

# Vibration and Damping of Steel Constructions

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## Abstract

Modern steel constructions are designed with slender proportions in order to reduce material consumption or to meet architectural trends. Sensitivity of such structures against vibrational response must be analysed in early design stages to ensure that additional masses and counter forces of damping devices can be safely borne.

**Keywords: Vibration, dynamic overload, fatigue, damping device, pedestrian bridge**

## 1. Introduction

Modern bridges, high-rise buildings, industrial facilities can be susceptible to vibration effects induced by dynamic influences such as wind, walking, running and bouncing of pedestrians, trains as well as cyclic loading. In addition to the static analysis dynamic calculations must be performed in order to estimate the dynamic response of the building. If vibration amplitudes exceed threshold values, damping devices represent an effective method to control accelerations. Energy introduced to structures from dynamic loading is transformed into vibration. Especially in case of structures designed with respect to economical use of materials or to specific design requirements, uncomfortable vibrations may occur. The properties of modern materials enable more and more slender structures, resulting in lower stiffness as well as in lower construction weight. Hence decreased stiffness shifts the characteristic frequencies of the structures towards levels that increase the danger of resonance excitement. Furthermore slenderness of modern structures reduces inertia resulting in smaller energy amounts necessary to initiate perceptible vibration. In case of resonance and weak damping structural damage may occur due of dynamic overloading or fatigue failure.

Typical vibration-sensitive structures are high-rise buildings, towers and pylons, chimneys, antenna and bridge constructions. Solely wind-induced vibration has to be taken into account for tower-like structures. Traffic-induced vibrations need to be considered in combination with wind forces for bridge constructions. Especially pedestrian bridges are habitually excited by traffic-induced vibrations. Dynamic loading is generated by walking and running as well as bouncing, whilst load sequences of cyclists are nearly negligible. Bouncing persons trying intentionally to induce vibration to the structure represent a special risk.

Not only main beams are subject to dynamic loading. At cable stayed bridges and suspension bridges also pylons and cables can be excited to vibration. Besides bridges large span floor systems in office buildings or sport halls or long flights of stairs are susceptible to vibration effects.

## 2. Damping with mass-springs-damper devices

Mass-spring-damper devices can highly improve structural damping if they are appropriately adjusted to natural frequencies and damping properties of the structure. Typical devices consist of additional masses that are connected to the vibrating structure with springs. Such tuned mass damper systems introduce counter forces to structures and reduce vibration amplitudes. A damping device gets activated by dynamic loads, while the movement of the construction is damped. High damping is desirable in order to cause a vast decrease of the residual oscillations as well as to damp a broader range of frequencies.

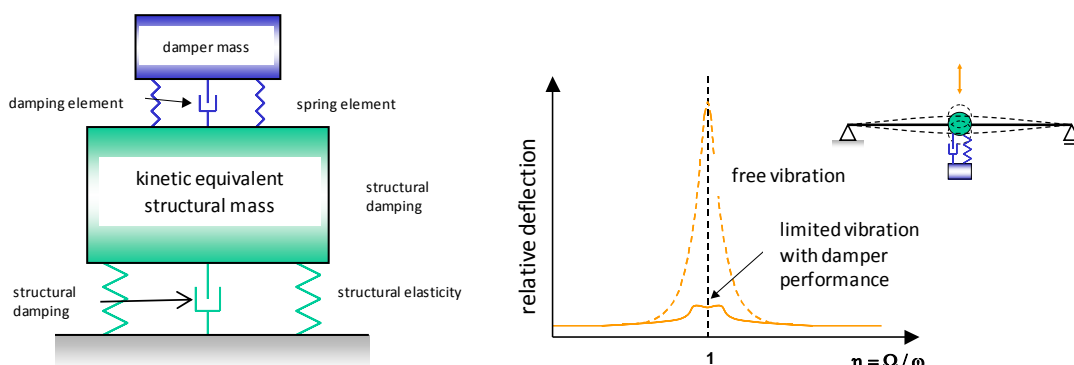


Fig. 1 Operating mode of a mass spring damping device

For this purpose different materials and systems have been developed such as elastomeric materials, frictional sliders or viscous fluids, which change the kinetic energy into heat. A recent development of viscous dampers is the electrical control for adjustment of the damping behaviour.

