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Innovative superstructure renewal method used for the conversion of ballasted turnout track into slab track mass-spring systems – without any traffic disruption

Turnouts and transition zones are the most maintenance-intensive track sections of a metro network, involving high costs. In order to minimise these high maintenance costs, as well as to reduce vibration emissions, Metro de Madrid is converting ballasted turnout tracks into vibration isolating mass-spring systems with highly effective, tried and tested polyurethane (PUR) elastomer mats. For this purpose, Metro de Madrid has developed a work method that allows all work to be performed solely during night-time traffic shutdown periods – without any traffic disruption. Measurements conducted both before and after installation of the vibration mitigation measure have confirmed its high effectiveness.

By: Jorge Blanquer, Head of Engineering and Maintenance of Civil Works, Architecture, Track, Cleaning & Environment, Metro de Madrid; L. Alejandro Chércoles Asensio, Head of Studies, Projects & Renewals, Track Department, Metro de Madrid; Juan Antonio Márquez Picón, Manager of New Business, Customer Services Department, Metro de Madrid; Markus Heim, Development Engineer, Research & Development, Railway Division, Getzner Werkstoffe GmbH, Bürs, Austria.

Metro de Madrid operates the second longest metro network in Europe, covering 293 route-km and featuring some 300 stations – it is one of the fastest growing metro systems in the world. The superstructure in the tunnels mainly consists of standard ballasted tracks with wooden sleepers and 54E1 rails. In general, the ballast bed has a thickness of 250-400 mm below bottom of sleeper. Trains are operated at a maximum speed of 60 km/h and have an axle load of 13 t.

On a metro network, as on any other railway network, turnouts constitute high-maintenance and cost-intensive track components. In order to minimise the maintenance demand of turnouts, as well as to reduce their negative vibration impact, Metro de Madrid is converting ballasted turnout tracks into slab track mass-spring systems, using highly effective vibration isolating polyurethane (PUR) elastomer mats (Figs. 1 and 2).

Mass-spring systems offer a number of economic and technical advantages, as compared to ballasted turnout track, including:

— a reduction in vibration emissions;
— a decrease in maintenance demand;
— a positive impact on life-cycle cost (LCC);
— an improvement in track quality;
— an increase in track service life;
— an increase in safety;
— an enhancement of passenger ride comfort.

Fig. 1: A typical transition zone (ballasted turnout track) near a station

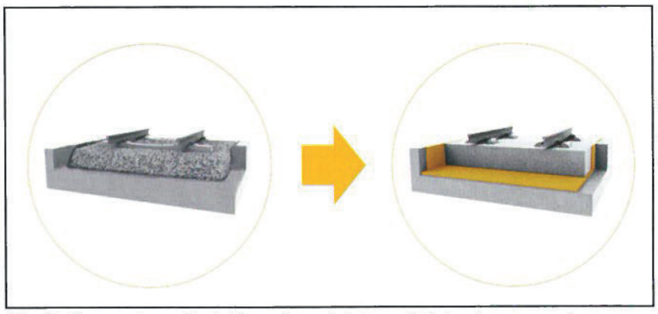


Fig. 2: Conversion of a ballasted track into a slab track mass-spring system with polyurethane (PUR) elastomer mats

EFFECTIVE VIBRATION ISOLATION OFFERED BY MASS-SPRING SYSTEMS

Vibrations resulting from the passage of trains can cause noise in nearby buildings; this problem is intensified with any increase in traffic density. Various measures can be undertaken to reduce the transmission of structure-borne noise – the adoption of the most suited one in a specific case depends on the prevailing technical and economic factors. As a general rule, the measures have to comply with the requirements that are defined in national standards governing noise and vibration limits.

In the case of a ballasted track, under-ballast mats can be installed to reduce vibrations, whereas elastic rail pads or baseplate pads are often favoured for slab track.

The most effective method to reduce vibrations, although the most costly one, is to install a mass-spring system, by means of which the entire concrete slab is elastically decoupled from the subsoil.

Vibration isolating effect (see Figs. 3 and 4)

The vibration isolating effect of a mass-spring system can be explained by means of the single-degree-of-freedom (SDOF) principle (see also Fig. 3) [1].

