in Fig. 18. As can be seen from Fig. 18, the same pattern is observed for the three population densities. Within the total analysis time, 25%-75% of the data volume at the moment

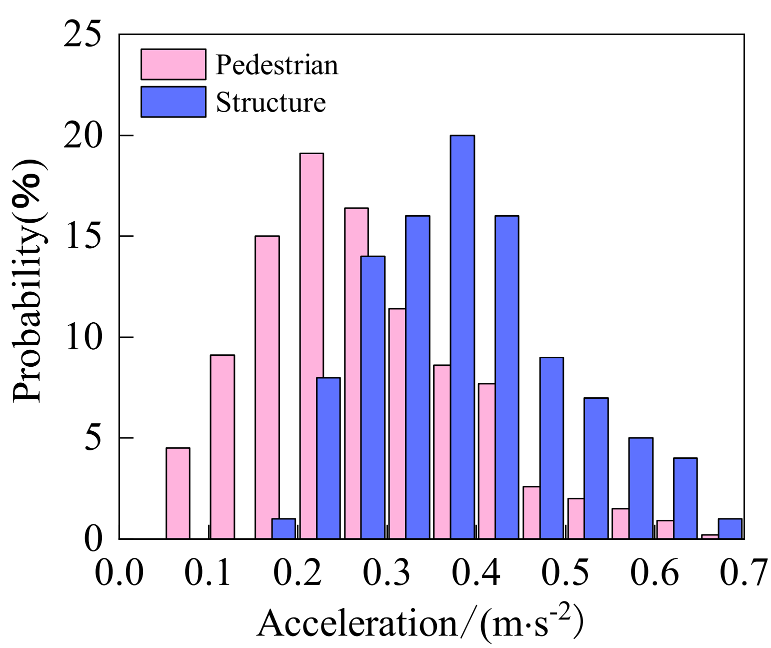

Fig. 15 Probability distribution of acceleration

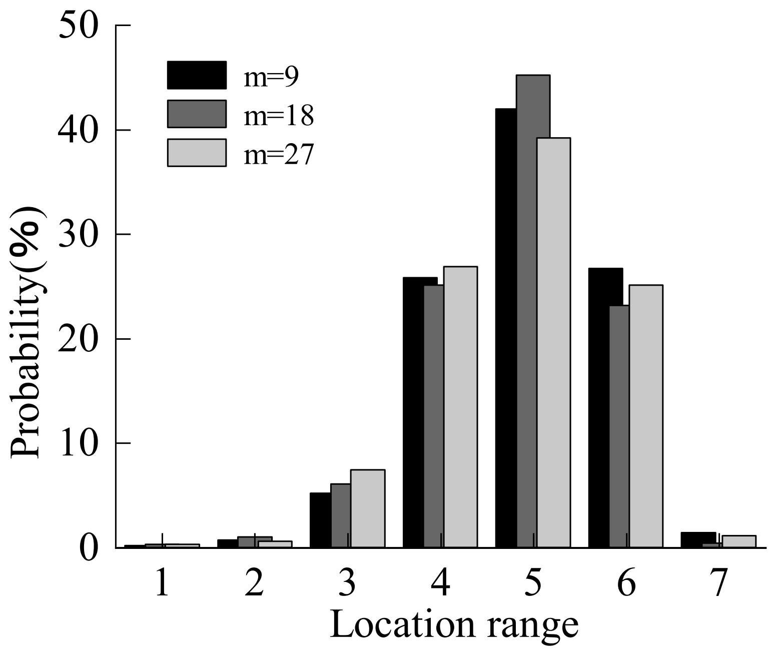

Fig. 16 Position distribution of pedestrian maximum acceleration response

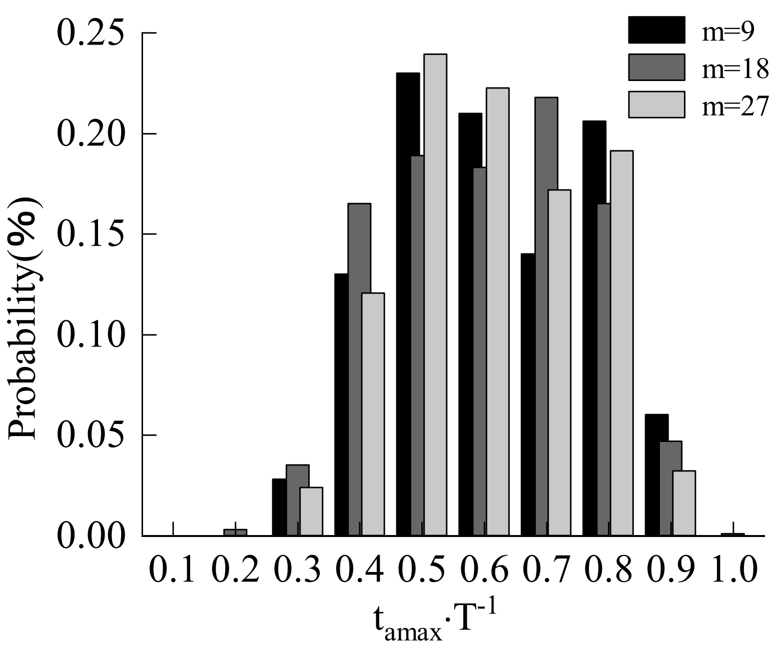

Fig. 17 Time distribution of pedestrian maximum acceleration response

of maximum response felt by pedestrians is before the peak acceleration of the structure, and the median, mean value is around "1". In general, the maximum pedestrian response and the peak acceleration of the structure basically maintain 'synchronous response'. In addition, the multiplicative difference between the maximum response felt by some pedestrians and the appearance moment of the structure peak response is due to the fact that the moment of appearance of the structure peak response of SAM is

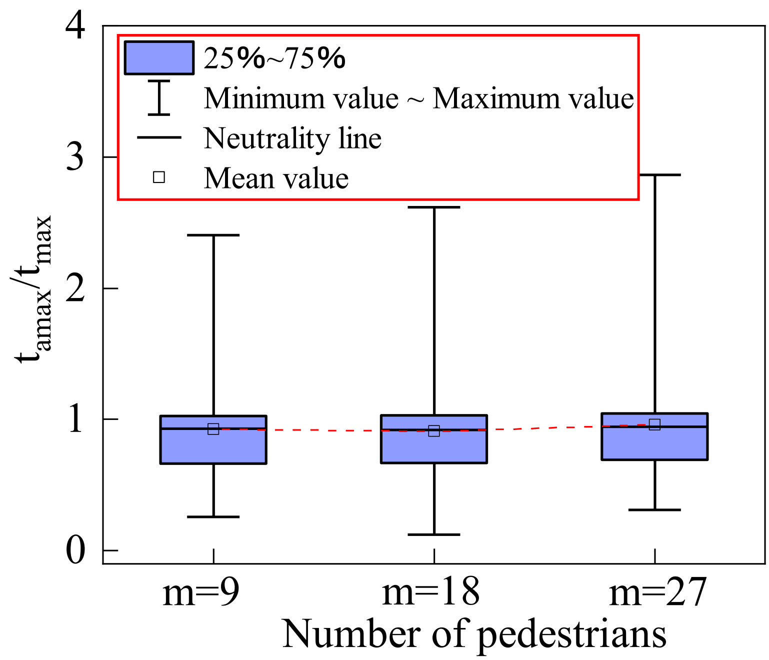

Fig. 18 Comparison of peak acceleration time

mostly concentrated in the middle of the total time course, and the pedestrians located at the front of the footbridge and the rear of the upper bridge fail to synchronize with the structure span peak response.

2.4 DEM-based realistic vibration response analysis of pedestrians