The general aim is to reduce the vibration of a certain characteristic frequency. Damping of diverse frequencies requires separate dampers. The operating mode of a mass spring vibration damper is depicted schematically in Fig. 1.

Usually the mass-spring-damper systems are characterised by tuned damping masses adjusted to the kinetic equivalent mass of the structure and by an optimized selection of springs with defined spring properties. Damper units should be placed at locations where maximum amplitudes of the considered mode shapes appear. A damper system will operate more effectively with large damping masses in relation to kinetic equivalent mass of the structure. Reasonable ratios of damping masses to kinetic equivalent masses are in a range between 2% and 5%. A mass-spring-damper system is effective in a narrow range of frequencies only due to its technical layout.

### 3. Numerical assessment of the vibration sensitivity

A numerical estimation of the vibration sensitivity of structures can be accomplished with computational methods. Besides the calculation of the natural frequencies with corresponding modes shapes simulations of time-dependent effects of a group of pedestrians and the dynamic reactions of the structure are possible. The procedure of a numerical vibration analysis is demonstrated for the Neulandbrücke in Leverkusen (Fig. 2). The construction has three spans, one centre span of 45m and two end spans of 39m. The main structural system consists of curved truss girders with pipe profile. The bridge deck is built as orthotropic plate that is connected in different heights due to the curved structure of the main girders (Fig. 2). In the plan view the bridge axis also features a curved line.

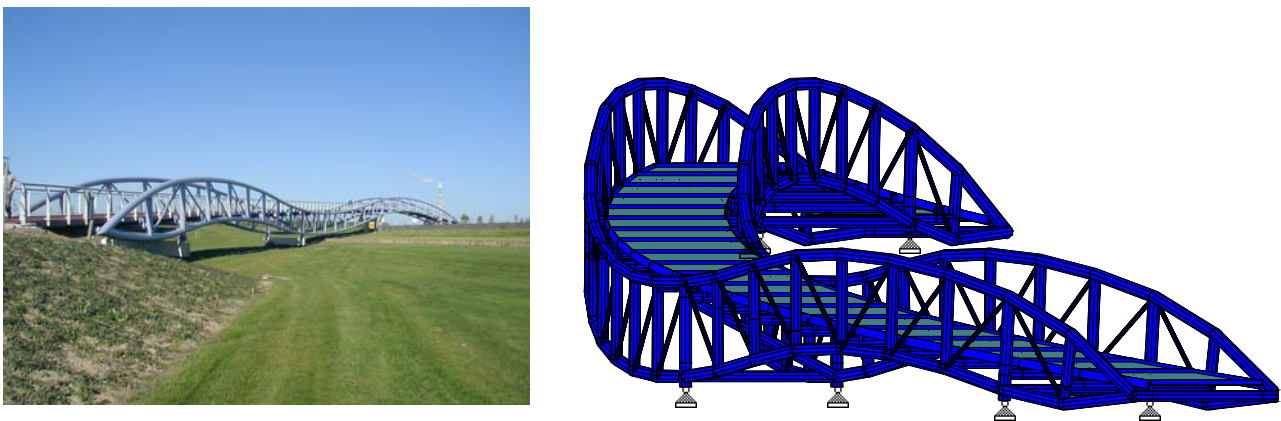


Fig. 2 Neuland Bridge (Leverkusen - D)

The first calculation step contains the modal analysis to ascertain the characteristic frequencies including the corresponding mode shapes. Mass participation factors are determined by a numerical calculation (Fig. 3). These allow an estimation of vibration intensities for the natural frequencies as well as a designation of corresponding translation directions.