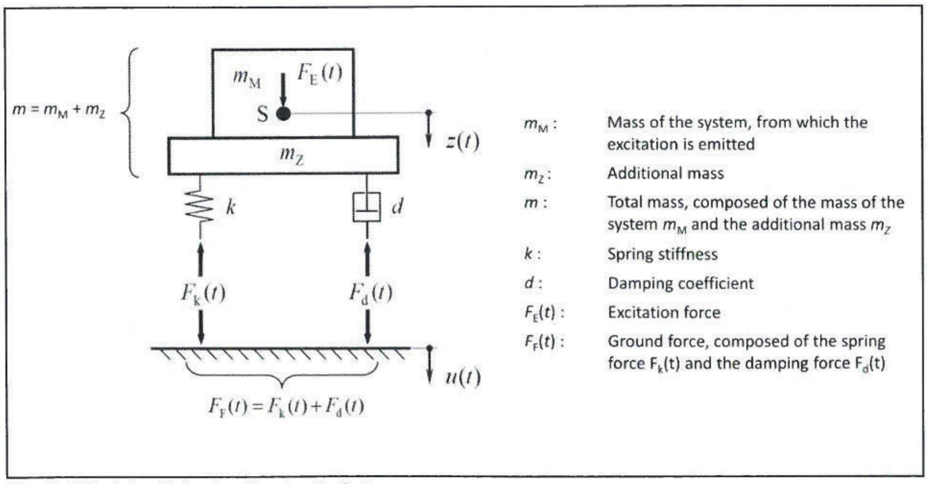


Fig. 3: Principle of elastic vibration isolation

The theoretical natural frequency (f_0) of the mass-spring system is derived from the dynamic effective mass (m) of the concrete slab and the train, as well as from the dynamic stiffness (k_{dyn}) of the elastic bearing.

In order to ensure that the vibration isolation is as effective as possible, the natural frequency should be significantly lower than the excitation frequencies. Irrespective of the type of elastic bearing used, the vibration isolating effect is only triggered when the ratio of the excitation frequency (f) to the natural frequency (f_0) is greater than $\sqrt{2}$ (see also Fig. 4). If this ratio is smaller, the dynamic force is distributed more intensively into the subsoil. Usually, the mass of the concrete slab is predetermined during the planning of the superstructure. Therefore, the final vibration isolating performance is defined by the dynamic properties of the elastic layer.

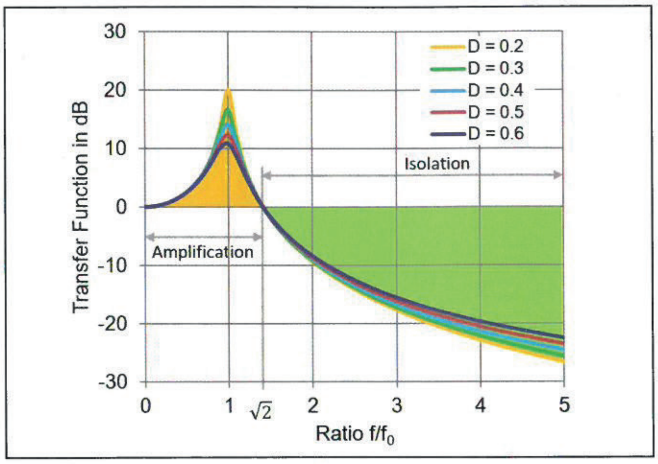


Fig. 4: Transfer functions of the single-mass-spring system (system damping (D) as the parameter)

The system damping comprises the damping of the elastic bearing and all of the other damping mechanisms that are present in the system. The vibration isolating effect is typically expressed as a logarithm of the input to output force ratio.

Sylomer®/Sylodyn® elastic bearing material

For over 30 years, Sylomer® and Sylodyn® polyurethane (PUR) elastomer mats made by Getzner have been successfully used as elastic bearing material in a good number of projects [2], [3], [4], [5], [6], [7], [8], [9]. Besides durable elastic properties, an accurate installation of the vibration isolation material at the worksite is extremely important. The mats, which are supplied either in 1.5 m wide rolls or as tailor-made plates that eases their installation, bend easily and can be cut to size using conventional knives. The mats can be installed as lost shuttering. For additional protection, they are fully bonded using adhesive tape that covers the joints, thus preventing structure-borne noise bridges.

