Study of human induced vibrations in a footbridge

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INTRODUCTION

Calculations were carried out to study the dynamic behavior of a singular footbridge in Bilbao, Spain. The goal of the study was to analyze the dynamic response of the structure, forced by pedestrian loads, and to assess the results obtained by comparing them with acceptability criteria. In order to evaluate the behaviour of the structure, simulations were carried out in both the frequency and the time domain.

The dynamic analyses were performed during the design phase of the project; the structure is undergoing construction at the time of writing this article.

STARTING DATA

Structural Configuration

The footbridge is a 142 meters long and 7.5 meters wide arch, built of stainless steel. The main span is a beam, simply supported at the abutments and also by eight ramped accesses, which combine structural and functional objectives. The span and ramps are formed by a U-section, reinforced with plates in the corners. A concrete slab and transversal profiles complete the section.

Because of the limited bearing capacity of the piles in the ground, sliding bearings are provided at the ends of the span and the ramps, thus the structure is a portal bridge rather than an arch. The singular character and asymmetry of the structure leads to unusual three-dimensional responses, even when subjected simply to its self weight or the pedestrian induced loads. Figure 1 shows the modeled geometry of the footbridge.

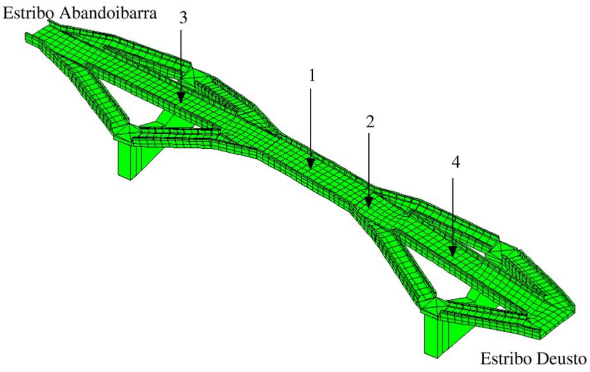

Figure 1: Geometry and discretization of the footbridge

Damping

Is well know that the damping ratio of the structure governs the response close to resonance. Generic coefficients are provided in the technical literature for different materials (Bachmann, 1995). However, this data may give only an initial estimation, because damping in the structure is often highly dependent on constructive details, like joints or boundary conditions.

Small damping can be assumed in metallic structures. In addition, in longitudinal structures damping ratio seems to decrease with length, for the same material (ERRI, 1998). On the other hand, the footbridge has a concrete slab and is supported on neoprene bearings, which can absorb some energy. After these considerations, damping ratio was assumed to be 0.5% for all the vibration modes.

Loads

In this kind of problems, the design demands are not obvious and need to be clarified at the outset.

Human step loads have been widely characterized with Fourier series for a single man actions, giving for different activities the corresponding amplitudes, frequencies and lag between harmonics.

The amplitude of the load is not the complete self weight of the pedestrian, but a fraction of it. This value may change with the activity (walking, running, ...), thus the applied load was scaled differently for every frequency (Bachmann, 1995).

Of special importance is the correlation between loads when various pedestrians are acting simultaneously. In a first approach the loads of different pedestrians can be assumed to be independent, thus the variables being uncorrelated. If it is the case, the resulting force is proportional to the square root of the number of pedestrians (Bachmann and Ammann, 1987). Further studies showed that there is some degree of synchronization in the walking of pedestrians with the structures (Fujino et al., 1993). In such situation, the resultant is proportional to the number of pedestrians.

As the higher the stiffness of the structure, the lower the synchronization between walkers, small synchronization is expected in a heavy and stiff structure like the present.

Acceptability Criterion

The human sensitivity to acceleration is dependent on the frequency of the action and also on the activity. Fortunately, some standards give an estimation of what can be considered as an acceptable acceleration. Following the code ISO 10137, a limit of g/20 was assumed to be comfort threshold of vertical acceleration for pedestrians.

MODELIZATION

Since the structure presents a three dimensional structural behavior, a three dimensional finite element was built. Span and ramps were modeled with shell elements, whereas reinforcement frames were build with beams. Some springs were provided at bearings, taking into account for the flexibility of the foundation piles. The dynamic calculations were carried out using the code ABAQUS/Standard (HKS, 2001).

Dynamic characterization

Total mass and stiffness of the footbridge were available in the design documentation of the footbridge. These data were used to calibrate the sophisticated finite element model. Once mass and stiffness were checked, the vibration frequencies and modes were extracted.

Since resonance occurs at the frequency of the forcing action, the modes of interest are those whose frequencies are bellow 4.0 Hz. These modes are depicted in Figure 2.

