Pitfalls in Structural Dynamics

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Excessive Vibrations from Weaving Machines

The building is a three storey concrete frame structure with a floor size of 22 m x 53 m. The girders of the first and second floor are of pre-stressed concrete. Load carrying shear walls existed only in the basement. It has been used to produce high quality textile filters for more than 30 years without any problems. 56 machines, each weighing 2.2 t, have been installed. In the course of time some walls have been removed to facilitate circulation. Then high speed weaving machines have been installed. At this point the horizontal vibrations reached an unacceptable level of almost 10 mm/s. The local engineer has been called in to reduce the vibrations.

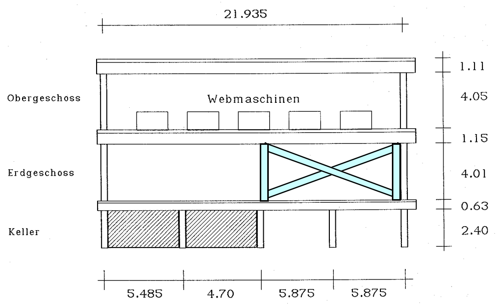


Fig. 1a Cross section of building, strengthened with steel trusses

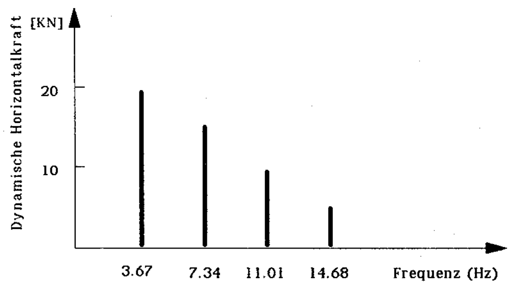


Fig. 1b Dynamic horizontal forces (assuming that 60 % of all weaving machines are in phase).

He decided to strengthen the building by some heavy I-shape steel trusses (size HEM 300) as shown in Fig. 1.a. The result was disastrous. Instead of a reduction this strengthening brought a doubling of the horizontal vibrations with peak horizontal velocities reaching 20 mm/s. Employees complained about sea sickness. Machines in the area of highest vibrations received no proper attention anymore.

What has happened? The building had - before strengthening with steel trusses – a second eigen-frequency in the order of 3 Hz, i.e. slightly below the main horizontal excitation of the weaving machines (see Fig. 1b). With the steel trusses the horizontal eigenfrequency increased and matched exactly the main excitation. The horizontal vibration amplitude doubled.

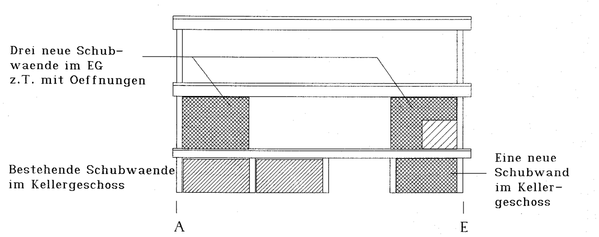


Fig. 1c Strengthening with four additional shear walls (cross section)

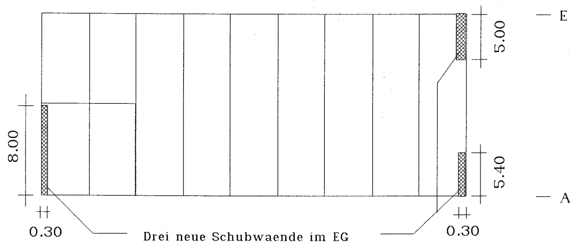
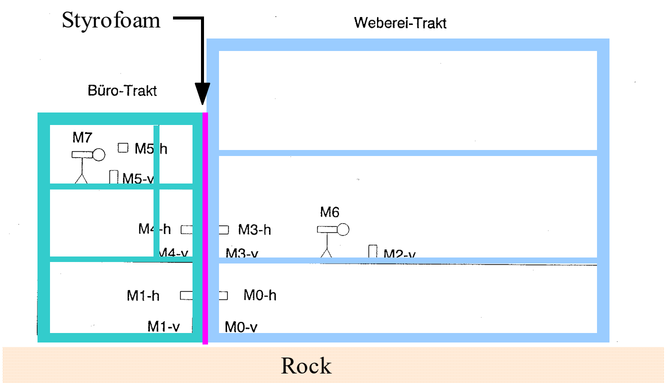
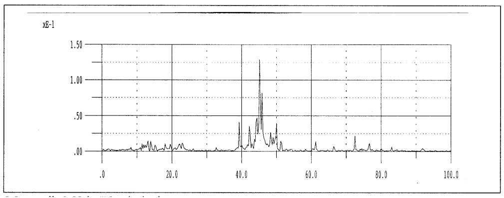
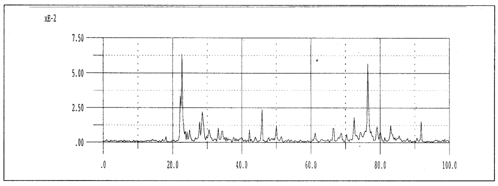
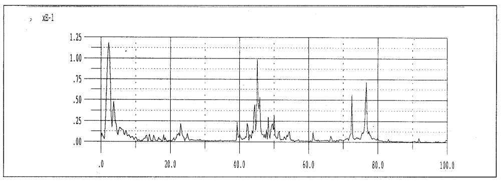


