Vibration and Structure-Borne Sound Isolation by means of Cellular Polyurethane (PUR) Elastomers[1]

BY

RÜDIGER G. WETTSCHURECK[2]

1. Introduction

Problems in construction work and civil engineering due to vibrations and/or structure-borne sound can be overcome by inserting elastic construction elements between the vibration or structure-borne sound-emitting part of the system and the area which has to be protected.

The system is tuned by adjusting the dynamic mass of the construction, the dynamic stiffness and the loss factor of the elastic elements.

It is quite common to use steel springs with hydraulic or viscoelastic dampers (see for example [1]) or reinforced bearings for this purpose. Quite complicated constructions are usually necessary to concentrate all loads on the elastic bearings and to distribute the load on the supporting structure.

This can be avoided if the load-bearing surface of the elastic elements is the same as the surface area of the construction and of the support. Cellular PUR elastomers offer this possibility.

Cellular elastomers differ from compact materials in that the starting material is added before or during the cross-linking of a foaming agent, resulting in the formation of internal cavities distributed evenly across the cross-section. These cells may be open or closed (i. e. joined to each other). In contrast to the materials usually designated as foams, cellular elastomers have a much greater density. The plastic matrix consists entirely of an elastomer. The stiffness of the material is determined by the stiffness of the plastic framework and not by the gas-filled cells.

This paper deals throughout with special PUR elastomers available on the market under the brand name of SYLOMER® (Registered trade mark of Getzner Werkstoffe GmbH, Bludenz-Bürs, Austria).

Obviously some of the relationships depicted in the following may also apply to other materials. However, when solving vibration problems in general, and in particular in the railway and construction sectors with which we are dealing here, it should be ensured that the materials used are examined for their suitability and have been proven under the loads which occur in practice.

2. Characteristics of the material

Cellular PUR elastomers are particularly suitable for sheet-type elastic bearings since their cellularity provides the volume required for dynamic deformation. Even when they are installed across the full area between stiff surfaces they do not lose their elasticity. There is no question of the inner cavities being contaminated by dirt or foreign bodies even with an open-celled structure because the small, finely distributed cells on the surface act as a filter [2].

2.1 Static stiffness

The deformation behaviour of elastomers is usually described by the load deflection curve.

Figure 1 shows the typical path of such a characteristic curve, in this instance for the material Sylomer P25 with a density of 510 kg/m³.

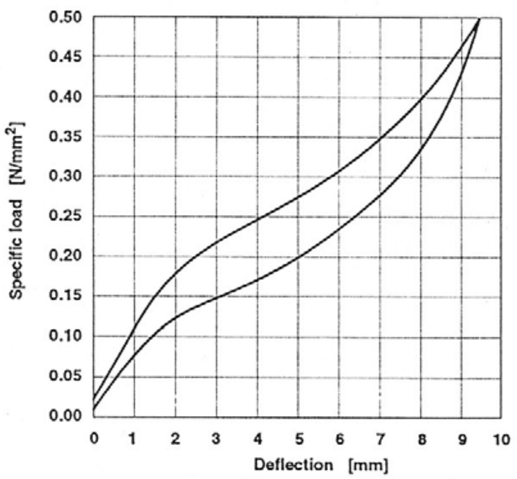

Figure 1: Load Deflection Curve of Sylomer® P 25. Thickness 25 mm, Density 510 kg/m³; Sample 300 x 300 mm²; Load Velocity 0.01 N/mm² s.

The gradient of the tangent to this curve is designated as stiffness. The load dependence of the stiffness must be taken into consideration when planning a protective measure. It must be designed in such a way that the constant load of the material lies as far as possible in the degressive area of the curve. The influence of "creep effects" is then generally negligible. Brief overloading of the material up to many times the constant load has no damaging effect. If more or less deflection is required for a particular load this can be achieved by adjusting the material thickness.

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[2] Dr.-Ing. habil. Rüdiger G. Wettschureck, Consulting Engineer in Technical Acoustics, Gstädtstraße 36, D-82439 Großweil, Telephone +49 (8851) 61 46 19, Facsimile +49 (8851) 61 46 20, Email: post@wettschureck-acoustics.eu, Web: www.wettschureck-acoustics.eu

[Until October 2004: Head of Technical Acoustics Department at Getzner Werkstoffe GmbH, Grünwald, Germany]

The position of the turning-point between the degressive and the progressive areas of the curve in relation to the pressure is dependent upon the density of the material.

Figure 2 shows this relationship for Sylomer. As shown, the “load capability” of the material varies with the density over three decimal powers.

Another possibility for adjusting the spring constant of an elastic bearing is provided by the variation of the bearing surface. By suitable choice of density, thickness and area of the bearing a large part of the requirements which occur in practice can be met.

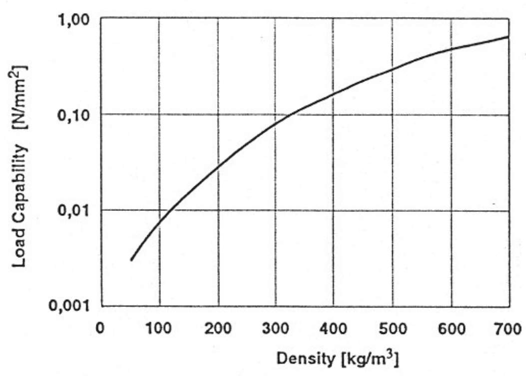


Figure 2: Load Capability of Cellular PUR - Elastomers (Sylomer®) as a function of material density.

2.2 Dynamic stiffness

As well as load dependence, the stiffness of all elastomers - including cellular elastomers - is dependent to a greater or lesser degree on the frequency. This dependency increases with increasing attenuation of the material. In contrast to static stiffness, in this case we are talking about the dynamic stiffness.

Figure 3 shows the relationship between stiffness, pressure and frequency for the material Sylomer P25, the deflection curve of which was shown in Figure 1. The bottom curve shows the behaviour of the static stiffness with a minimum at the turning point between the degressive and progressive areas of the deflection curve.

The two curves above this show the path of the dynamic stiffness for two selected frequencies, 5 Hz and 40 Hz. This figure shows how important it is to use dynamic stiffness rather than static stiffness when calculating vibration insulation measures. On the other hand, however, the curves also show that in a relatively large load range a rough estimate can be made using an almost constant dynamic stiffness; in this case with a stiffness of 0.09 N/mm³ in a load range of up to 0.25 N/mm².

