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SERVICEABILITY LIMIT STATES OF LATERAL VIBRATION OF FOOTBRIDGES INDUCED BY PEDESTRIANS ESTIMATED BY FIELD MEASUREMENTS

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ABSTRACT

Cable supported bridges have both structural rationality and elegant features, and are very attractive. However, they are relatively vulnerable to dynamic forces. A relatively rare type of vibration occurred on a few cable-supported bridges; the girder vibrated laterally with a frequency of about 1.0 Hz, when a large number of people were crossing the bridge. Field measurements were conducted on the three bridges in Japan and their details are presented. They are useful to clarify the mechanism of this vibration and to design practical bridges. Observing the pedestrians' behavior on these bridges, the serviceability limit state is considered. Pedestrians feel the vibrations and some of them become uncomfortable when the girder vibration amplitude is about 10 mm (equivalent to a velocity of about 60 mm/s and an acceleration of about 300 mm/s^2). But, most of them can walk normally. At an amplitude of about 25 mm (equivalent to a velocity of about 140 mm/s and an acceleration of about 750 mm/s^2), some pedestrians have difficulty in walking at a normal pace and touch handrails from time to time. At an amplitude of 45 mm (equivalent to a velocity of about 250 mm/s and an acceleration of about 1350 mm/s^2), people often lose balance and some of them stop walking temporarily to support themselves. Some of the senior people are unable to walk. At an amplitude of 70 mm (equivalent to a velocity of about 450 mm/s and an acceleration of about 2100 mm/s^2), which occurred on the London Millennium Footbridge, it was reported that many people felt unsafe and were unable to walk. Therefore, the girder amplitude of about 25 mm (equivalent to a velocity of about 140 mm/s and an acceleration of about 750 mm/s^2) would be the serviceability limit. These values are compared with those specified by other codes.

KEYWORDS

Lateral vibration of footbridges, field measurement, cable-supported bridges, serviceability limit states.

INTRODUCTION

Cable supported bridges have both structural rationality and elegant features, and are very attractive. However, they are vulnerable to dynamic forces. A relatively rare type of vibration occurred on a few cable-supported bridges; the girder vibrated laterally with a frequency of about 1.0 Hz, when a large number of people were crossing the bridge. The authors conducted field measurements on three bridges in Japan (T-bridge: cable-stayed bridge, M-bridge and W-bridge: suspension bridges) and their details are presented. They are useful to clarify the mechanism of this vibration and the serviceability limit state for lively footbridges.

The T-bridge (Toda Park Bridge), a cable-stayed footbridge, suffered lateral vibration induced by pedestrians in 1989 (Figure 1). The bridge connects the motor boat race stadium and the bus terminal. The girder vibrated laterally with a frequency of 0.93 Hz, the natural frequency of the first lateral mode, when a large number of people crossed the bridge after the final race was over (Figure 2). This type of lateral vibration had not been reported before and research was conducted to clarify the mechanism (Fujino *et al.* 1993; Nakamura *et al.* 2002; Nakamura 2004).

The same vibration problem occurred on the London Millennium Bridge, a suspension footbridge with very shallow cable sags, in 2000. The lateral response of the London Millennium Bridge was much larger than that of the T-bridge, and the bridge was closed for 20 months until the vibration was suppressed by viscous and tuned mass dampers (Dallard *et al*. 2001).

The M-bridge (Maple Valley Bridge) is a suspension footbridge built in 1999, crossing the dam lake. It has suffered lateral vibration since it was open (Nakamura *et al*. 2003; Nakamura *et al*. 2006). The girder vibration is fairly large and some pedestrians feel unsafe. This vibration seems to be different from that on the T-bridge because the first lateral natural frequency of the bridge calculated by FEM is about 0.3 Hz, which differs fthe usual synchronous frequency. Field measurements were therefore carried out to confirm the mechanism of this lateral vibration. Accelerometers were attached not only to the girder but also to pedestrians to clarify the interactions between pedestrians and the girder.

Figure 1. Toda Park Bridge (T-Bridge)

Figure 2. Congested conditions with many pedestrians on the T-Bridge

Figure 3. Maple Valley Bridge (M-Bridge)

The W-bridge (Water Village Bridge) is also a suspension footbridge built in 1995, crossing the dam lake. The main span length and the width is nearly the same as the W-bridge. Field measurements were out to compare the dynamic behaviors of the M-bridge and also confirm the serviceability values for the lateral vibration.