According to the DEM for crowd loading, if the number of stable people on the footbridge $m = 18$ and one dynamic balancing process is considered, the total number of people in a single analysis is 36, so as to achieve the balance of input and output, and so on for the other numbers. The peak acceleration response distribution of the stable number of 18 is shown in Fig. 19. It can be seen that the maximum vibration response of the pedestrian sense of the DEM obeys the normal distribution N $(0.360, 0.153^2)$, which is wider than the SAM distribution. The mean difference between the pedestrian-perceived vibration response and the peak acceleration of the structure is significant, with the mean peak acceleration of the structure being about 1.5 times higher than that perceived by the pedestrian.

The location distribution of the maximum acceleration perceived by pedestrians is shown in Fig. 20. It can be seen that the position of the maximum response is basically distributed in the whole span of the footbridge, and the proportion of the interval increases first and then decreases. Among them, the proportion of interval 5 is the largest, and the proportion of the three population densities exceeds 30%. Figure 21 shows the distribution of the emergence moments of the maximum acceleration perceived by pedestrians. The moments of maximum response appear mostly concentrated in the early part of the total time course, the frequency of each lower interval [0,0.1 T] accounted for 52.1%, 32.5% and 30.8% of the total sample, mainly because SDM has reached the maximum number of bridge deck at the moment of $t = 0$. Unlike OAM