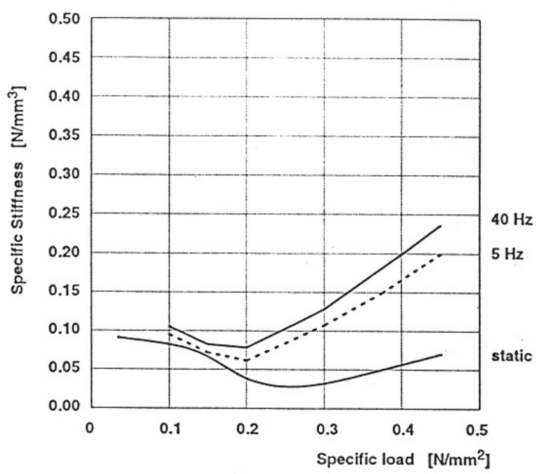


Figure 3: Static and Dynamic Stiffness of Sylomer® P 25. Thickness 25 mm, Density 510 kg/m³.

The fact that this cannot be assumed for every material is shown by the example in Figure 4. Here the stiffness of a highly profiled, double-layer rubber mat is shown. We can see the very great influence of load and frequency on the stiffness. A technical calculation of vibration insulation measures using static stiffness would here result in very great errors.

A further interesting aspect emerges when we compare the deflection curves of the two materials.

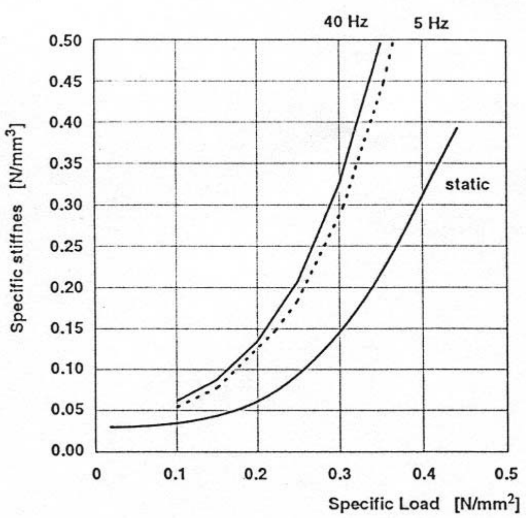


Figure 4: Static and dynamic stiffness of a profiled rubber mat (two layers).

Figure 5 shows the curve of the profiled rubber mat. At a pressure of 0.15 N/mm² the two mats have more or less the same dynamic stiffness. At this pressure a load deflection of approx. 3.7 mm occurs in the case of the rubber mat whilst for the Sylomer material it is only 1.5 mm. Thus for elastomer materials it is not always correct to say that large deflection travel equals great effectiveness. The path of the deflection curve, which for cellular materials such as Sylomer is typically degressive, allows soft elastic bearings with high efficacy to be achieved with unusually small load deflection.

3. Examples of typical applications in railway tracks

3.1 Ballasted tracks with ballast mats

3.1.1 General description of Sylomer ballast mats

Sylomer ballast mats have been in use since 1975 for the elastic bedding of ballasted railway tracks. Its most important areas of application are:

> Isolating against structure-borne noise of railway lines in densely populated regions: subways, commuter and long distance lines in urban areas.
> Protecting vibration sensitive constructions and buildings with high sound isolation demands, such as concert halls, museums, historic sites, hospitals and vibration sensitive laboratories and production installations.
> Reducing radiation of secondary air-borne noise from bridge constructions.
> Increasing track position stability and reducing ballast compression of tracks on a hard substructure, especially of high speed tracks.

Ballast mat installation should reduce the static and dynamic forces caused by traffic and transfer them into the substructure as evenly and as reduced as possible.

All this can be achieved by the construction and the advantageous material characteristics of Sylomer ballast mats.

The mat's top layer consists of a Sylomer type with high density and high tensile strength. The density is between 500 and 800 kg/m³. This layer deforms under the ballast weight. The ballast stones are stabilized in their respective positions. The contact surface is enlarged, and the forces are transferred more easily to the lower damping layer.

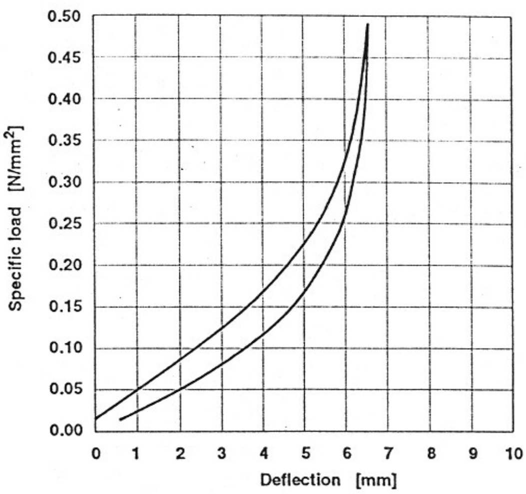


Figure 5: Load Deflection Curve of a profiled rubber mat (two layers)

The damping layer also consists of cellular Sylomer sandwiched in one or two layers according to the mat type. The density is selected according to the desired stiffness.

The ballast's rough corn, and the uneven, sharp-edged form of the ballast stones lead to an extremely uneven load on the ballast mat. Only 1/2 to 1/3 of the mat surface is in actual contact with the ballast. The contact area is even lower for mats made of compact elastomers without volume compressibility. But because Sylomer ballast mats are compressible on all points of their surface, the ballast bed can evenly deflect under the load of the train. Thus, it avoids relative displacement of ballast stones, fine granulation and the resulting track settlement.

Selecting the right mat thickness and density avoids a stressing of the material into the progressive area of its load deflection curve (see for example Fig. 1). The mat demonstrates no static and dynamic stiffening under increasing loads.

The mat's stiffness is selected according to the demands on vibration insulation, the super-structure properties (ballast height, sleeper dimensions and spacing, rail type) and the traffic conditions (axle load, maximum speed).

According to the standards of the German Railways [3], ballast mat stiffness is defined by the line which intersects its load deflection curve at two given points (i. e. 0.02 N/mm² and 0.10 N/mm²). This static stiffness is called the "bedding modulus".

