HIGH ATTENUATION SLEEPER

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ABSTRACT

The environmental impact consideration have become a crucial subject for people living alongside or above underground railway lines. The main concern is related to noise and vibrations disturbance.

The present article details the development of a high attenuation sleeper which, with an adapted resilient layer, will provide a significant vibration mitigation close the highest achieved track ground borne noise attenuation, as known floating track slab.

The main objective is to provide a cost effective alternative to this ultimate solution. Besides the vibration mitigation performance, subsequent objective is also to provide a more compact and easy to install track system. Compared with a conventional floating slab track, the result is a high track laying ratio and a reduction of the tunnel section required to install such a track system.

INTRODUCTION

These last decades, rail transportation has known an amazing development notably in an urban environment through the construction of railway lines at grade, mainly dedicated to tramway operation or .underground lines mainly dedicated to metro operation.

In the same time the environmental impact consideration have become a crucial subject for people living alongside lines or above underground lines. The main concern is related to noise and vibrations disturbance.

This disturbance has two origins: the direct noise or vibration from the railway traffic and the noise indirectly produced by the vibration of the building walls, the so-called re-radiated noise.

This is usually achieved by introducing an adequate resilient layer in the track system to provide the required attenuation.

Providing a vibration mitigation with the track is now commonly encountered, especially on urban projects (LRT MRT).

The present article will present the development of a high attenuation sleeper which with an adapted resilient layer will provide a significant vibration mitigation close the highest achieved track ground borne noise attenuation, as known floating track slab.

BACKGROUND

Starting from the booted sleeper system, named S3, installed on the Section 2 of the Channel Tunnel Rail Link (CTRL), in operation for more than one year and a half, ALSTOM Transport and SATEBA have explored the limits in combining the lowest existing resilience with a high sleeper mass.

Another benchmark was considered and it is a conventional floating track slab which consist of rubber pads, bearing a concrete slab which is holding on its top the fastening systems and the rails.

This system is considered as the most performing one regarding vibration attenuation.

After a complete analysis of critical parameters, a special design has been drawn. The resulting anti-vibration solution is a high-performance system suiting areas where vibration mitigation and/or attenuation of re-radiated noise are required.

This results in the development of a track system with vibrations mitigation performance in between the two benchmarks described above.

DESIGN OF A HIGH ATTENUATION SLEEPER

The main goal of the new High Attenuation Sleeper system is to mitigate the ground-borne noise and vibration generated by the vehicle traffic and keep the slab track system compliant with the geometrical requirements of the technical design standards.

A benchmarking approach was first implemented with the objective of getting a performance in vibration mitigation which is better than CTRL2 S3 and close to the conventional floating slab track.

Once a combination of stiffness and mass, which could achieve the required performance, was found it was important to study the mechanical behaviour of this track system.

Benchmarking approach for defining vibration mitigation performance

Conventional floating slab track

For reference, a conventional floating slab track (FST) currently under installation in Taipei on the Orange Line extension was taken in account (see Figure 1).

It typically consists of mini slabs made of pre-cast concrete elements installed on cylindrical rubber pads. This type of trackform has been widely used in Hong Kong.

The following parameters were considered to carry out simulations : dynamic stiffness of 11.2MN/m/ml of rail, and axle load of 160kN running at 90km/h.

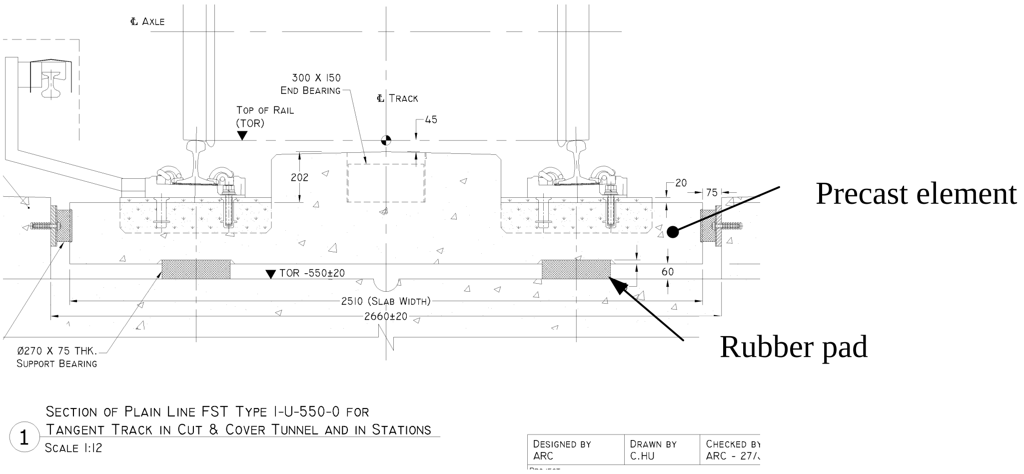

Figure 1 : Typical section of Taipei floating slab

CTRL S3 trackform

CTRL S3 trackform was installed over 20 Km of slab track in tunnel. It consists of twin-block sleepers (see overview below in Figure 2) equipped with rigid boots or hulls, an elastic pad is placed in the bottom of each hull and bears the lower face of the concrete block, lateral pads are placed all around the vertical perimeter of each block.