Fig. 1c Strengthening with four additional shear walls (plan view)

To cure the problem a dynamic FE analysis has been carried out to study the effects of three different strengthening layouts. Finally the solution shown in Fig.1c,d has been adopted. This solution carries the horizontal forces safely to the foundation and increases the eigenfrequencies and also the damping. The first horizontal eigenfrequency was calculated to be at 3.0 Hz, the second at 5.5 Hz. Thus the main excitation frequency of 3.67 Hz was between the two lowest frequencies and did not cause resonance. For higher excitation frequencies a coincidence with eigenfrequencies could of course not be excluded. A reduction of 80 % has been calculated for the frequency range of the main horizontal excitation (3.67 Hz). Measurements carried out after the strengthening showed that a reduction of slightly over 90 % has been achieved.

Structure born Sound in office building adjacent to production building	
A new office building has been erected adjacent to the already existing building for weaving machine production and testing. The production building contained showrooms to exhibit and demonstrate the latest of weaving machines. In the office building meetings with prospective clients should be held. Very soon it became clear that the noise level in the office building was just too high.	
 **Fig. 2a** Cross section of office building (left) and production building (right)	 **Fig. 2b** Spectrum for vibration of wall in meeting room  **Fig. 2c** Spectrum for vibration of floor in meeting room  **Fig. 2d** Spectrum for vibration of sound pressure in meeting room

The two buildings have their foundation on the same rock layer, giving the vibrations a good transmission path from one building to the other. Furthermore the isolation between the two buildings consisted of a layer of Styrofoam having a thickness of 15 mm. Actually the wall of the already existing production building has been used as halve of the formwork for the new office building.

Extensive vibration and sound measurements yielded the following results: The noise in the meeting rooms is clearly produced by structure borne sound. The spectrum of the sound pressure is – as can be seen from Fig. 2b to d – a superposition of the wall and floor vibration spectrum. The noise level in the meeting rooms was in the following range:

- Weaving machines in operation in production building: 51 to 53 dBA
- Only air conditioning system in operation: 44 to 45 dBA
- All machinery switched off: 24 to 25 dBA

The measurements proved also that the vibration path is partly over the common rock slab as well as through the Styrofoam isolation.

To improve the unsatisfactory situation three possibilities have been discussed:

- Remove the Styrofoam by use of a gigantic rope saw.
- Use elastic support for walls in office building
- Change the use of the office building

Excessive Vibration from Centrifuges

Four centrifuges have been installed on a platform resting on four steel columns as shown in Fig. 3a. The platform is a plate consisting of a concrete slab with 12 cm thickness resting on steel girders. The engineer designed the platform with the main frequency of the centrifuges in mind. With normal centrifuge operation of 600 rpm an excitation frequency of 10 Hz was assumed. For this excitation a platform having an eigenfrequency of 7 Hz was judged to be adequate. However already on the first test run the platform vibrated violently. Measurements yielded the response curve of Fig. 3.b and showed a maximum vertical amplitude of 13 mm/s (see Fig. 3.c). Clearly the eigenfrequency of the platform was not 7 Hz but rather 10 Hz and coincided wit the main excitation.