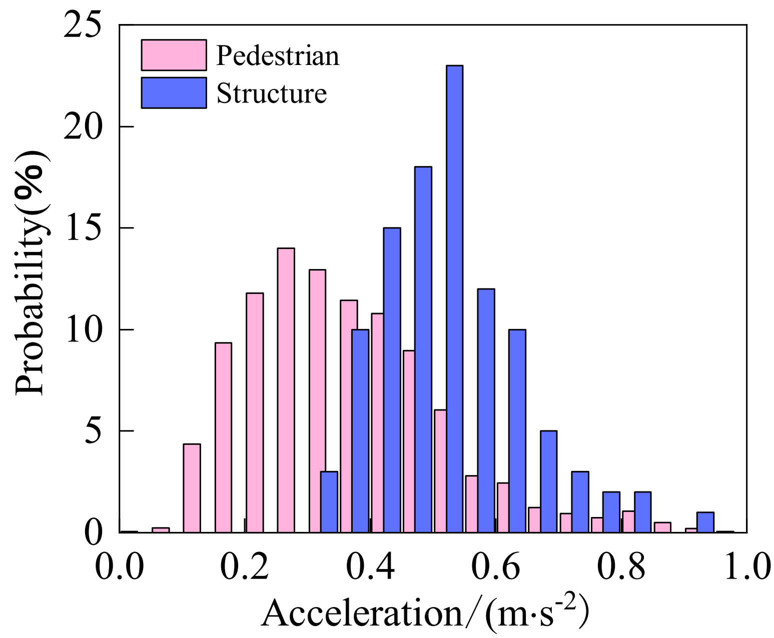

Fig. 19 Acceleration probability distribution

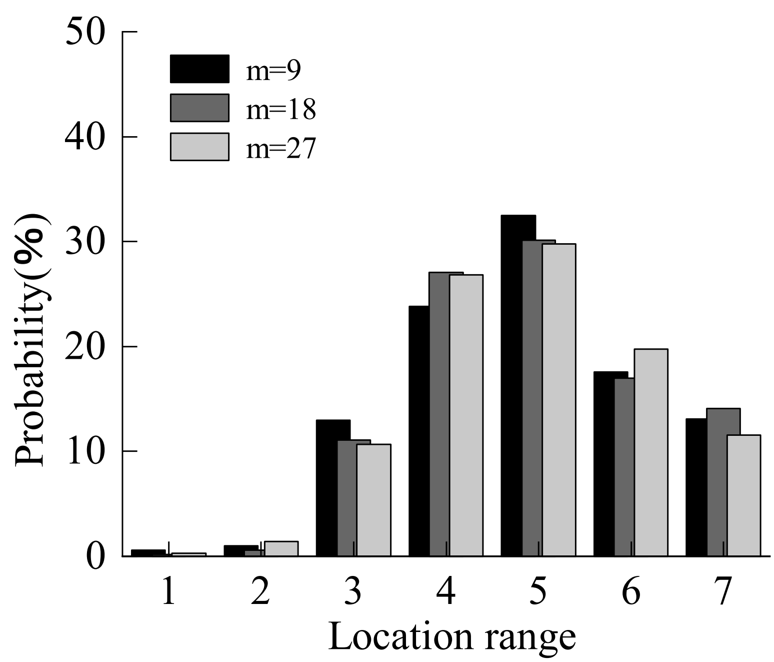

Fig. 20 Location distribution of pedestrian maximum response

and SAM, the structure has been able to produce peak acceleration in the early period, and the chance of maximum vibration response felt by pedestrians on the bridge has increased significantly at this time.

Comparison of the moments of peak acceleration is shown in Fig. 22. As can be seen in the Fig., the median line is below "1", indicating that more than half of the