CTRL2 S3 has a dynamic stiffness of 16.5MN/m/ml of rail, and was designed according to the following characteristics :

Vehicles	*Axle load*	*Max. Speed*	*Normal Cant Deficiency*
Eurostar high speed trains	17 t	230 Km/h	130 mm
Domestic passenger trains	14.5 t	200 km/h	130 mm
Freight trains	22.5 t	140 km/h	- 90 (cant excess)

Table 1: Input data for CTRL S3 trackform

Details of the development of CTRL2 S3 trackform were provided during Railway Engineering 2005 (cf. [1])

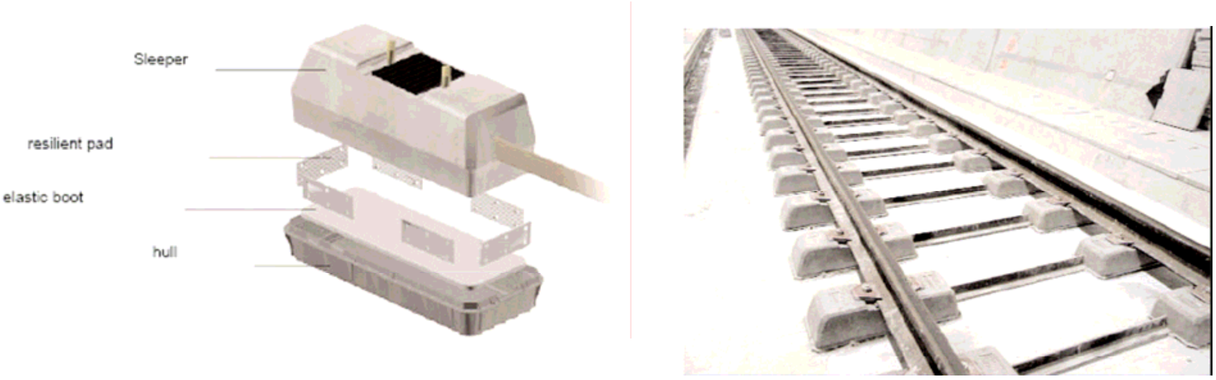

Figure 2 : CTRL2 S3 Typical view

The vibration attenuation provided by a resilient track system shall be quantified in insertion gain , in 1/3rd of octave bands, relative to a reference track system.
All other parameters remain equal (e.g. rolling stock, speed, ground conditions, vibration prediction location), the insertion gain, in each 1/3rd of octave band, is the difference between the vertical vibration velocity levels predicted for the resilient track and the reference track.

$$IG(f) = L_{\text{Resilient track},f} - L_{\text{Reference},f}$$

Where:

L : vertical vibration velocity level
f : 1/3rd octave band vs. frequency (Hz)

Based on the characteristics detailed above for conventional floating slab track and CTRL2 S3, simulations of insertion gain were carried out.

Insertion gain graphs are showed in Figure 3.

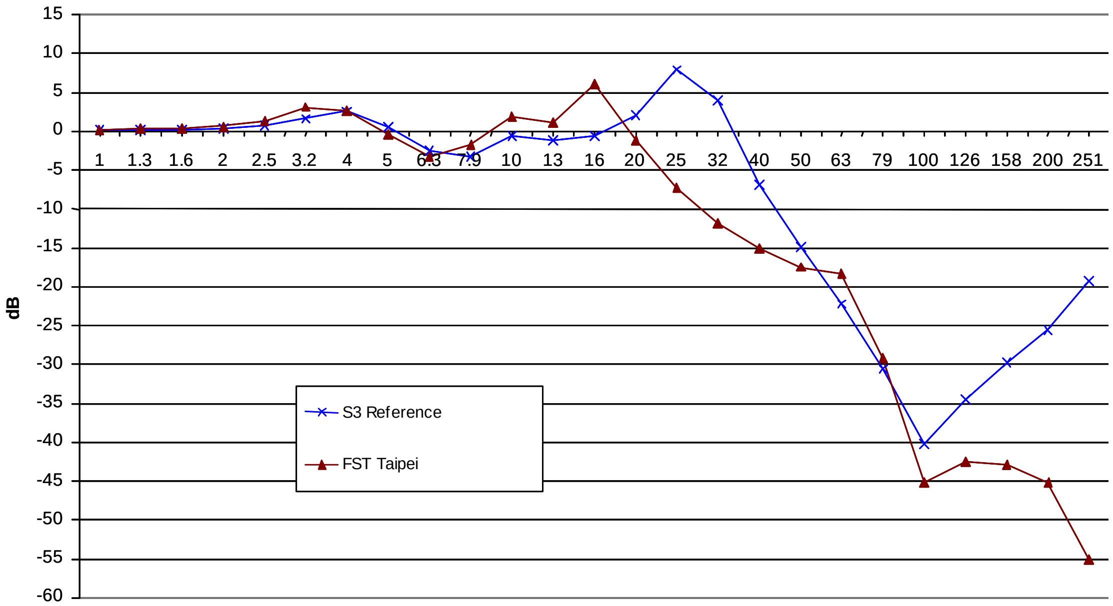

Figure 3 : Insertion gain simulation (S3 and FST)

The insertion gain of the High Attenuation Sleeper could then be set regarding these two benchmarks, through a parametric study where varying parameters were essentially mass and stiffness as detailed in Table 2.