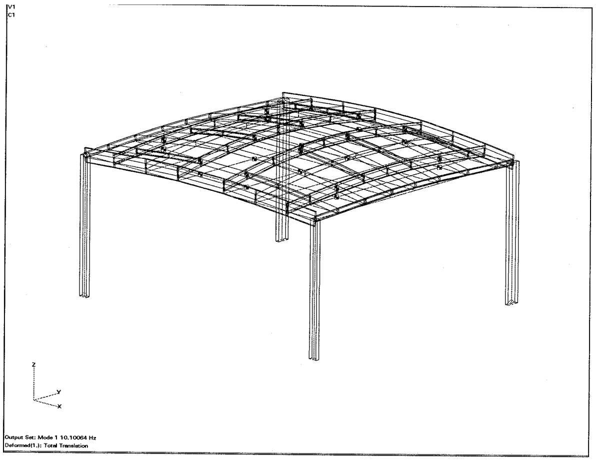


Fig. 3a FE-Model for original centrifuge platform

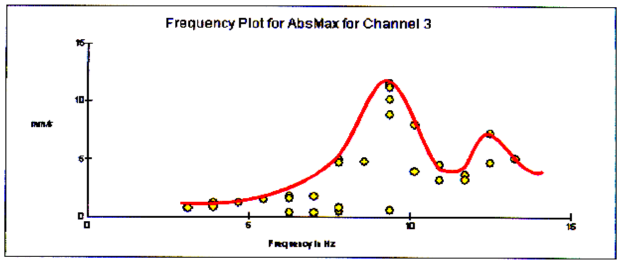


Fig. 3b Response curve of platform

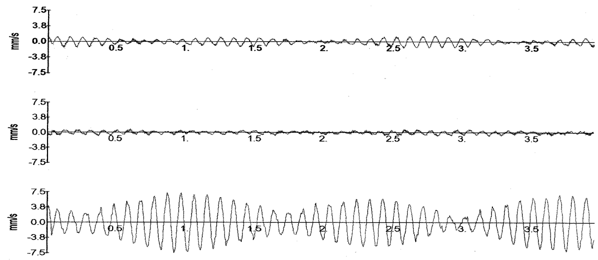


Fig. 3c Vibration measurement (hor1, hor2, vert) on platform

The reason for the ill-behaviour of the platform is the contact between the concrete and the steel girders. The engineer assumed that the concrete plate and the steel girders act independently. This assumption is – at least for static consideration – on the safe side. For the dynamic consideration this assumption is wrong. The concrete slab sticks to the steel girders and acts therefore as a composite plate with a much higher inertia than the two elements considered separately. The concrete slab had thus an eigenfrequency of 10 Hz, which coincided with the main excitation frequency.

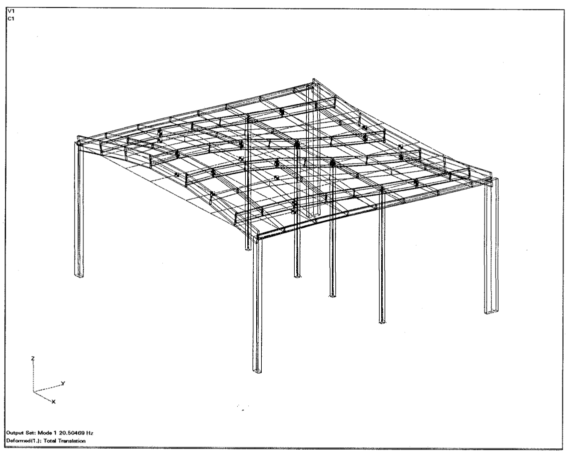


Fig. 3d FE-Model for strengthened centrifuge platform

The solution to the problem was the installation of four additional columns as shown in Fig. 3d. The fundamental eigenfrequency of the plate reached 20.5 Hz and no excessive vibrations could be felt.

The dynamic FE-analysis showed the following results:

- Original plate (no composite model): 7.5 Hz
- Original plate (with composite model): 10.1 Hz
- Plate with 4 additional columns: 20.5 Hz

Structure Borne Noise from Weaving Machines

In the upper floor of a prefabricated industrial building 12 weaving machines have been installed, while the ground floor was still being used for repair and maintenance of heavy trucks. With the onset of the weaving activity, people working in the ground floor complained about the noise level. With all weaving machines in operation a noise level of 80 dBA has been measured in the ground floor. This level is – even for a truck repair shop – not really acceptable.

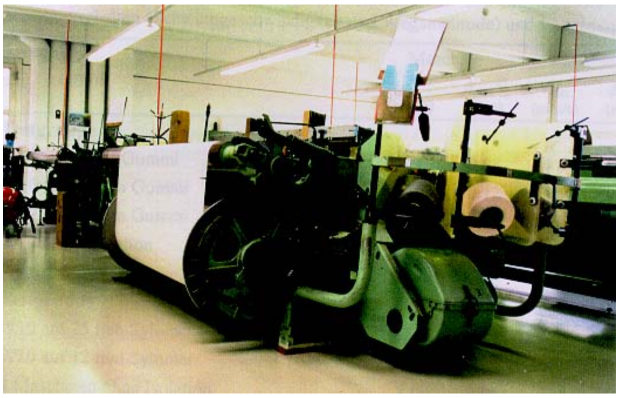


Fig. 4a Weaving machines in the upper storey

Fig. 4b View of the prefabricated ceiling from the ground floor

The local engineer suggested to put special soft spring elements under the weaving machines with the effect that the noise level dropped considerably but floor vibrations rising up to 10 mm/s due to resonance with the pre-stressed concrete floor. Furthermore the cost for all 12 machines would have been prohibitive.