This paper presents the field measurements carried out on these three bridges and analyzed dynamic properties. The mechanism of the lateral vibration is clarified by the interactions between the pedestrians and the girder. Then, the serviceability of lateral vibration is proposed and discussed.

Figure 4. Water Village Bridge (W-Bridge)

FIELD MEASUREMENT ON THE T-BRIDGE

The T-bridge has a main span of 134m, a side span of 45m and two cable planes with 11 stays per plane (Figure 5). The girder is a steel single-box girder with orthotropic deck with a web height of 1.8m and a width of 6.05m.

Field measurements were carried out on race days to find the nature and mechanism of the vibration (Fujino *et al.* 1993, Nakamura *et al.* 2002, Nakamura 2004). Accelerometers were attached to the lower flange inside the box girder in the vertical and lateral directions. Figure 6 shows the lateral displacement of the girder during the congested period, which is a clear sinusoidal wave with amplitude of about 8mm and with a frequency of 0.93Hz.

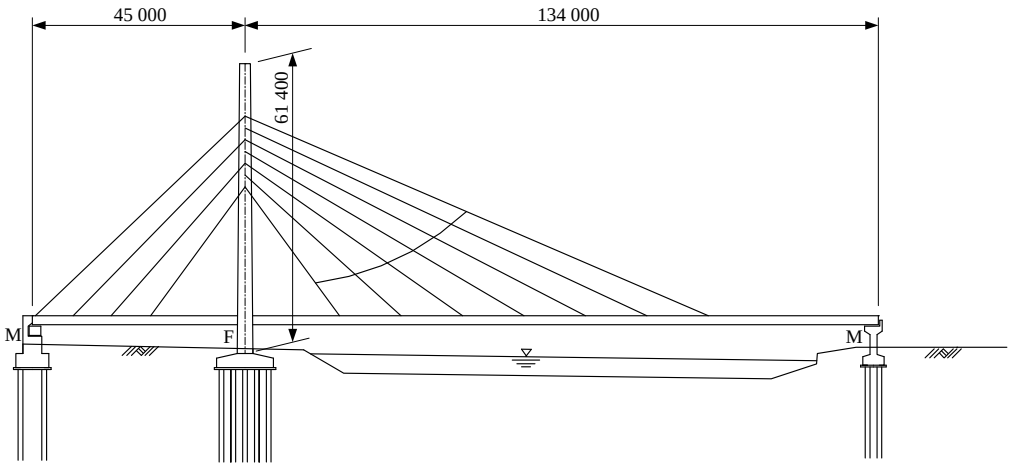

Figure 5. Layout of the T-bridge

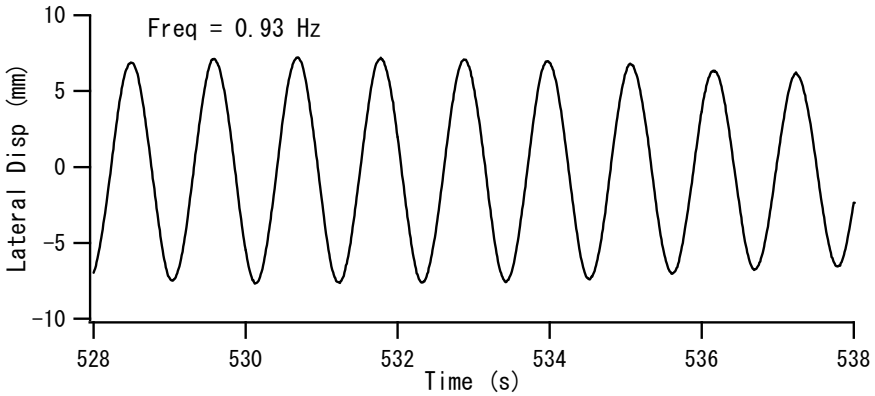

Figure 6. Lateral girder displacements on T-Bridge

FIELD MEASUREMENTS ON THE M-BRIDGE

The M-bridge is situated in a famous scenic place and attracts many tourists. The M-bridge has a main span of 320m and two back spans of 60m each (Figure 7). The tower is 26.2m high and made of steel pipes. A cable consists of seven spiral strand ropes with each diameter of 46mm. The girder consists of two steel H-beams, not having stiffening trusses or box girders, and is therefore very flexible in the vertical direction. To resist wind forces, the girder is stiffened by sway bracings consisting of steel H-beams and is also supported by wind ropes on a near-horizontal plane (4 degrees below the pure horizontal plane). The deck has a width of 1.5m, consisting of two layers; the wooden plates on top of the steel open grating slabs.