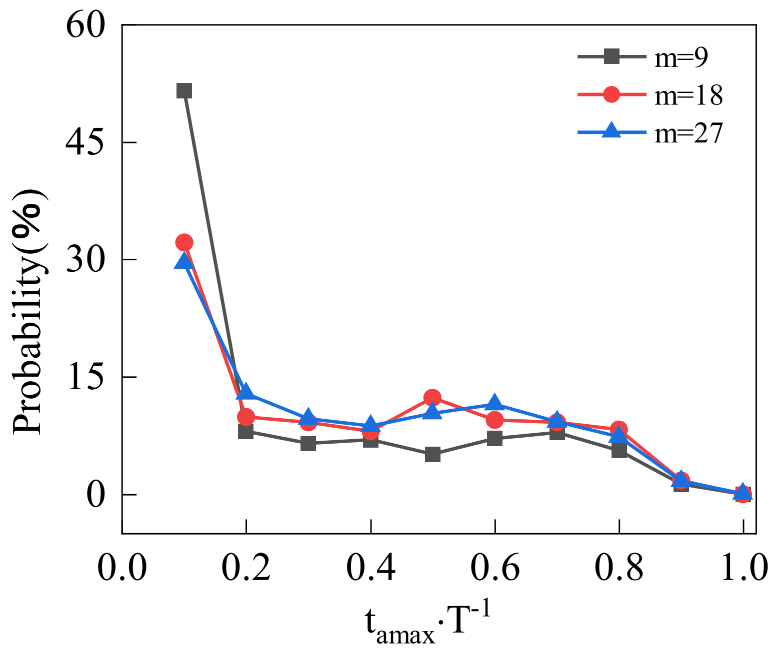

Fig. 21 ime distribution of pedestrian maximum acceleration response

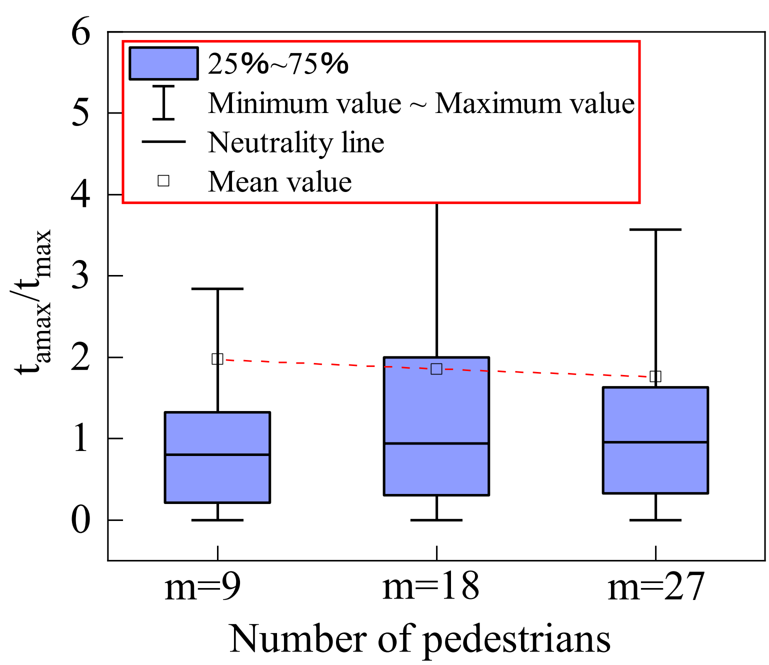

Fig. 22 Peak acceleration time comparison

pedestrians felt the maximum vibration response before the peak acceleration of the structure, but the mean value is around "2". This is due to the fact that the peak response of the structure is generated in the middle to early part of the total analysis time, while the pedestrians at the end of the bridge in the SDM model feel the maximum vibration response later, resulting in a larger mean value overall.

2.5 Comparative discussion

In order to further analyze the characteristics of the four models and their differences, $m = 18$ as an example, the following discussion:

(1) Pedestrian realistic maximum vibration response: The comparison results of pedestrian realistic vibration responses under the four random walking models are shown in Fig. 23. It can be seen that due to the consideration of pedestrian synergy, OAM is significantly larger than the other three models in terms of range and mean value, while SDM and SAM are basically the same, slightly smaller than DEM. The mean values of the maximum realistic acceleration of the four models are 0.540 m/s^2,0.305 m/s^2,0.271 m/s^2 and 0.363 m/s^2, respectively.

(2) Pedestrian real maximum response position distribution: The comparison results of the maximum vibration response position are shown in Fig. 24. It can be seen that the position distribution of the four types of models is mainly in the middle of the bridge span. SDM and DEM have pedestrians on the bridge deck at $t = 0$, and some pedestrians feel the maximum vibration response in interval 7, which is more uniform than the other two models. The distribution of SAM and OAM is basically the same. The proportion of residents in interval 5 is the largest, accounting for 45% of the total sample, which is 15.3% and 22.4% higher than that of SDM and DEM respectively.

(3) Comparison of pedestrian sense and peak response of footbridge: The comparison of t_{amx}/t_{max} of different models is shown in Fig. 25. The mean value and range of OAM and SAM are the same, while SDM is similar to DEM. It can be seen that the distribution characteristics mainly depend on the walking mode of pedestrians. In