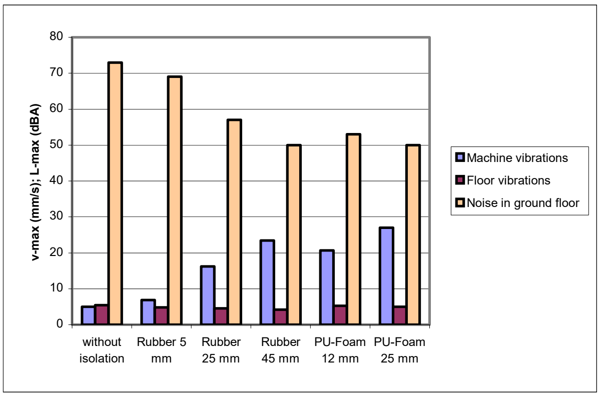


Fig. 4c Effect of different rubber and PU-foam pads

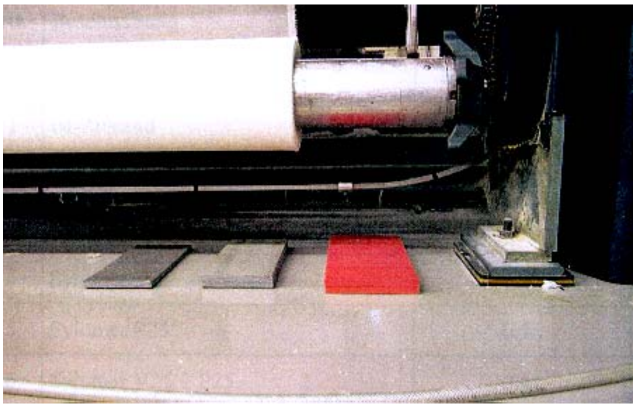


Fig. 4d Samples of rubber and PU-foam pads

A more effective solution was to use rubber or PU-foam pads. They are easy to install and do not cost a fortune. Furthermore tests can be carried out without much effort until the right level of “softness” is reached. As can be seen from Fig. 4c the vibrations of the weaving machine increase with increasing softness of the pads, while the noise level in the ground floor decreases. The vibrations of the floor did – in this case – not vary much. The task was thus to chose the right compromise between noise reduction and increase of machine vibration. Finally the solution with 12 mm PU-foam from SYLOMER has been adopted. The vibration level of the floor (prefabricated, prestressed elements) with 5 mm/s maximum velocity and 0.1 mm displacement amplitude was well within the acceptable limits.

Propagation of Vibrations through a Concrete Underpass

With a distance of approximately 100 m to the hydro power station the architect did not expect, that vibrations from the turbines could cause any problems in the house he was designing on the other side of the motorway. However his client is now complaining about a constant noise which causes sickness and headache and does not let him sleep during the night.

Fig. 5a Hydro power station

Fig. 5b Concrete underpass

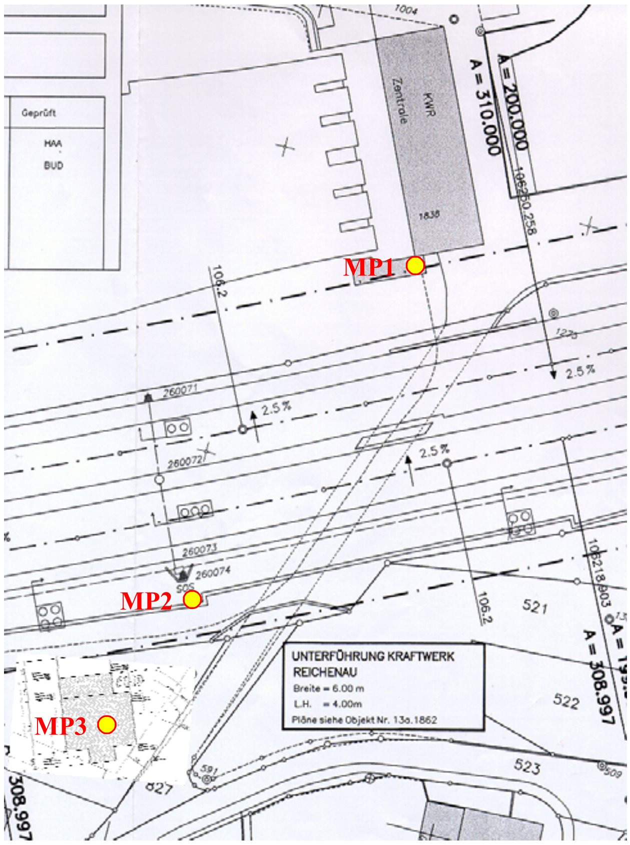


Fig. 5c Plan of hydro power station, underpass and affected building

Measurements at the foundation of the hydro power station showed a constant vibration of 0.15 mm/s. In a distance of 100 m the vibration at the foundation was still at 0.025 mm/s. Due to amplification values between 0.05 and 0.13 mm/s at 31 Hz are measured in the house. With a radiation efficiency of 10 dB this converts to 31 to 39 dBA, a value not very comfortable during night time.

