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# Monitoring in-service performance of fibre-reinforced foamed urethane sleepers/bearers in railway urban turnout systems

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**Abstract.** Special track systems used to divert a train to other directions or other tracks are generally called 'railway turnout'. A traditional turnout system consists of steel rails, switches, crossings, steel plates, fasteners, screw spikes, timber bearers, ballast and formation. The wheel rail contact over the crossing transfer zone has a dip-like shape and can often cause detrimental impact loads on the railway track and its components. The large impact also emits disturbing noises (either impact or ground-borne noise) to railway neighbors. In a brown-field railway track where an existing aged infrastructure requires renewal or maintenance, some physical constraints and construction complexities may dominate the choice of track forms or certain components. With the difficulty to seek for high-quality timbers with dimensional stability, a methodology to replace aged timber bearers in harsh dynamic environments is to adopt an alternative material that could mimic responses and characteristics of timber in both static and dynamic loading conditions. A critical review has suggested an application of an alternative material called fibre-reinforced foamed urethane (FFU). The full-scale capacity design makes use of its comparable engineering characteristics to timber, high-impact attenuation, high damping property, and a longer service life. A field trial to investigate *in-situ* behaviours of a turnout grillage system using an alternative material, 'fibre-reinforced foamed urethane (FFU)' bearers, has been carried out at a complex turnout junction under heavy mixed traffics at Hornsby, New South Wales, Australia. The turnout junction was renewed using the FFU bearers altogether with new special track components. Influences of the FFU bearers on track geometry (recorded by track inspection vehicle 'AK Car'), track settlement (based on survey data), track dynamics, and acoustic characteristics have been measured. Operational train pass-by measurements have been analysed to evaluate the effectiveness of the replacement methodology. Comparative studies show that the use of FFU bearers generates higher rail and sleeper accelerations but the damping capacity of the FFU help suppress vibration transferring onto other track components. The survey data analysis suggests a small vertical settlement and negligible lateral movement of the turnout system. The static and dynamic behaviours of FFU bearers appear to equate that of natural timber but its service life is superior.

**Keywords:** fibre-reinforced foamed urethane bearers; field trial; railway turnout grillage; track geometry; stability; vibration; material design and analysis; performance monitoring

## 1. Introduction

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Railway urban turnout is a special track system used to divert a train from a particular direction or a particular track onto other directions or other tracks. It is a structural grillage system that consists of steel rails, points (or called ‘switches’), crossings, steel plates, rubber pads, insulators, fasteners, screw spikes, beam bearers (either timber, polymer, steel or concrete), ballast and formation, as shown in Figure 1 (Andersson and Dahlberg 2003). Traditional turnout structures are generally constructed using timber bearers. The timber bearers allow the steelwork to be mounted directly onsteel plates that are spiked or screwed into the bearers. The traditional turnout structure generally imparts high impact forces on to its structural members because of its blunt geometry and mechanical connections between closure rails and switch rails (i.e., heel-block joints) (Remennikov and Kaewunruen 2007, Sanchez *et al*. 2013, Cai *et al*. 2013).

A turnout is an inevitable structure in railway tracks whose crossing imparts a significant discontinuity in the rail running surface. The wheel/rail interaction on such imperfect contact transfer can cause detrimental impact loads on railway track and its components (Wu and Thompson 2003, Kaewunruen and Remennikov 2010, Awad and Yusaf 2012). The transient vibration could also affect surrounding building structures. In addition, the large impact emits disturbing noises to railway neighbors (Thompson 2010). The impact and ground-borne noises are additional to the normal rolling noise. Many previous studies have predicted impact forces and noise using numerical models. However, only a few have implemented impact mitigation strategies in the field and even fewer field trial reports are available in the literature (Thompson 2010). The impact mitigation strategies at an urban turnout include wheel/rail transverse profiling and longitudinal profiling of crossings, increased turnout resilience and damping, changes to rolling stocks, external noise/vibration controls, etc.

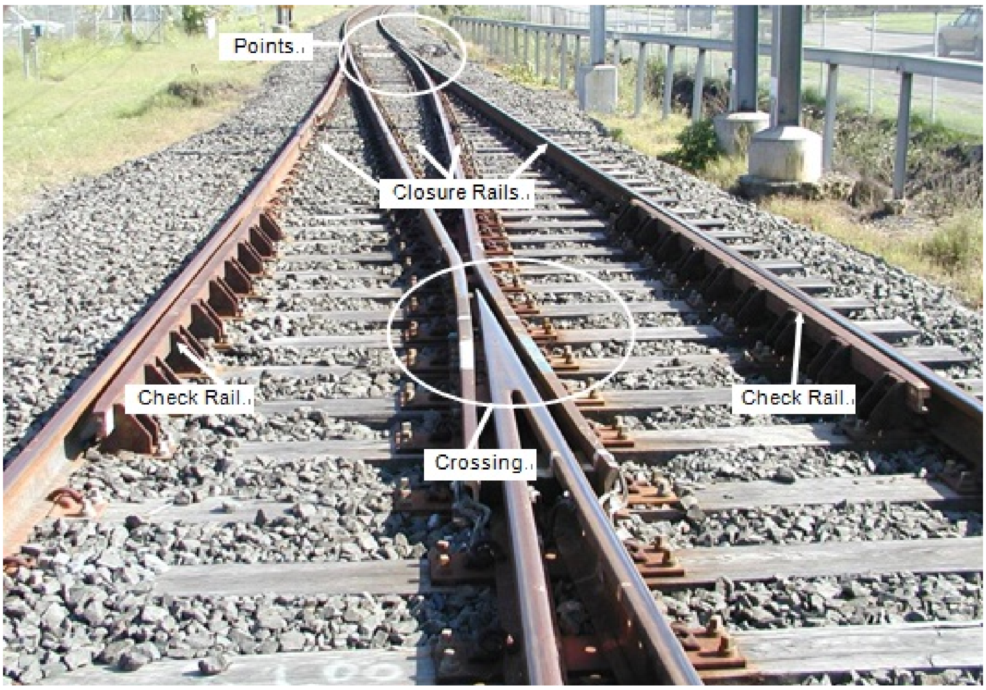



Fig. 1 Typical turnout structure and geometry

Table 1 Timber species for railway turnout application (RailCorp 2012)

| Group | Common Name | Scientific Name |
|---|---|---|
| Group 1 | Ironbark Grey | E. Siderophloia |
| | Ironbark Grey | E Paniculata |
| | Ironbark Grey | E Drepanophylla |
| | Ironbark Red (broad leaved) | E Fibrosa |
| | Ironbark Red (narrow leaved) | E Creba |
| | Ironbark Red | E Sideroxylon |
| | Gum Slaty or Box Slaty | E Dawsonil |
| | Box White | E Albens |
| Group 2 | Box Grey | E Microcarpa |
| | Box Grey | E Moluccana |
| | Tallow wood | E Microcorys |
| | Gum Grey | E Punctata |
| | Gum Grey | E Propinqua |
| | Gum Forest Red | E Tereticornis |
| | Mahogany White | E Acmeniodies |