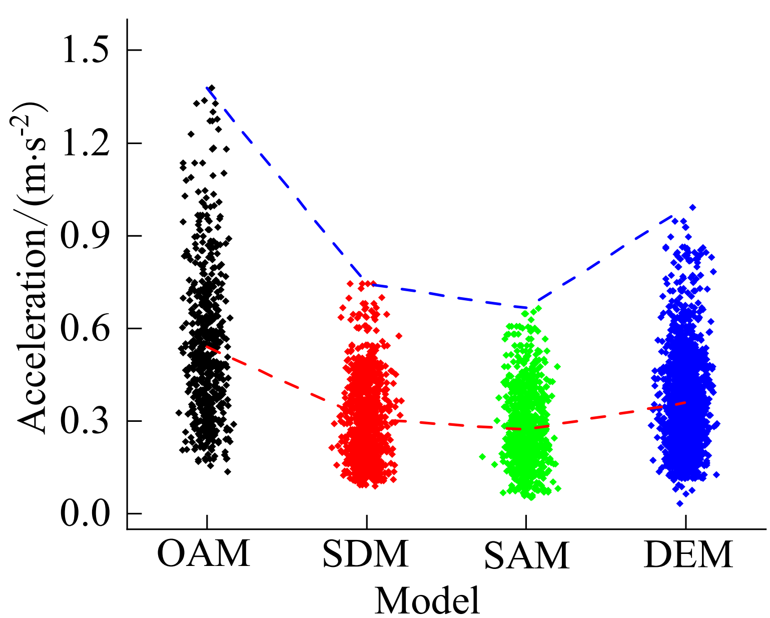

Fig. 23 Comparison of pedestrian maximum vibration responses of different models

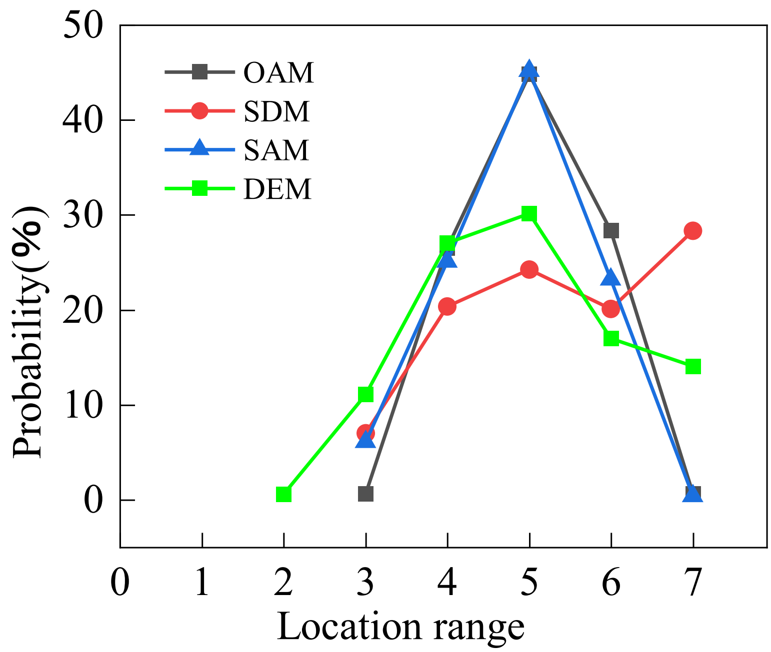

Fig. 24 Comparison of location distribution of maximum vibration response of different models

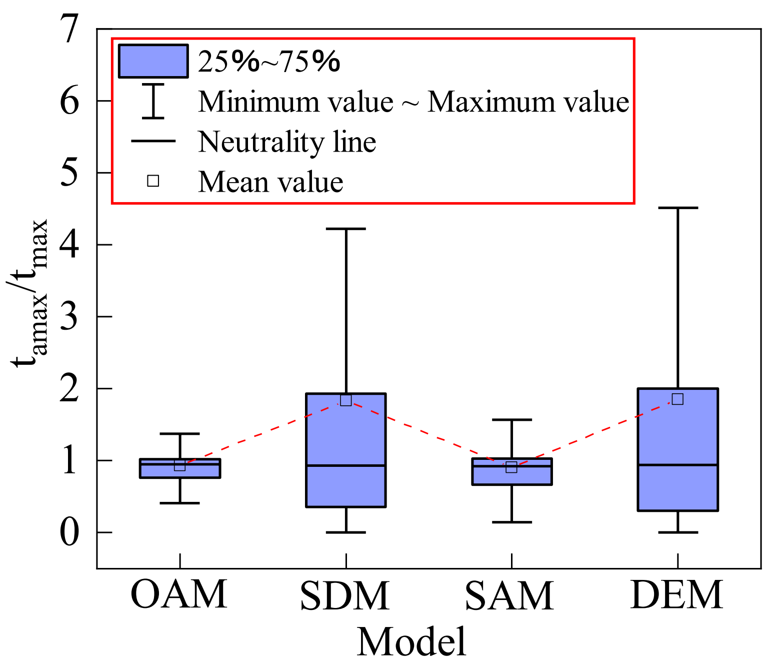

Fig. 25 Comparison of t_{amx}/t_{max} of different models

addition, the probability of "synchronous response" of SDM and DEM is significantly lower than that of OAM and SAM. Although the median line is at the same level, the distribution of the ratio of occurrence time is more discrete, and the mean value is twice that of the other two models.

