Synchronic Excitation in Footbridges due Human-Induced Forces in Lima Peru

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Abstract. Structural analysis of human-induced induced vibrations in pedestrian bridges due to the passage of pedestrians is presented. An antecedent of this phenomenon is the Millennium Bridge located in the city of London, which had to close to the public, shortly after its inauguration due to unexpected lateral vibrations produced by the passage of people across the bridge. The present research analyses this effect on a pedestrian bridge in Lima, for transverse, lateral, longitudinal and torsion movements, due to the passage of pedestrians walking with a period similar to the modal periods of the structure corresponding to each direction of movement, finding displacement and acceleration responses. A software Puente.exe was developed to find the response of the peruvian footbridge due the synchronic excitation.

1. Introduction

Some bridges have had serious structural problems because extra vibrations were induced by pedestrians. The displacement and acceleration induced by these vibrations must be taken into account for the proper design of those structures. In the current report, those effects are analyzed and revised due to vibration lateral, longitudinal, transverse and / or torsion presented on a footbridge located in Lima, Peru. This footbridge is loaded by external forced induced due the pedestrians.

Pedestrians, while walking, generate forces which are transmitted to the footbridge. People passing through a bridge transmit vertical forces synchronized with a period of walking, lateral and longitudinal forces due to friction between the shoe with the slab of the bridge, and torsion due a possible eccentricity between the axis of the bridge and the line through the pedestrian. Those events could create troubles, because the community would not rather use those footbridges by insecurity. The investment to build the footbridge would be down.

One case of this phenomenon is the Millennium Bridge. The bridge is located in London, England and opened to the public on June 10, 2000, on which an estimated 80,000 to 100,000 people crossed it. Like any structure, the Millennium Bridge has been designed to an expected level of movement, however, when large groups of people crossed the bridge, lateral movements occurred more than expected. When the pedestrian bridge was opened to use and pedestrians walked on a slab, there were unexpected lateral acceleration, which were every sensitive to pedestrians. It was necessary to close the bridge for further evaluation and reinforcement. The maximum displacement of the platform was approximately 70mm. [2]

There are other bridges having different structures than the Millennium Bridge and those have experienced significant lateral vibrations when they have been congested, such as The Road Bridge at
the port of Auckland in 1975. These cases have not been published extensively and therefore the phenomenon is not well known.

2. A Synchronic excitation – tolerance of vibration

When people walk, it creates a pattern of repeated forces making the mass of the structure vibrate up and down. This phenomenon is additional to the gravity load by the weight of pedestrians. The phenomenon creates a vertical force fluctuation of about 250 N. which is repeated with each step. There is also a small oblique force caused by the shaking of our body because our legs are slightly apart. This force of about 25 N. goes to the left when it rests on the left foot and right when it rests on the right foot and repetitions occur with each successive step [3].

The balance of the footbridge under the pattern of load explained was not significantly affected by vertical movements; however, movements are not tolerated by perpendicular forces. If the walking surface begins to oscillate, pedestrian must put his foot a little more separated from the other to seek stability and strength (lateral) oblique increases. This tendency towards synchronization has the effect that every step that begins to work increasing the movement of the slab. While the movement progresses, it moves with the same period of motion of the surface. Also tend to widen the position, thereby increasing the lateral force. The effect explained increase with a greater number of people. The individual patterns of response vary but most of the crowd interacts with the surface and develops a lateral move in sync. This phenomenon is referred to as synchronous lateral excitation [3]. Some design codes recommend use vibration tolerance, in order to design more stiffness structures members.

Approximate levels of acceptability for vibration acceleration are defined as a function of the human perception to vibrations. A common human problem is that motion causes the pedestrian to become concern about the safety of the structure, where danger of structural collapse is not an issue. There is no enough number of design codes which treat this. Some examples of design codes are and the Ontario Bridge code. [1]

The British bridge design code takes pedestrian response to vibrations into account by the acceleration serviceability expressed by the following equation:

\[ A_{\text{limit}} = 0.5 f_1^{0.5} \text{[m/s}^2\text{]} \]  

This formula works for fundamental natural frequencies \( f_1 \) (in Hz) less than 5 Hz.

The Ontario bridge code [1] the serviceability acceleration limit is given by:

\[ A_{\text{limit}} = 0.25 f_1^{0.78} \text{[m/s}^2\text{]} \]  

This level of vibration is not provided for in the design of the bridge. This excessive movement due to vibration may occur in other bridges, existing or under construction, for a lateral frequency below 1.3 Hz and with a sufficient number of pedestrians. [2] This frequency was measured by non-destructive vibration tests.

3. Measurement of the force from the walking pedestrian

The vibration induced by the people is a mobile force caused by walking pedestrians. The force induced by them on the bridge has been measure by dynamics tests, measuring the displacement and the acceleration on the bridge slab. According to several studies [1, 5, 6] the frequency of this vibration is 2 Hertz with a standard deviation of 0.175. For this investigation the variation is considered as that in figure 1. To simulate the horizontal effects, the friction force between the person and the audience is considered by a force function based on that shown in figure 1, and using a friction coefficient = 0.2\( \mu \). Horizontal Force is shown in the figure 2.
Figure 1. Forcing function resulting from footfall overlap during walking with a step rate of 2 Hz [1].