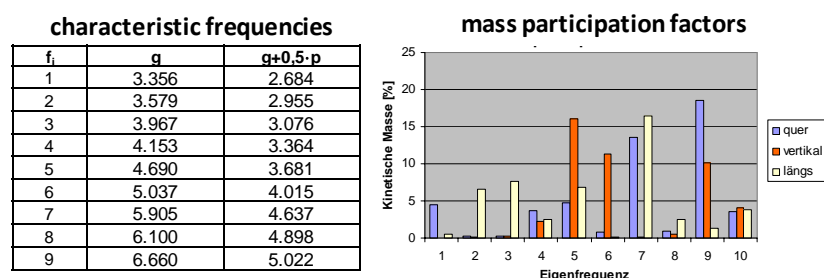


Fig. 3 Calculated characteristic frequencies and mass participation factors of Neuland Bridge

One essential demand for the dynamic evaluation of pedestrian bridges is the estimation of expected accelerations induced by the action of pedestrians. The accelerations are usually used as criterion for a decision whether an adequate reduction of the vibration can be achieved by the structural damping or additional damping measures are necessary. Based on scientific research of biomechanics of walking and running realistic load functions can be formulated to calculate response by means of a time-history-analysis. Time-dependent translations, velocities and accelerations for all

directions of each arbitrary node of the model can be calculated. Accelerations for all directions due to synchronous walking with a pedestrian distribution equivalent to  $0.375\text{kN/m}^2$  and a step-frequency  $2.0\text{Hz}$  are exemplarily shown in fig. 4. Response spectra reveal that 4<sup>th</sup> and 5<sup>th</sup> characteristic frequencies are excited whilst first three mode shapes contribute marginally to vibration. The maximum value of the acceleration in vertical direction is  $a_v = 0.76\text{m/s}^2$ . The lateral acceleration reaches  $a_q = 0.16\text{m/s}^2$ . The corresponding maximum vertical deflection amplitude in the evaluated mid-span location is  $z = 1.45\text{mm}$ . The maximum values of acceleration for the considered load combination permit the operation of the bridge without additional damping devices. Analogous to the described approach, further load combinations must be calculated for a comprehensive estimation of the dynamic properties. This initial analysis should be performed during the structural design phases for new constructions.

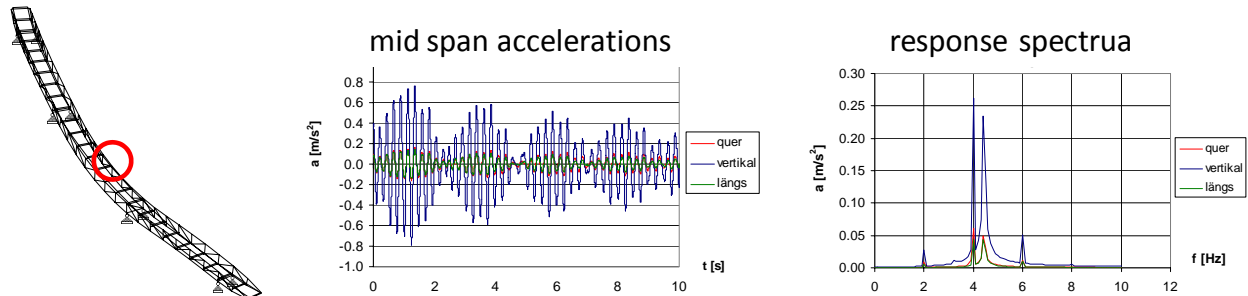


Fig. 4 Calculated accelerations and response spectra for 2 Hz excitation

#### 4. Damping against vertical vibration

Whereas in the Neuland Bridge no additional damping was necessary the surrounding conditions of the bridge in the next example required the installation of damper devices. The pedestrian bridge “de Abandoibarra” in the centre of Bilbao consists of a main beam with of 142m total length supported by sidewise spreading ramps (Fig. 5).