A decisive variable in respect of the structure-borne sound isolation which can be achieved with a ballast mat is its dynamic stiffness, which is to be determined in the relevant load and frequency range (see for example [3]).

3.1.2 Ballast mats in a railway tunnel

The new concert hall in Munich in Germany had to be shielded from the structure-borne sound emitted from two parallel railway tunnels (suburban trains - S-Bahn) with very dense traffic (see Figure 6).

Appropriate measures had to be taken to ensure that the background noise level in the concert hall did not exceed the specified limit of 25 dB(A) even when trains were running through the tunnels, in order that the hall could also be used for recordings [4].

Measurements taken on the site of the concert hall and calculations showed that the following level reductions ΔL had to be achieved [5]:

Frequency [Hz]	31	40	50	63	80	100	125	160
ΔL [dB]	0	10	18	13	9	6	5	8

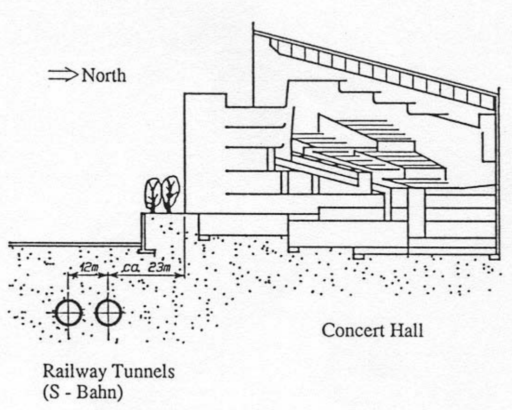


Figure 6: Munich Philharmonic Hall: Cross section with position of the railway tunnels.

Three solutions were evaluated:

> a room in a room construction,
> a 20 m deep slot with elastic filling between the building and the railway tunnels, and
> the mounting of ballast mats in the tunnels between ballast and tunnel floor.

The last solution was realised.

Whilst the trains were not running at night the ballast mat type Sylomer B851 was installed in the two tunnel tubes to a length of 345 m using a specially developed procedure [6]. The ballast mat was designed for the load conditions of the S-Bahn operating with a bedding modulus of 0.02 N/mm³ in accordance with [3]. In the relevant load and frequency range it has a dynamic stiffness of approx. 0.04 N/mm³ on average. It is made up of three layers and has a total thickness of 55 mm [5].

The structure-borne sound was measured during the passage of trains of type ET420 at 6 measuring points along the wall of each tunnel before and after insertion of the ballast mat.

The results from one measuring point are shown in Figure 7 as an example. The efficiency of the attenuation measure (the insertion loss of the ballast mat) was determined as the mean difference between 1/3-octave-band spectra (energy mean from 6 measuring points and 10 train passages) for the situations without and with ballast mats in both tunnel tubes [5].

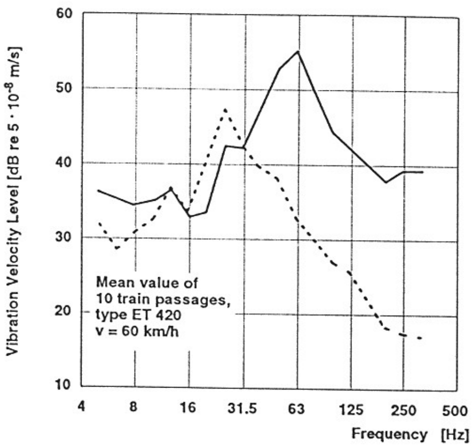


Figure 7: $^1/_3$-octave-band-spectra of vibration velocity levels measured at the tunnel wall during train passages.

—— without ballast mat
- - - - - - with ballast mat, type Sylomer® B851

The results are shown in Figure 8 for both the southern and the northern tunnel.

At the same time a simple calculation model for determining the insertion loss of ballast mats has been developed for the German Federal Railways. Well-known methods for calculating elastic mounts have been applied to the mechanical system formed by the vehicle, the tracks and ties on ballast, a ballast mat, and the ground plate of the railway tunnel.

As outlined in [7] to [9], this system can be described by the simple dynamic model shown in Figure 9.

For calculating the insertion loss ΔL_e of a ballast mat, which is efficient only with its stiffness s_M

$$s_M = s''_M \cdot S_W \cdot (1 + j \cdot d_M) \qquad (1)$$

where

s''_M is the dynamic stiffness of the ballast mat,
d_M is the loss factor of the ballast mat,
S_w is the effective area of the ballast, determined by the conical load distribution underneath the tie [8], and
j is the imaginary unit,

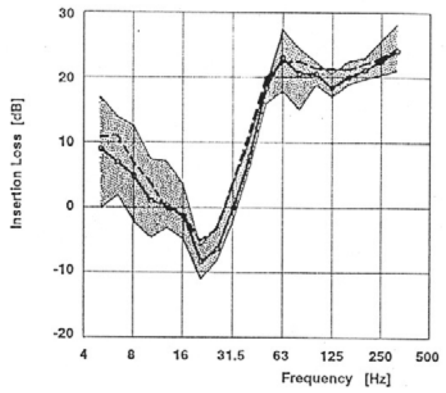


Figure 8: Insertion loss of the ballast mat, type Sylomer® B851; results from 6 measuring points at each wall of the two parallel railway tunnels near the Munich Philharmonic Hall.

mean value and scatter, southern tunnel
mean value, northern tunnel

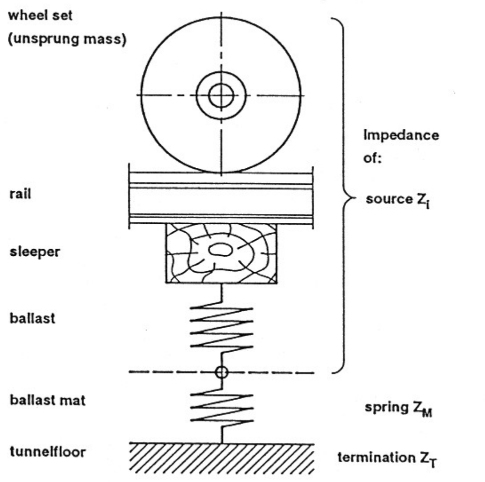


Figure 9: Analytical model of vibration isolation systems with ballast mats.

the following formula applies[3]:

$$\Delta L_e = 20 \cdot \lg \left| 1 + \frac{s_s / s_M}{1 - \left(\frac{\omega_0}{\omega} \right)^2} \right| \quad dB \qquad (2)$$

where:

s_S is the ballast stiffness

ω is the radian frequency, and

ω_o is a characteristic resonance radian frequency, which for ordinary rail-grill and ballast is mainly determined by the ballast stiffness s_s and by the unsprung mass *M* of the wheel set.

