LONG-TERM EFFICIENCY OF BALLAST MATS INSTALLED IN
THE RAPID TRANSIT RAILWAY TUNNEL NEAR THE
PHILHARMONIC HALL OF MUNICH, GERMANY

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Abstract. In 1983, ballast mats of type Sylomer® B 851 were installed in a rapid transit railway tunnel near the Philharmonic Hall of Munich, Germany, in order to shield it from the structure-borne noise emitted from the passage of trains. In 2001, after 18 years of use under extremely demanding load conditions, tests were conducted to determine the long-term effectiveness of the noise mitigation measure adopted. Since their installation, the ballast mats have been exposed to more than 760 million load tons. With the Class ET 420 multiple unit trains that are operated on the line featuring an axle load of 160 kN, this represents a fatigue load of more than 45 million load cycles, which is almost four times the value required as a prerequisite for approval for installation in track operated by German Rail (DB AG). This paper presents the results of laboratory tests that have been carried out on samples of ballast mat removed from the tunnel to determine the static and dynamic parameters of the ballast mats after use under extremely demanding load conditions, and of vibration measurements carried out in the tunnel during the passage of trains to determine the long-term efficiency of the ballast mats installed. The results of these tests indicate that the ballast mats have performed exceptionally well over a period of 18 years under extremely high operational loads. The stringent requirements set for the reduction of structure-borne noise when the mats were originally installed are still fully complied with. The good performance of the ballast mats is very well illustrated by a statement in the report of a test laboratory involved in the evaluation of the ballast mats, which reads “.....full functionality of the ballast mats can be expected for at least another 30 years, provided that the loads on the mats remain at the same level”.

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INTRODUCTION

At the beginning of the 1980s, the cultural centre “Am Gasteig” was built in the immediate vicinity of one of the main rapid transit railway lines in Munich, Germany. Besides other facilities, it houses a concert hall for the philharmonic orchestra and the municipal library (Fig. 1).

In order to shield, in particular, the concert hall from the structure-borne noise emitted from the rapid transit railway tunnel, which features very dense traffic, 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 tunnel and, thus, also ensuring that the hall could be used for recordings [1]. Measurements taken at the site of the concert hall, and respective calculations, showed that a remarkable reduction in vibration levels in the frequency range of approx. 31 Hz – 200 Hz had to be achieved [2] (see also [3]). Of the solutions that were discussed at that time, i.e. a room within a room construction, a 20 m deep slot with an elastic filling between the building and the railway tunnel, or the installation of ballast mats in the tunnel, the last measure was adopted. Ballast mats of type Sylomer® B 851, which were designed for the load conditions of the rapid transit system, featuring a bedding modulus of 0.02 N/mm³ in accordance with [4], were installed in the two tunnel tubes (north and south) over a length of 345 m.

The results from measurements of the structure-borne noise, carried out before and after installation of the ballast mats during the passage of trains, showed a very good consistency with the insertion loss values predicted using a “single-degree-of-freedom (SDOF) model” [5], [6], and completely met the requirements according to [1].

Over the past twenty years, ballast mats have been employed with similarly good results at many locations, both during the construction of new lines and - as has become increasingly common in the recent past - during the retrofitting of existing lines [7]. Despite the very good results and experience gained with ballast mats (see for example [8], [9]), customers are increasingly requesting additional evidence of the long-term functional suitability of the products installed.

The rapid transit railway line near the Philharmonic Hall of Munich is a good location to investigate the long-term properties of Sylomer® ballast mats, taking the type B 851 as an example. Since their installation in 1983, the ballast mats have been exposed to more than 760–10⁶ load tons.

This paper presents the results of laboratory tests that have been carried out on samples of ballast mat removed from the tunnel to determine the static and dynamic parameters of the Sylomer® B 851 ballast mat, and of vibration measurements carried out...
in the tunnel during the passage of trains to determine the long-term efficiency of the ballast mats installed.

LABORATORY TESTS

In December 1999, after almost 17 years in operation, samples of the Sylomer® B 851 ballast mat were removed from the south tube of the rapid transit tunnel near the Philharmonic Hall of Munich, in order to examine the long-term properties of this product. Two ballast mat samples, each featuring a dimension of approximately 600x1200 mm², were removed from two different areas of track (Fig. 2, for more details see [10]).

The removed samples were inspected visually, and their static and dynamic stiffness determined. Also, a comparison with the parameters specified in the quality control report prepared when the ballast mats were installed in 1983, was carried out [11], [12].