Fig. 5d Affected building

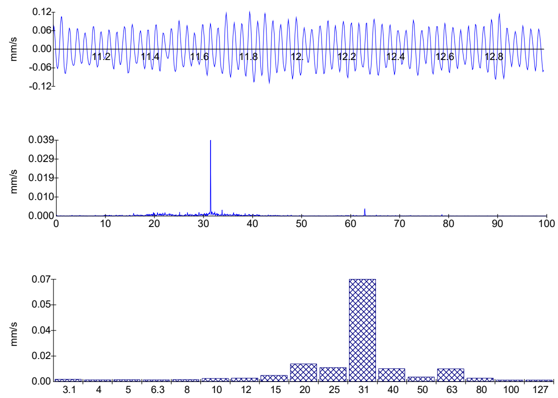


Fig. 5e Floor vibrations in building

The reason for this unexpected strong transmission is the concrete underpass. Vibrations are transmitted with very little damping from the power station to the house. During construction an isolating layer should have been installed at foundation level.

Vibration Problems in a Textile Factory

The weaving machines have been moved to the new hall with its slender construction, having a span between columns of almost 12 m. The vibrations, although not alarming, caused some concern. Tests have been carried out to explore possibilities to reduce the vibrations.

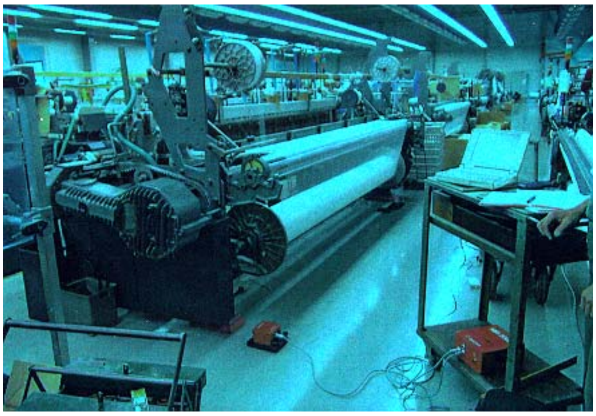


Fig. 6a Vibration measurement under weaving machine

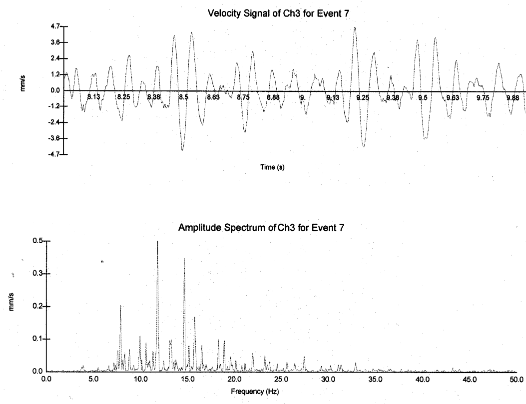


Fig. 6b Vibration time history and amplitude spectrum

The machines were initially mounted on relatively stiff rubber pads. It was assumed that softer pads should bring some reduction in floor vibration. However - as can be seen in Fig. 6d - the vibrations increased with increasing thickness. Only with a layer thickness of 75 mm a reduction could be achieved. This layer thickness was however not acceptable for the machine operation. Thus the original pads were maintained and the vibration of 4 mm/s has to be tolerated.

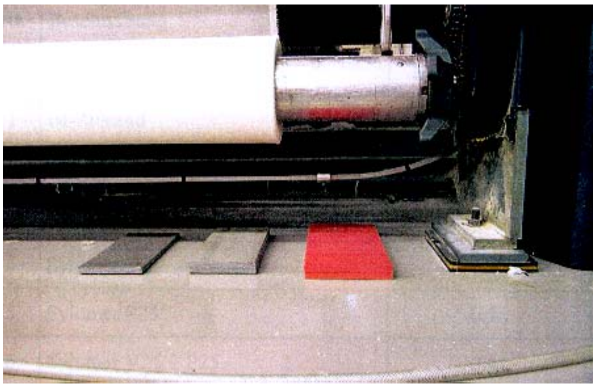


Fig. 6c Samples of different isolation pads

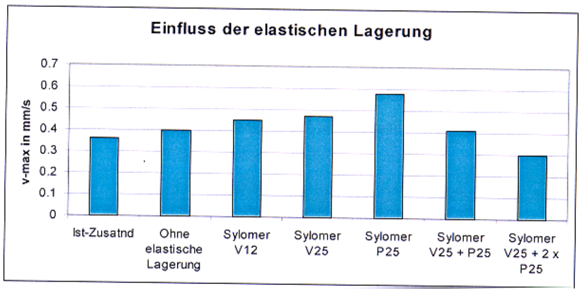


Fig. 6d Influence of isolation pads with different thickness

To understand this behaviour we have to know that the floor had an eigenfrequency of 12 Hz. The main excitation of the weaving machine is – as can be seen in Fig. 6b - at 8, 12 and 15 Hz. With increasing thickness of the isolation pads the dominant excitation shifts from 15 to 12 Hz leading to resonance with the eigenfrequency of the floor. With pad thickness in excess of 50 mm the dominant frequency shifts towards 8 Hz bringing the excitation out of resonance.