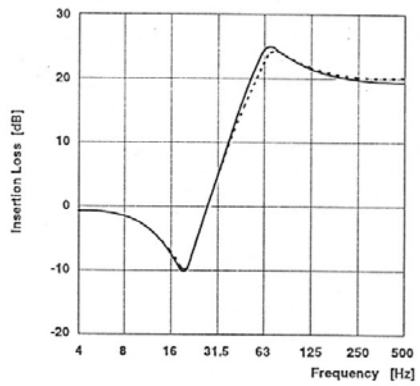


Figure 10: Calculated insertion loss of the ballast mat, type Sylomer® B851, under a ballast with the stiffness $s_s = 5 \cdot 10^8$ N/m (1 + j 0.5) and an unsprung mass m = 3000 kg.

Parameter: terminating impedance Z_T
——— elastic half space with $s_T = 5 \cdot 10^9$ N/m
······ 0.8 m thick concrete plate with $Z_T = 10^7$ Ns/m

Thus

$$\omega_0 \approx \sqrt{\frac{s_S}{M}} \qquad (3)$$

Figure 10 shows numerical results for the ballast mat, type Sylomer B851, with the stiffness $s_M = 56 \cdot 10^6 \cdot N/m \cdot (1 + j \cdot 0.2)$, calculated for different terminating impedances Z_T of the tunnel floor and for different parameters specified at the bottom of this figure (for more details see [9]).

The calculated data are in good agreement with the results of measurements taken in the railway tunnel in Munich near the new Philharmonic Hall during train passages (compare Fig. 10 with Fig. 8). The essential parameters for calculating the insertion loss of ballast mats in a tunnel (with high input impedance of the tunnel floor) turn out to be the unsprung mass of the wheel sets, the stiffness of the ballast and the stiffness of the elastic ballast mat.

[3] It has been taken into account that in normal tunnels the impedance of the tunnel floor Z_T is large compared with the source impedance Z_i, so that the original formula for the insertion loss can be simplified as follows [7]:

$$20 \cdot \lg \left| 1 + \frac{j\omega / s_M}{1/Z_i + 1/Z_T} \right| \approx 20 \cdot \lg \left| 1 + \frac{j\omega / s_M}{1/Z_i} \right|$$

3.1.3 Ballast mats on a railway bridge

The experimental bridge in Munich consists of 10 parallel superstructures, each in three parts, in what is known as a reinforced concrete bridge in composite construction [10]. The acoustical investigations were carried out on the two edge superstructures of tracks 1 and 10 which have the same construction.

A cross-section of these is shown in Figure 11. This shows that the bridge floor, which is approx. 0.4 m thick (including protective concrete layer) lies on a steel supporting structure consisting of two I-beams each approx. 0.8 m high.

Prior to installing the ballast bed ballast mats of the type Sylomer D229 were laid on the edge superstructure Nr. 10 for experimental purposes. With a bedding modulus of 0.03 N/mm³ the ballast mats met the requirements of [3]. The dynamic stiffness of the ballast mat is in the relevant frequency and load range approx. 0.07 N/mm³ (measuring frequency 40 Hz; static pre-load 0.06 N/mm²).

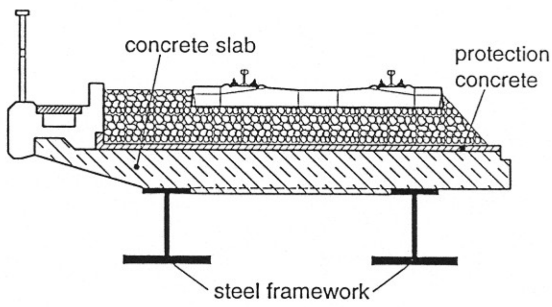


Figure 11: Cross section of the investigated reinforced concrete bridge in Munich (composite construction).

After completion of the bridge structure-borne sound and air-borne sound measurements were taken on edge superstructures 1 and 10 (without/with ballast mat) whilst a test train was passing over [11].

The state of the rail travelling surfaces, of the superstructure and the vehicles (test train) were equal within the constriction of what is technically possible.

The effectiveness of the ballast mat, i.e. its insertion loss, was determined from the structure-borne sound measured on the underside of the concrete slab without/with ballast mat during passages of the test train (energetic mean over 5 measuring points and at least three train passages each).

The measuring results are shown in Figure 12.
The difference between the velocity level spectra without/with the ballast mat is the insertion loss of the ballast mat, which is shown in Figure 13 (continuous curve).

In addition the result of an estimate is shown which was determined on the basis of the calculation model given in Figure 9.

According to this, the following relationship applies to the calculation of the insertion loss ΔL_e of a ballast mat (see [8], [9] and [10]):

$$\Delta L_e = 20\lg\left|1 + \frac{1/Z_{USM}}{1/Z_i + 1/Z_{Br}}\right| \quad dB \qquad (4)$$

where:

Z_{USM} is the spring impedance of the ballast mat (USM) taking into account wave propagation in the deflection layer from approx. 500 Hz,

Z_i is the source impedance from the source acting on the top side of the ballast mat,

Z_{Br} is the terminating impedance acting on the underside of the ballast mat, i. e. in the present instance the input impedance of the bridge floor.

For Z_{Br} >> Z_i and for a positive insertion loss $\Delta L_e > 0$ formula (4) can be simplified as follows

$$\Delta L_e \approx 20 \cdot \lg|Z_i| - 20 \cdot \lg|Z_{USM}| \quad dB \qquad (5)$$

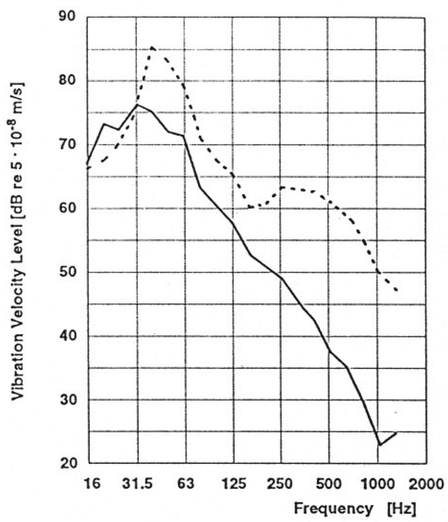


Figure 12: ¹/₃-octave-band-spectra of vibration velocity levels, measured at the concrete slab (bottom side) of the investigated reinforced concrete bridge during the passage of trains, type ET420 with a speed of 100 km/h (mean value of three train passages).