Test results

The visual inspection of the removed samples showed clearly that the load distribution layer, i.e. the protection layer in the ballast contact area, was in very good condition [11]. It showed slight plastic deformations, but no damage (for example, perforations). The pattern of the imprint marks caused by the ballast showed that the ballast grains were very well embedded in the surface of the ballast mat. The lower, resilient layers were completely intact as well.

The static load deflection curve in the load range up to approx. 0.25 N/mm² was determined for a piece taken from each of the two samples, each with a dimension of 300x300 mm² [11]. In accordance with the special requirements (which deviate from those found in [4]) that were established in the tender documentation for the mitigation measure in 1983, a bedding modulus $c_{\text{actual}}$ was determined, based on the load deflection curve for both samples, which was then compared with the nominal value of $c_{\text{target}} \pm 12.5\%$ specified in the tender documentation.

The analysis indicated that the average bedding modulus obtained from the measurements carried out on the two samples was in the range $c_{\text{actual}} = c_{\text{target}} + 10\%$, i.e. the nominal value requirements from the original tender documentation were still complied with [11].

The dynamic stiffness of a ballast mat sample was determined using the so-called ‘direct method’ as per ISO 10846-2 [13], with the boundary conditions specified in [4]. Fig. 3 shows a picture of the test rig used. Fig. 4 shows an example of the results of a measurement carried out as per [12], with a static pre-load level of 0.06 N/mm², which is characteristic for the operation of rail rapid transit systems as per [14]. The sample used in this case had a dimension of 200x200 mm². For the purpose of comparison, Fig. 4 also shows the results of the original measurements carried out on three samples of ballast mat before installation in 1983 [15].
It is evident that the stiffness results for the recently removed sample are somewhat higher than those obtained for the samples at the time of installation. In this respect, however, it should be noted that, due to cost considerations (railway operating conditions in the tunnel, etc.), the recently removed samples could only be taken from two very restricted areas. Also, quality control regulations for ballast mats allow for deviations of $\pm 15\%$ from the required nominal value. On the whole, based on the results presented in Fig. 4, it can be said that no serious changes in the dynamic load deflection properties of the ballast mats had occurred during the 17 years of use under extremely demanding load conditions.

Consequently, it was expected that, given similar boundary conditions in the tunnel (types of vehicle operated, rail running surface, track stiffness, etc.), a similar level of efficiency of the mitigation measure would be determined from the vibration measurements that were going to be carried out in the tunnel during the passage of trains, as was found after the ballast mats were installed in 1983.

**VIBRATION MEASUREMENTS DURING THE PASSAGE OF TRAINS**

In order to obtain reliable and meaningful results from these measurements, it was crucial that all parameters that are of influence on the generation of structure-borne noise were the same as those at the time of previous measurements, or at least comparable to the extent technically possible. In this respect, the smoothness of the rails or, more specifically, the condition of the rail running surface is of great importance.

In the summer of 2000, in preparation for the measurements, an inspection of the condition of the rail running surface was carried out in the relevant section of the tunnel. It was determined that the running surface of the rails was in very poor condition, so that it would not be possible to carry out the measurements at that time. An evaluation of the detected rail surface defects by the responsible department of DB AG yielded that they could not be remedied by rail grinding and that, therefore, also based on considerations of vehicle movement dynamics (vehicle/track interaction) but, in particular, with a
view to reducing the structure-borne noise emissions, replacement of the rails was necessary (for details see [10]).

Measurement procedure

In April 2001, following replacement of the rails, the new rails were ground as is common practice, in order to remove manufacturing defects and to create an optimal rail profile (see, for instance [16]: “preventive grinding“). After a break-in period of roughly three weeks, optimum rail running surface conditions were present for the measurements of structure-borne noise in the tunnel section under study [17], as was the case before and after installation of the ballast mats in 1983.

The locations of the measurement points set up in the north and south tubes of the tunnel are illustrated in Fig. 5. Four measurement points for each direction of travel were set up on the tunnel walls, at a height of approx. 1.5 m above top of rail, at the same locations as originally used for the measurements that were carried out before and after installation of the ballast mats in 1983.

For each direction of travel, three of the measurement points were in the area fitted with ballast mats, while one measurement point was located outside this area (see Fig. 5, Mp 6 and Mp 7). Piezo-electric acceleration pick-ups were used as measurement devices, which were fitted on the existing, still intact original mounts, consisting of aluminium plates affixed with adhesives to the tunnel walls.

