Control of footstep vertical vibration for Vierendeel truss – supported steel footbridges

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Abstract: In this paper three dimensional static and dynamic analyses for steel pedestrian bridges have been carried out. The footbridges considered are of a total length of (20, 30, 40 and 50m). The bridge is considered to act as continuous of two equal spans or as a two simply supported spans disconnected at the intermediate support. The latter design philosophy is advantageous in case of vehicle accidents so that only one half of the bridge will need maintenance. The bridge skeleton consists of two Vierendeel trusses acting as the main edge girders and the deck consists of parallel transverse sections covered with a steel plate. The BS5400 has been adopted in the present study for the footstep vibration serviceability. The bridge fundamental frequency and deck acceleration have been obtained and compared with the tolerable limits to avoid human discomfort. The analysis parameters were the bridge span, the height of the Vierendeel truss and whether the bridge is simply supported or continuous. Results have shown that for the continuous bridges of spans less than or equal to 15m, the frequency is greater than the minimum limit and the vibration serviceability requirement is satisfied for the height range of the Vierendeel truss. For spans equal to or greater than 20m the frequency is less than the limit and the deck acceleration has been checked. For the simply supported bridges of spans 10m to 25m the frequency is less than the limit and the deck acceleration has been checked. For the same section properties the maximum acceleration has been increased by (10% to 50%) as compared with the continuous cases. Depending on the mass and stiffness for different analysis cases, a regression analysis has been done to develop equations for estimating the fundamental frequency.

1. Introduction

Footbridges are usually light in weight due to their relatively small design live load as compared with the conventional vehicular bridges. This results in a reduced global stiffness and reduced mass per unit deck area, especially for long span footbridges. Consequently, care should be taken to avoid the annoying human feeling due to footstep vibration.

Usually the force-time histories induced by people during walking or jumping across the bridge are difficult to be estimated. This depends on many factors such as the pacing rate, floor type, people weight (single or crowd cases), shoes type and how energetic they are during walking or jumping.[1], [2]. Some attempts had been made to measure the impact force – time history of a human footstep in laboratories and a typical result is as shown in figure (1) .[3],[4].
Due to the complex phenomenon of walking or jumping, the load-time histories (for single or crowd pedestrian cases) on decks of footbridges are difficult to be estimated and most International Codes of practice allowed designers not to do forced dynamic analysis if the fundamental natural frequency exceeds a specified limit, ([5],[6],[7]).

2. Review of some relevant previous studies and codes of practice

Unger and White,[8] and the American Institute of Steel Construction,[9] gave a major conclusion that the first mode frequency affects the dynamic characteristic of the floor under human footsteps. Arch bridges have been studied by Dulinska and Murzyn,[10] and tubular footbridges have been studied by Jarwali and Shunichi,[11] They concluded that the main influencing factor is the fundamental frequency. Also a concise literature review about this subject can be found in [2] and [3].

The BS5400,[5] states that the nominal live load for footbridges is 5.0 kN/m² for spans ≤ 36m and if the fundamental natural frequency of a footbridge f (without the live load) exceeds 5.0Hz, the vibration serviceability limit state is satisfied. But if f ≤ 5.0Hz, the maximum deck vertical acceleration should be determined and compared with the maximum limit of 0.5√ f m/s² using the following equation:

\[ a_{\text{max}} = 4\pi^2 f^2 y_s K \Psi \]  

where:
- \( a_{\text{max}} \) = max. deck acceleration (m/s²)
- \( f \) = fundamental natural frequency (Hz).
- \( y_s \) = static deflection due to one person of weight 0.7kN standing at midspan, (m).
- \( K \) = a factor depending on the number of spans:
  - For single span, \( K =1.0 \)
  - For two spans, \( K =0.7 \)
- \( \Psi \) = a dynamic factor depending on the logarithmic decrement of decay of vibration (damping effect) \( \delta \) and bridge span, for steel \( \delta = 0.03 \). The value of \( \Psi \) can be obtained from BS5400,[5].

The BS5400 Standard gives an alternative method to estimate the maximum deck acceleration by performing a dynamic analysis under the effect of a pedestrian load of \((180 \sin 2\pi f t , \text{ in N})\) moving at a constant speed of 0.9f along the bridge.

According to AISC, [9] the maximum deck acceleration can be estimated by the following equation:

\[ \frac{a}{g} = \frac{p \exp(-0.35f \delta)}{\beta W} \]  

where:
- \( \frac{a}{g} \) is the maximum deck acceleration in fraction of gravity.
f is the fundamental frequency (Hz)
p is a constant force, 0.41kN for footbridges.
β is the modal damping ratio.
W is the floor weight. (kN)
According to AASHTO,[2] the design live load is 4.35 kN/m² and the fundamental frequency f is given by:

\[ f \geq 2.86 \ln \left( \frac{180}{W} \right) \]  

where:
f is the fundamental mode frequency (Hz).
W is the weight of the supported structure, including dead load only, (Kips).