Due to the complex behaviour of weaving machines the prediction of vibrations with mathematical models is quite difficult. Very often simple experiments as described above are more convenient.

The Influence of Post-Tensioning on Eigenfrequency

Light-weight concrete is for many applications an ideal material. Care has to be taken hoever if it is used for structures susceptible to vibrations. The engineer designing the bus terminal in Fig. 7a was aware of this problem and argued that post-tensioning would increase the eigenfrequency of the floor slab. The post-tensioning had already been applied to part of the floor, when mechanical difficulties cropt up. It was decided that the effect of post-tensioning should be verified by measurements.

Fig. 7a Light-weight concrete floor slab for bus terminal

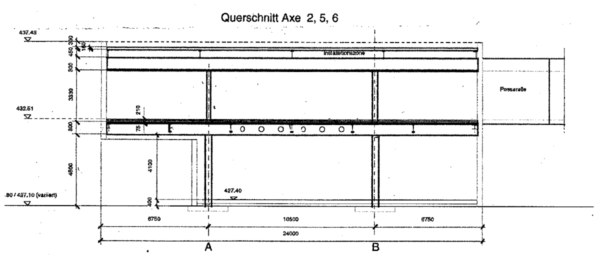


Fig. 7b Cross section of bus terminal

Measurements have been carried out in a systematic way, as shown in Fig. 7c. In Fig. 7d and 7e the vibration time history and the corresponding amplitude spectrum are compared for the section without post-tensioning with the post-tensioned section. Obviously the vibration time histories are virtually identical and also the main frequencies of the two systems exhibit only minor differences.

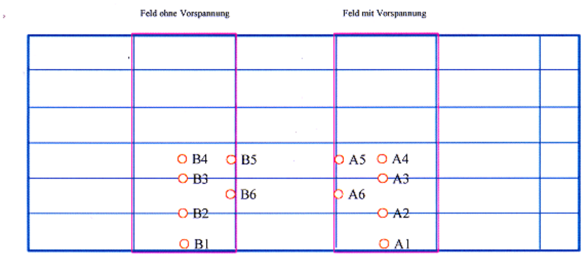


Fig. 7c Plan view with position of vibration sensors

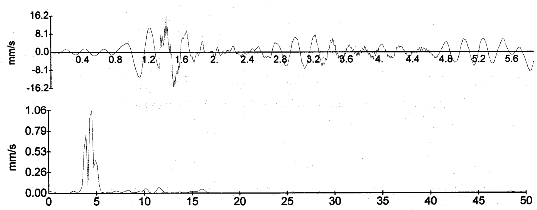


Fig. 7d Vibration time history and amplitude spectrum for section without post-tensioning

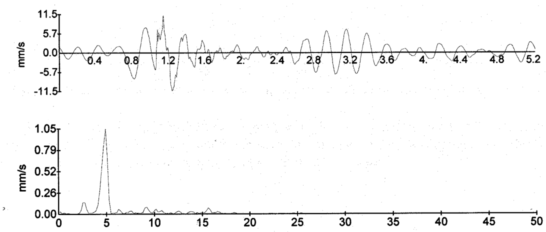


Fig. 7e Vibration time history and amplitude spectrum for post-tensioned section

Post-tensioning (and also pre-stressing) in itself does not affect the eigenfrequency of a structure. This is due to the fact that the applied forces are internal forces. However due to the closing of cracks a slight increase in eigenfrequency can be observed. In the example above an increase of 8% has been observed.

Vibrations of a light-weight concrete floor slab

The two top floors in the 15 storey building had to be built – for several reasons – in light-weight concrete. Vibration measurements during construction showed that the vertical eigenfrequencies were between 5.9 and 6.1 Hz. For the intended use as office space the dynamic behaviour of the floor seemed perfect.

Fig. 8a Light-weight concrete floor slab in construction

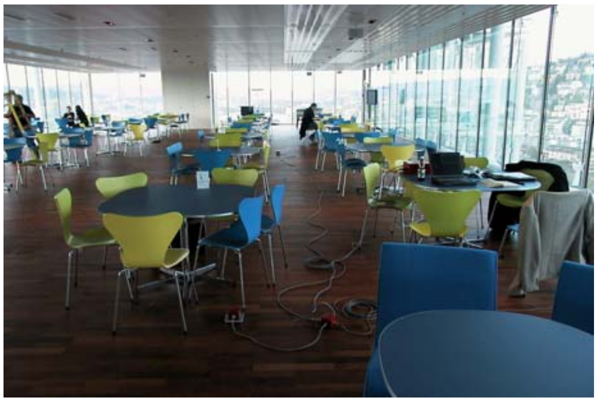


Fig. 8b Canteen with light-weight concrete floor shown left

After completion of the building the top floor with it's magnificent view was converted into a canteen. In a canteen the movement of people is somewhat more frequent than in ordinary office space and people sitting at a desk wondered about the vibrations of the floor. Measurements carried out in the canteen proved that the eigenfrequency of the floor was still between 5.2 and 5.4 Hz, a value which is perfectly appropriate for a restaurant. The peak velocities however were in the order of 2 to 5 mm/s and reached – when a person was running through the canteen - values of 8.5 mm/s (Fig. 8c)..