Characteristics	*Range of values*
Mass	200 to 400kg
Stiffness of under sleeper pad	6 to 10MN/m/lm

Table 2 : Varying parameters

The results of these simulations lead up to a combination of stiffness (approx. 8MN/m/lm) and mass (approx. 400kg) which could achieve the required performance.

The reference track which was considered is defined as below in Table 3 :

Track component	*Data*	*Value*
Rail		
	Profile	UIC60
Rail pad		
	Spacing	0.6m
	Dynamic stiffness	270 MN/m
	Loss factor	0.2
Slab track		
	Concrete	BC5
	Thickness	0.5m
	Width	3m
Soil		
	Soil’s modulus	372MPa
	Poisson’s ratio	0.47
	Soil density	2000kg/m3
	Loss factor	0.2

Table 3 : Reference track data

Mechanical behaviour of a sleeper on a highly resilient layer

Once the vibration mitigation performance have been fixed, the subsequent step of the development was oriented towards the mechanical performance of the new resilient track system.

When a very low stiffness pad is placed under sleeper, it is indeed important to study the mechanical behaviour of the sleeper whether it is of a twin-bloc type or a mono-bloc type.

Consequently simple modelling were setup (see Figure 4 and Figure 5) describing these two main types of sleepers.

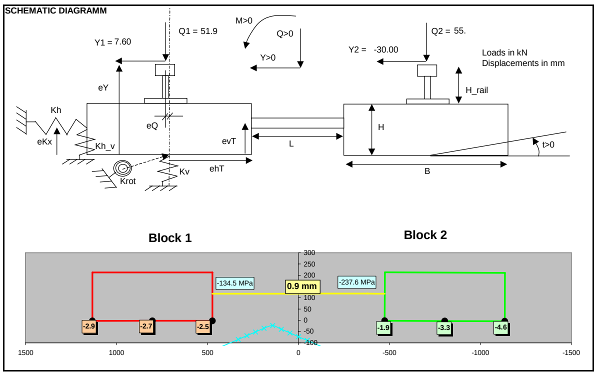

Figure 4 : Twin-bloc sleeper modellling

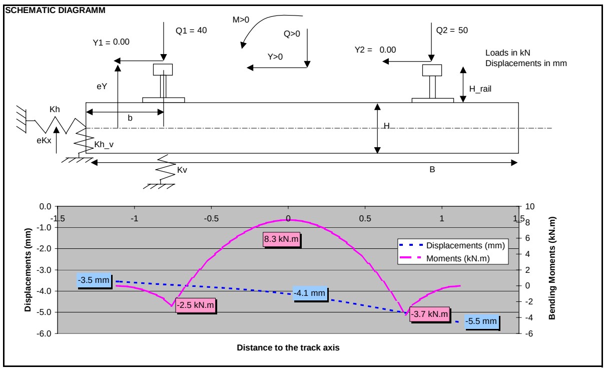

Figure 5 : Monobloc sleeper modelling

Notations of loads applied to the track were as per Figure 6 below :

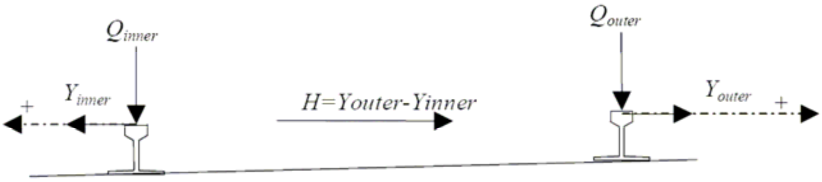

Figure 6: Parameter notation

The mechanical behaviour was studied taking into account of the dynamic loads which were determined with the input data detailed below, based on a metro operation :

Characteristic	*Parameter*	*Adopted value*
Longitudinal level (mm)	σ(LL) = Root mean square on a 25m basis = NL(LL)	0.85
Alignment (mm)	σ(A) = Root mean square on a 25m basis = NL(A)	0.6
Track geometry index (mm), U = 2NT+D	U=2.6 x σ(LL)	2.2
Track geometry (short wave)	A	0.2 (Good rail and track geometry)
Minimal radius (m)	R	300
Cant deficiency (mm)	Id	150
Revenue speed (km/h) (1.10xRevenue Speed)		90
Speed (km/h)	V	100
Axle loads (kN)		180
Maximum nominal wheel load (kN)	Q_N	90

Characteristic	*Parameter*	*Adopted value*
Maximum unsprung mass per wheel (kg)	UM_{max}	1125
Height of the centre of gravity: (mm)	h	1500
Bogie wheelbase (m)		2.40
Rail profile		60E1 (UIC60)

Table 4 : Input data for determination of loading cases

Vertical loads

The vertical wheel load applied to the track can be described as the sum of 4 terms:

$$Q = Q_N + \Delta Q_{Curve} + \Delta Q_{SM} + \Delta Q_{UM}$$

Where

Q_N : Nominal wheel load in kN

ΔQ_{Curve} : Quasi-static wheel load due to cant deficiency(I_d)