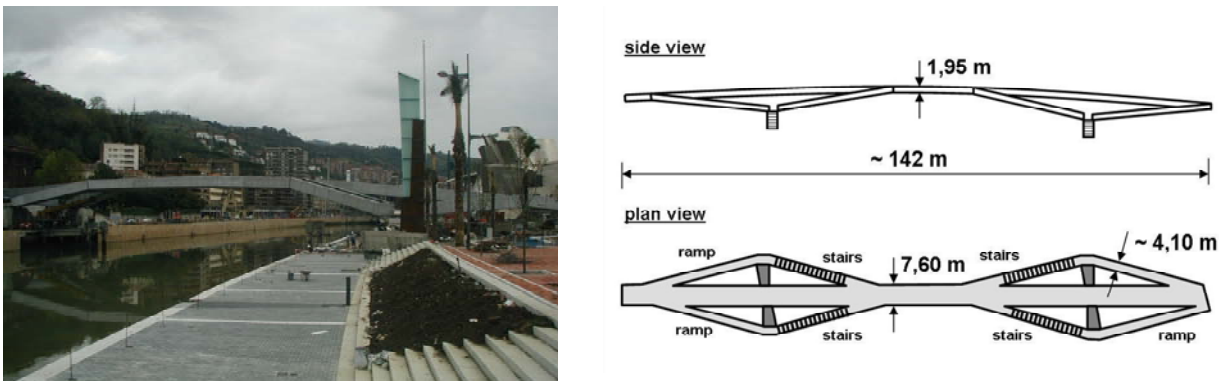


Fig. 5 Pedestrian bridge De Abandoibarra in Bilbao

The main beam and ramps with trough cross-sections are made of stainless steel. The complex structure with main supports at the ramp ends led to the decision to ascertain the vibrational characteristics using experimental procedures. The results of numerical analyses would be too uncertain for this construction with the intricate boundary conditions. Vibration measurements in a final construction phase provided information of characteristic frequencies and mode shapes including locations of maximum vibration amplitudes. In the response spectra of typical step frequencies from pedestrian walking, three vibration modes could be identified. The existing structural damping determined in the test program would be sufficient for a safe limitation of accelerations induced by usual walking.

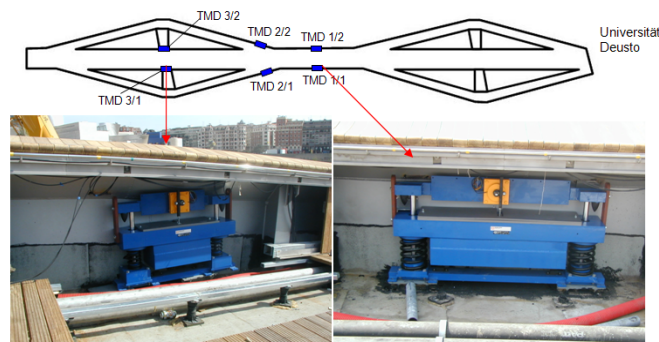


Fig. 6 Installation of damping units in the through walls

However the construction is located in the cultural centre of the city with the local special feature that during ceremonies for the victory of the regional professional football club fans celebrate on the canal bridge while players are passing by on a boat. Therefore a decision for dampers installation was drawn. The damping concept includes vertical vibration dampers in the walls of the trough cross-section that must be placed invisibly behind a continuous timber cladding influencing the design of the mass-damper components.

For each damped characteristic frequency one coupled damper set was installed in the middle of the bridge, in the ramp section and in a quarter point of the main beam. Vibration dampers with electric adjustment control were applied, which were developed by the company Maurer and Sons in Munich within the scope of a European research project. For a verification of damping effects, a second series of measurements was conducted after completing the assembling work. Series of measurements of the vertical accelerations in the middle of the bridge with the corresponding frequency spectra for synchronised walking with 20 test persons are exemplarily shown in figure 7. The first test was carried out with transportation lock of damper masses and later repeated test with operating dampers. The measuring records revealed a clear reduction of the vibration velocities under approximately identical test load sequences. Whereas the damped frequency  $f_1 = 1.8\text{Hz}$  is dominant in the frequency spectrum with blocked dampers, its intensity with active dampers is significantly reduced. The effectiveness of damping devices in other locations was evaluated with further local excitation tests.