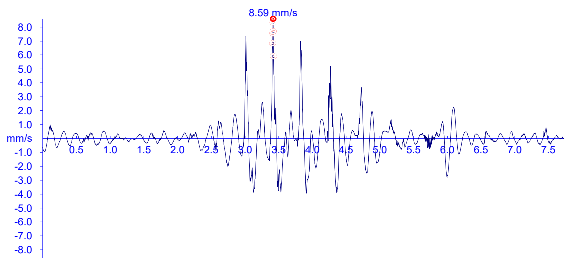


Fig. 8c Vibration time history

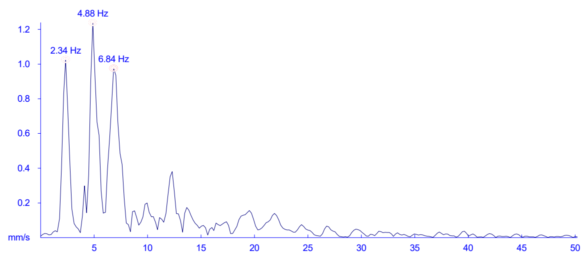


Fig. 8d Amplitude spectrum for signal in Fig. 8c

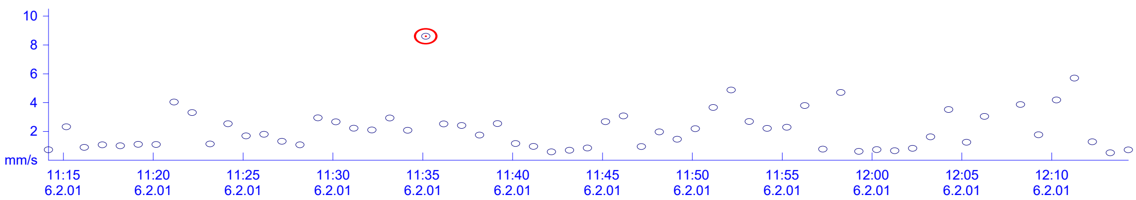


Fig. 8e Peak velocities recorded during one hour

Light-weight concrete slabs are susceptible to vibrations. Due to their low unit mass impulsive excitations can induce considerable vibrations. For normal concrete slabs a check of the eigenfrequency is in most cases sufficient, as only harmonic excitation can lead to excessive vibrations. For light-weight concrete slabs in addition a check of the behaviour under impulsive excitation – like the steps of a running person - should be included.

Vibrations in a theatre

The Aula shown in Fig. 9a is designed as a rectangular inclined cantilever platform. The platform rises at an angle of some 20^o from the front row to the top row. The lower edge (with the front row) is clamped into a foundation block (below the floor) while the other three edges of the platform are free. The width of the platform is in the order of 10 m, the length of the platform (in the direction of the cantilever beams) approximately 8 m.

The platform showed considerable vibrations, which made it necessary to install two tension cables between the free edge of the cantilever platform and the floor beneath (see Fig. 9b). With these two pre-stressed cables the system should be stiffened and the vibrations reduced.

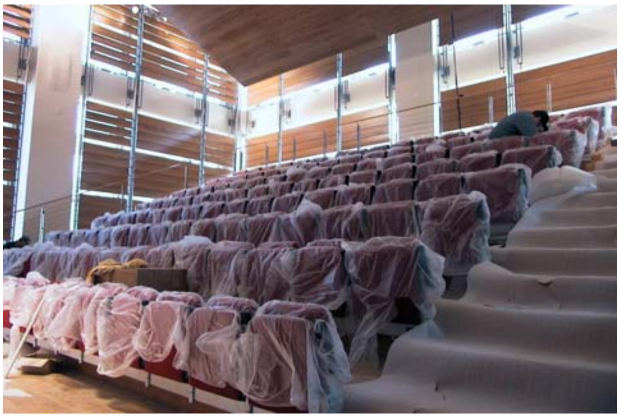


Fig. 9a Seat rows on cantilevered platform

Fig. 9b Rear view; 2 tension cables between the free edge of the cantilever platform and the floor beneath stiffen the system.

Measurements carried out after the installation of the tension cables showed that the eigenfrequency has increased somewhat but that the vibrations were still considerable. With three persons exciting the platform purposely at resonance maximum velocities of 50 mm/s could be achieved. This corresponds to a maximum acceleration of 2 m/s^2 or a displacement amplitude of 2 mm.