3 Probabilistic analysis of comfort based on pedestrian perception

In order to further analyze the errors of the pedestrian maximum vibration response and the mid-span peak acceleraion of the structure as the basis for comfort evaluation, the OAM and SAM are taken as examples to carry out the probabilistic comfort evaluation. The cumulative probability distribution of the maximum vibration response of the pedestrian sense and the peak acceleration of the mid-span of the structure is shown in Fig. 26. It can be seen from Fig. 26 that when the comfort evaluation is carried out with the cumulative probability exceeding the comfort limit, according to the recommendation of the literature (Feng et al. 2013), the acceleration limit is taken $a_{max} = 0.35mgs^{-2}$. The cumulative probability of OAM based on pedestrian sense and mid-span of the structure is 66.2% and 83.0%, respectively, and the SAM is 23.5% and 36.3%, respectively. The comfort evaluation results of different indicators vary greatly, and the maximum error of cumulative probability exceeds 25%. Although the limits recommended by different specifications are different, regardless of how to select the limits, the comfort level of pedestrian acceleration is obviously improved, and it shows that the comfort evaluation results based on mid-span peak acceleration are too conservative.

The maximum response of pedestrian reality is used as the comfort evaluation index, which undoubtedly promotes the development of comfort evaluation to a more refined direction. However, there is a disadvantage at the same time. It is necessary to extract the response time history of pedestrian reality. For the comfort evaluation of random crowds with multiple working conditions, the task is large (Li et al. 2022). To solve this problem, this paper adopts the numerical analysis method, by fitting the probability distribution curve of pedestrian maximum real response and mid-span peak acceleration, to obtain the relative relationship between the two, so as to derive the cumulative probability distribution of pedestrian maximum real response according to the mid-span peak acceleration for comfort evaluation. From the above analysis, it can be seen that the maximum vibration response and mid-span peak acceleration of pedestrians obey the normal distribution. Therefore, "φ", "a" are defined as the vibration response reduction factor in this paper. The expression is:

$$\varphi = \frac{\mu(a_{tmax})}{\mu(a_{tmax})} \tag{6}$$

$$a = \frac{\sigma(a_{tmax})}{\sigma(a_{tmax})} \tag{7}$$

In the formula: $\mu(a_{tmax})$, $\sigma(a_{tmax})$ is the mean and standard deviation of the maximum vibration response of the pedestrian, and $\mu(a_{max})$, $\sigma(a_{max})$ is the mean value of the mid-span peak acceleration.

The mean acceleration, standard deviation and vibration response reduction coefficient of each walking mode are obtained by fitting, as shown in Table 1. It can be seen from Table 1 that the range of vibration response reduction coefficients φ and a under different walking modes is [0.65–0.75] and [0.90–1.30], respectively.