Table 2 Timber design for railway turnout application (RailCorp 2012)

| **Cross Section** (mm) | **Application** | **Standard timber lengths supporting turnouts and crossovers** (m) |
|---|---|---|
| 250 x 180* | General | 2.8, 3.0, 3.2, 3.4, 3.6, 3.8, 4.0, 4.2, 4.4, 4.6, 4.8, 5.0, 5.2, 5.4, 5.8, 6.0, 6.2, 6.4 |
| 250 x 200* | Points (motor) | 2.8, 3.0, 3.2, 3.4, 3.6, 3.8, 4.0, 4.2, 4.8, 5.0, 5.2 |

*tolerance: length +50mm –0mm; width +10mm –0mm; thickness +10mm –0mm

Although a new method of geometrical design has been adopted for tangential turnouts, the transfer zone at a crossing nose in complex turnout system still imposes high-frequency forces to track components. Under static and high-intensity impact loading conditions, timber bearers have a long proven record that they can provide firmed support to such turnouts. The structural timber bearers in turnout systems are usually in Strength Group 1 (Standards Australia 2001, RailCorp 2012) and the typical timber species are tabulated in Table 1. Based on the strength, Table 2 displays the design dimensions of timber bearers in a variety of railway turnouts with nominal design spacing of 600mm (or between 500 mm and 700 mm). It is important to note that timber bearers for supporting points and crossing structures may be designed using the beam on elastic foundation analysis (similar to traditional railway sleepers) but one must take into account additional factors:

- Extra length of timber bearers in comparison with standard sleepers
- Centrifugal forces through curved pairs of rails
- Forces and bending moments induced from points motors and other signalling equipment
- Impact forces induced by wheel-rail interaction
- Mechanical rail joints (maximum spacing of bearers is 600 mm)

Currently, the procurement of high-quality long timber bearers used in complex turnout systems is very difficult for either construction or renewal process in Australia. Problems with long timber turnout bearers (i.e., >4 m.) include localised weakness, large deformation, warping or unstable dimensions that can easily cause obstructions during the turnout assembly resulting in a poor geometry of new turnouts. Then, the wheel/rail interaction over such poor short-pitch irregularity induces impact force and vibration that exacerbates the condition and undermines the service life of turnout components and the integrity of turnout system as a whole (Kaewunruen and Remennikov 2009a, b, Kaewunruen 2012, 2013a, b).

The difficulty to seek for high-quality timbers has led to two possible alternatives in practice: first, to use the concrete long bearers with splice plates; second, to use the alternative material (i.e., Fibre-reinforced Foamed Urethane or so-called FFU; composite materials, plastic rubber materials, etc.) with the similar characteristics as a timber. A critical review has suggested a field trial of FFU material because of its high-impact attenuation, high damping property, high UV resistance, and long service life. As a result, the complex turnout junction with aged timber bearers at Hornsby NSW Australia was renewed in 2010 using FFU material. There were five stages of construction: note that the first turnout was constructed in October 2010 and the double slips were installed in late June 2011. Also, due to the light weight of FFU bearers, a special arrangement was designed to maintain lateral stability to the turnouts (Kaewunruen 2009, 2011).

This paper focuses on the application of FFU material to complex railway turnout structure. It demonstrates the static and dynamic *in-situ* performance of the alternative FFU material as a like-for-like replacement of timber bearers. This study involves material design, full-scale application, detailed inspection, turnout settlement monitoring, geometry data analysis, train-track interaction, sound pressure and vibration measurements of the double slips, and benchmarking with other field data (Kaewunruen 2012).


Fig. 2 Transfer zone at crossing where a conical wheel traversing a v-crossing (removal of white paint showing the wheel contact band) and running over a dip angle inducing impact force [1, 2]

## 2. Interaction of train and turnout structure

The wheel/rail contact over the crossing transfer zone has a dip-like shape where the wheel trajectory is not smooth. The accurate shape of the wheel trajectory (running top) and dip angle will depend on the wheel and running rail profiles. The associated dip angles, which are the acute angle between the tangents to the wheel trajectory at the point where it abruptly changes direction, can then be estimated from the wheel trajectories, as illustrated in Fig. 2.

### *2.1 Turnout forces*

It is generally assumed that the high frequency impact force ($P_1$) that occurs either at a nose or at a wing rail has little effect on the rail foot (Railtrack 2002). On the other hand, the dynamic $P_2$ force (the second peak in the impact force history) has significant influence on the crossing components. The distance from the point of impact to the point of the peak impact force depends on a number of factors including train speed. The common damage zones to be considered are the rail foot within 0.75 m of any joints to plain rail; and the base of the crossing in transfer zone (extending 0.75 m on both sides of the pick up point); and other components in vicinity of the crossings.

In a calculation of $P_2$ force, the track damping $C_t$ is normally negligible. For plain tracks, it is commonly found that the track mass is relatively low in comparison with the wheel set mass and is then neglected. In contrast, for a turnout crossing, the track mass tends to be of significance and it cannot be neglected. Jenkins *et al*. (1974) has proposed a formula for estimating a dynamic $P_2$ force as follows:

$$P_2 = P_0 + 2\alpha \cdot v \cdot \left[\frac{M_u}{M_u + M_t}\right]^{\frac{1}{2}} \cdot \left[1 - \frac{\pi \cdot C_t}{4\sqrt{K_t \cdot (M_u + M_t)}}\right] \cdot \left[K_t \cdot M_u\right]^{\frac{1}{2}} \tag{1}$$

where

$P_2$ = Dynamic vertical force (kN)
$P_0$ = Vehicle static wheel load (kN)
$M_u$ = Vehicle unstrung mass per wheel (kg)
$2\alpha$ = Total joint angle or equivalent dip angle (rad)
$v$ = Vehicle velocity (m/s)
$K_t$ = Equivalent track stiffness (MN/m)
$C_t$ = Equivalent track damping (kNs/m)
$M_t$ = Equivalent track mass (kg)