Field measurements were conducted for two days in November, 2002 (Nakamura *et al*. 2003; Nakamura *et al*. 2006). Accelerometers in the lateral direction were attached to the base of the handrails at five positions of L/8, L/4, 3L/8, L/2 and 9L/16 (L: span length), as shown in Figure 8. Accelerometers were also attached to the waist belt of a person. This person walked on the bridge among other pedestrians. Measured acceleration data were sent by a telemetry link and received at the tower. When he crossed the girder accelerometer positions, he clicked the button to make a signal, which was also sent to the receiver at the tower. This helped in determining the person's position.

Measured acceleration records are transformed to displacements by integrating the accelerations twice. Components in the low frequency range under 0.2 Hz are removed in this process. Typical lateral displacements are shown in Figure 9. These were obtained when the person with accelerometers walked through the L/4 position. The lateral displacements on the L/4 position show near sinusoidal waves with a maximum amplitude of 24 mm and with frequency of 0.88Hz. This corresponds to the third asymmetric mode of the girder.

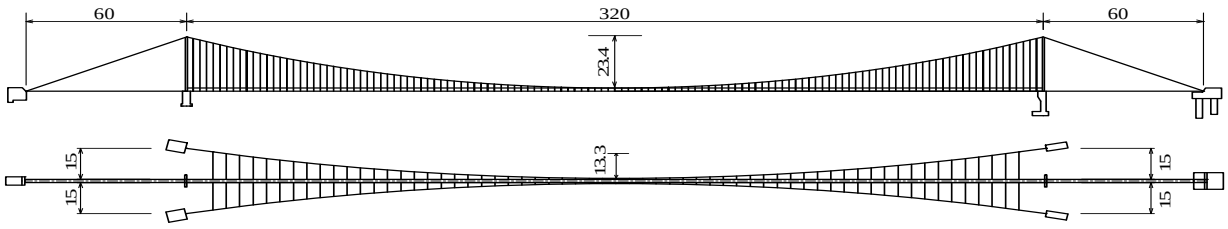

Figure 7. Layout of M-Bridge

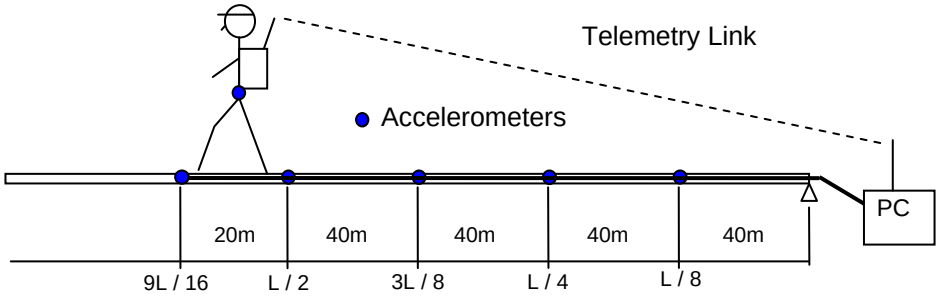

Figure 8. Arrangement of accelerometers

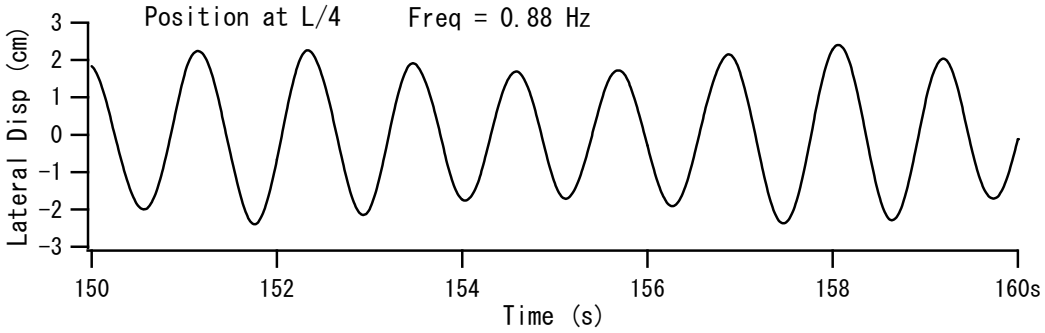

Figure 9. Measured lateral girder displacements on M-Bridge

FIELD MEASUREMENTS ON THE W-BRIDGE

The W-bridge has a main span of 315m with a width of 1.7m, which is almost the same dimension of the M-bridge. The girder consists of two steel H-beams, not having stiffening trusses or box girders. To resist wind forces, the girder is supported by wind ropes on a near-horizontal plane which is 35 degrees below the pure horizontal plane. This is much larger than the M-bridge storm cable with 4 degrees below the pure horizontal plane.