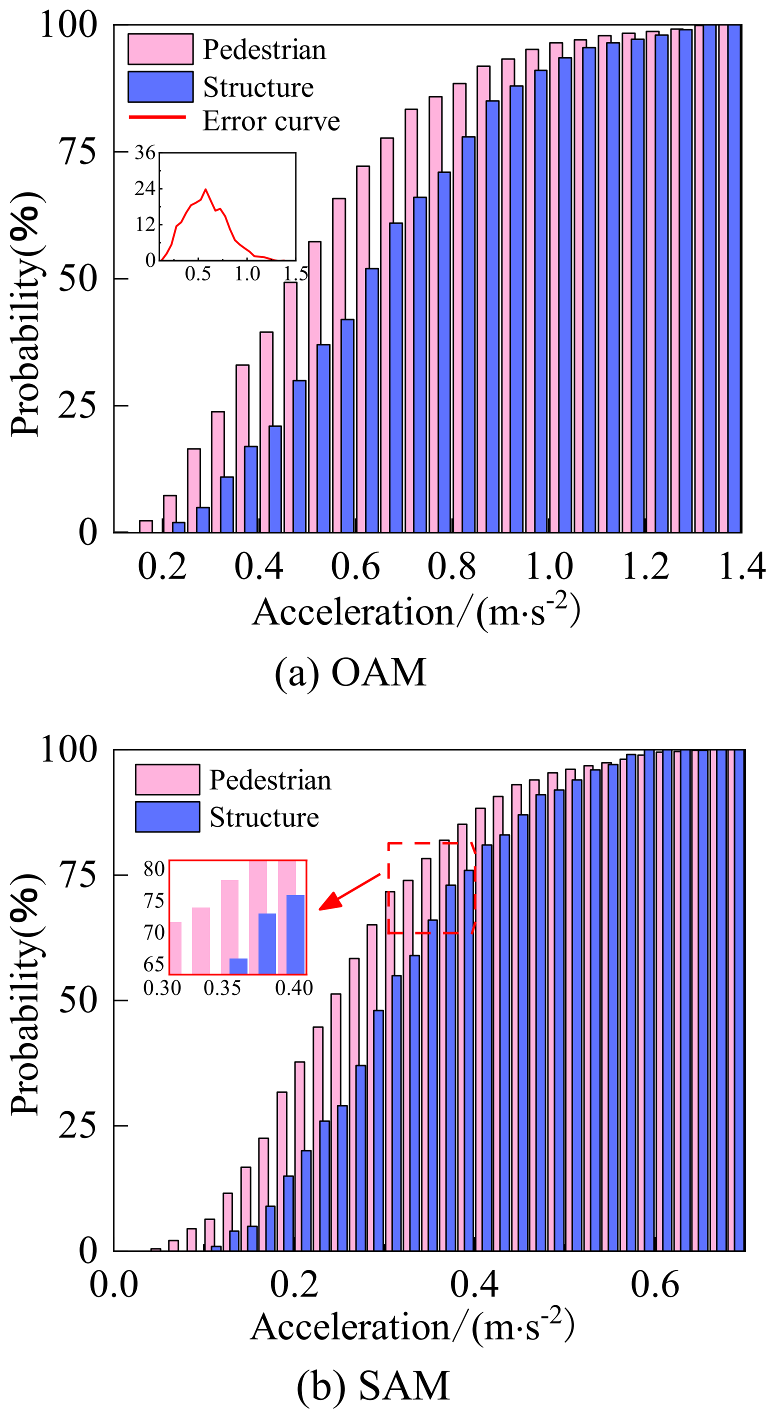

Fig. 26 Cumulative probability distribution of pedestrian maximum acceleration

Table 1 Response distribution parameters and vibration response reduction coefficient statistics

working condition		Pedestrian real maximum vibration response/(mgs^{-2})		Structural mid-span peak acceleration/(mgs^{-2})		Vibration response reduction factor	
		mean value	standard deviation	mean value	standard deviation	φ	a
OAM	9	0.401	0.276	0.541	0.308	0.730	0.897
	18	0.54	0.239	0.663	0.250	0.752	0.958
SDM	9	0.197	0.077	0.270	0.075	0.731	1.025
	18	0.305	0.122	0.443	0.104	0.696	1.168
	27	0.442	0.173	0.609	0.147	0.727	1.176
SAM	9	0.194	0.084	0.266	0.076	0.729	1.107
	18	0.271	0.118	0.391	0.111	0.693	1.056
	27	0.367	0.181	0.487	0.185	0.752	0.982
DEM	9	0.231	0.097	0.341	0.084	0.676	1.160
	18	0.360	0.153	0.512	0.118	0.667	1.291
	27	0.500	0.156	0.699	0.123	0.723	1.264

According to the vibration response reduction factor defined in this paper, the cumulative probability distribution of the maximum vibration response of pedestrians can be obtained by the following formula:

$$P(x) = \int_{-\infty}^{x} \frac{1}{\sqrt{2\pi\sigma_{max}/a}} e^{-\frac{(x-(u_{max}/\varphi))^2}{2(\sigma_{max}/a)^2}} dx \tag{8}$$

The comparison between the calculation results and the actual values is shown in Fig. 27. The actual cumulative probability values are consistent with the calculation results of Eq. (8). The maximum error of the results under the two walking models does not exceed 5%, which meets the accuracy requirements and further verifies the correctness of the proposed method. At the same time, the fitting curve obtained by the vibration response reduction coefficient can better reflect the distribution of the maximum vibration response of pedestrians, which can be used for quantitative evaluation of human-induced vibration comfort.

4 Conclusion

Based on four random walk models, the correlation and distribution between the maximum vibration response and the mid-span peak acceleration were studied. The main conclusions from this study can be summarized as follows:

The maximum acceleration felt by pedestrians under the four models approximately obeys a normal response distribution, and the mean value is smaller than the peak acceleration across the middle. Among them, SDM and SAM have the same value range, while the acceleration response distribution of OAM is more discrete, and the maximum values of the value range are 2.07, 2.1, and 1.42 times of the other three models, respectively.