At first, the passages of both types of train that are operated on the Munich rapid transit system were measured, i.e. the Class ET 420 (old) and the Class ET 423 (new) multiple unit trains. However, in the further evaluations, only the results for the ET 420 multiple unit trains were used, as comparison with the earlier measurement results was only possible with this type of vehicle.

Evaluation of measurement results

Evaluation of the measurement results was carried out in an identical manner as of those obtained in 1983 (for details see [10], [17]).

From the resulting spectra for each individual passage of train, the energetic mean value of the 1/3-octave-band spectrum of vibration velocity levels was determined for all passages of train per measurement point, and then compared with the corresponding spectra obtained from the measurements carried out immediately before and after installation of the ballast mats in 1983.

Fig. 6a shows an example of this comparison for a single measurement point outside the area fitted with ballast mats, and Figs. 6b and 6c for one measurement point
each within the area fitted with ballast mats, in the north and the south tube of the tunnel, respectively.

In order to compare the long-term efficiency of the ballast mats to that measured immediately after their installation in 1983, the 1/3-octave-band level differences were determined for each measurement point, using the mean vibration velocity spectra for the situations “before installation” and “18 years after installation”, from which then the arithmetical average for the three measurement points combined, for each direction of travel (north and south tube of the tunnel), was calculated. The mean value of this 1/3-octave-band vibration velocity level difference for the situation “18 years after installation” was then depicted graphically as a function of the 1/3-octave-band centre frequency and compared to the corresponding mean value for the situation in June 1983, i.e. immediately after installation of the ballast mats.

Figs. 7a and 7b show the comparison for the north and the south tube of the tunnel, respectively (in this paper, the “insertion loss” of the ballast mats is not referred to, but rather the level difference, as is illustrated in Figs. 7a and 7b. This is because, due to a range of practical reasons, the level difference observed at the measurement points outside the area of ballast mats is not used as a corrective factor, as was done when the insertion loss was determined at the time of installation of the ballast mats in 1983).

At first glance, the diagrams in Figs. 7a and 7b show no significant loss in efficiency of the ballast mats, even after 18 years of use under extremely demanding load conditions. A minor increase in the system’s resonant frequency can be observed in Fig. 7a (see the area of negative level difference), in conjunction with another minor level difference in the higher frequency range, which allows one to draw the conclusion that, in their interaction with the ballast, there has been a slight increase in the stiffness of the ballast mats. As explained earlier in the discussion of the test rig results, this in-
crease in stiffness is probably not due to the ballast mat alone; it is more likely that due to deterioration of the ballast condition, as well as other contamination and related settling in the ballast bed, the effective loaded mat area per sleeper and, consequently, also the effective dynamic stiffness of the mats have increased (for more details on this issue, in particular the formulae for the effects described, see [5] and [6]).

In the results for the south tube of the tunnel, shown in Fig. 8, the aforementioned effects seem to be even more pronounced at first glance. But, if one takes into account that, compared to the conditions after installation of the mats in 1983, no discernible shift in the system’s resonant frequency, which is primarily determined by the unsprung wheelset mass and the (effective) dynamic stiffness of the ballast mat (see [5], [6]), has occurred, then the currently somewhat lower level difference shown in Fig. 8 for the frequency range above roughly 63 Hz cannot be attributed to a stiffening of the ballast mats. According to the usual, well-substantiated models for the description of vehicle/track interaction (see, for example, [5], [18], [19], [20]), the level reduction achieved by a ballast mat in this higher frequency range is primarily determined by the relation of the dynamic ballast stiffness to the (effective) dynamic stiffness of the mat.

Thus, if a stiffening of the ballast mat for the aforementioned reasons cannot be the reason for the slightly lower level difference vis-à-vis 1983, then the observed effect can be explained if one assumes that the stiffness of the ballast bed has decreased in the meantime.

**CONCLUSIONS**

The results of the tests and analysis described in this paper indicate that the Sylomer® B 851 ballast mat has performed exceptionally well over a period of 18 years under extremely high operational loads of more than $760 \cdot 10^6$ load tons. The stringent requirements set for the reduction of structure-borne noise when the mats were originally installed are still fully complied with. Even the fact that the mats were submerged in water, as was found when the samples were removed (see [10]), had no detrimental impact on the efficiency of the ballast mats.
These studies which, to a certain extent, can be considered as a long-term, practical test of Sylomer® ballast mats in general, clearly show that a long-term, very high level of efficiency can be ensured using these products.

REFERENCES