### *2.2 Track stiffness*

Track stiffness $K_t$ can be estimated using a beam on elastic foundation model. The deflection under a point load can be written as

$$K_t = \frac{P}{y} = 8\beta^3 EI \tag{2}$$

$$\beta = \left[\frac{k_f}{4EI}\right]^{\frac{1}{4}} \tag{3}$$

where

E = Young's modulus

I = Moment of inertia of the rail or crossing section

$k_f$ = foundation modulus (track modulus)

$$k_f = 4.104P_o \text{ (axle load in tonnes) } +14.61, \text{ MPa} \tag{4}$$

### *2.3 Equivalent track mass*

Considering the bearer spacing of 600mm, a bearer mass of 600kg (half can be associated with the crossing), a mass per unit of the crossing is 120 kg/m, the track mass per unit rail length (m) can be estimated as 620 kg/m. The equivalent track mass (lumped) at crossing $M_t = 3m/2\beta$. Thus, $M_t$ is varied from 705 kg to 756 kg.

### *2.4 Crossing design issues*

It is evident that the track stiffness at crossing is much higher than normal plain tracks, resulting in a higher impact force. A concern in crossing design is that the foundation might be subjected to excessive bearing pressure and the track components will degrade dramatically due to the equivalent dip angle. The impact attenuation capacity might be compromised, leading to ballast pulverisation and nuisance noise. Accordingly, the sleepers/bearers' material design must take into account the nature of loading conditions, operational parameters, maintenance reliability, and material life cycle.

## 3. Material and design: Fibre-reinforced foamed urethane (FFU)

FFU bearers are made of continuous glass fibre reinforced rigid polyurethane foam. The foam contains advantages over plastic and wood, e.g., durability and corrosion resistance, electrical insulation, light weight and strength, and good fabrication/assembly/coating. Contrary to concrete, the high damping characteristic of FFU bearers would be beneficial to the impact and vibration absorption at turnout crossings transferring to supporting components. Fundamental engineering properties of the FFU material are tabulated in Table 3 (Sekisui 2012). The material design for turnout sleeper/bearer application usually considers flexural bending moments resulted from vertical train-track interaction as shown in Eqs. (1)-(4). In railway operational practice, the dynamic vertical load ($P_2$) by a wheel of train wagon is usually controlled or limited to 230 kN force by appropriate maintenance schemes (RailCorp 2012b). Note that this value does not take into account any high-frequency impact forces imposed on top of the quasi-static design load ($P_2$). The high-frequency impact force or so-called $P_1$ often causes rapid deterioration of crossings, fastening systems, and low-damping concrete bearers. Naturally, the dynamic content of $P_1$ is filtered by material damping characteristics (i.e., in timber or in FFU).

The typical characteristic FFU compressive strength is 58 MPa (note that sleepers/bearers' concrete compressive strength after 28 days is about 50 MPa). It was evidenced that the

30-year-old FFU material retained the compressive strength of around 55 MPa. The design flexural ($\sigma_m$) and shear ($\sigma_s$) stresses can be obtained using Eqs. (5) and (6), respectively

$$\sigma_m = My/I \tag{5}$$

$$\sigma_s = P/A \tag{6}$$

where M is design bending moment, P is the design shear force, y is the fibre arm length, I is the moment of inertia, and A is the area of the beam cross section.

Table 3 Basic properties of FFU material in comparison with timber bearers

| **Properties** | **Australian hardwoodb earers**[1] | **Birch bearers**[2] | **FFU bearers**[2] | | | |
|---|---|---|---|---|---|---|
| | | | **New** | **After 10 years** | **After 15 years** | **After 30 years** |
| Service life (years) | 5-10 | 5-10 | 50 | 40 | 35 | 20 |
| Density ($kg/m^3$) | 1050 - 1120 | 750 | 740 | 740 | 740 | 740 |
| Bending strength (MPa) > 70 | 65 | 80 | 142 | 125 | 131 | 116 |
| Vertical compression strength (MPa) > 40 | 60 | 40 | 58 | 66 | 63 | 55 |
| Shear strength (MPa) > 7 | 6.1 | 12 | 10 | 9.5 | 9.6 | 7 |
| Elastic modulus (MPa) > 6000 | 16,000 | 7100 | 8100 | 8044 | 8788 | 8414 |
| Fatigue flexural strength | 50,000 cycles at 40 MPa | 50,000 cycles at 40 MPa | 1 million cycles at 94 MPa | | | |
| Hardness (MPa) | 10 | 17 | 28 | 25 | 17 | |
| Water absorption ($mg/cm^2$) < 10 | 137 | 137 | 3.3 | 3.3 | 3.3 | 3.3 |
| Impact bending strength (MPa) | | | | | | |
| @ 20 C | - | 20 | 41 | - | - | - |
| @ -20 C | - | 8 | 41 | - | - | - |
| Destructive voltage (kV) | | | | | | |
| - dry (>20,000) | | | | | | |
| - wet (>20,000) | 8 | 8 | >25 | >25 | >25 | >25 |
| | <1 | <1 | 22 | 24 | 23 | 25 |
| Insulation resistance (Ω) | | | | | | |
| - dry (> $1.0\times10^4$) | | | | | | |
| - wet (> $1.0\times10^4$) | $6.6\times10^7$ | $6.6\times10^7$ | $1.6\times10^{13}$ | $2.1\times10^{12}$ | $3.6\times10^{12}$ | $8.2\times10^{11}$ |
| | $5.9\times10^4$ | $5.9\times10^4$ | $1.4\times10^8$ | $5.9\times10^{10}$ | $1.9\times10^9$ | - |
| Dog spike pull-out strength (kN) > 15 | 25 | 25 | 28 | 28 | 23 | 22 |
| Screw spike pull-out strength (kN) > 30 | 40 | 43 | 65 | 39 | 44 | 33 |

[1]Timber bearer properties are derived from AS1720 Strength Group 2 (Standards Australia 2001)
[2]Birch timber bearer properties are derived from the technical datasheet (Kaewunruen 2009, Sekisui 2012)

Under revenue train services (RailCorp 2012c), the FFU sleepers were designed to accommodate quasi-static flexural stresses (serviceability) between +/- 15 and +/- 40 MPa depending on the complexity and length of turnout structures. The quasi-static shear stress resultants are in between 2 and 3 MPa. As a result, the factor of safety is about 1.75 (with allowable material reduction factor of 0.5). In the field installation, FFU bearers with the cross section of 250 mm x 180 mm were thus utilised throughout. This cross section was designed to ascertain that the pressure redistribution onto ballast layer is less than 750 kPa (Australian Standards 2003).