------ without ballast mat
—— with ballast mat, type Sylomer® D229

i. e. the insertion loss can be estimated from the difference between the impedance levels.

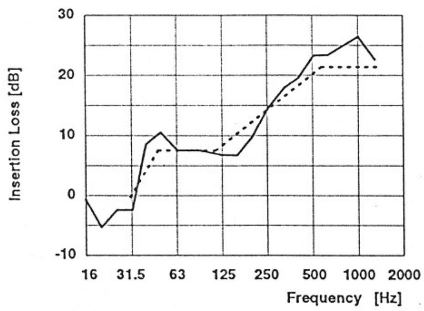


Figure 13: Insertion loss of the ballast mat, type Sylomer® D229, mounted on a reinforced concrete bridge (composite construction) in Munich.

——— measured (level difference according to figure 12)
- - - - - estimated (impedance level difference according to figure 14)

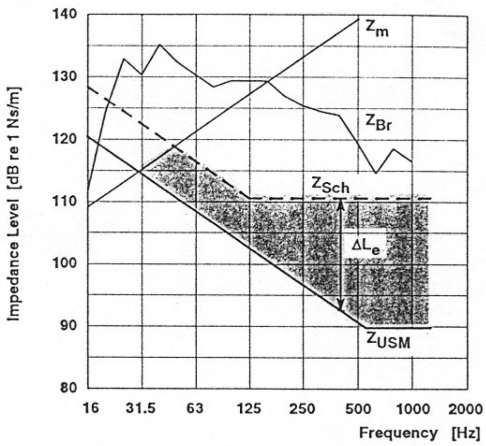


Figure 14: Impedance level characteristics 20lg |Z| for estimation of insertion loss ΔL_e of the ballast mat, type Sylomer® D229.

Z_m impedance of unsprung mass
Z_{Br} measured input impedance of concrete slab
Z_{Sch} impedance of ballast bed (wave guide model)
Z_{USM} impedance of ballast mat (wave guide model)

It should be noted that below the resonance radian frequency $\omega_0 = \sqrt{s_s / M}$ (M = unsprung mass of the wheel set, s_S = ballast stiffness, see also Section 3.1.2 and [8]) Z_i is given by the mass impedance Z_m and above this frequency by the impedance of the ballast bed Z_{Sch}. The latter is defined as spring impedance taking into account wave propagation in the ballast from approx. 125 Hz (see [10] and [12]).

Figure 14 shows the variables required for determination of the insertion loss of the ballast mat. In addition, Z_{Br} shows a measuring result for the mean point impedance of the bridge floor with shaker excitation which can be stated as the lower limit for the impedance rates effective during excitation by trains [13].

According to the above approximation formula (5) the insertion loss ΔL_e of the ballast mat can be read off as the difference in impedance levels and, as mentioned above, is shown in Figure 13 together with the measuring result. It should be noted that with this estimate resonance effects have not been taken into account (see intersection of Z_m with Z_{Sch} or Z_{USM} in Figure 14).

Figure 13 shows good accordance between the calculated estimates and the measured insertion loss of the ballast mat investigated.

Since the input impedance of the approx. 0.4 m thick concrete floor of the bridge was not included in the calculation because $Z_{Br} >> Z_i$ and Z_{USM}, it may be concluded that the input impedance of the bridge floor does not need to be known in order to forecast the effectiveness of ballast mats on concrete bridges with a comparable floor construction (thickness of concrete slab), similar to the circumstances in tunnel constructions with a concrete tunnel floor (see for example [8] and [9]).

The circumstances in the case of the “dynamically soft” steel bridges are different and their floor impedance, as shown by the results of measurements on 10 bridges of different types of construction, may be more than the power of ten below that of the concrete bridge investigated here [14].

Here a reliable forecast can only be produced if the “representative” input impedance of the floor is known either from new measurements or by calculation. However, in both cases this is associated with relatively great uncertainty if the work is to be kept within reasonable limits.

In view of the practical applications of the results obtained from the acoustical investigations carried out on the concrete bridge in Munich, e.g. in connection with the planning of new tracks to be constructed, it should be noted that as a result of the installation of the ballast mat of type Sylomer D229 the air-borne sound immediately under the bridge, i.e. where the direct rolling sound of the trains but not the sound radiated from the bridge itself is shielded, was reduced by around 13 dB(A).

3.2 Elastically supported ballastless track

The Federal German Railways have developed a ballastless superstructure which has been optimised in constructive and acoustical aspects [15] for use on solid bridges in future new tracks to be built. This is known as a ballastless track of the modified “Rheda type” [16].

The aim of the development work was to use suitable measures to ensure that the sound radiated when trains pass over bridges with a ballastless track is no greater than in the case of bridges with a conventional ballasted superstructure.

The experiments were carried out on the railway bridge over the river Amper at Fürstenfeldbruck near Munich, which is constructed as a continuous prestressed concrete hollow beam bridge.

After extensive preliminary trials the first step was to remove the ballasted superstructure from one track of the double-track bridge and then to install the ballastless track (first stage).

Figure 15 shows the experimental bridge and the structure of the ballastless track in cross section.

After this first stage of conversion the ballastless track was laid more or less stiffly on top of a 1.2 mm thick plastic sheet (see part 3a in Fig. 15) on top of the concrete hump (see part 2 in Fig. 15) which is non-positively supported by the bridge floor.

The required elasticity of the track was achieved by the elastic rail fastening of the type Ioarv 300 shown in Figure 16 (see for example [16]).

Elastic base plate pads of the type Zwp 104 (see part 3 in Fig. 16) made of the material Sylomer were installed; it was with these that the greatest structure-borne sound damping effect was achieved in preliminary trials on a test rig and on an operational track when compared with other base plate pads [17].