Effectiveness (insertion loss) prediction of selected measure

The vibration isolating effect of a mass-spring system can be estimated using the single-degree-of-freedom (SDOF) principle noted earlier. Irrespective of the local conditions, the insertion loss is determined only by the natural frequency of the mass-spring system and the system damping.

The vibration isolating measure is designed based on the dynamic effective masses, which usually are predetermined, and the selected elastic mat (more complex models take other conditions, such as the stiffness of the tunnel invert, the kind of soil above the tunnel, the impact in the frog section and others into account).

In the case of the Metro de Madrid project, for which Sylomer® elastic base and side mats with a 25 mm thickness are used, and taking into account a concrete slab thickness of 400 mm and an unsprung wheelset mass of 15% for the 13 t axle-load trains, a natural frequency of 20 Hz has been calculated.

The shear modulus of the vertical side mats contributes to the overall vertical stiffness. This results in higher natural frequencies and must hence not be neglected. Due to the effect of the side mats, the natural frequency is increased by approx. 2-3 Hz.

METRO DE MADRID PROJECT – CHALLENGES, WORK METHOD AND ACHIEVED EFFECTIVENESS

The superstructure renewal project of Metro de Madrid has had a number of challenges that have been met successfully. By adopting an innovative work method, all work is carried out solely during night-time traffic shutdowns, thus without any disruption to train services. The vibration isolating measure adopted has been very effective, as measurements have confirmed.

Challenges

The high density of underground tracks can pose considerable challenges for planners – not least when it comes to implementing vibration mitigation measures. The major challenge is the short time windows that are usually available for track work during the night – in the case of the Metro de Madrid superstructure renewal project just 2.5 hours, during which not only the actual renewal work itself, but also the logistics of the construction equipment, tools, materials, etc., have to be managed. Further, limited space, poor lighting and ventilation make the work even more challenging. Because of these reasons, the strategic planning of the Metro de Madrid project requires a considerable amount of expertise in design, logistics and implementation. A coordinated cycle-based process ensures a smooth project execution.

Metro de Madrid has developed an innovative work method that allows all work to be carried out solely during the 2.5-hour night-time traffic shutdowns, thus without any disruption to train services – allowing a single 60-80 m long turnout section to be renewed in stages in about 75 night-time traffic shutdowns (for safety reasons, it is recommended to enforce a speed restriction for the track sections that are being renewed. Furthermore, during the entire renewal process, the respective track should always be kept under close observation). The work method adopted on Metro de Madrid consists of several work stages, as alluded to in the following.

Work method adopted (see also Figs. 5-10)

Upon completion of the topographic survey of the respective track section, work starts by removing the turnout and installing a supporting skeleton for both tracks using timber sleepers. Following this, the ballast is removed and, then, the track skeleton is supported with concrete blocks and secured horizontally with wooden wedges or wooden struts.

Before installing the elastic bearing, a compensation layer must first be applied to the tunnel floor and, then, the elastic bearing can be installed, i.e. placing of the polyurethane (PUR) elastomer mats onto the tunnel floor – a full functionality of the mass-spring system can only be guaranteed if the elastic vibration isolation layer is properly installed and structure-borne noise bridges are avoided (Figs. 5 and 6).

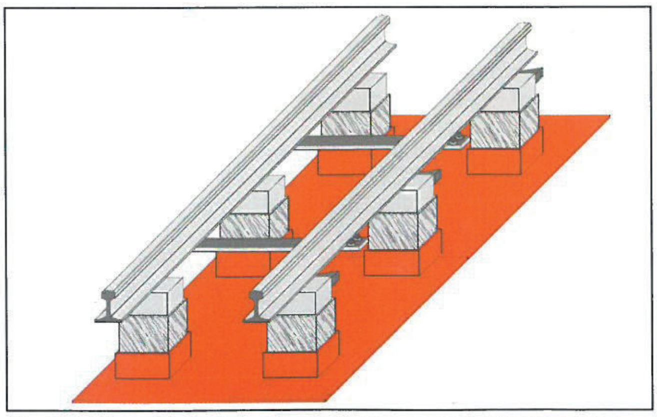


Fig. 5: A schematic drawing of the temporary supporting track skeleton and the installed PUR elastomer mats (coloured area)