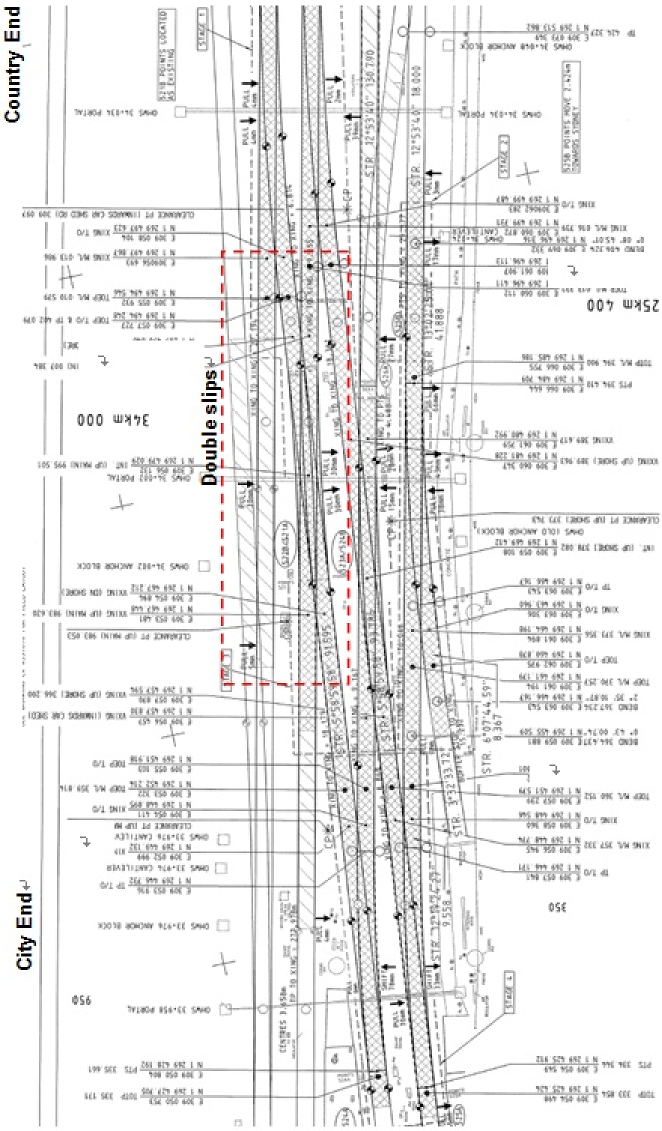



Fig. 3 Design geometry layout of Hornsby Junction

## 4. Field trial

The full-scale trial site is at Hornsby, New South Wales. Because of the complexity of the junction, the sets of urban turnouts were constructed in different stages and timeframes.

The junction comprises of five set of turnouts, a set of single slips and a set of double slips. This aspect was a key benefit of FFU usage in a way that permits such construction stages, of which those four stages (see Fig. 3) are:

- Stage 1: Tangential turnouts: 521B & 523B (October 2010)
- Stage 2: Tangential turnouts: 525B (February 2011)
- Stage 3: Single slip / Double slips: 522B/521A & 523A/524B (June 2011)
- Stage 4: The rests: 524A/522A & 525A (June 2012)

In this study, the double slips as shown in Fig. 4 were chosen for geometry analyses, noise and vibration measurements, and performance evaluations. The construction processes of the brown-field turnout started from the removal of aged components and preparation of formation and track bed. Fig. 5 shows the deteriorated condition of timber bearers replaced by the FFU materials at Hornsby. The junction construction was divided into a number of stages, which created certain requirements to monitor and control the quality of each stage and of the junction as a whole. Quality control must be achieved to ascertain that the components can withstand traffics over their life cycle.

It is noted that RailCorp's Engineering and Construction Standards (RailCorp 2012d) were applicable at the time of the work. They define general construction tolerances of plain tracks, which cover alignment of turnouts and special trackwork. The general survey alignment limit is +/- 15 mm (lateral offset) and for superelevation is +/- 5 mm. These tolerances indicate an acceptance of the turnout positioning and precision. Figs. 6-9 show the construction processes of a turnout using FFU bearers. Because the junction reconstruction consisted of several stages, the interface between stages required special consideration during the upgrade. The formation shall comply with construction standards and engineering specifications to ensure that the renewed infrastructure is of value for money throughout its whole life.