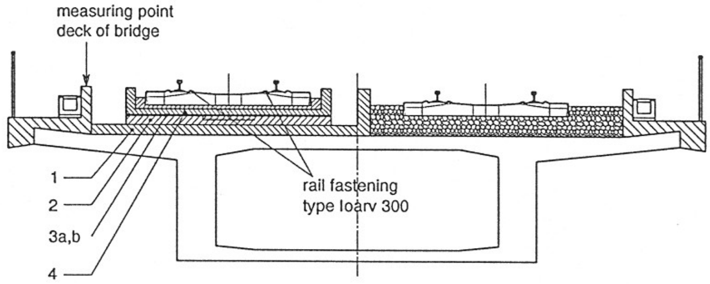


Figure 15: Cross section of the reinforced concrete bridge crossing the Amper river at Fürstenfeldbruck near Munich, with details about the construction of the mounted ballastless track, type "Rheda" (modified).

1: supporting slab
2: concrete humb
3a: plastics sheet in case of nonelastically supported slab track (first stage)
3b: Sylomer® L12 (12mm thick) in case of elastically supported slab track (second stage)
4: permanent way slab

In a second stage a 12 mm thick elastomer mat of the type Sylomer L12 (see part 3b in Figure 15) was inserted between the concrete humb and the permanent way slab instead of the plastic sheet. With this construction we investigated the extent to which the sound radiation of the bridge can be further reduced (in comparison with a bridge with a ballasted superstructure and ballast mat).

The acoustic effects of the realized measures were documented by extensive measurements of structure-borne and air-borne sound before and after the conversion measures [17], [18]. The measurements were always taken during the passage of a test goods train consisting of electric locomotive + 10 ballasting wagons + electric locomotive at a speed of 80 km/h. Some of the very extensive measuring results are shown below.

Figure 17 firstly shows mean spectra of the structure-borne sound determined from measure-ments, each made at three identical measuring points on the bridge deck (see also Fig. 15).

We can see that over the entire frequency range the structure-borne sound initiated in the bridge structure is already considerably reduced with the “stiffly” supported ballastless track (first stage) in comparison with the bridge with a ballasted superstructure.

A further clear reduction in the structure-borne sound level was achieved for frequencies from around 80Hz, up to 20 dB in the frequency range around 250 Hz, by supporting the track slab elastically on Sylomer L12. As with any type of elastic support, the increase in the structure-borne sound level which occurred in the area of the resonance frequency of the elastically supported track slab (in this instance approx. 31 Hz) must be accepted physically. It occurs where expected based on the results of preliminary trials.

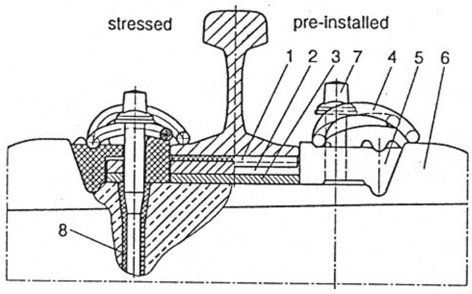


Figure 16: Resilient rail fastening, type Ioarv 300 of Deutsche Bahn AG, vertically and horizontally adjustable.

Part 1: rail pad, 2 to 12 mm thick; Part 2: base plate;
Part 3: Resilient base plate pad (ZWP 104), 10mm thick;
Part 4: prestressing clip; Part 5: angle guiding plate;
Part 6: concrete sleeper; Part 7: sleeper screw;
Part 8: screw dowel.

Figure 18 shows the result of the air-borne sound measurements at a measuring point immediately below the bridge. This measurement location is particularly suitable for clarifying the acoustic effectiveness of the measures implemented because here the rolling sound of the trains is largely shielded.

It emerges that the air-borne sound in the immediate vicinity of the bridge, i. e. the air-borne sound radiated by the bridge itself, was reduced considerably by the installation of the ballastless track with elastic rail fastening in the entire frequency range in comparison with the bridge with a ballasted superstructure.

By supporting the ballastless track on the Sylomer L12 elastic mat the sound radiation in the frequency range in which the “droning of bridges” and thus according to previous experience also the nuisance of the sound radiation of bridges is to be regarded as particularly critical [14], [19], was again able to be reduced clearly.

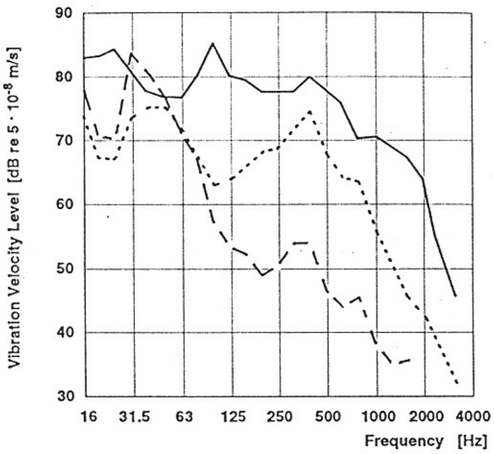


Figure 17: $^1/_3$-octave-band-spectra of vibration velocity levels, measured at the deck of the "Amper-bridge" during the passage of a test goods train on different kinds of track with a speed of 80 km/h.

——— normal ballasted track
- - - - - - nonelastically supported ballastless track (first stage)
— — elastically (on Sylomer® L12) supported ballastless track (second stage)

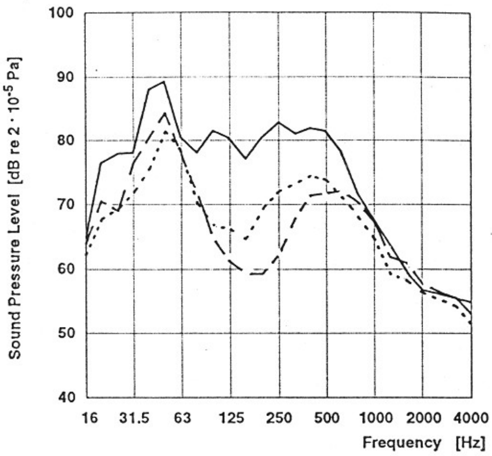


Figure 18: $^1/_3$-octave-band-spectra of sound pressure levels, measured 2m below the bottom plate of the "Amper-bridge" during the passage of a test goods train on different kinds of track with a speed of 80 km/h.