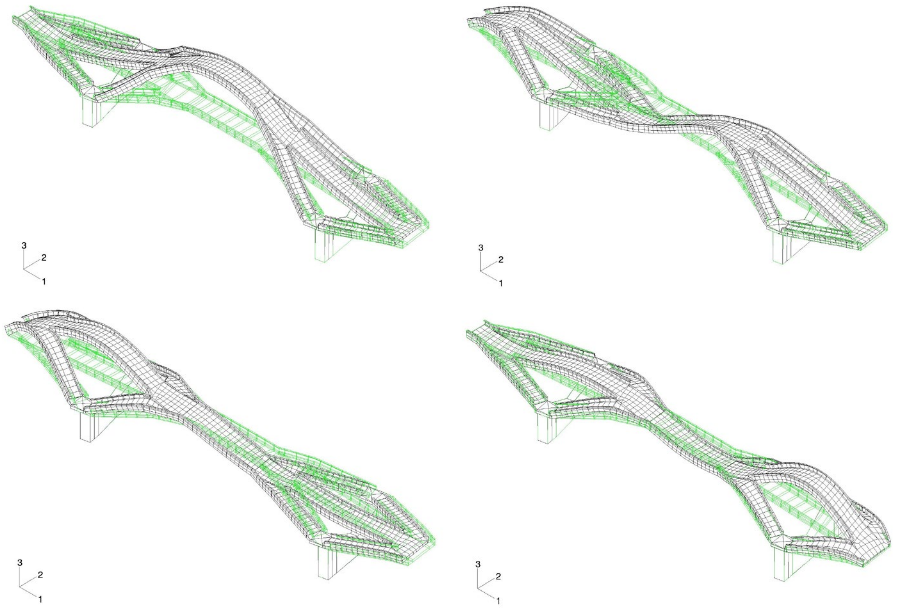

Figure 2: Vibration modes and frequencies (1.34, 2.47, 2.80 and 3.47 Hz)

Human Loads

Steady-state loads were applied in some locations of the footbridge, labeled from 1 to 4 in Figure 1. The most convenient numerical procedure is to solve the problem in the frequency domain. A swept was done for a wide range of frequencies, giving the dynamic amplification of the acceleration for the oscillating load.

The numerical procedure used consists on projecting the solution on a reduced modal basis of 50 eigenvectors, which gives very fast and accurate solutions.

If we consider the scenario of one pedestrian walking on the footbridge, the solution obtained in the frequency domain can be considered as conservative for two reasons: (1) the load acts for a limited time, so maybe the steady-state would never be reached, and (2) the influence of a moving load is not all the time as important as at mid-span.

Therefore, a moving load was simulated on the model, oscillating at the frequency of interest. This time domain analyses can somehow evaluate the safety factor of frequency domain analysis.

RESULTS

Steady-state accelerations for a single man action are depicted in Figure 3. It can be shown that there is no amplification in the range 1.8-2.2 Hz, where most of actual loads are applied.

Very infrequent, but perceptible accelerations can occur if the footbridge is loaded at higher frequencies, corresponding to more energetic activities than walking, such running or jumping. It can be seen that only the acceleration related with the 4th mode frequency is above the comfort threshold.

Time domain analyses showed that the safety factor due to the non-stationary conditions is low, thus the steady-state amplifications are reached soon.

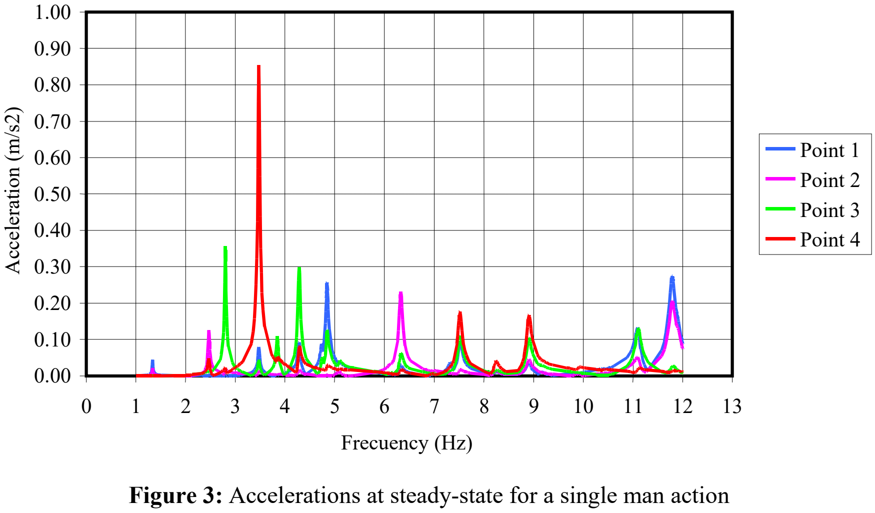

Figure 3: Accelerations at steady-state for a single man action

Steady-state accelerations for a single man action can reach the comfort threshold, but only in very singular cases. For multiple pedestrian load cases, most of the actions will be around 2.0 Hz. Only a few people might force the structure at these unusual resonant frequencies. In this case the acceleration could reach values higher than the obtained.

The response of the structure can be improved easily with vibration absorbers, tuned to the optimum frequencies. Classical formulas extracted from the literature (Den Hartog, 1956) were used to pre-design four Tuned Mass Dampers (TMD), placed in points 1 to 4 in Figure 1. Table 1 shows the calculated parameters.