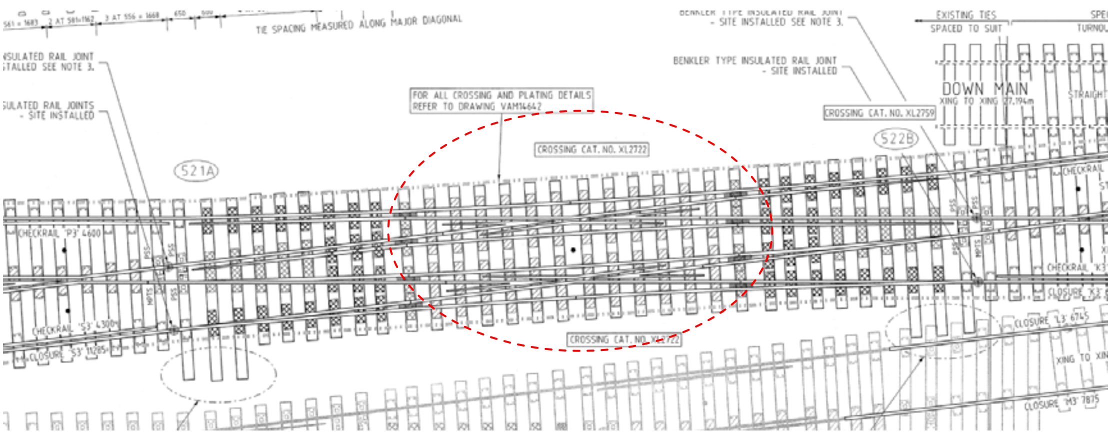



Fig. 4 Field layout of double slips (521/522) at Hornsby NSW

Fig. 5 Condition of aged timber bearers

Fig. 6 Formation preparations for Stage 3

Fig. 7 Cross section at interface between Stages 2 & 3

Fig. 8 Compaction test of capping layer

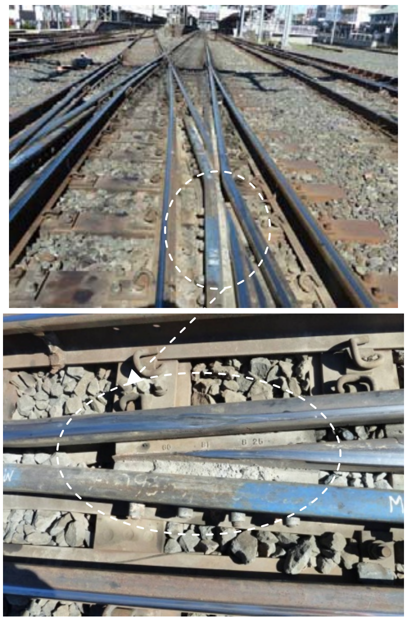
Fig. 9 Double slips installation and resurfacing

(a) at 521B Pt

(b) at 522B Pt

(c) close-up to see general line through the double slips

(d) close-up to see the line through the turnout road from Northern Line



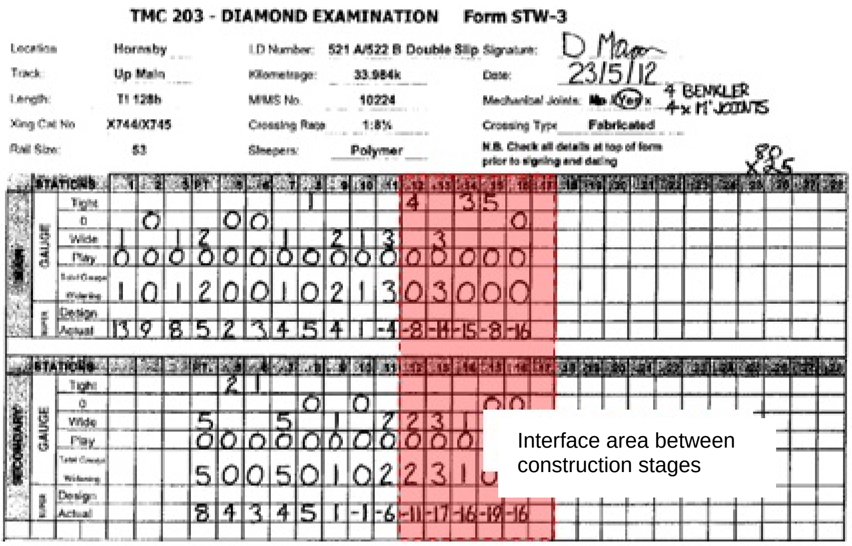
(e) country end k1-crossing

Continued-

(f) a joint gap at a mechanical joint

(g) full junction with FFU bearers at Hornsby

Fig. 10 General condition of the double slips



**TMC 203 - DIAMOND EXAMINATION Form STW-3**

| | | | | | |
|---|---|---|---|---|---|
| Location | Hornsby | I.D Number: | 521 A/522 B Double Slip | Signature: | D Mason |
| Track: | Up Main | Kilometrage: | 33.984k | Date: | 23/5/12 |
| Length: | T1 128h | MIMS No. | 10224 | Mechanical Joints: | No/Yes x 4 BENKLER 4 x M' JOINTS |
| Xing Cat No | X744/X745 | Crossing Rate | 1:8½ | Crossing Type | Fabricated |
| Rail Size: | 53 | Sleepers: | Polymer | N.B. Check all details at top of form prior to signing and dating | 80 x 25 |

| MAIN | STATIONS | 1 | 2 | 3 | PT | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 | 26 | 27 | 28 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| GAUGE | Tight | | | | | | | | 1 | | | | 4 | | 3 | 5 | | | | | | | | | | | | | |
| | 0 | | O | | | O | O | | | | | | | | | | O | | | | | | | | | | | | |
| | Wide | 1 | | 1 | 2 | | | 1 | | 2 | 1 | 3 | | 3 | | | | | | | | | | | | | | | |
| | Play | O | O | O | O | O | O | O | O | O | O | O | O | O | O | O | O | | | | | | | | | | | | |
| | Total Gauge Widening | 1 | 0 | 1 | 2 | 0 | 0 | 1 | 0 | 2 | 1 | 3 | 0 | 3 | 0 | 0 | 0 | | | | | | | | | | | | |
| SUPER | Design | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| | Actual | 13 | 9 | 8 | 5 | 2 | 3 | 4 | 5 | 4 | 1 | -4 | -8 | -11 | -15 | -8 | -16 | | | | | | | | | | | | |

| SECONDARY | STATIONS | 1 | 2 | 3 | PT | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 | 26 | 27 | 28 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| GAUGE | Tight | | | | | 2 | 1 | | | | | | | | | | | | | | | | | | | | | | |
| | 0 | | | | | | | | O | | O | | | | | O | O | | | | | | | | | | | | |
| | Wide | | | | 5 | | | 5 | | 1 | | 2 | 2 | 3 | 1 | | | | | | | | | | | | | | |
| | Play | | | | O | O | O | O | O | O | O | O | O | O | O | | | | | | | | | | | | | | |
| | Total Gauge Widening | | | | 5 | 0 | 0 | 5 | 0 | 1 | 0 | 2 | 2 | 3 | 1 | 0 | | | | | | | | | | | | | |
| SUPER | Design | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| | Actual | | | | 8 | 4 | 3 | 4 | 5 | 1 | -1 | -6 | -11 | -17 | -16 | -19 | -16 | | | | | | | | | | | | |



Fig. 11 Example of field inspection sheet of the double slips – showing good geometrical condition of turnout systems at the critical location

## 5. Condition monitoring

Note that the double slips were installed in June 2011. The track configuration consists of 60 kg rails, fabricated crossings, Pandrol fastening system (e-Clip type), FFU bearers, ballast bed and formation. The track caters mixed traffic (passenger and freight trains) and the operational speeds are 60 km/h for freight trains and 80 km/h for passenger trains. However, almost all of the electric passenger trains stop at Hornsby station. The axle load of freights could be up to 25t.