——— normal ballasted track
- - - - - - nonelastically supported ballastless track (first stage)
— — elastically (on Sylomer® L12) supported ballastless track (second stage)

With increasing lateral distance from the bridge the rolling sound radiated directly by the train becomes more and more dominant, which moreover only exists to the side of the railway line. Here the known effect described in detail in [14] using measuring results and a calculation model was observed, according to which the rolling sound when travelling on a ballastless track of the type realized here is greater than when travelling on a ballasted superstructure because on the one hand the sound-absorbing effect of the ballast is missing - which can be compensated by appropriate absorbent coverings [19]. On the other hand because the sound radiation of the wheel/rail system has increased in a frequency range partly determined by the damping and the stiffness of the elastic base plate pad due to the elastic disconnection of the rails from the concrete floor (see Fig. 16) made necessary by the system (for details see [14]).

A similarly constructed elastically supported ballastless track using the "Rheda" type superstructure was mounted in 1994 in the 4,692 m long Säusenstein tunnel which is an important part of the future high-speed track between Vienna and Salzburg in Austria. The residential buildings at the eastern portal of the tunnel had to be protected from structure-borne sound caused by the passing trains so that the KB-value (weighted vibration intensity [23]) does not exceed the threshold KB = 0.1 (just perceptible).

In order to meet these demands the stiffness of the mats which had to be mounted between the tunnel floor and the reinforced concrete track slab was specified in such a way that the rail deflection was limited to 1.0 mm and the required isolation values (8 dB at 50 Hz) were met.

This means that, for example, the vertical natural frequency of the superstructure under traffic load has to be about 25 Hz. This corresponds to an attenuation value of 9 dB at 50 Hz, which was calculated for the performed measure using the 25 mm thick mats of the type Sylomer L 25. To adjust the track stiffness at the transition to the stiff superstructure, the transition zones were fitted with stiffer mats. At the end of the tunnel in the transition area to the ballasted track a ballast mat was laid on the subgrade in addition to guard rails.

4. Example of a production plant with elastically supported foundation

The *"Metallwerk Plansee in Reutte",* Austria was to be expanded by a further rolling mill for the production of molybdenum sheets.

From initial estimated calculations it was already able to be determined that if the rolling mill foundations were established on the natural rock the criteria of increased protection of the neighbouring area from the vibration immissions exerted by the operation of the plant could not be met [21]. For this reason the total foundations of the rolling mill had to be elastically supported.

The known solutions from heavy engineering with deeply tuned foundation supports using steel springs or viscoelastic dampers (see for example [1], [22]) are out of the question here because the unrestricted accessibility of the supporting elements necessary for the revisions required could only have been achieved by expensive constructional measures which the factory wanted to avoid [21].

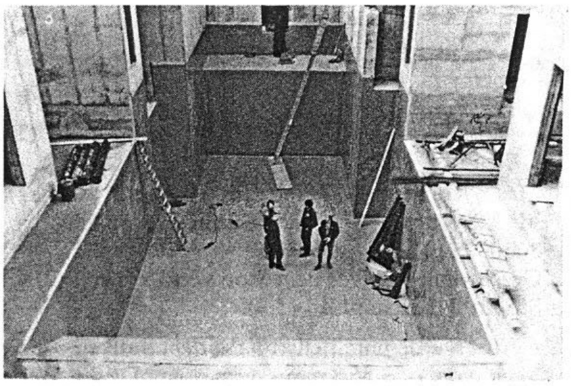
For this reason an elastic support was planned which in addition to the dynamic criteria to be met also had to meet the following important requirements:

> full surface area (specific pressure!),
> chemical resistance to mountain streams,
> durability and thus maintenance of the dynamic parameters,
> practical applications of the product underpinned by sufficient technical measurements.

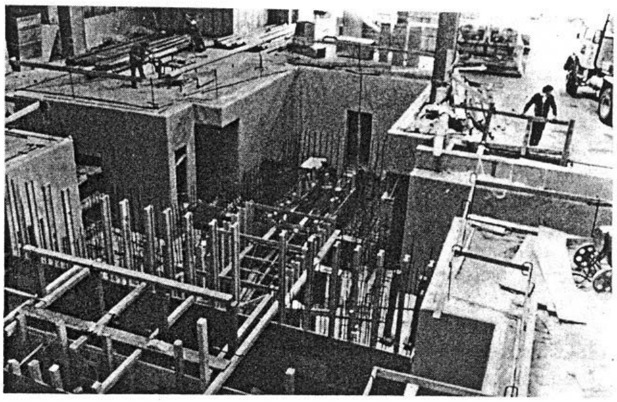
After extensive examination of several products available on the market the decision was taken to use an elastic support on Sylomer. Details of the design and constructional execution are given in detail in [21].

Figure 19 conveys an impression of the lower area of the concrete trough for accommodation of the elastically supported foundation block.

The foundation has a horizontal surface area of 224 m², is 8 m deep and has a total weight (incl. machinery) of 2300 tons. The whole horizontal surface area was covered by mats, type Sylomer M 25, of 400 kg/m³ density; for covering the vertical surface softer mats, type Sylomer R 25 with a density of 220 kg/m³, were used. Both mats have a thickness of 25 mm.



a)



b)

Figure 19: View on the foundation of a steel rolling mill.

a) during placing of Sylomer®
b) during installation of reinforcement

After completing the construction a structural dynamic test was made in order to check the functioning of the elastic support.

Figure 20 shows a top view of the rolling mill investigated with the position of a vibration exciter and different measuring points during this test.

In Figure 21 one can see frequency characteristics of vibration velocities which were measured at the points shown in Figure 20 while exciting the foundation at the position shown.

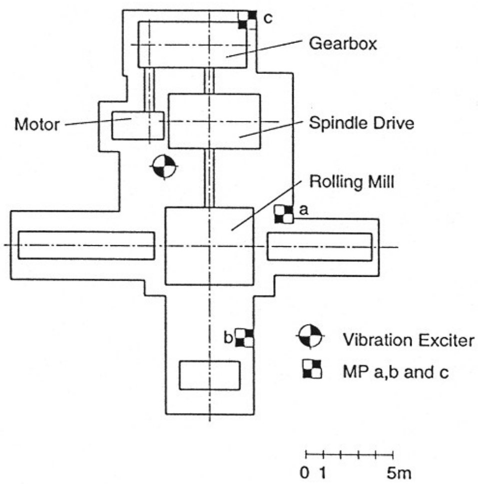


Figure 20: Top view of a steel rolling mill in Plansee, Austria with position of exitation and of measuring points (MP).