3. Applications
The footbridges considered in the present study are of a total length of (20, 30, 40 and 50m). The bridge is considered to act as continuous of two equal spans or to be of two simply supported spans disconnected at the intermediate support. The latter design philosophy is advantageous in case of vehicle accidents so that only one half of the bridge will need maintenance or replacement. The flooring system consists of Vierendeel trusses of a height ranging between 1.05m and 1.70m acting as the main edge girders and the deck consists of parallel transverse steel sections covered with a 6mm steel plate. The BS 5400 will be adopted for the serviceability requirements of footsteps vibration.

Figure (2) shows the finite elements model for the continuous footbridges that have been considered in this study together with the section properties for members. Similar geometry has been adopted for the simply supported bridges with two column supports at each end. For both cases a 2.5m deck width has been assumed. It has been assumed that the bridge stairs do not contribute in the vibration problem and can be excluded from this model since it can be supported properly within the road shoulders.
The section properties given in figure (2) were selected after performing many three dimensional static finite elements analysis under a pedestrian load of 5.0 kN/m² and limiting the stresses within the allowable limits of BS5400 assuming a steel of 350 MPa yield strength. STAAD.Pro V8i has been used in this study. The results indicated that the governing case for which the stresses approaches the threshold of limits is the continuous bridge of 25m span and of 1.7m height Vierendeel truss for which the stresses were 169 MPa and 131 MPa in tension and in compression respectively. Consequently the section properties were kept the same for all other bridge cases and only three analysis parameters were adopted which are the span, the height of the Vierendeel truss and whether the bridge is simply supported or continuous. This means that the total number of case studies is 32. For each bridge case the maximum bridge deflection (under live load) was found and compared with the allowable limit. Global buckling analysis has been performed for each case study to avoid the singularity (and hence, the buckling) in the difference between the global and geometric stiffness matrices and to satisfy the serviceability limit state requirements.

Thereafter, three-dimensional dynamic analysis was performed for each case to determine the mode frequencies and eigenvectors.

4. Results and discussion
The first mode frequencies have been determined and plotted against the Vierendeel truss height for the continuous and for the simply supported cases as shown in figures (3) and (4), respectively. Figure (3) indicates that for continuous bridges of spans less than or equal to 15m the frequency is greater than the 5Hz limit of BS5400 and the vibration serviceability requirement is deemed to be satisfied for any height of the Vierendeel truss. However, for spans equal to or greater than 20m the frequency is less than 5Hz and the deck acceleration should be checked according to BS5400, equation (1). Figure (4) indicates that for the simply supported bridges of spans range of 10m to 25m the frequency is less than 5Hz for any height of the Vierendeel truss and the deck acceleration should be checked according to BS5400, eq.(1). Figure (5) shows typical first mode shapes.

Results have shown that for the simply supported cases the fundamental frequency has been decreased by (9% to 70%) due to the reduced stiffness.

![Figure 3. First mode frequencies for the continuous footbridges.](image-url)
Figure 4. First mode frequencies for the simply supported footbridges.

The maximum deck accelerations are determined for bridges having first mode frequency less than 5 Hz together with the maximum deflection under live load and are given in Table (1). Buckling analysis has been made using the same finite elements scheme and the results indicated that all bridge cases considered are far from the buckling threshold.
**Figure 5.** Typical first mode shapes

**Table 1.** Maximum deck acceleration and maximum deflection values

| Span length | Bridge handrail height | Simple supported span type | Continuous span type |
|-------------|------------------------|----------------------------|----------------------|
|             |                        | Max. deflection (mm)       | Deflection limit (mm) | a) Max. (m/s²) | a) Limit (m/s²) | Max. deflection (mm) | Deflection limit (mm) | a) Max. (m/s²) | a) Limit (m/s²) |
| 10          | 1.05                   | 5.72                       | 27.78                | 1.596          | 0.961          | 4.89                  | 27.78               | Above 5 Hz.       |                  |
| 10          | 1.20                   | 5.06                       | 27.78                | 1.082          | 0.894          | 4.39                  | 27.78               | Above 5 Hz        |                  |
| 10          | 1.35                   | 4.84                       | 27.78                | 1.714          | 1.024          | 4.20                  | 27.78               | Above 5 Hz        |                  |
| 10          | 1.60                   | 4.40                       | 27.78                | 1.857          | 1.060          | 3.86                  | 27.78               | Above 5 Hz        |                  |
| 15          | 1.05                   | 11.55                      | 41.67                | 1.090          | 0.844          | 9.84                  | 41.67               | Above 5 Hz        |                  |
| 15          | 1.20                   | 10.29                      | 41.67                | 0.957          | 0.827          | 8.88                  | 41.67               | above 5 Hz        |                  |
| 15          | 1.35                   | 9.45                       | 41.67                | 0.937          | 0.839          | 8.40                  | 41.67               | above 5 Hz        |                  |
| 15          | 1.60                   | 8.40                       | 41.67                | 0.857          | 0.827          | 7.68                  | 41.67               | 1.151             | 1.204             |
| 20          | 1.05                   | 21.00                      | 55.56                | 1.052          | 0.815          | 15.84                 | 55.56               | 0.943             | 0.962             |
| 20          | 1.20                   | 18.90                      | 55.56                | 0.898          | 0.795          | 14.40                 | 55.56               | 0.891             | 0.960             |
| 20          | 1.35                   | 17.01                      | 55.56                | 0.839          | 0.787          | 13.20                 | 55.56               | 0.821             | 0.943             |
| 20          | 1.60                   | 13.86                      | 55.56                | 0.791          | 0.784          | 11.04                 | 55.56               | 0.798             | 0.940             |
| 25          | 1.35                   | 25.43                      | 69.45                | 1.040          | 0.776          | 23.52                 | 69.45               | 0.792             | 0.821             |
| 25          | 1.50                   | 22.95                      | 69.45                | 0.954          | 0.773          | 20.88                 | 69.45               | 0.674             | 0.806             |
| 25          | 1.60                   | 21.38                      | 69.45                | 0.960          | 0.790          | 18.00                 | 69.45               | 0.513             | 0.784             |
| 25          | 1.70                   | 19.66                      | 69.45                | 0.764          | 0.761          | 17.04                 | 69.45               | 0.375             | 0.737             |
Table (1) indicates the following:

1. For all the simply supported cases considered, the maximum deck acceleration exceeds the tolerable limits and strengthening is required to increase the bridge stiffness. This can be achieved by using larger member sections and / or increasing the Vierendeel truss height. Using the latter strengthening proposal for heights in excess of 1.70m with a top cords bracing will make it possible to have a useful glazed roof for the footbridge.

2. For all continuous bridge cases considered the maximum deck acceleration are less than the tolerable limits.

3. For all simply supported and continuous bridge cases considered the maximum deflection under live load is less than the limit of L/360.

4. For the results concluded in 1 and 2 above, it is evident that the continuous footbridge is more economical as expected but it may need higher maintenance or rehabilitation cost than that for the two simply supported equal spans bridge in case of vehicle accidents.

Depending on the mass (or weight W) and stiffness for different analysis cases, a regression analysis has been made to develop equations for estimating the fundamental frequency for such type of footbridges. Since the value of $y_s$ of equation (1) is a stiffness dependent parameter, hence the frequency $f$ has been correlated with $W$. $y_s$. The regression analysis has been made between the fundamental frequency and the value of $W\cdot y_s$ for all bridge models considered in this study, where $y_s$ is as defined in eq.1 and W is the weight of the bridge. The value of $y_s$ has been obtained using STAAD.Pro V8i and an Excel sheet (Using Microsoft Excel 2013) has been made for calculating $W\cdot y_s$ in one column and the fundamental frequency in the second column. Hence, this sheet represents the regression data and the regression analysis, and the trend lines were obtained from the Microsoft Excel and shown in figures 6 and 7.

![Figure 6. The effect of mass and static deflection on fundamental frequency of simply supported bridge.](image-url)
Figure 7. The effect of mass and static deflection on fundamental frequency of continuous bridge.

From the regression analysis the following equations are obtained for the fundamental frequency:

For the simply supported bridge

\[ f = 3.218 \exp(-0.021W_{ys}) \]  

(4)

For the continuous bridge

\[ f = 14.451 \exp(-0.123W_{ys}) \]  

(5)

where

\( f \), \( W \) and \( y_s \) are as defined in equations (1) and (3).

5. Conclusions

The following conclusions may be drawn from the results of analysis for the footbridge type considered in the present study:

1. For the continuous bridges of spans less than or equal to 15m the frequency is greater than the 5Hz limit of BS5400 and the vibration serviceability requirement is deemed to be satisfied for the height range considered of the Vierendeel truss. However, for spans equal to or greater than 20m the frequency is less than 5Hz and the deck acceleration should be checked. For the simply supported bridges of spans in the range of 10m to 25m, the frequency is less than 5Hz for any height of the Vierendeel truss and the deck acceleration should be checked.

2. Although the use of a two equal simply supported spans instead of two continuous spans is advantageous from future rehabilitation or replacement point of view, the results have shown that (for the same section properties and span) the simply supported bridge needs larger member sections and/or higher Vierendeel trusses. This is because its fundamental frequency is less than the tolerable limit and the maximum acceleration has been increased by (10% to 50%) as compared with the continuous cases.

3. To achieve the frequency limit requirement larger sections (and hence more cost) are required when adopting the simply supported spans design philosophy. This may be considered as an advanced payment for reducing the probable erection and replacement or rehabilitation cost.
for the two spans continuous bridge in case of future accidents, since the whole continuous bridge may need maintenance or replacement.

4. The regression equations obtained for the bridge types of the present study can be useful for estimating the bridge fundamental frequency before performing the three dimensional dynamic analyses.

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