A visual inspection was carried out on 17 August 2012 in conjunction with a review of detailed inspection sheet previously done at the double slip (23 May 2012). Fig. 10 shows the recent condition at Hornsby double slips (23 May 2012). The visual inspection was done in consultation with Local Team Manager. The inspection confirmed that the turnouts are in very good condition. There has not been any sign of ballast pulverisation or any excessive movements of turnouts and attached signalling gears. Figure 11 shows the recent inspection of the double slip. The inspection showed good conditions of double slips after a year of service, except that the gauge was slightly wide.

## 6. Track geometry data analysis & monitoring

The geometry data from 2010 to 2012 had been recorded using ‘AK Car’ Geometry Recording Vehicle. The review of these track geometry data was aimed at examining basic track parameters (top, line, gauge, cross level and twist) in each stage of its life cycle.

*Gauge:*

Track gauge is defined as the distance between the gauge points on the face of each rail. The default gauge point is 16 mm from the azimuth (maximum y point) on the rail surface. AK car recognises the known distance between laser cameras instrumented on its bogie, so that the resulting gauge measurement is the difference between the optimal gauge (1435 mm) and the measured gauge (Pacific Real Time 2009).

*Superelevation:*

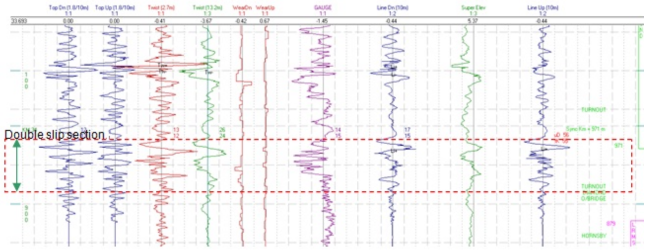
Superelevation (or so-called crosslevel) is defined as the height of one rail above the other. The superelevation is calculated from all four of the inertial measurement package components installed on the AK Car body, consisting of two single-axis fibre optic rate gyroscopes (measuring roll and yaw in terms of turning angles); two accelerometers (measuring vertical and lateral accelerations); and a signal conditioning board (Pacific Real Time 2009).

*Top:*

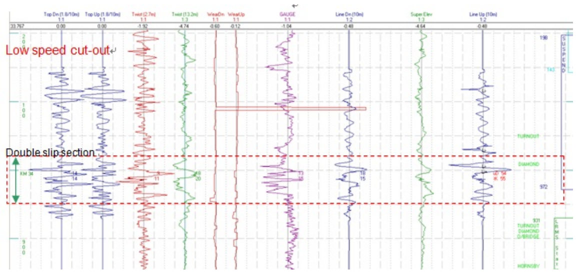
Track surface is defined as the evenness or uniformity of track in short distances measured along the top of the rails. Under load of AK Car body, top surface of rails and vertical alignments can be measured by either a mid chord offset or by a space curve method. The AK Car uses the former method (calculating a versine at 1.8 m) by adopting 10 m chords (Pacific Real Time 2009).

*Line:*

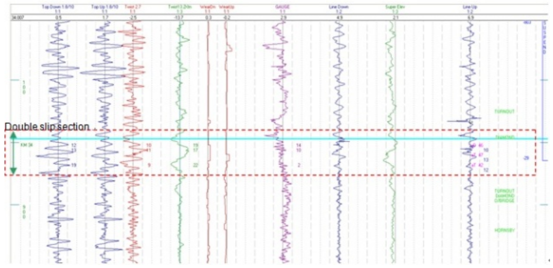
Line or horizontal alignment is defined as the local variation in curvature of each rail of track. It should be zero on the tangent or straight track so that the AK Car 'measured line data' represents the deviation from zero. In a curve, the deviation will be from the uniform alignment over a specified distance, in this case, of 10m chords (Pacific Real Time 2009).



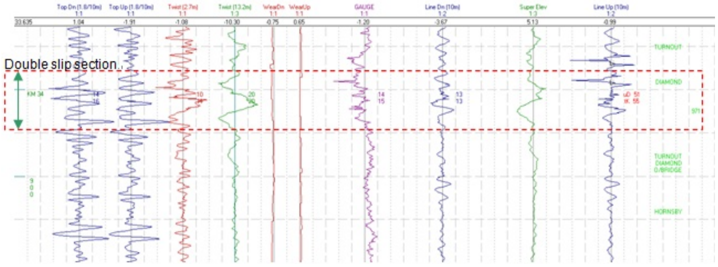

(a) Record on 28 May 2010 between km33.915 and km33.985 (before renewal)




(b) Record on 03 Jun 2011 between km33.950 and km34.020 (Just before renewal)

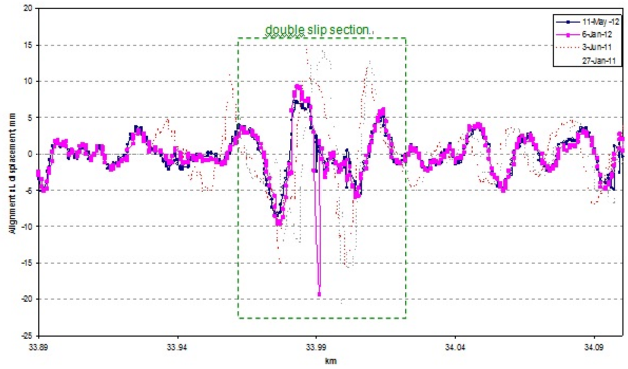



(c) Record on 01 Sep 2011 between km33.950 and km34.015 (after renewal)

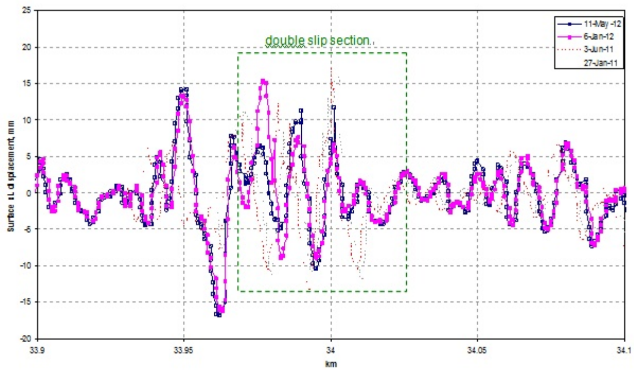



(d) Record on 06 Sep 2012 between km33.955 and km34.020 (after renewal)