Fig. 6: Installation of the vibration isolating mats

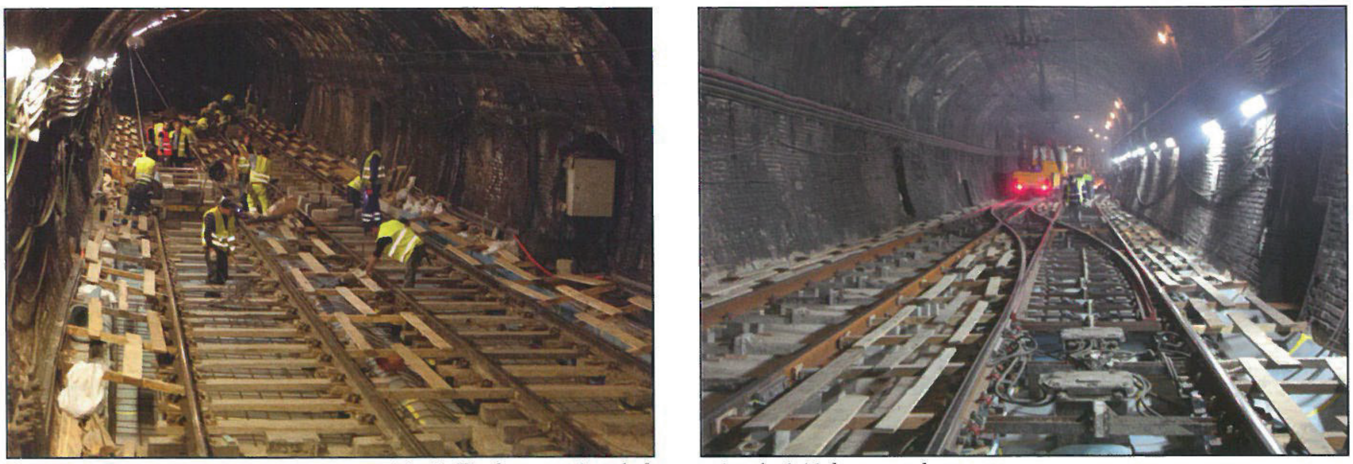


Fig. 7: Final preparations before pouring the initial concrete layer

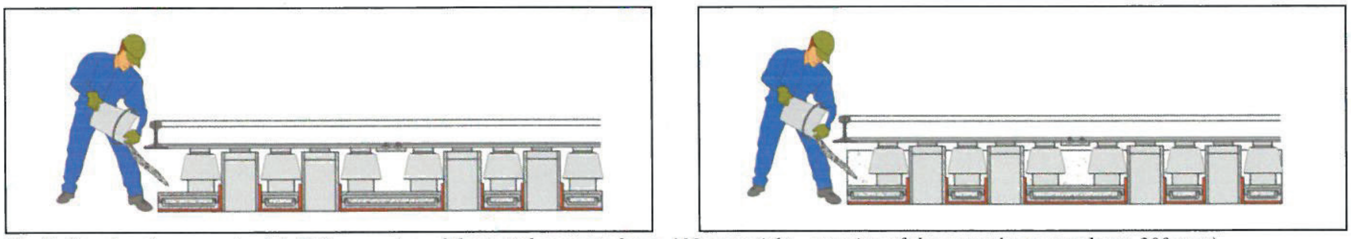


Fig. 8: Creating the concrete slab (left – pouring of the initial concrete layer, 100 mm; right – pouring of the second concrete layer, 300 mm)

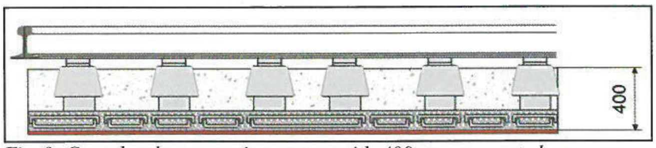


Fig. 9: Completed mass-spring system with 400 mm concrete layer

Fig. 10: Completed transition zone (turnout on a slab track mass-spring system)

Once the polyurethane (PUR) elastomer mats have been installed on all lateral surfaces, such as the support structure and the shafts, the reinforcement is installed and the initial 100 mm of the concrete support slab is created (Fig. 7). The concrete is poured onto the subsoil via air shafts. Subsequently, the turnout sleepers, the rail fastenings and the remaining turnout components are pre-assembled.