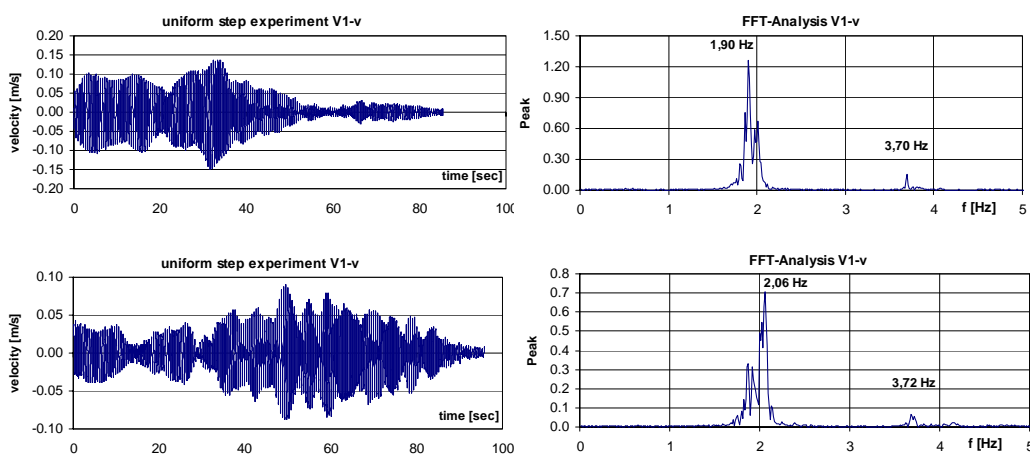


Fig. 7 Acceleration diagrams and response spectra for excitation with 20 Persons with blocked/released

## 5. Damping against horizontal vibration

In most cases vibrations of pedestrian bridges require vertical damping units. As an example for a bridge a necessity for horizontal vibration control, the damping concept of the pedestrian bridge Port Tawe in Swansea Great Britain is presented. Along with vibration excitation caused by lateral forces from pedestrians, vibrations induced by wind especially from the exposition to airflow from the open see, had to be considered. The bridge structure is a curved beam which is hanged to a slightly inclined pylon with cables in a harp layout (Fig. 8).

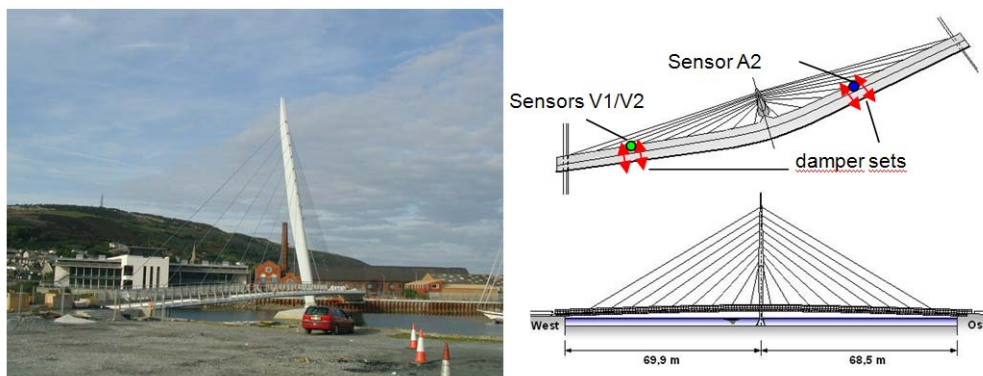


Fig. 8 Side view and main dimensions of the pedestrian bridge Port Tawe in Swansea UK

The total length of the bridge is approximately 140m. The cross section of the bridge is a trapezoidal hollow box of welded steel plates. Cantilever girders for support of an extra bike lane (Fig. 9) are fixed sidewise to the box section at the opposite side of the cable links to the main beam. Four horizontal damping devices with defined mass and adopted

spring constants were installed below the pavement in positions corresponding to fig. 8. Horizontally guided mass dampers (each 1,900kg) with four springs and a frequency tuning for  $f=1.22\text{Hz}$  were newly developed considering the narrow installation space (Fig. 9). The specified damping properties were supported by additional viscous damping elements after fine adjustment and testing in laboratory facilities at the University of Armed Forces in Munich.