$\Delta Q_{Curve} = \frac{2 \cdot Q_N \cdot I_d \cdot h}{e^2}$ with h : height of the centre of gravity of the axle and e=1500 mm (distance between wheel circles)

ΔQ_{SM} : Dynamic load due to sprung masses

ΔQ_{UM} : Dynamic loads due to unsprung masses

Note : ΔQ_{DYN} :Dynamic loads = $\Delta Q_{DYN} = \Delta Q_{UM} + \Delta Q_{UM}$

Transversal loads

The transversal loads Y_{outer} and Y_{inner} can be derived from the following formulas:

$$Y_{outer} = H + Y_{inner}$$

With $Y_{inner} = \mu Q_{inner}$

With μ : the quasi-sliding coefficient between the rail and the wheel ($\mu = \frac{135}{150 + R}$ for typical wagon with R the curve radius)

And $Q_{inner} = Q_N \left(1 - 2 \frac{I_d \cdot h}{e^2} \right)$.

H refers to the total transverse load applied to the track by the axle.

$$H = \Delta H_{Curves} + \Delta H_{dyn}$$

Where

ΔH_{Curves} : Quasi-static transverse load due to cant deficiency (I_d)

ΔH_{DYN} : Dynamic loads due to the track geometry defects (as per vertical loads)

Loads cases for mechanical behaviour

The following loads cases have been defined :

- Nominal case : MB1
- Extreme case for running vehicles MB2
- Load case due to a stopped vehicle: MB3

Load distribution factor

After determination actual dynamic vertical stiffness of the track system, an appropriate distribution factor of the train load will be calculated by using the Zimmermann formula, applied to 2 axles.

The distribution factor of the transverse load, will be the constant and conservative value of 0.5.

Zimmermann formula for one wheel is given by:

$$\rho = \frac{1}{2\sqrt{2}} \sqrt[4]{\frac{s^3 \times K_{dyn}}{EI_{xx}}}$$

With

s the sleeper spacing

EI_{xx} the rail bending stiffness

K_{dyn} the vertical dynamic stiffness

The different distribution factors depending on the vertical dynamic stiffness are detailed below :

Kdyn (MN/m)	Load distribution
5	0.263
6	0.267
7	0.271
8	0.275
9	0.278
10	0.282

Table 5 : Load distribution factor vs stiffness

Sleeper loads

The different loads applied on the sleepers are given in table below for each load case :

Effort	*MB1-1*	*MB1-2*	*MB2-1*	*MB2-2*	*MB3*
Qo	39.35	39.35	42.35	42.35	19.47
Qi	22.52	34.90	20.76	34.37	30.03
Yo	27.65	32.98	38.69	35.61	0.00
Yi	9.70	15.03	8.94	5.86	9.60

Table 6 : Loads applied on sleepers

Results - twin-bloc sleeper

The results obtained for a twin-bloc sleeper are detailed in the table below:

		MB1-1		*MB1-2*		*MB2-1*		*MB2-2*		*MB3*	
Twin-bloc	*Unit*	*Block1*	*Block2*	*Block1*	*Block2*	*Block1*	*Block2*	*Block1*	*Block2*	*Block1*	*Block2*
Gauge widening	mm	-3.59		-3.86		-5.07		-5.37		0.08	
Tie-bar maximum stress (<0 for traction)	MPa	388.96	901.82	473.71	1026.43	467.57	1190.58	297.62	1064.46	-105.31	-97.01

Table 7 : Results for twin-bloc sleeper

Results monobloc sleeper

The results obtained for a monobloc sleeper are detailed in the table below:

		MB1-1		*MB1-2*		*MB2-1*		*MB2-2*		*MB3*	
Monobloc	*Unit*	*Inner*	*Outer*	*Inner*	*Outer*	*Inner*	*Outer*	*Inner*	*Outer*	*Inner*	*Outer*
Gauge widening	mm	-0.03		0.05		-0.29		-0.21		0.54	
Bending moment at sleeper centre	kN.m	2.50		3.50		0.96		2.06		5.32	

Table 8 : Results for monobloc sleeper

Conclusion on the mechanical behaviour of sleepers

The standard twin-block system showed its limits when the resilient pad stiffness is low, whereas with the same loads the monobloc system behaviour is acceptable. This system seems to be, mechanically speaking, more efficient for the development of a booted sleeper which could reach the floating slab track performances.

The main limitation of twin-block sleeper that could be noticed are :

- The vertical displacement which is too important
- The stress in tie-bar becomes too high and reaches the plastic state
- The track gauge widening under loading reaches the maximum tolerances

And the selected solution, i.e. monobloc sleeper (see 3D-view showed below on Figure 7) has the following advantages :

- It provides extra weight for vibration attenuation
- It provides negligible gauge widening
- It is a standard sleeper design :
    - Concrete pre-stressed sleeper
    - Similar to the one used on ballasted track