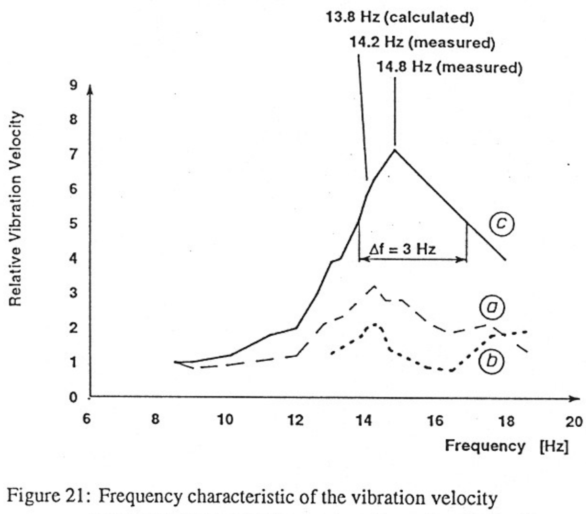


Figure 21: Frequency characteristic of the vibration velocity measured at three positions a, b and c on the elastically supported foundation of a steel rolling mill according to figure 20.

According to the calculation the resonance of vertical, translatory vibrations should occur at 13.8 Hz. It was measured at 14.2 Hz.

Tilting frequencies could not be measured because the position of the exciting machine was near to the centre of gravity. Finally it should be pointed out that this kind of extensive elastic support keeps the pressure exerted to the underground at its lowest possible value.

5. Example of an elastically supported residential building

A residential building in Frankfurt am Main in Germany is situated directly on top of a subway tunnel. A cross-section and a top view of this situation is shown in Fig. 22.

To protect this building from structure-borne sound caused by the subway trains vibration isolation against the subway tunnel had to be provided. The building is divided into a vibration-isolated part with shops and flats and a non-isolated part with parking decks and function rooms.

About half of the isolated part of the building is provided with a cellar. In this area the foundation plate lies extensively on 50 mm thick Sylomer mats. Sectionally there are mat types of differing stiffness. They have been selected in a manner to secure a uniform sinking displacement under the weight of the building.

On the other side of the isolated part the ceiling of the ground floor rests on piles topped by reinforced elastic bearings, as shown in Fig. 22. The aim of the whole isolation measure was to reduce the structure-borne sound level by at least 10 dB at frequencies above 60 Hz.

As with all such applications, it is not possible to measure the insertion loss of the elastic bearing because the building is constructed only once in the same manner in the same place. Fortunately in this case it was possible to measure the vibration levels in the two sections of the building.

First of all measurements in the completed building showed a vertical natural frequency of about 20 Hz, which is

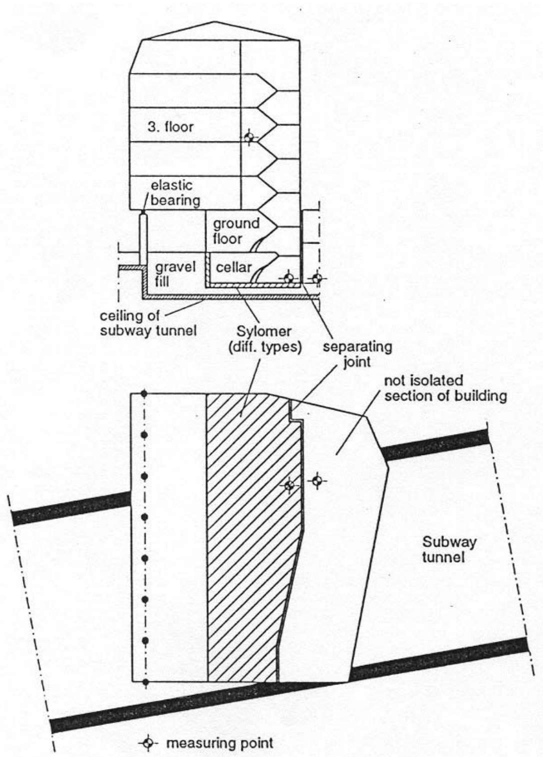


Figure 22: Residential building above a subway tunnel in Frankfurt/Main, Germany.
Schema of the elastic foundation and positions of vibration measurement points.

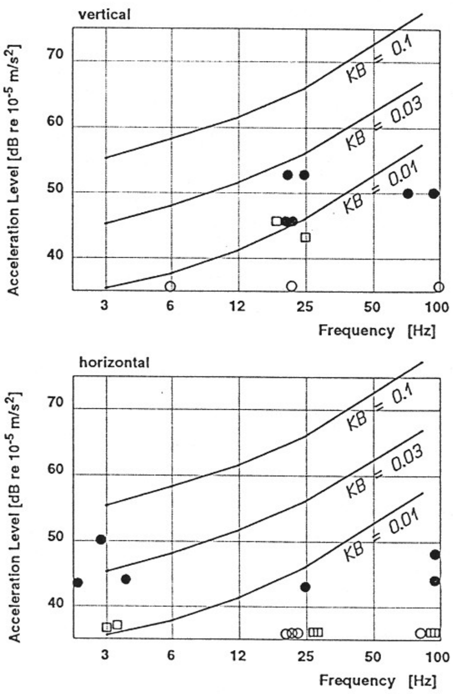


Figure 23: Elastically supported residential building in Frankfurt/Main, Germany.

Results of vibration measurements:
- ● cellar, not isolated section
- ○ cellar, isolated section
- ▢ 3rd floor, isolated section

(level of background vibrations: 40 dB)

in good agreement with the value expected from the dynamic stiffness of the mats and the estimated specific loads of the building.

More specific results of vibration measurements during train passages in the subway tunnel [24] are given in Fig. 3. The results indicate that the isolation system works very well. Vibrations cannot be felt at any place in the building. Train passages in the subway tunnel can hardly be heard even in the cellar of the isolated section. The vibration levels remain under the recommended limits of DIN 4150 [23].

6. Conclusion

Avoiding or damping of structure-borne sound and vibrations is a field involving the interaction of construction, acoustics and chemical engineering.

Cellular PUR elastomers such as Sylomer can help to find simple, effective and economic solutions to vibration problems.

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