The distribution of the maximum vibration response perceived by pedestrians is related to the walking pattern of the crowd. Among them, the distribution patterns of OAM and SAM are similar, and the locations of the maximum vibration response

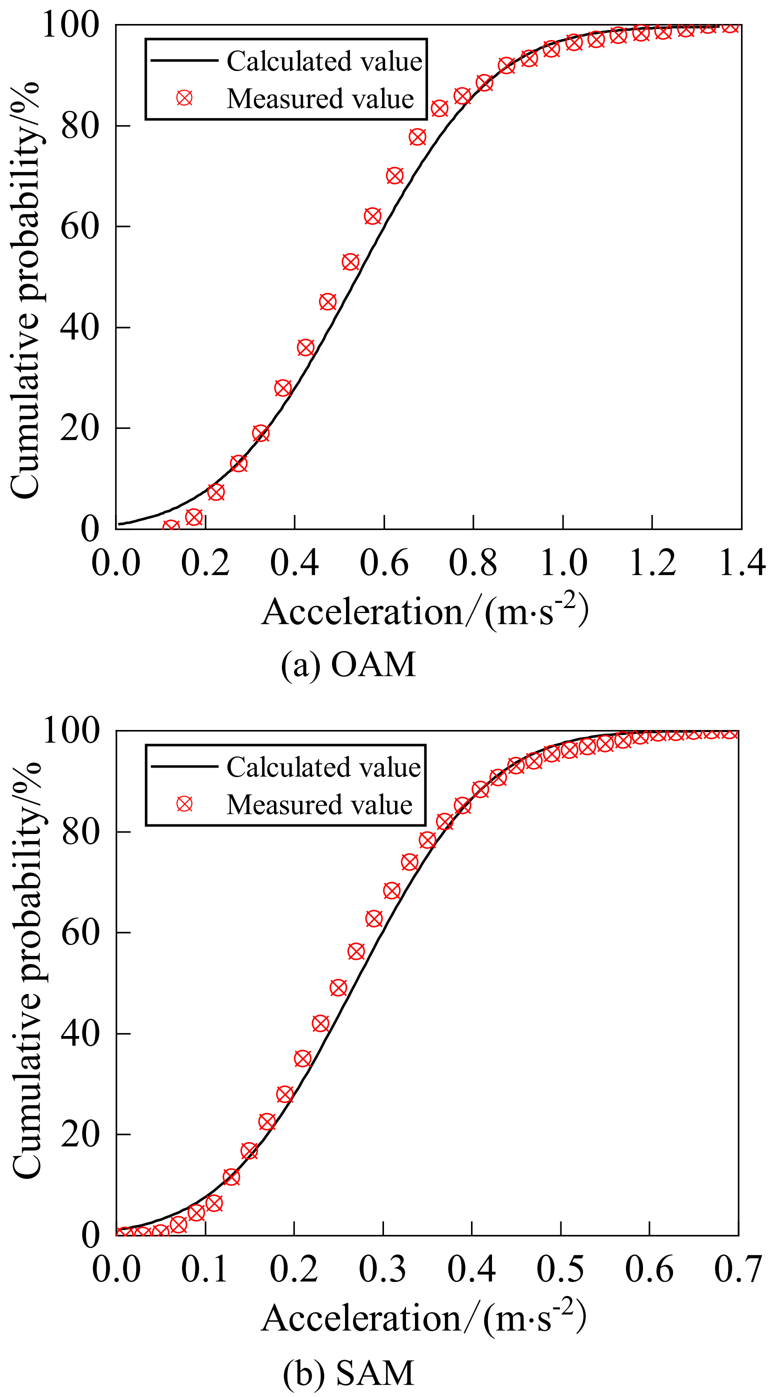

Fig. 27 Comparison of calculation results

perceived by pedestrians are concentrated in the [4L/7,6L/7] interval, and the moments of occurrence are distributed in the middle of the total time range. The SDM and DEM already had pedestrians on the bridge at the initial moments, and the locations where the maximum response appeared were relatively evenly distributed, with the highest proportion of pedestrians located near the lower bridge section. The moments when the maximum vibration response appeared within T/10 of the total time course accounted for the largest proportion, 42.1% and 51.8% of the total sample, respectively. In addition, the probability of "simultaneous response" was significantly higher for OAM and SAM than for SDM and DEM.

Taking the maximum vibration response felt by pedestrians as the evaluation index can effectively overcome the conservative problem of traditional comfort evaluation method. based on the results of numerical analysis, the vibration response discount factor was defined, and the cumulative probability distribution of the maximum vibration response felt by pedestrians was obtained from the peak acceleration in the span of the structure with a maximum error of no more than 5% under the condition of satisfying the accuracy. The results of this type can be used for quantitative comfort assessment.

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Authors' contributions
Yuhao Feng: Writing original draft, Formal analysis. Deyi Chen: Project administration, Review. Zhenyu Wang: Experiment. Shiping Huang: Data processing. Yuejie He: Editing. All authors read and approved the final manuscript.

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Availability of data and materials
Supplementary data to this article can be received from the corresponding author on reasonable request.

Declarations

Competing interests
The authors declare that there is no conflict of interest regarding the publication of this paper.

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