Figure 2. Frictional forcing function considered.

4. A peruvian footbridge case and puente software developed

One Peruvian pedestrian bridge was analyzed in order to study this phenomenon of vibration. This bridge is located in the city of Lima, Peru. It consists of two 21mts spans; each one is articulated by neoprene supports at both ends to 2 meters for each column, as figure 3 shows. The two extreme columns are circular in cross section with a height of 7.00 m., and the central pillar has oval cross section.

A linear elastic analysis was performed in order to calculate the dynamic properties of the current footbridge such as vibration modes. The software used was SAP2000 [7] making a structural model on this. The three-dimensional analytical model of the bridge was developed for obtain the following dynamic characteristics:

Table 1.- Dynamics properties of the structure.

| Mode          | Frequency (Hz) | Period(sec) |
|---------------|----------------|-------------|
| M1 Transversal| 2.239          | 0.4466      |
| M2 Lateral    | 2.253          | 0.4439      |
| M3            | 3.293          | 0.3037      |
| M4            | 3.336          | 0.2997      |
| M5 Vertical   | 4.012          | 0.2492      |
| M6            | 5.313          | 0.1882      |
| M7 Twist      | 7.473          | 0.1338      |
The dynamic properties were calculated. The first mode of the system is associated with the fundamental mode of the bridge and is a movement across the axis of the bridge. The second mode is associated with lateral movement, the sixth mode is predominantly vertical movement, and the seventh shows the torsion mode. Those properties are used to calculate the acceleration tolerance.

| Frequency (Hz) | Equation 1 | Equation 2 |
|---------------|------------|------------|
| 2.239         | 74.815     | 47.067     |
| 2.253         | 75.045     | 47.295     |
| 4.012         | 100.155    | 74.407     |
| 5.31          | 115.217    | 92.713     |

The current results were calculated using classical and conventional analysis methods. However, the synchronic excitation is not considered on those types of structural analyses. It is necessary to make a more complete analysis in order to consider the synchronic excitation.

PUENTE.EXE software was developed in order to analyze the effects of vibration caused by pedestrian loads. The software has a graphic interaction with the user (figure 4). This software is based on the modal displacements of the structure obtained by SAP2000, obtaining values of displacements, velocities and accelerations 6 degree of freedom (DOF) each node of the bridge deck. PUENTE.EXE works with different number of people walking on the bridge, as well as the distances between pedestrians and separation between their legs. This software considers the maximums vibration effects occurred under synchronic excitation, vibration effects such as resonance.

When the period of the applied force is similar to the natural period of structure, resonance is reached. This event produces the maximum amplification of the structural response. Looking to find the maximum responses of the structure (resonance), analyzed the bridge was subjected to periods associated with transverse movements, lateral, vertical and torsion. It shows the effect of amplification of responses when the period of the loads due to pedestrian approaches the period of the structure. Increasing the mass or if the structural configuration of the bridge is different, the period of pedestrians can reach some of the periods of the modes of the structure, presenting the phenomenon of resonance. The value of damping for this work was 0%, no viscous properties on concrete material for this specific case was considerate.

![Figure 4. PUENTE.EXE software graph interaction with user. Dash lines represent a line of pedestrian walking on the footbridge. Torsion mode shape is expected for this eccentric line of load due pedestrian location.](image)
PUENTE.EXE calculates responses to cycle and moving different quantities of punctual loads. The structure was analysed for the walking of one person and 50 people, and unit load (force / self-weight pedestrian = 1), to calculate responses of different weights of different pedestrians, the answer will be the value obtained by the program PUENTE.EXE amplified by the weight of the pedestrian. The results expected have cycle patterns of displacement and accelerations.

5. Results of vibration analysis

It is presented the results of the analysis performed by PUENTE.EXE per each case of fundamental mode shape of the footbridge. Each mode shape represents each type of vibration case would appear on case load pattern (due pedestrian loads) carry out on the footbridge. Displacement and acceleration were calculated considering the synchronic excitation explained. The results are listed below.

5.1 To the first mode of vibration, there is the increase of responses (displacements and accelerations) over time pedestrian travel through the bridge deck. The bridge reaches resonance in the transversal direction to start 13seg the pedestrian walk. The bridge is moving freely. The structure has a zero damping to seek maximum responses (Vibration Free System). For the walking of one person with about 60 kilos, the peak displacement is 0.254cm and an acceleration of 50 gals, but 50 people have 12cm and 2390gals. Maximum responses appear on left extreme of the footbridge.

![Figure 5. (a) First mode shape of the footbridge and 50 pedestrians case response of the transversal vibration analysis.](image)

![Figure 5. (b) Displacement and acceleration under 50 pedestrian transversal load and $\beta=5\%$.](image)

5.2 To second mode ($T = 0.443$seg), the bridge reaches resonance in the lateral direction to start 25seg the pedestrian walk. The bridge is swinging freely. The structure has a zero damping to seek maximum responses (Vibration Free System) like transversal direction. For the passage of a person of about 60 kilos, the peak displacement is 0.242cm and an acceleration of 48 gals, but 50 people have
12cm and 2420gals. Maximum response effects appear at 5.50m and 27.00m from the left extreme of the footbridge.