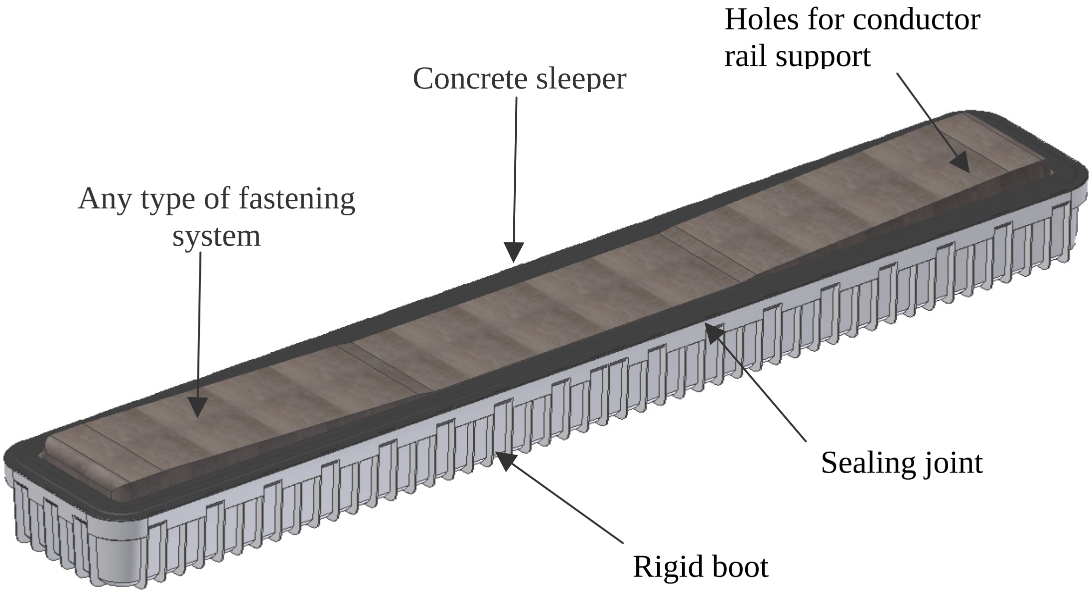

Figure 7 : View of monobloc sleeper

The sleeper mass and the stiffness that were set for the development of the High Attenuation Sleeper system were respectively 400kg approximately and 5MN/m static, approximately. These values ensures the highest noise and vibration mitigation performance. However the vibration mitigation performance can be adjusted, if required, for example sleeper weight can be reduced.

Compared with CTRL2 S3 trackform, the concept of rigid boot or rigid hull was kept as it provides the advantages of :

- Minimising parasitic vertical friction that increases the actual stiffness of the system and
- Facilitating sleeper replacement, if necessary.

LABORATORY TESTS

A prototype was manufactured according to the characteristics resulting from the design phase and a laboratory testing was then achieved to assess, on one hand, the vibration mitigation performance and on the other hand, the mechanical performance of the monobloc sleeper.

Vibration mitigation performance

Objectives

The main purpose of this test is to evaluate the vertical dynamic stiffness of the mono block booted sleeper in range of frequencies between 8Hz and 250Hz.

Test schematic

Figure 8 below presents a schematic of the test rig for the vibration test. This type of rig also correspond to that shown in EN ISO 10846-2. It allows determining the acoustic stiffness of the tested element using the approach called the “direct method”. The blocking mass m2 is an important parameter since it has to behave as a rigid element in the frequency range of interest in order to evenly distribute the forces. The excitation mass m1 has to provide a uniform loading on the tested element; it has to be as small and light as possible and as the same time has to behave as a rigid element in the frequency range of interest. The displacement of both masses is then measured as well as the blocking forces.