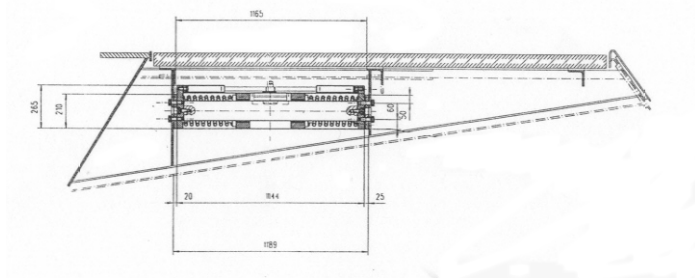


Fig. 9 Bridge cross-section in cantilever area



Fig. 10 Horizontal damping device

The damper design was carried out based on numerical modal analyses. These dampers were configured in a way that enables a later adoption by modifying the damper mass through supplementing or detaching steel plates in order to cover the differences between the numerically calculated natural frequencies and confirmed values of measurement series. The confirmation of the damper function had to be done on the bridge structure. The vibration excitation of the construction was obtained with a twitching test displacing the main beam of the bridge laterally with a cable winch followed by an instantaneous release. Therefore a notch with a defined failure force was installed into the pull cable. With this excitation combination of various release loads the characteristic frequencies with their vibration intensities could be determined as well as the structural damping behaviour. Tests were carried on with blocked and with operational dampers for comparison purposes. Examples of measuring curves of the acceleration with blocked and active dampers are graphically plotted in figure 11. Damping action can be clearly identified. The measuring location  $A_2$  is marked in fig. 8.

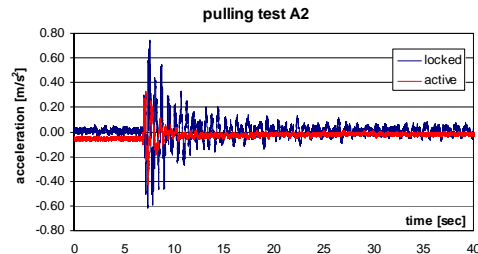


Fig. 11 Acceleration curves locked versus activated

For a verification of vibration analyses and an interpretation of measurement results, response spectra of the vibration velocities are depicted in fig. 12 for sensor  $V_1$  and in figure 13 for sensor  $V_2$ . The vibration intensities revealed an approximately linear relation to the excitation forces. The chart of the horizontal response spectrum in figure 13 confirms that the dominant horizontal fundamental frequency  $f_{1h}=1.25\text{Hz}$  could be effectively controlled.

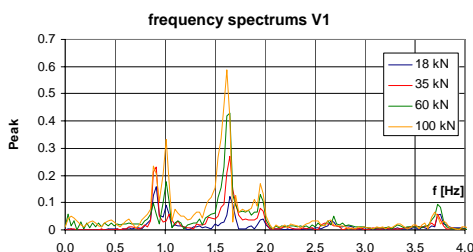


Fig. 12 Frequency spectra sensor V1

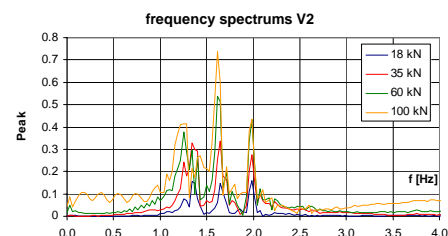


Fig. 13 frequency spectra sensor V2

## 6. Special structural features

Another category of vibration sensitive bridge systems covers cable-stayed bridges. As one example for this type of bridges theoretical and measuring vibration tests on the pedestrian bridge Bennauer Steg near Zurich in Switzerland are

explained. The construction consists of a main beam with a length of 82m that is hanged to an inclined pylon (figure 14 and 15).