Continued -




(e) alignment geometry data record




(f) surface geometry data record

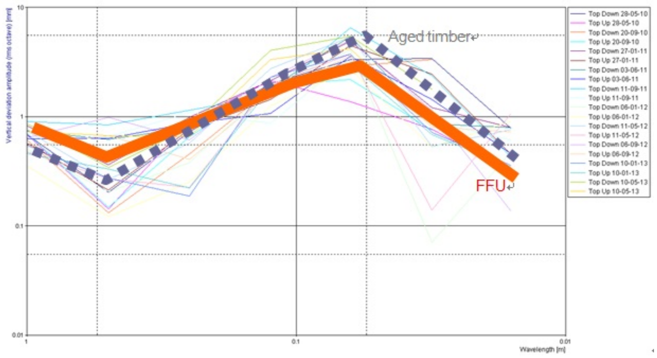
Fig. 12 AK Car geometry data

*Geometry and Its Interpretation:*

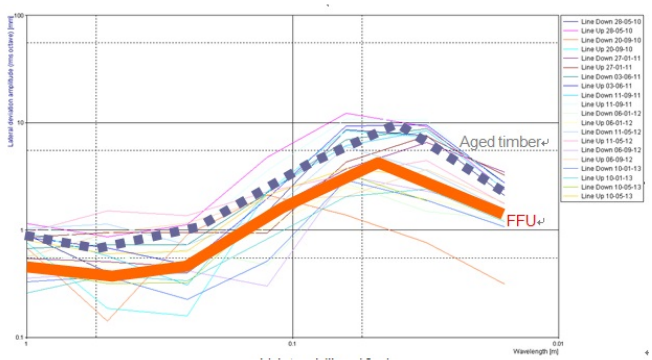
The AK Car geometry data were collected in order to firstly examine the recorded location of tracks as shown in Fig. 12. Note that there were some variations of kilometrages among the AKCar data. The track location data records are found to be consistent with a minor variation (max 5-10 m different). There are some systematic errors of track recordings especially at turnout crossings, which require careful selection and analysis of data.

It is found that the geometry parameters show a promising performance after the renewal of the double slips (showing as '*diamond*' in the plots). It can be seen from Fig. 12 that the smoothness of the track section after reconstruction is just slightly better. The unevenness of top and line decreases slightly after the installation of the FFU materials and new turnout components.

Figs. 12(e) and 12(f) show some of the alignment and surface data recorded by the track geometry car (20 m-wavelength records). The reconstruction of the double slip has clearly improved the lateral positioning of the turnout, while the improvement on the vertical position of turnout is unclear at this stage. This could be due to the un-settlement of ballast supporting the turnout after re-construction (without dynamic stabiliser).




(a) vertical (top 1.8/10 m)




(b) lateral (line 10 m)

Fig. 13 Fourier spectra of track geometry at the double slips (km33.970 to km34.020)

Fourier analyses (using FFT: Fast Fourier Transform) have been carried out using the zoom-in 50 m section of the double slip from km33.970 to km34.020. The analyses display the track geometry changes with respect to track wavelength as demonstrated in Fig. 13. The root-mean-squared Fourier spectra (rms octave) imply that the average deterioration rate of vertical deviation (top 1.8 / 10 m cord) and lateral deviation (line 10 m) of FFU turnout is slower compared with the rate of aged timbered turnout. However, it is important to note that the aged turnout with timber bearers had been deteriorated for a certain time. Further monitoring in the future will help identify more accurate prediction of FFU performance.

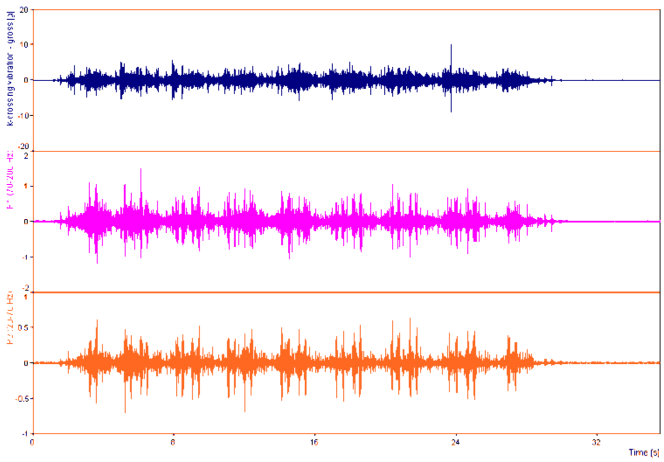
The results also show that the vertical deviation amplitude of the turnout with FFU bearers is higher than the top of timber at the low frequency band (note that FFU's elastic modulus is lesser than F22 hardwood timber's). Fig. 13 confirms that FFU material has slightly lesser static stiffness compared with hard wood timbers. On the other hand, at the wavelength of about 60 mm (associated with high-frequency turnout impact), the peak top deviation amplitude of FFU bearers is lesser than the top of timber. This is because new FFU bearers have higher damping than aged timber bearers and they could then perform better under high frequency vibrations.

In addition, the overall lateral deviation (line 10 m cord) of the turnouts with FFU bearers tends to behave better laterally, in comparison with ones supported by poor timbers. Especially at the low wavelength range (high frequency band), the FFU lateral deformation performance on average is less than the turnout with aged timbers.

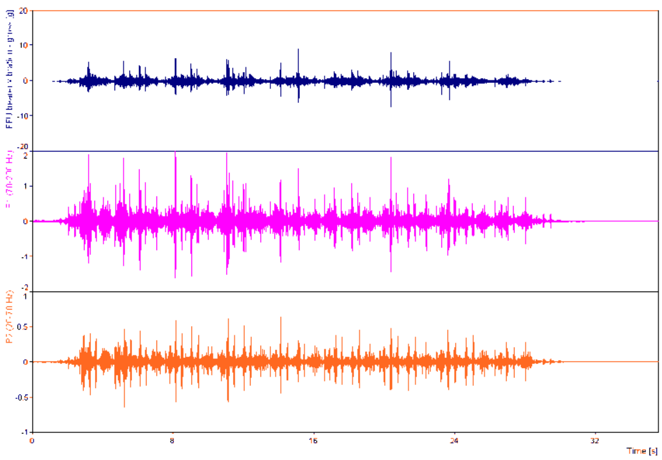
## 7. Monitoring dynamic systems performance

A numbers of accelerometers were installed at the rail web, base plates and bearers at k-crossing and at the interface between FFU bearers and concrete sleepers. High speed camera was used to read the dynamic displacement of the turnout. A sound level meter was installed at 7.5 m from the nearest k-crossing of the diamond. Train speed radar was installed at a nearby OWH mast (Kaewunruen 2011, 2012).

