SEQUOIA

SMART SOLUTIONS FOR VIBRATION MONITORING

CASE STUDY

GEA FOR ADVANCED STRUCTURAL DYNAMIC ANALYSIS

ANALYSIS OF CIVIL STRUCTURES - EXPO MERLATA PEDESTRIAN BRIDGE

ABSTRACT

Civil structures and in particular bridges and footbridges, in the testing phase, must be verified by not only static but also dynamic point of view. GEA System is able to meet the dynamic requirements, especially as regards the analysis of structural damage and human comfort. It is very well suited in those cases where there is a need to monitor works that have a linear development, thanks to the possibility of using very long cables and synchronize up to 16 sensors with just one central unit.

An application of the GEA System, regarding the monitoring of vibrations induced on the main EXPO Milan Pedestrian Bridge of Cascina Merlata, which stands above both the railway line and the highway, is shown here.

The customer, in testing phase, had the need to use the GEA System to perform some tests of dynamic characterization, in order to identify the main frequencies, eigenmodes and damping of the structure in question.

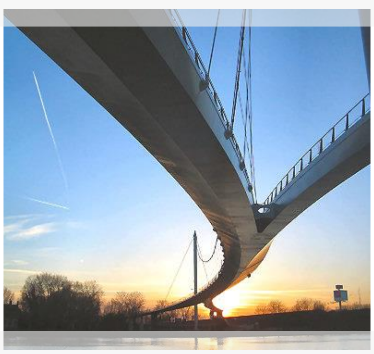
Through the support of Sequoia IT's staff, the customer has been facilitated in the execution of standard procedures for a better data acquisition.

The tests were carried out by testing separately two spans of Cascina Merlata Pedestrian Bridge, through the use of six GEA sensors and supplied long cable.

MODAL ANALYSIS

BACKGROUND

Modal analysis is the study of the dynamic properties of structures under vibrational excitation. In structural engineering, modal analysis uses the overall mass and stiffness of a structure to find the various periods at which it will naturally resonate. These periods of vibration are very important to note in earthquake engineering, as it is imperative that a building's natural frequency does not match the frequency of expected earthquakes in the region in which the building is to be constructed. If a structure's natural frequency matches an earthquake's frequency, the structure may continue to resonate and experience structural damage.



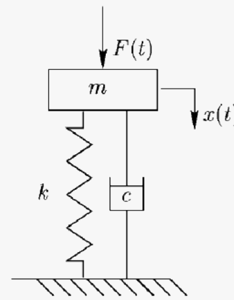
DYNAMICS OF FOOTBRIDGE AND HUMAN INTERACTION

Pedestrian loads are difficult to model because of their hazardous aspects: weight of the pedestrians, walk velocity, number of pedestrians, distribution of the pedestrians over the bridge etc. Vibrations of a footbridge can have influence on pedestrians in such a way that pedestrians have to adjust their pace or feel uncomfortable.

Footbridges as oscillators

A footbridge can only act as an oscillator if dynamic load is applied. A dynamic load is a load that varies over the time, in contrary to a static load which stays constant over the time.
An oscillator can have one or more degrees of freedom (DOF).

Generally, an oscillator with one DOF can be represented as shown in the figure.
It behaves according to the follow second order differential equation, which is an important formula for dynamics:



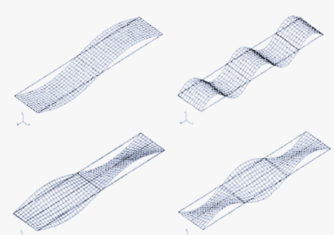
$$m\ddot{x}(t) = c\dot{x}(t) + kx(t) = F(t)$$

where *F(t)* represents the external force on the footbridge (e.g the pedestrians walking, the wind, etc.) variable in time; *m* the mass of the footbridge; *k* the stiffness of the main girders of bridge; *c* the damping of the structure and *x(t)* the displacement of the mass in the time.

Natural vibration modes

A mode of vibration is a characteristic pattern or shape in which a bridge vibrates. Footbridges can have many vibration modes which can be determined by a modal analysis. The actual vibration of a footbridge is generally a combination of all the vibration modes.