Field measurements were carried out for two days in September and October 2012. A group of 10 people crossed the bridge in line with the same rhythm of 0.87 Hz and 0.66Hz, which were found the dominant frequencies of the girder lateral vibrations by analyzing the ambient data. It is judged that the former corresponds to the third asymmetric lateral mode and the latter corresponds to the second symmetric lateral mode. Figure 10 shows the lateral displacement of the girder at the quarter span position and that of the cable at the span centre at a walking frequency of 0.87Hz. Figure 11 shows the lateral displacements of the girder and the cable at the span centre at a walking frequency of 0.66Hz. It is interesting to know that the amplitude of the cable is larger than the girder at a frequency 0.87Hz , and that of the girder is larger than the cable at a frequency 0.66Hz.

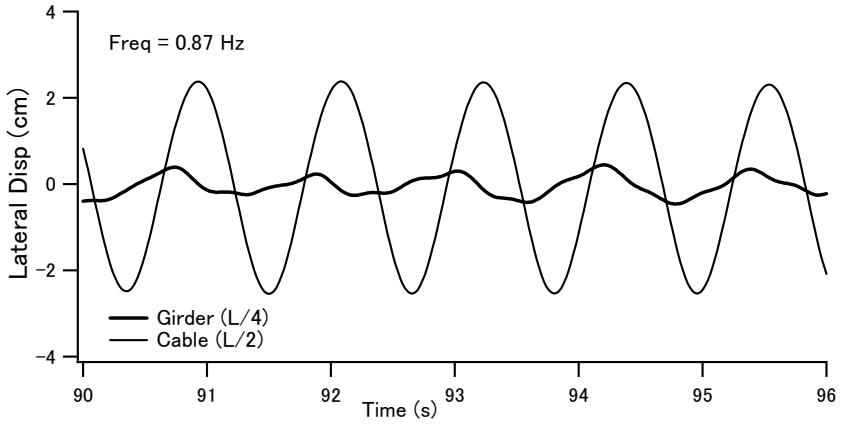

Figure 10. Measured lateral displacements on W-Bridge

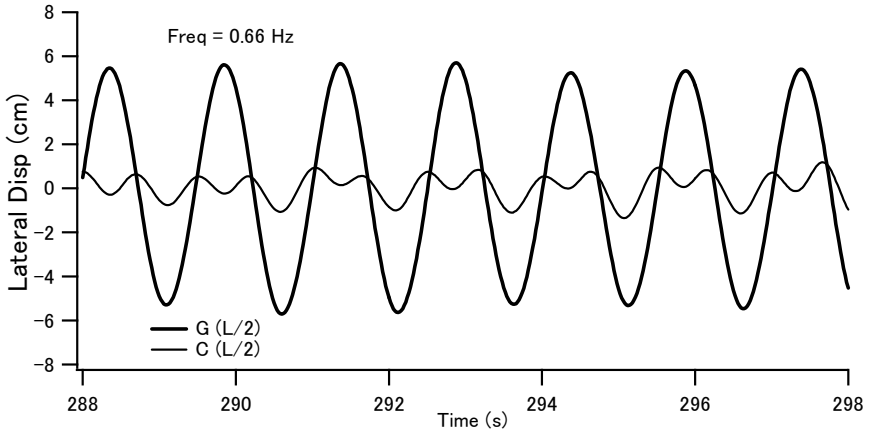

Figure 11. Measured lateral displacements on W-Bridge

PESDESTRIAN FORCES AND RESONANCE WITH GIRDER

Although it is widely known that people walk with a frequency about 2Hz, it is not commonly known but about 10% of the vertical loading works laterally when people walk (Bachmann *et al*. 1987). The gravity center of the body moves laterally when a person steps in with his right and left foot in turn, which induces the lateral dynamic force (Figure 12). Frequency of this lateral loading is therefore about 1Hz, which is close to the bridge lateral frequency of about 0.93 Hz. So, this lateral dynamic force induced by pedestrians can be a resonant force for the vibration of the girder and some stay cables whose natural frequencies are closer to this frequency (Figure 12).