**Figure 6.** (a) Second mode shape of the footbridge and 50 pedestrians case response of the lateral vibration analysis.

**Figure 6.** (b) Displacement and acceleration under 50 pedestrian lateral load and $\beta=5\%$.

5.3 To the fifth mode ($T = 0.188\text{seg}$), the bridge reaches resonance $13\text{seg}$ vertical movement to start the walk from the pedestrian. The bridge is swinging freely. The structure has a zero damping to seek maximum responses (Vibration Free System). For the walking of a person of about 60 kilos, the peak displacement is 0.856cm and acceleration of 59 gals, but for 50 people is 4.28cm and 2920gals. Maximum response effects appear at 11.00m and 32.50m from left extreme of the footbridge.

**Figure 7.** (a) Fifth mode shape of the footbridge and 50 pedestrians case response of the vertical vibration analysis.
5.4 To the seventh mode \((T = 0.134\text{seg})\) the bridge reaches resonance \(11\text{seg}\) vertical movement to start the walk from the pedestrian. The bridge is swinging freely to twist movement. The structure has a zero damping to seek maximum responses (Vibration Free System). For the passage of a person of about 60 kilos, the maximum displacement is reached \(4.16E-4\text{cm}\) and acceleration of \(0.944\text{gals}\), but for 50 people has \(0.0152\text{cm}\) and \(33\text{gals}\). Maximum response effects appear at \(11.00\text{m}\) and \(32.50\text{m}\) from left extreme of the footbridge as vertical response case.

![Figure 7.](image)

**Figure 7.** (b) Displacement and acceleration under 50 pedestrian vertical load and \(\beta=5\%\).

![Figure 8.](image)

**Figure 8.** (a) Seventh mode shape of the footbridge and 50 pedestrians case response of the torsion vibration analysis.

![Figure 8.](image)

**Figure 8.** (b) Displacement and acceleration under 50 pedestrian torsional load and \(\beta=5\%).
Table 3. Summary of Results.

| Weight Pedestrian | 60 kg | Damping β=0% |   |   |   |
|-------------------|-------|--------------|---|---|---|
|                   |       | TRANSVERSAL  | LATERAL | VERTICAL | TWIST |
| Mode Period       | 0.4466 | 0.4439 | 0.2492 | 0.1338 |
| 1 pedestrian      | Displacement(cm) | 0.254 | 0.242 | 0.856 | 0.00042 |
|                   | Acceleration(gals) | 50 | 48 | 59 | 0.944 |
| 50 pedestrians    | Displacement(cm) | 12 | 12 | 4.28 | 0.0152 |
|                   | Acceleration(gals) | 2390 | 2420 | 2920 | 33 |

|                   |       | Damping β=5% |   |   |   |
| Mode Period       | 0.4466 | 0.4439 | 0.2492 | 0.1338 |
| 1 pedestrian      | Displacement(cm) | 0.055 | 0.0146 | 0.0127 | 0.000042 |
|                   | Acceleration(gals) | 9.06 | 2.93 | 5.39 | 0.0713 |
| 50 pedestrians    | Displacement(cm) | 0.461 | 0.317 | 0.0913 | 0.0004 |
|                   | Acceleration(gals) | 77.6 | 63.2 | 75.4 | 0.703 |

6. Analysis of the results
The resonance can be reached if the frequency period of walking people on the footbridge is similar or has the same value of the bridge’s natural period. The effects produced by the pedestrian bridge must be considered. The bridge may not necessarily be pedestrian, but any other modal having a period that is similar to the passage of people (low stiffness, greater mass, characteristics of pedestrian bridges, or pedestrian platforms in the vehicular bridge wings). It is necessary consider and make vibration analysis.

Due vibration analysis performed on the Peruvian footbridge, it was analyzed the responses of the bridge are not considering the damping of the concrete, this in order to observe the phenomenon of amplification of dynamic response. For design calculations must take into account the damping. The program PUENTE.EXE also considers this parameter. The results have been compared with the tolerance limit presented.

It is found that due transversal, lateral and vertical excitation the footbridge must have troubles on vibration, especially on the acceleration. Values of acceleration results calculated for 0% damping and show that they are exceeding the tolerance limits, on 20 more times than tolerate values. Accelerations calculated reach 2400 gals and the tolerance limits is less than 115 gals. For 5% damping case, concrete material damping, the acceleration response of the footbridge is close to tolerance values. The footbridge may have serious troubles on its use. Bridge designer must consider synchronic excitation on the design.

7. Conclusion
Due the many real examples on the world, the bridge designer must take into account this phenomenon, whose care is largely the perception of pedestrians. There are precedents that show these vibrations as shown. As Peruvian footbridge case, acceleration performed on the structure can reach and exceed human perception tolerance. These tolerance limits of acceleration must be compared with the vibration analysis response explained on the present research.

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