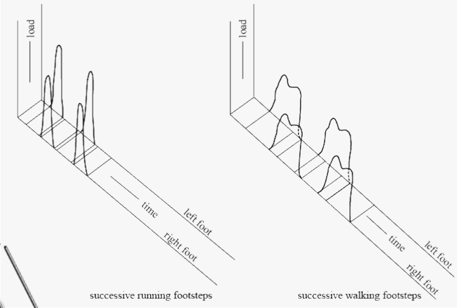
Generally, a bridge will get in the vibration mode that requests the less energy, coming from pedestrians. Energy can also have other sources, like wind. Each vibration mode has its own natural frequency. Thus, one could state that the vibration modes which natural frequency lies in the range of the one of pedestrian loads is the most susceptible to occur.



Forces induced by pedestrians

The center of gravity of the human body is located at about 55% of its height and makes a sinusoidal motion during walking, both in vertical and horizontal directions. The force thus has three components: a vertical, a longitudinal and a lateral. The vertical component is the largest: up to 40% of the body weight. The lateral and longitudinal components are considerably smaller.

Walking, running or jumping each produce a different loading curve over time as well as frequencies in which the oscillations can occur.
During normal walking the vertical forces are centered at a frequency in the range of 1.3 - 2.4 Hz, corresponding to the pace rate. For running the frequencies lie in the range 2 – 3.5 Hz, according to a research of Matsumoto (1978).



Synchronization between bridge and pedestrian

Synchronization between pedestrians and the structure is called Lock-in. It expresses the phenomenon by which a pedestrian crowd, with frequencies randomly distributed around an average value and with random phase shifts, will gradually coordinate at common frequency of the footbridge and enters in phase with the footbridge.

Lock-in in transverse direction is the most likely to occur and is also known as Synchronous Lateral Excitation (SLE). This is due to the fact that pedestrians are much more sensitive to lateral vibrations than to vertical vibrations.
A good example of a bridge on which such a phenomenon occurred is the Millennium Bridge in London, which vibrated severally laterally during opening in June 2000 when hundreds of people were walking over it.

Dallard et al. investigated the Millennium Bridge and concluded that during SLE the produced dynamic force by the pedestrians was proportional to the lateral velocity of the deck: $F_L(t) = kv_L(t)$. By investigating more bridges, he found out that SLE could occur to any bridges with a lateral frequency of 1.3 Hz under the condition that sufficient number of people would cross the bridge at the same time.

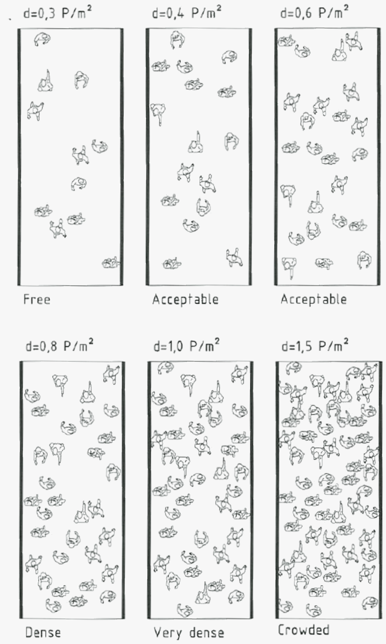
Interaction between pedestrians and footbridges

There is a certain interaction between pedestrians and the structure of footbridges. Two phenomena can be distinguished: one concerns the change of properties of the footbridge when humans are using the bridge; the other is the synchronization of the walking pattern between pedestrians and synchronization of humans with the structure, under certain circumstances.

A change in dynamic properties is the more likely to happen to light structures where human loading can have significant impact on the structure compared to a non-loaded structure: the mass and the damping can increase and thus this can have effect on the natural frequency of the footbridge.

Synchronization between pedestrians is mainly dependent on the pedestrian density on a footbridge. At low densities pedestrians are free to walk without obstacles (other pedestrians). When the path becomes denser, pedestrians are less free to choose their pace and adjust to the surrounding.