Vibration mode of the footbridge	1	2	3	4
Frequency (Hz)	1.34	2.47	2.80	3.47
Modal mass (kg)	449,000	100,000	161,000	246,000
Optimum frequency of TMD (Hz)	1.337	2.445	2.782	3.456
TMD mass (kg)	1000	1000	1000	1000
Stiffness of TMD springs (kN/m)	70	235	305	470
Optimum damping in TMD springs (%)	2.88	6.03	4.78	3.88

Table 1: TMD pre-design parameters

Once the TMD parameters were obtained, they were also included in the finite element model. Every TMD was represented by mass, spring and dashpot elements with the properties presented in Table 1.

Then, extraction of vibration modes and frequency domain analyses were repeated. The new values of amplifications are presented in Figure 4.

It can be seen that the peaks are split and the magnitude is reduced more than a half. The new accelerations remain below 0.5 m/s^2 in all the frequency range.

The induced split moves the location of the peaks, but it can be seen that no resonance is induced in the 2.0 Hz environment.

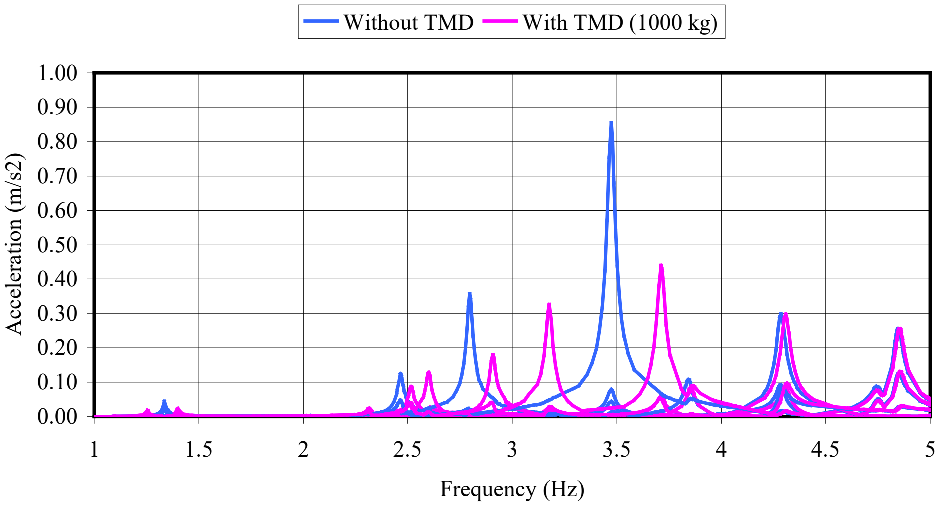

Figure 4: Accelerations with and without TMDs

Finally, the sensitivity of the results with the TMD masses was assessed. Analyses with values of 500, 1000 and 4000 kg were carried out. The results showed that an increase in the TMD mass leads to a small reduction of the peak magnitude. However, it sharps the peak, thus reducing the range of amplification. For the sake of illustration, comparisons for different values of mass for the TMD placed at point 4 are showed in Figure 5.

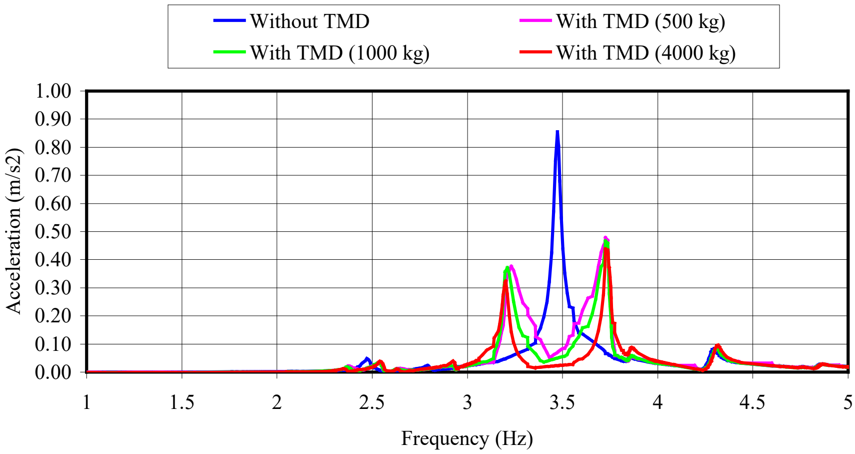

Figure 5: Gains for different values of TMD mass

CONCLUSIONS

A complete study has been carried out in order to assess the dynamic behavior of a footbridge during the design phase. The conclusions extracted from the work conducted are:

- The footbridge has no vibration frequencies in the range 1.8-2.2 Hz, that ensures a good performance when subjected to usual walking loads, even in multiple load cases.
- Amplifications remain always below the comfort threshold, except for a forcing frequency of 3.5 Hz, which is very infrequent.
- The placement of TMDs in the structure reduces the amplifications in infrequent load cases, dividing the acceleration by a factor of two. The effect of increasing the masses of the TMDs is to reduce the range of the amplifications, rather than lower the peaks.

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