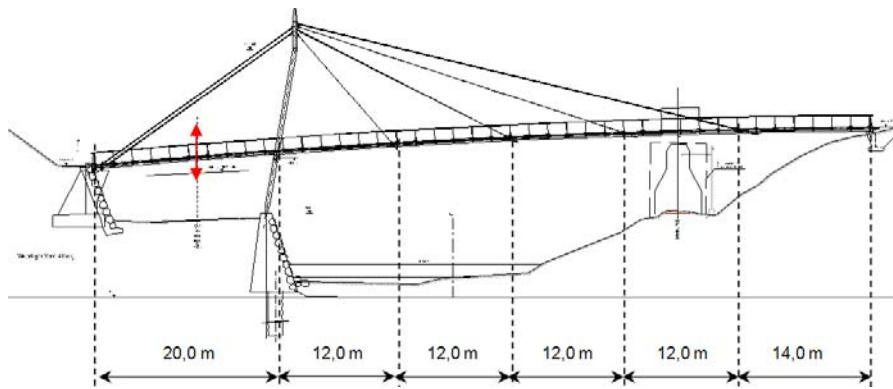


Fig. 14 Side view of Bennaer Steg with main dimensions



Fig. 15 Side view of Bennaer Steg

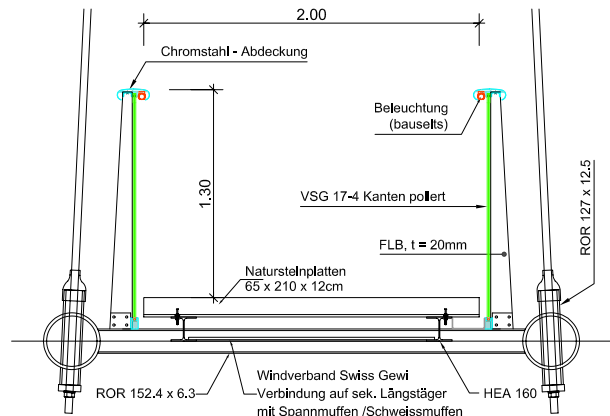


Fig. 16 Cross-section

The stiffening girder consists of two pipe profiles at the cross-section edges, which are linked with transverse girders in a distance of 2.0m. Auxiliary longitudinal girders of rolled steel profiles supporting the granite block pavement are placed on that. The balustrade is screened with laminated thermally-toughened glass (Fig. 16). Experimental vibration analyses and the evaluation of measuring results are demanding, since the frequency spectra of the evaluated measurement signal will be strongly overlaid by vibration behaviour of the cables. An interpretation of the measuring values is considerably eased by analytical examination of natural frequencies of cables depending upon the cable lengths and cable forces. Figure 17 covers some studies of natural frequencies of cables of the Bennaer Steg.

natural frequencies of cables depending on pre-stressing

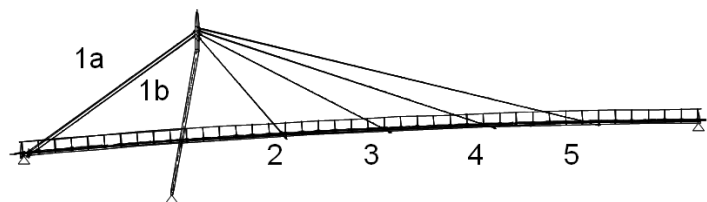
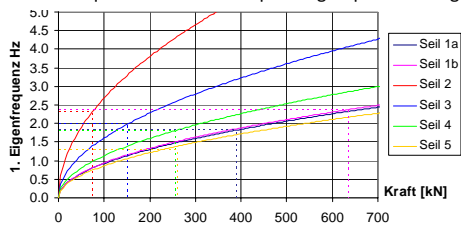


Fig. 17 Characteristic frequencies of cables depending on pull forces

One feature of the cables is generally that higher characteristic frequencies are multiple of their fundamental frequency. Hence it is possible to distinguish the vibration characteristics of cables in the frequency domain from the main beam properties. A short time range from an ambient vibration measurement (2s) with the corresponding frequency spectrum is depicted in fig. 18. The characteristic frequency of 1.6Hz with its multiples 3.16Hz, 4.78Hz, 6.44Hz and 8.12Hz can be assigned to cable vibrations, which influenced measurement recordings for the main beam. Further frequencies of 1.94Hz, 2.75Hz, and 3.83Hz can be associated with the main beam and the pylon.