In order to validate this mechanism, a couple of tests were carried out on the bridge with about 30 students. First, it was attempted to excite the bridge by jumping together on the deck with a frequency of 2Hz, by jumping randomly, by running and so on, however, the bridge did not respond at all. Second, a couple of stays were shaken laterally by hands in their natural frequency. The girder responded to this but the amplitude was very small. Next, the students sidestepped with a right and left foot in turn with a frequency of 0.93 Hz. The girder then responded with the lateral amplitude of about 6.5mm and some of the stays also vibrated significantly, which was very similar to the actual phenomenon, occurred on the bridge during congestion. It was surprising that only 30 people could vibrate the whole bridge easily. It was thought that this was the main loading which caused the lateral vibration induced by pedestrians.

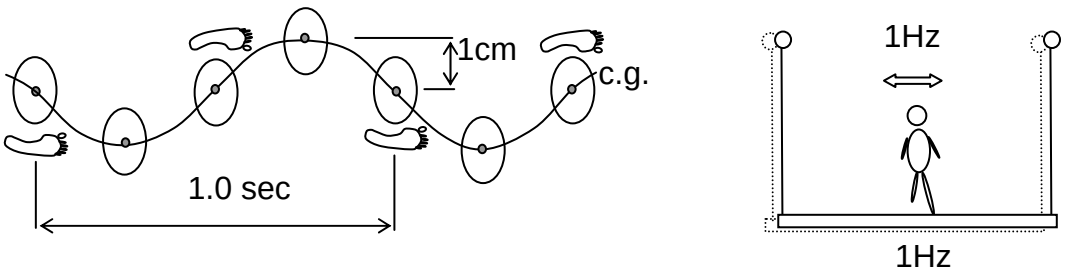

Figure 12. Mechanism of lateral vibration induced by pedestrians

INTERACTION BETWEEN PEDESTRIANS AND GIRDERS

However, if pedestrians walk randomly, the lateral dynamic forces would have different phases and be canceled. One more thought was needed to solve this phase problem. It is then assumed that, when people walk on a vibrating deck, they adjust their walking to the movement of the moving deck. When the deck moves to the right, the person would also move to the right and step in with his right foot. When the deck moves to the left, the person would also move to the left and step in with his left foot. In this way, pedestrians would synchronize themselves to the bridge vibration.

Fujino et. al set a video camera in the building adjacent to the bridge and recorded the movement of the pedestrians (Fujino *et al.* 1993). Pedestrians were randomly selected and the lateral motions of their heads were digitized on the monitor by a microcomputer (Figure 13). The traces of the two head motions were amazingly similar and they moved with exactly the same frequency and phase. This supports strongly the assumption that synchronization of pedestrians occurred on the T-bridge. However, the phase difference between the girder and the pedestrians was not clarified.

When pedestrians walk randomly, the lateral dynamic forces would have different phases and be canceled. It was confirmed on the T-bridge that some of the pedestrians walked together with the same frequency and phase. However, the phase difference between the girder and the pedestrians was not found. Figure 14 shows the lateral displacements of the M-bridge girder at the L/4 position and the pedestrian, when the pedestrian walked through the L/4 position. This clearly shows that the pedestrian walks with the same frequency of the girder, which is also confirmed by spectral analyses. This proves that the pedestrian synchronizes to the vibrating girder. The maximum displacement of the pedestrian is 43mm, which is much larger than the girder displacement of 24mm. It is also understood from Figure 14 that the pedestrian's phase is between 120 and 160 degrees ahead of the girder. External forces supply energy to excite a structure when the forces' phase is between 0 and 180 degrees ahead of the structure.

Figure 15 shows the measured lateral response of the M-bridge when the girder displacements reached about 45mm, which was one of the maximum amplitudes among the measured cases. The pedestrian walked through the L/4 position in this case. The pedestrian was tuned with the girder vibration in the first part of this record, but was not tuned after that. It seemed that the pedestrian lost balance and stopped walking temporarily at this point because of the large girder movement. When he resumed walking, he was tuned with the girder again. These "tuned" and "not tuned" conditions appeared repeatedly. The pedestrians' displacements are about 40mm and are almost the same as that in Figure 14, where the maximum girder response is 24mm. This indicates that the excitation force does not increase further when the girder vibration becomes very large, and the girder response converges to a certain level. Therefore, this lateral vibration is not a divergent type of vibration.