It becomes clear that synchronization of pedestrians is more likely to occur at higher densities, when people are not able to walk freely and are dependent on other pedestrians.



STANDARDS

The National Standards of each European country still prevails at the moment (e.g ISO 2631, DIN 4150, etc.).

However three parts of the Eurocode deal about pedestrian loads or structural requirements:
- Eurocode 0 (EN 1990:2002 “Basis of Structural Design”): Annex A2.4.3.2 gives the comfort criteria for pedestrians;
- Eurocode 1 (EN 1991-2:2003 “Actions on Structures”): paragraph 5.7 deals with pedestrian loads on bridges;
- Eurocode 3 (EN 1993-2:2006 “Design of Steel Structures”): paragraph 7.9 deals with the performance criteria for pedestrian bridges.

EXPO MERLATA FOOTBRIDGE

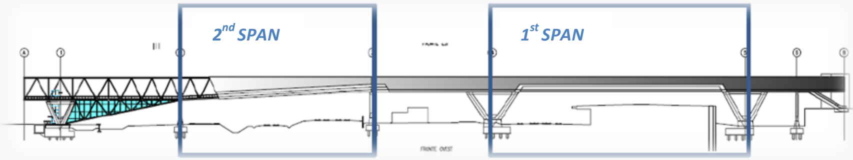
EMPLOYED METHODOLOGY AND INSTRUMENTS

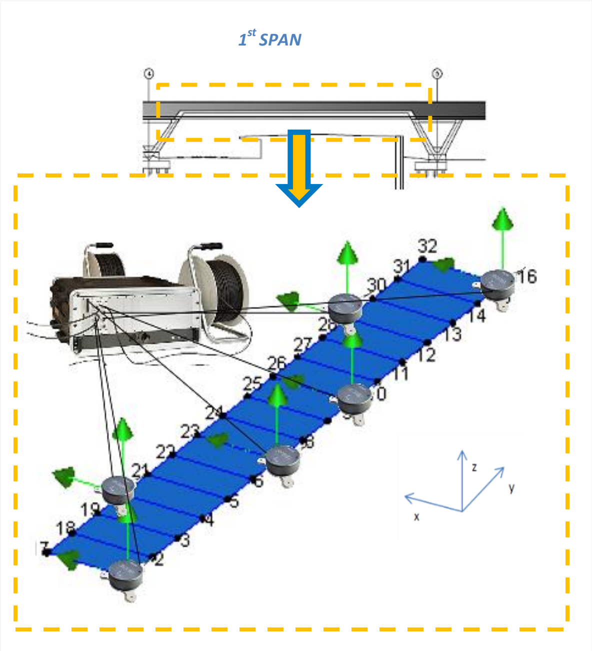
The dynamic characterization tests have been performed using accelerometer measurements and analyzing the data with OMA (Operational Modal Analysis) techniques.

Dynamic characterization tests have been useful in order to identify main frequencies, shape modes and damping of the structure in question. The tests have been carried out on two spans of the footbridge, highlighted on the right figure.

- The two spans have been tested separately and independently.

- On both spans, 6 digital triaxial accelerometer sensors model GEA have been positioned appropriately to provide a clear indication of the main vibration modes.





- The signal sampling in acquisitions was made at 1024 Hz, which is enough to acquire the data needed to evaluate the main frequencies of the structure, however, lower than 20 Hz.

- The structure was "excited" both by "environmental" vibrations such as the trains transit below, especially in the Span 1, and induced by the walking / running of employees on the structure.

- The synchronization among the six GEA sensors (<5 microseconds) is guaranteed by the measurement system that includes HubSync.