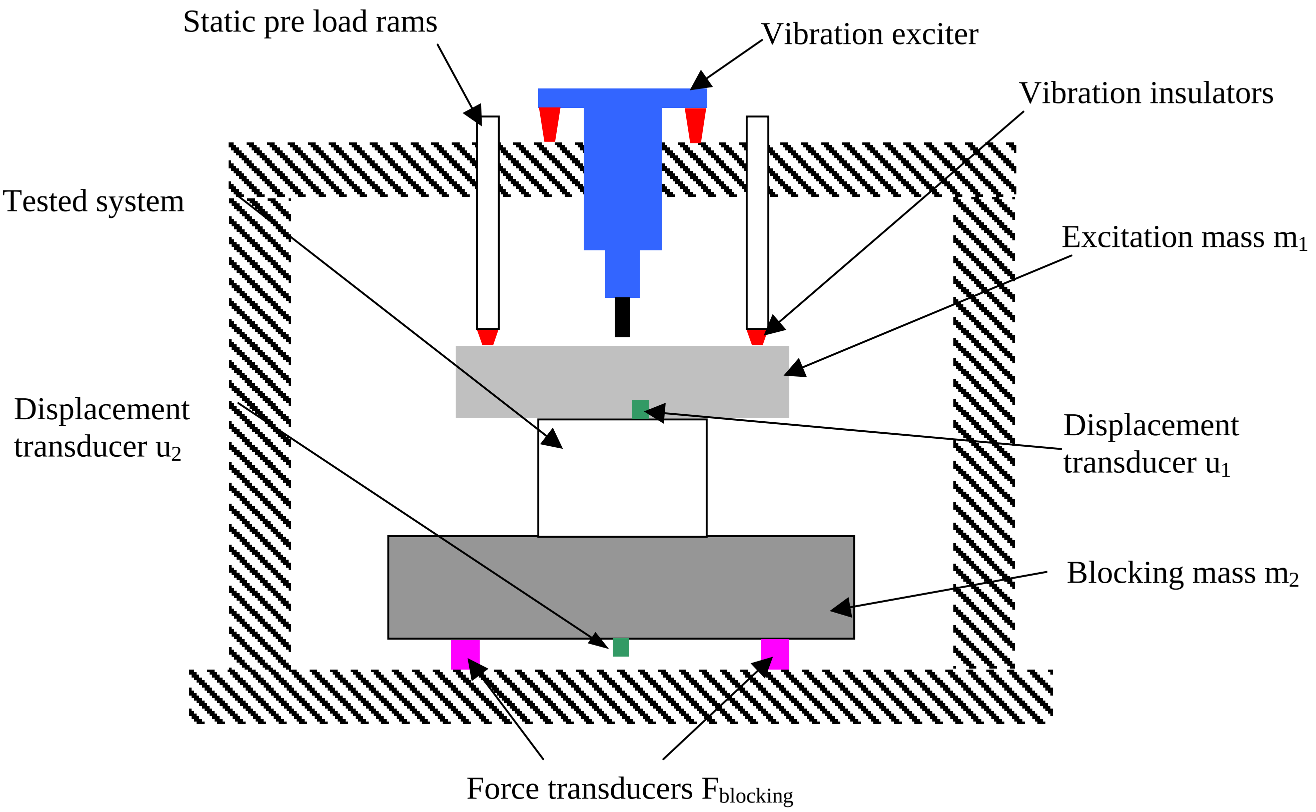

Figure 8 : Schematic of test rig

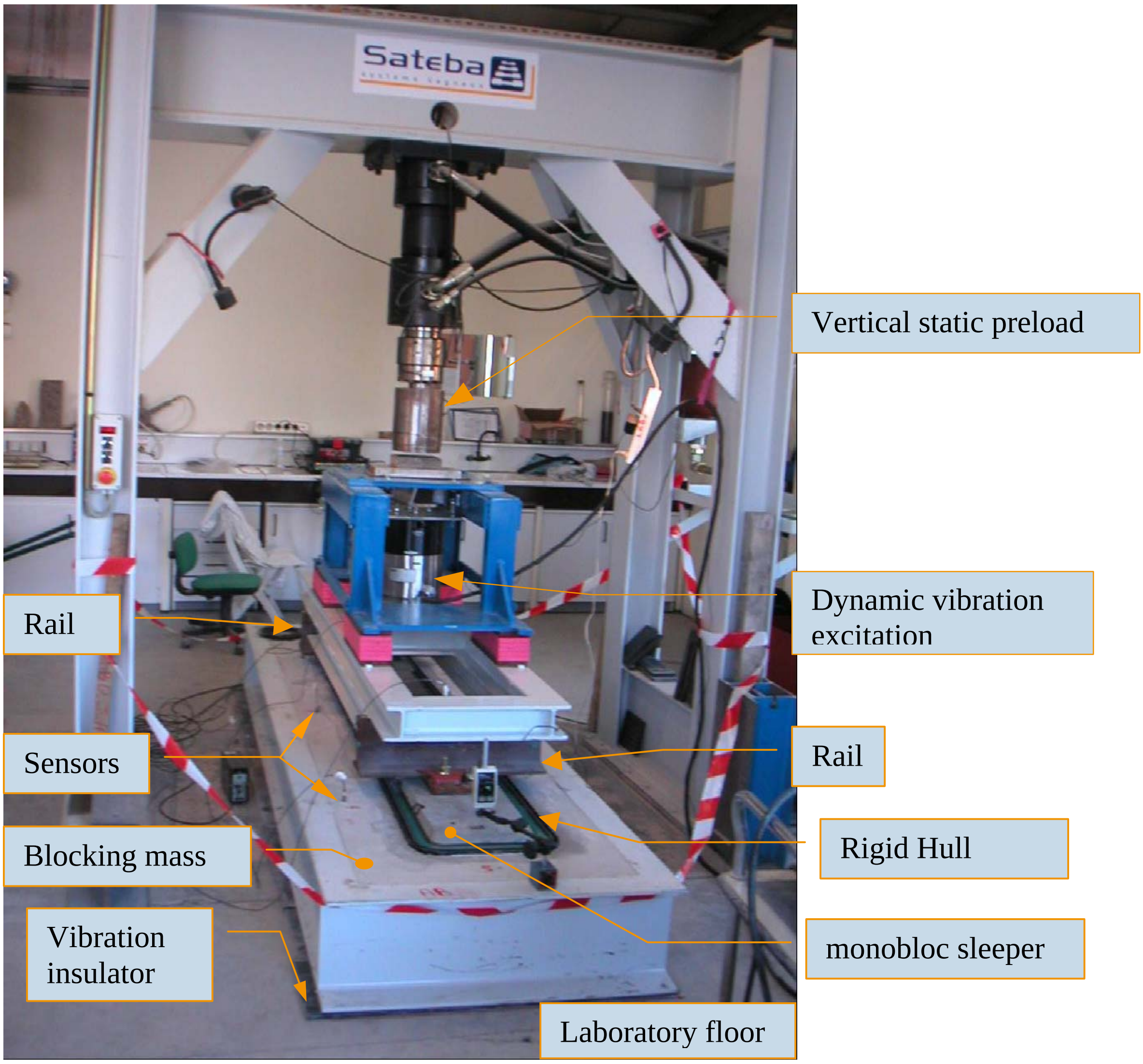

Figure 9 : Picture of test rig

Several accelerometers were fixed on the blocking mass as shown below :