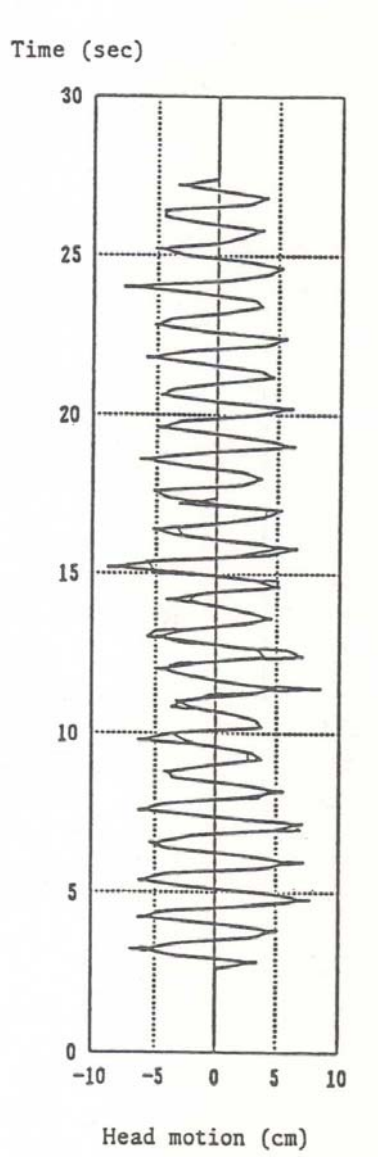

Figure 13. Head movements of two pedestrians on T-bridge

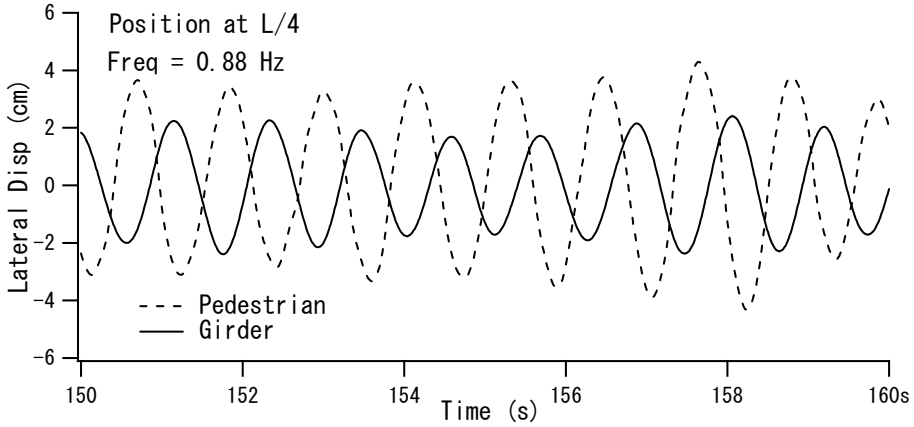

Figure 14. Measured interactions between the pedestrian and the girder on M-bridge

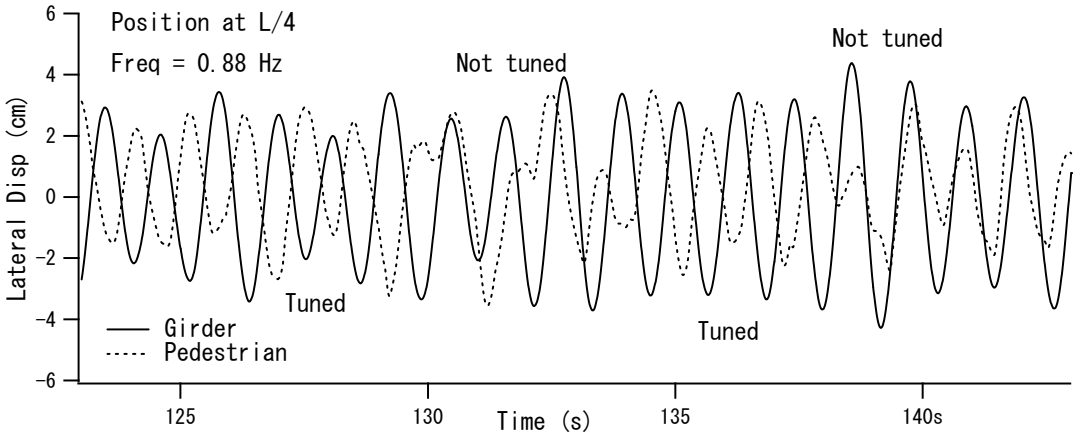

Figure 15. Measured interactions between the pedestrian and the girder on M-bridge

Figure 16 and Figure 17 shows the lateral displacements of the girder, the cable and the pedestrian on the W-bridge. They also show that the pedestrian walks with the same frequency of the girder proving that the pedestrian synchronizes to the vibrating girder. It is also understood from Figure 14 that the pedestrian's phase is about 120 degrees ahead of the girder.