After the shuttering for the longitudinal and lateral drainage, and the shafts and the signalling devices have been completed, the track panel can be adjusted and levelled with the support of a track geometry measuring car.

Following this, the concrete support slab is built up to its full height (400 mm) in several phases, whereby a temporary loosening of the rail fastening bolts allows a de-stressing of both the rails and the concrete support slab (Fig. 8).

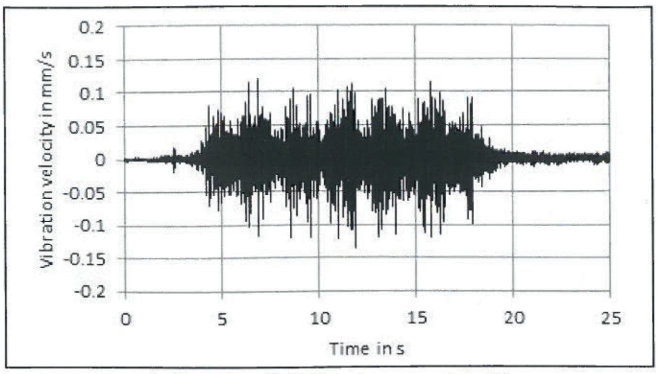
Finally, the shuttering and temporary supporting blocks are removed and then the gaps left behind by the supporting blocks are lined with polyurethane (PUR) elastomer mats and sealed with concrete – the concrete support slab is now finished (see Fig. 9). Rail welding and final cleaning conclude the renewal work (Fig. 10).

Effectiveness of superstructure renewal confirmed by measurements

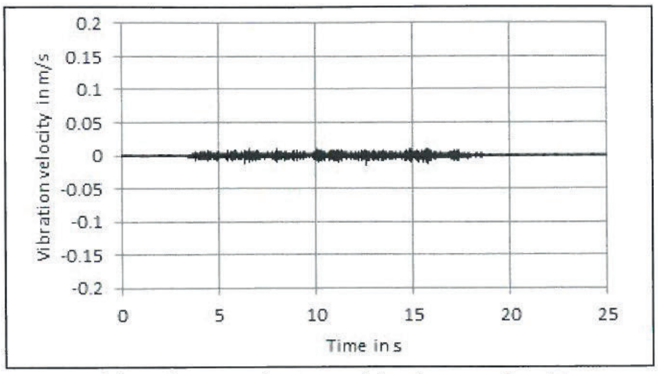
In order to prove the effectiveness of the installed vibration mitigation measure and, therefore, that of the superstructure renewal, vibration measurements were conducted at two different turnouts both before and after the renewal work [10], [11]. The measurements were conducted at street level directly above the turnout frog as there, due to rail discontinuity, abrupt broadband track excitations above the frequency range were to be expected during the passage of trains (Fig. 11).

Fig. 11: Vibration measurements conducted at street level

Fig. 12 shows an example of typical time signals of the vertical vibration velocity that were measured during train passages both before and after the superstructure was renewed.



ballasted track (before the renewal work)



slab track mass-spring system (after the renewal work)

Fig. 12: Typical time signals of the vertical vibration velocity [10], [11]
top: ballasted track (before the renewal work),
bottom: slab track mass-spring system (after the renewal work)

As can be observed from Fig. 12, before the renewal work, maximum vibration velocities of more than 0.1 mm/s were recorded, whereas measurements conducted following the renewal work showed a decrease in vibrations by a factor of 10.

Fig. 13 shows the measured 1/3-octave-band spectra of vibration velocity levels, averaged for the two turnouts (both before and after the renewal work) and several train passages, and the corresponding insertion loss factor [10], [11].