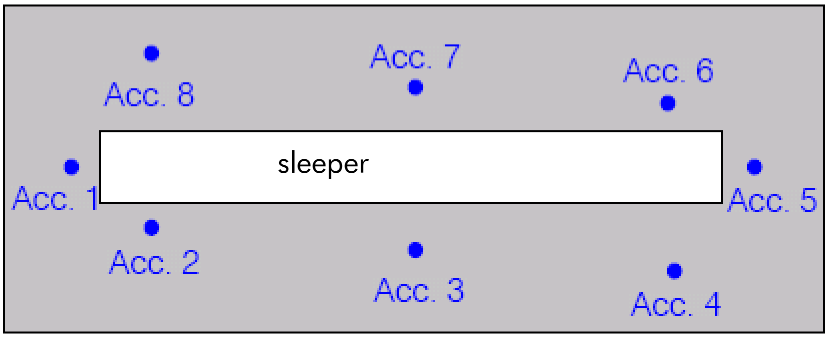

Figure 10 : Arrangement of accelerometers on blocking mass

The results of the vibration tests detailed hereafter were obtained with the following characteristics of the track system :

Characteristics	*Values*
Length	2580mm
Mass	~420kg

Characteristics	*Values*
Lateral pad : (x 6)	Hardness 75 Shores
Under sleeper pad in 2 pieces	Sylodyn NB thickness 20mm
Rail	60E1 (UIC60)

Table 9: Track system characteristics for vibration test

Results of vibration tests

The vertical dynamic stiffness K_{dyn} of the track system was measured at different frequency (detailed on first line) and with increasing static preload (detailed in first column) as detailed below :

K_{dyn} (MN/m)	*8Hz*	*16Hz*	*31.5Hz*	*64Hz*	*125Hz*
0kN	5.18	6.31	9.95	34.36	71.86
32kN	8.56	8.17	14.08	32.98	72.96
40kN	8.27	8.51	13.48	28.83	86.99
50kN	9.55	10.61	14.83	36.89	468.39
64kN	11.28	11.98	15.71	33.66	149.4

Table 10 : K_{dyn} function of frequency and static preload

Presented under graph format at 8Hz :

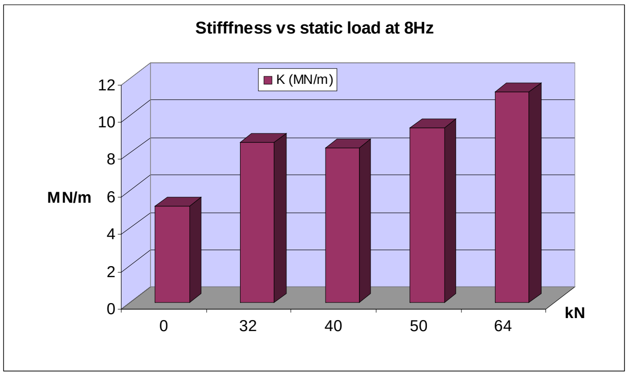

Figure 11: K_{dyn} vs. static load at 8Hz

To conclude with the vibration tests that have been carried out on prototype, the results of vertical dynamic stiffness are very satisfactory. And the expected vibration mitigation performance associated is reached with such low values.

Mechanical test

The main purpose of this test is to evaluate the degradation of each component (lateral pads, sleeper pad, hull) during a loading test.

The loading test is made on one sleeper installed in a blocking mass (see Figure 12).