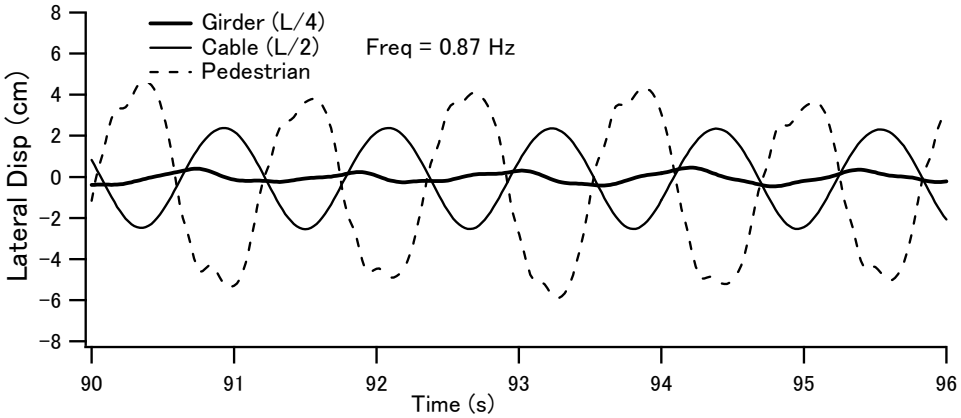

Figure 16. Measured interactions between the pedestrian and the girder on W-bridge

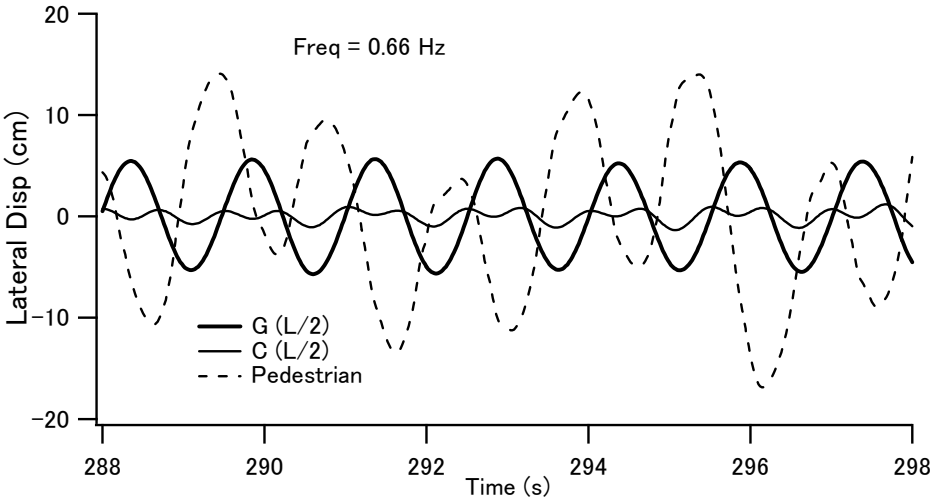

Figure 17. Measured interactions between the pedestrian and the girder on W-bridge

EVALUATION OF SERVICEABILITY FOR LATERAL VIBRATION

Observing the pedestrians' behavior on the T-bridge and the M-bridge, pedestrians feel the vibrations and some of them become uncomfortable when the girder vibration amplitude is about 10 mm (equivalent to a velocity of about 60 mm/sec and an acceleration of about 300 mm/sec^2). But, most of them can walk normally. At an amplitude of about 25 mm (equivalent to a velocity of about 140 mm/sec and an acceleration of about 750 mm/sec^2), some pedestrians have difficulty in walking at a normal pace and touch handrails from time to time. At an amplitude of 45 mm (equivalent to a velocity of about 250 mm/sec and an acceleration of about 1,350 mm/sec^2), people often lose balance and some of them stop walking temporarily to support himself. Some of the senior people are unable to walk. At an amplitude of 70 mm (equivalent to a velocity of about 450 mm/sec and an acceleration of about 2,100 mm/sec^2) occurred on the London Millennium Footbridge, it was reported that many people felt unsafe and were unable to walk.