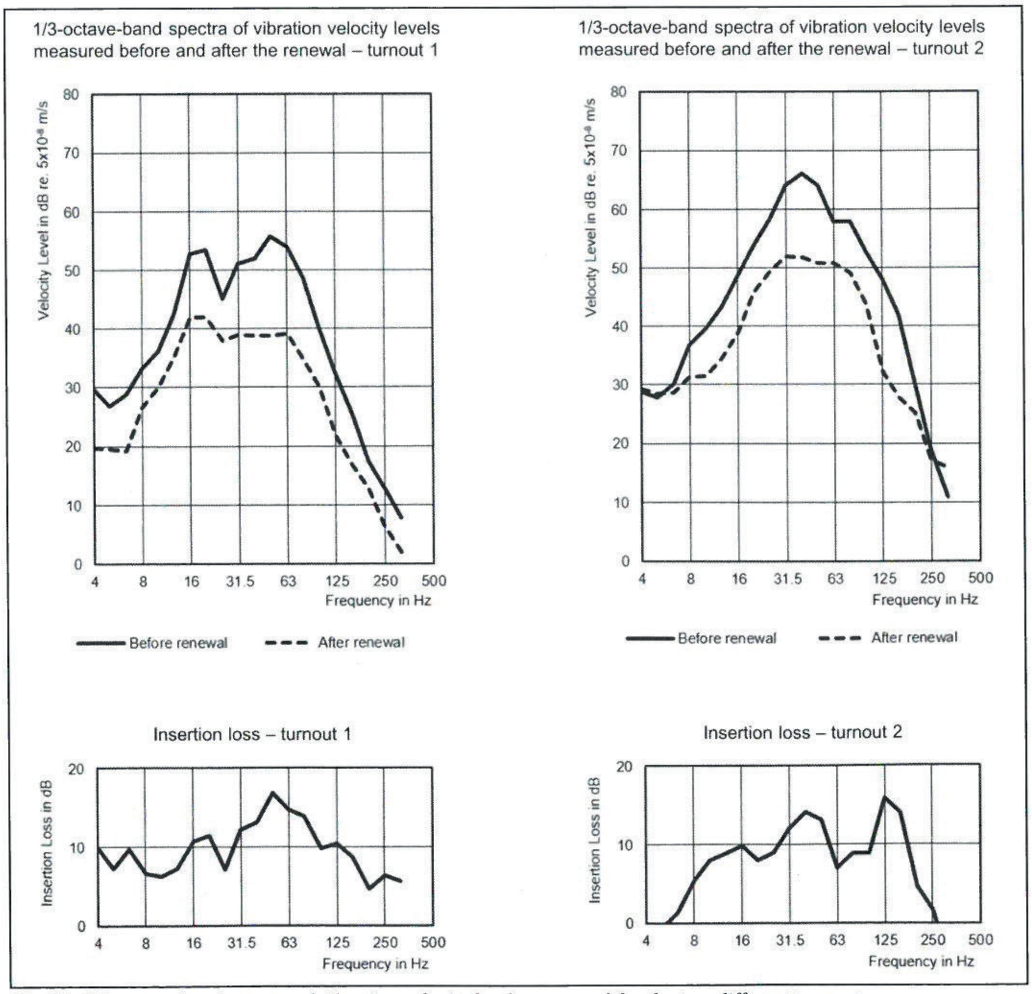


Fig. 13: 1/3-octave-band spectra of vibration velocity levels measured for the two different turnouts – in both cases, both before and after the renewal work [10], [11]

An evaluation of all the results obtained has demonstrated that the implementation of the mass-spring system has resulted in a broadband vibration reduction for both turnouts.

A vibration velocity reduction of 8-16 dB has been achieved in the frequency range critical for secondary airborne noise, i.e. 40-160 Hz, which corresponds to a vibration isolating efficiency of 60-84% – this means that residents in nearby buildings can expect similar reductions in vibrations and secondary airborne noise.

CONCLUDING REMARKS

Metro de Madrid has converted several ballasted turnout track sections into slab track mass-spring systems, in order to reduce vibrations and structure-borne noise, thereby adopting an innovative superstructure renewal method that allows work to be carried out without any disruption to the metro services.

By installing highly efficient polyurethane (PUR) elastomer mats, an optimum vibration isolation has been achieved. The vibration velocity reductions of 8-16 dB that were noted in the frequency range critical for secondary airborne noise, i.e. 40-160 Hz, corresponds to a vibration isolating efficiency of 60-84%.

Currently, ten ballasted turnouts (each 60-80 m long) in the tunnel areas of Metro de Madrid have been converted into vibration mitigating slab track mass-spring systems without any train service interruptions.

As a result of the extremely positive experience gained thus far, another three turnouts are being converted this year; it is scheduled to renew further turnouts in the next few years.

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