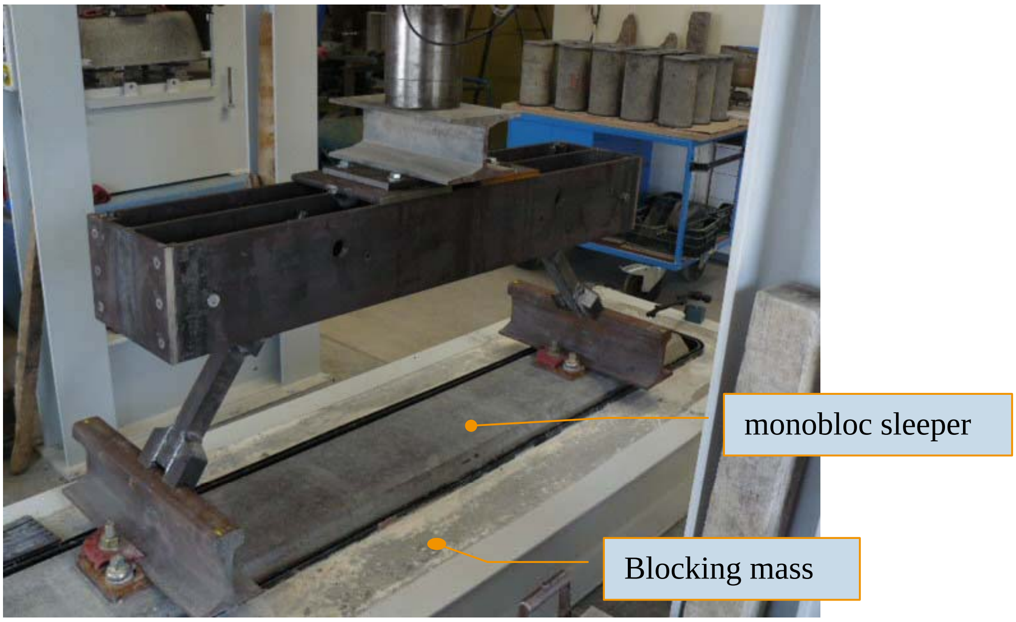

Figure 12 : Picture of mechanical test rig

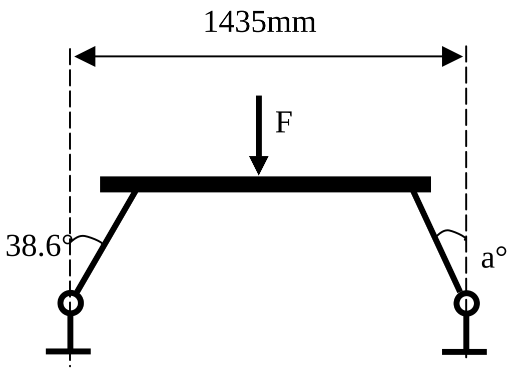

Figure 13 : Schematic of applied loads

Inclined loads were applied on the prototype with different angles on one side to simulate loadings on tangent track and curved track.

angles a can take two values: 38.6° (vehicle in straight line) or 10°.(curve)

In addition two different frequencies have been applied in order to first simulate bogie passage considering a pivot distance of about 15m at 100km/h (2Hz) and second to simulate wheel passage (5Hz).

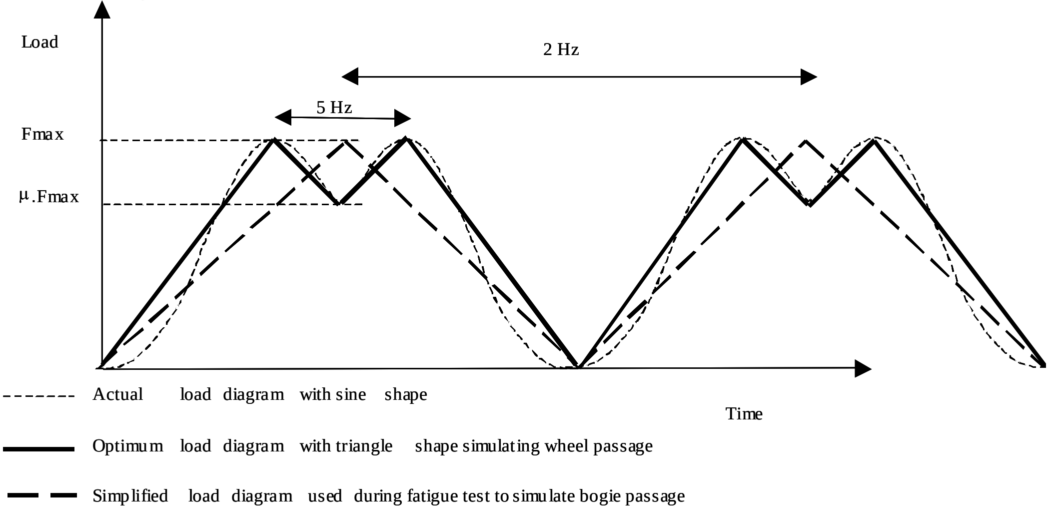

Figure 14 : Cyclic loading diagrams

The fatigue test with inclined loads have been achieved according to the following phases :

- 1M Cycles @ low frequency (3 Hz) applied load between 10kN et 75kN, centred, inclined at 38°
- 0.5MCycles @ moderate frequency (5 Hz) applied load between 30/40kN et 75kN centred , inclined at 38°

- 2M Cycles @ low frequency (3 Hz) applied load between 10kN et 75kN, inclined at 10° and 38°
- 1 M Cycles @ moderate frequency (5 Hz) applied load between 30/40kN et 75kN, inclined at 10° and 38°.

The total number cycles applied is 4.5 million. Following that test, the vertical static stiffness has remained constant, and no pad or rigid hull wearing have been observed (the mass of each component has not changed).

CONCLUSIONS

A sleepered track system with rigid booted sleepers can reach a sufficient level of vibration mitigation and can be considered as an alternative to a conventional floating slab track system.

The choice of a monobloc sleeper vs. twin-bloc sleeper has been validated. This type of sleeper provide a bigger mass and a higher stability of track.

Laboratory testing on prototype has been very satisfactory.

The tests pertaining to the performance of vibration mitigations and vertical stiffness give very good results. And from the mechanical tests under a high number of cyclic loading no degradation of the prototype could be observed.

REFERENCES

[1] Achieving S3 or the development of a highly resilient high-speed slab track for the channel tunnel rail link (Jean-Pierre Bergoend & Bruno Petin & Ian Robertson, 2005)