Table 1. Evaluation of serviceability for lateral vibration (Nakamura 2003, Nakamura *et al*. 2006)

Displacement (cm)	Velocity (cm/s)	Acceleration (cm/s^2)	Evaluation of serviceability
1.0	6	30	Pedestrians notice the vibration but do not care and walk naturally.
2.5	14	75	Some pedestrians feel difficulty in walking naturally and touching handrails.
4.5	25	135	Pedestrians cannot walk naturally. Some of them lose balance or stop walking.
7.0	45	210	Walking is dangerous and a bridge should be closed.

Setra guideline proposes the four comfort level for lateral vibrations induced by pedestrians as follows (Setra 2006).
Level-1: Maximum comfort, acceleration less than 0.15m/sec^2, pedestrian does not feel the vibration
Level-2: Average comfort, acceleration 0.15-0.3 m/sec^2, pedestrians slightly notice the vibration
Level-3: Minimum comfort, acceleration 0.3-0.8 m/sec^2, pedestrians notice the vibration but can endure it
Level-3: Uncomfortable, acceleration over 0.8 m/sec^2

Comparing the observation on the three bridges and the Setra guideline, the girder amplitude about 10 mm (equivalent to a velocity of about 60 mm/sec and an acceleration of about 300 mm/sec^2) would be the serviceability limit from a conservative point of view. It could be judged in some cases that the girder amplitude of about 25 mm (equivalent to a velocity of about 140 mm/sec and an acceleration of about 750 mm/sec^2) would be the serviceability limit. If the girder vibration exceeds this limit, counter measures would be required to reduce the vibration amplitude

CONCLUSIONS

Field measurements were carried out on the three cable supported bridges which were excited laterally by the pedestrian induced forces. The mechanism of this vibration, interaction between pedestrians and the girder, and the serviceability limit states were clarified.

Results of field measurements:

On the T-bridge the girder lateral displacement during the congested period was a clear sinusoidal wave with amplitude of about 8mm and with a frequency of 0.93Hz. This corresponds to the first symmetric mode of the girder.

On the M-bridge the lateral displacements on the L/4 position show near sinusoidal waves with a maximum amplitude of 24 mm and with a frequency of 0.88Hz. This corresponds to the third asymmetric mode of the girder.

On the W-bridge a group of 10 about people crossed the bridge in line with the same rhythm of 0.87 Hz and 0.66Hz, which correspond to the third asymmetric lateral mode and latter corresponds to the second symmetric lateral mode, respectively. The amplitude of the cable is larger than the girder at a frequency 0.87Hz , and that of the girder is larger than the cable at a frequency 0.66Hz.

Pedestrian forces and resonance with girder

The gravity center of the body moves laterally when a person steps in with his right and left foot in turn, which induces the lateral dynamic force. Frequency of this lateral loading is therefore about 1Hz. When this is close to the bridge lateral natural frequency, the pedestrian induced force can be a resonant force for the vibration of the girder.

Interaction between pedestrians and the girder:

On the T-bridge it was found that two pedestrians moved with exactly the same frequency and phase.

On the M-bridge the pedestrian walks with the same frequency of the girder, and the pedestrian's phase is between 120 and 160 degrees ahead of the girder.

On the W-bridge the pedestrian walks with the same frequency of the girder and the pedestrian's phase is about 120 degrees ahead of the girder.

Evaluation of serviceability for lateral vibration:

Observing the pedestrians' behavior on these bridges, the serviceability limit state is considered. Pedestrians feel the vibrations and some of them become uncomfortable when the girder vibration amplitude is about 10 mm (equivalent to a velocity of about 60 mm/s and an acceleration of about 300 mm/s^2). But, most of them can walk normally. At an amplitude of about 25 mm (equivalent to a velocity of about 140 mm/s and an acceleration of about 750 mm/s^2), some pedestrians have difficulty in walking at a normal pace and touch handrails from time to time. At an amplitude of 45 mm (equivalent to a velocity of about 250 mm/s and an acceleration of about 1350 mm/s^2), people often lose balance and some of them stop walking temporarily to support themselves. Some of the senior people are unable to walk. At an amplitude of 70 mm (equivalent to a velocity of about 450 mm/s and an acceleration of about 2100 mm/s^2), which occurred on the London Millennium Footbridge, it was reported that many people felt unsafe and were unable to walk. Therefore, the girder amplitude of about 25 mm (equivalent to a velocity of about 140 mm/s and an acceleration of about 750 mm/s^2) would be the serviceability limit.

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