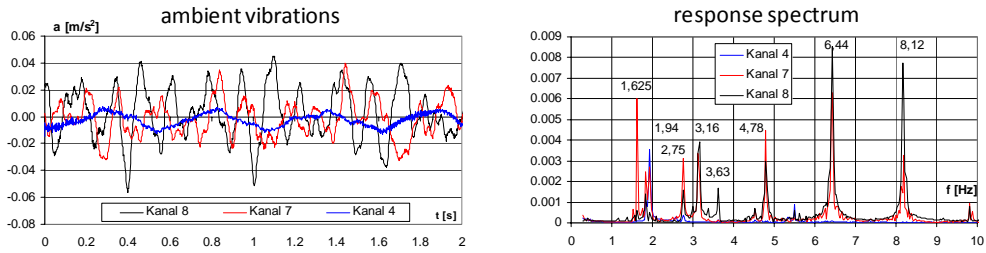


Fig. 18 Measuring curve of ambient excitation with response spectrum

Excitation tests with 13 persons walking on an effective frequency of  $f_e = 1.6\text{Hz}$  provide measurement curves as shown in fig. 19 after instantaneous termination of the excitation at the stiffening girder (canal 8) and at the pylon (canal 7). In the frequency spectra characteristic frequencies of cables with 1.6Hz and its multiples appear clearly. The amount of the acceleration amplitudes indicates a requirement for damping devices at stiffening girders as well as at cables.

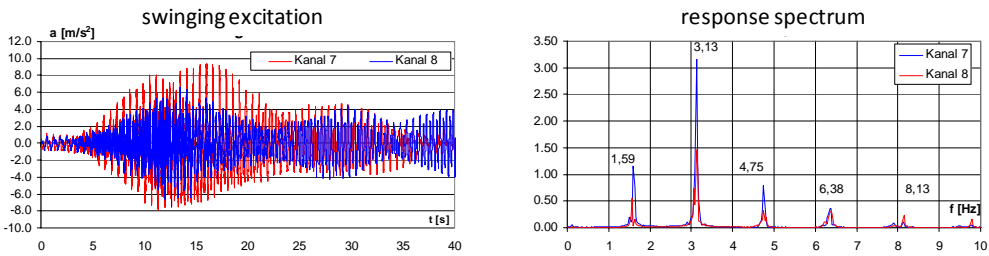


Fig. 19 Measuring curve of swinging excitation with response spectrum

Some examples of new bridge constructions with necessities of damping provisions are presented in the following sequence of figures.

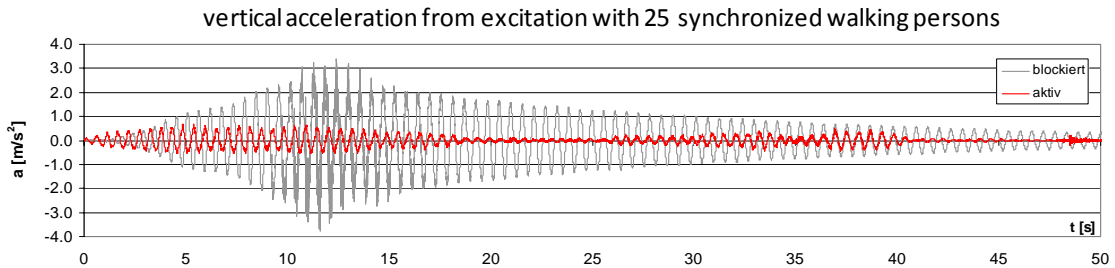


Fig. 20 Pedestrian bridge between Reichstag and Lehrter Bahnhof, Berlin/Germany



Fig. 21 European Patent Agency, Munich/Germany



Fig. 22 BMW-World, Munich/Germany



Fig. 23 Urstein/Austria



Fig. 24 Limassol/Cyprus

## 7. Summary

This article accounts for some typical structures that are sensitive against vibrational response. By means of some examples of pedestrian bridges damping concepts are presented and positive effects are outlined by means of measuring plots. Theoretical backgrounds are highlighted as well as methods for numerical analysis of vibrational properties of structures. A good match between simulation methods and experimental procedures is demonstrated. In the range of presented bridges structures with vertical sensitivities and with critical horizontal responses are selected. Secondary effects from special structural features on measured accelerations and velocities are explained by means of an example of a cable stayed bridge. Slender bearing structures should be evaluated against vibrational response in early design stages in order to ensure a safe bearing behaviour considering additional masses and counter forces of damping devices and to ensure an appropriate fatigue resistance.