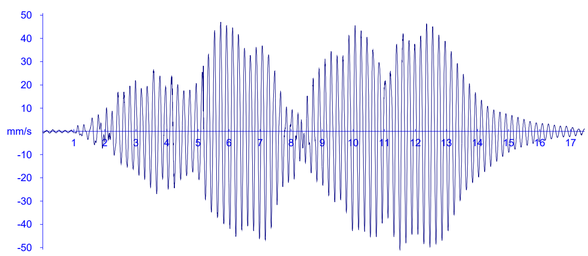


Fig. 9c Vibration time history due to harmonic excitation by 3 persons

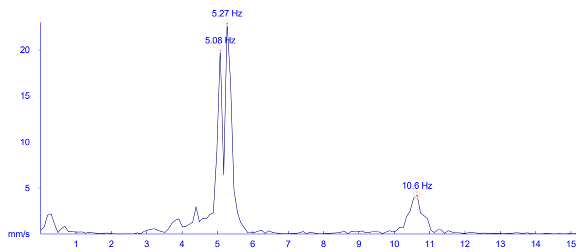


Fig. 9d Amplitude spectrum for signal in Fig. 8c

It should be noted that the pre-stressing forces of the tension cables have no influence on the dynamic behaviour of the cantilever platform. It is only the cross section of the cables and the E-modulus of the steel that enters the equation of motion. Comparing the small cross section of the cables with the huge cross section of the cantilever we cannot expect too much from these cables.

One solution to the problem is to install damping elements at the lower end of the tension cables. Care has to be taken that no slip exists in these damping elements. For moderate excitation the relevant displacements are in the order of 0.2 mm. Ordinary dampers have a slip in excess of this and would not be effective. Another possibility is the installation of tuned dampers.

Increasing the Eigenfrequency of a Concrete Slab

The new production hall has been finished in time and most of the production units have been moved to their new positions. However the quality of the produced elements (high precision pharmaceutical pump parts) was not adequate and production had to be stopped. The vibrations of the concrete floor were just too high and a solution to the problem had to be found without delay.

Fig. 10a Test with eight struts near each column to achieve doubling of eigenfrequency

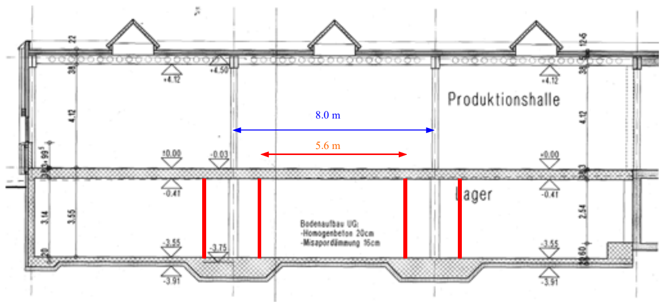


Fig. 10b Section with proposed struts to reduce free span from 8.0 m to 5.6 m in order to increase eigenfrequency from 14 Hz to 28 Hz

One proposal was to decrease the free span between the columns. As an experiment to prove the appropriateness of this solution eight steel struts have been installed close to each column (giving a total of some 120 struts). It was argued that the actual span of 8.0 m would be reduced to 5.6 m. Given the fact that the eigenfrequency is proportional to $1/L^2$ the frequency would increase from 14 Hz to 28 Hz.

Fig. 10c Test with eight struts in midfield to achieve an increase from 14 Hz to 18 Hz

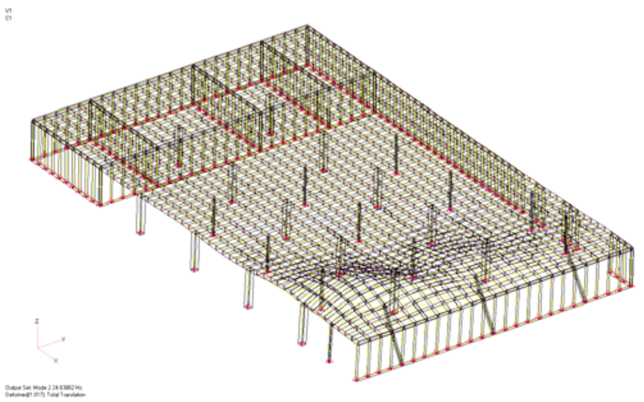


Fig. 10d Dynamic FE-model to simulate effect of strengthening with additional columns.

A close look at the proposal in Fig.10b should reveal that this method cannot be successful. The steel struts with a cross section of 7 cm^2 are much weaker than the existing columns. They act more like soft springs giving a slight increase to the fundamental frequency. Measurements proved that the increase was not more than 1 Hz.

It should be noted that very substantial cross sections are needed to stiffen an existing structure which has already considerable stiffness. In the case of a concrete slab with 40 cm thickness we cannot expect that steel rods with 7 cm^2 cross section will bring about much change.

For the development of dynamic strengthening it is imperative to use simulation with FE analysis as shown for instance in Fig. 10d. Our imagination is in general quite good enough to assess the sizing for a static problem. But for a dynamic problem we are in most cases at a loss.