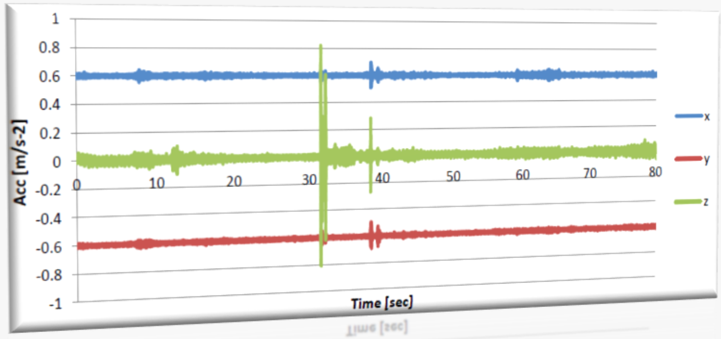
- The sensors, which weigh more than 500 g, were simply laid on the floor of the structure.

- The sensors have been placed at equally spaced points along the longitudinal axis of the span and on both sides to take into account possible torsional modes

EXAMPLE OF ACQUIRED DATA

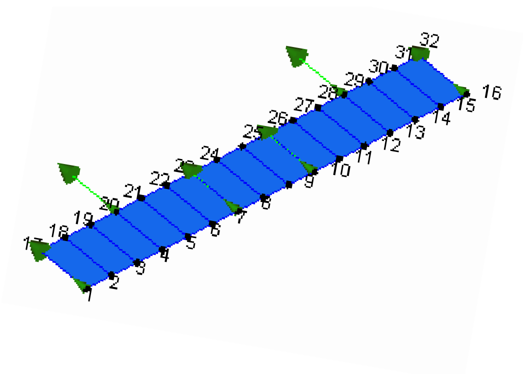
On the span in question many acquisitions have been made. Each one has had duration of about 100 seconds (enough to have a significant sample of data, in order to stabilize the results within the frequencies of interest).

In order to simplify the analysis and to identify the main Transversal modes, a subset of data corresponding to the horizontal accelerations measured has been used. To identify the main Vertical and Torsional modes the same procedure has been done.

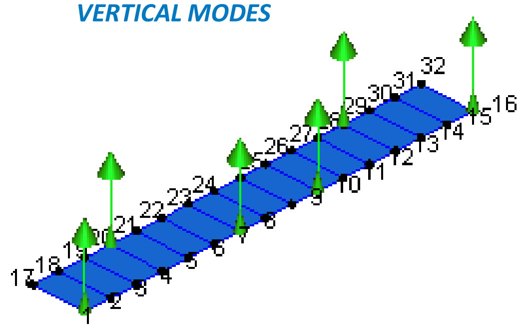


Spectral analysis has allowed to clearly identifying frequencies and main modal shapes.

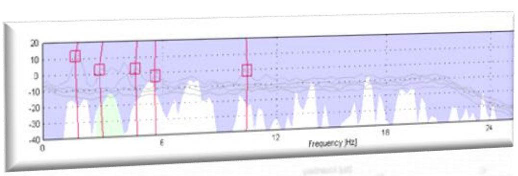
TRANSVERSAL MODES



VERTICAL MODES



FREQUENCIES



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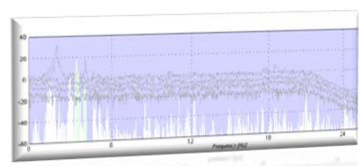
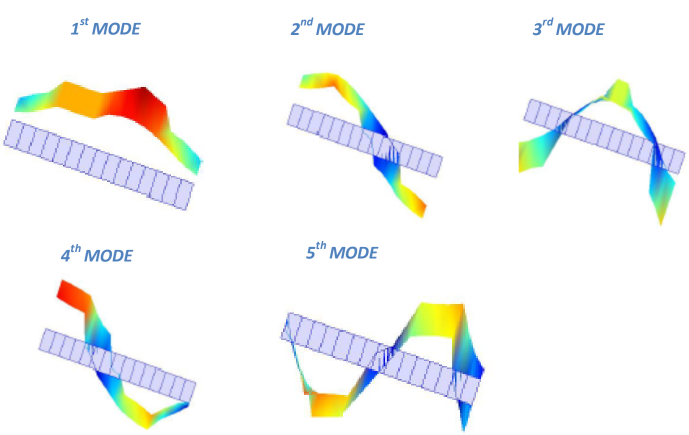


MODAL SHAPES



MODAL SHAPES