Fig. 14 shows vibrations of k-crossing and the supporting bearer. The vibration characteristics of the double slips show the large amplitude of vibrations at the k-crossing and it has been damped out considerably by the FFU bearers. Note that the steel crossing is mounted directly onto steel plates on the bearers. It is also found that the rigid body motion is the key contributor to the damage of turnout-track substructure at the interface between FFU bearers and concrete sleepers (see Figs. 14(c) and 14(d)).

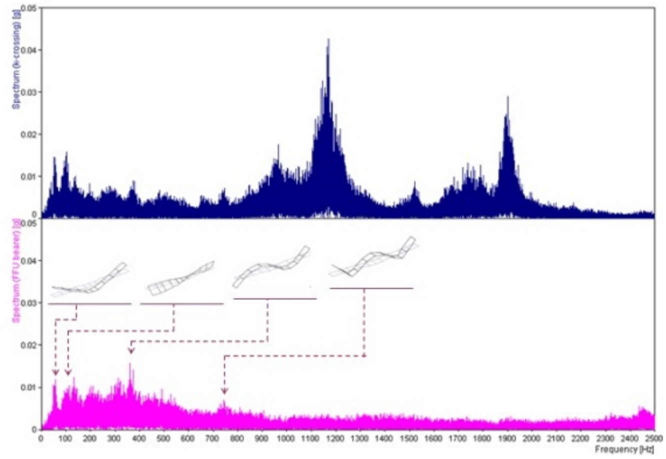



(a) k-crossing vibration frequency effect

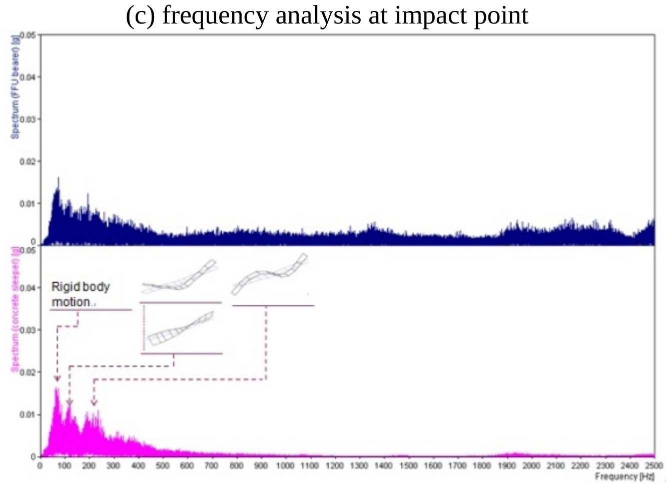



(b) FFU bearer vibration frequency effect

Continued -




(c) frequency analysis at impact point




(d) frequency analysis at interface between concrete sleepers and FFU bearers

Fig. 14 Vibration data of a pass-by train (Passenger train, X-Up Main)

Similar arrangements were carried out at another location for an application of FFU material as half sleepers on a concrete viaduct. Track decay rate and structural-borne noise were measured by Noise and Vibration Unit (RailCorp 2011). The raw measurement data was obtained for re-analysis in this paper. Fig.15 shows the direct comparison of dynamic performance of hard wood half sleepers and FFU half sleepers. The FFT results show that FFU material has slightly lesser dynamic stiffness (lower resonant frequencies) and statistically has higher damping coefficients particularly at high frequency range.

Table 4 Survey data monitoring of double slips (Hornsby 521-523) – 10 June 2012

| POINT | DESCRIPTION | TRACK | Pull (mm) | Lift (mm) |
|---|---|---|---|---|
| 25 | 523B Pts. LH Switch Tip | Up Main | 0.000 | 32.000 |
| 26 | 523B Pts. RH Switch Tip | Up Main | 0.000 | 28.000 |
| 27 | Punch Mark opposite Theoretical Xing Point | Up Main | 0.000 | 19.000 |
| 28 | Theoretical Xing Point (Top of Rail RL 181.106 ) | Up Main | 1.000 | 19.000 |
| 29 | Punch Mark 'V' XING Double Slip | Up Main | 0.000 | 28.000 |
| 30 | Punch Mark 'V' XING Double Slip | Up Main | 0.000 | 27.000 |
| 31 | 522B Pts. LH Switch Tip (As marked in the 4ft.) | Up Main | 2.000 | 19.000 |
| 32 | 522B Pts. RH Switch Tip (As marked in the 4ft.) | Up Main | 2.000 | 28.000 |
| 33 | 522B Pts.LH Switch Tip (521B is marked in the4ft.) | Down Shore | 0.000 | 25.000 |
| 34 | 522B Pts.RH Switch Tip(521B is marked in the 4ft.) | Down Shore | 0.000 | 28.000 |
| 35 | Punch Mark LH 'K' XING | Up Main | 0.000 | 38.000 |
| 36 | Punch Mark RH 'K' XING | Up Main | 0.000 | 40.000 |
| 37 | Punch Mark LH 'K' XING | Up Main | 0.000 | 44.000 |
| 38 | Punch Mark RH 'K' XING | Up Main | 0.000 | 43.000 |
| 39 | 521A Pts.LH Switch Tip(522A is marked in the 4ft.) | Up Main | 4.000 | 30.000 |
| 40 | 521A Pts.RH Switch Tip(522A is marked in the 4ft.) | Up Main | 4.000 | 45.000 |
| 41 | 521A Pts. LH Switch Tip (As marked in the 4ft.) | Down Shore | 7.000 | 40.000 |
| 42 | 521A Pts. RH Switch Tip (As marked in the 4ft.) | Down Shore | 7.000 | 55.000 |
| 43 | Punch Mark LH 'V' XING | Up Main | 0.000 | 45.000 |
| 44 | Punch Mark RH 'V' XING | Up Main | 0.000 | 44.000 |
| 45 | Up Main, Running Face Up Rail | Up Main | 7.000 | 31.000 |
| 46 | Up Main, Running Face Down Rail | Up Main | 7.000 | 28.000 |
| 47 | Turnout Back Face (70mm O/S) Up Rail | Up Shore | 5.000 | 22.000 |
| 48 | Turnout Running Face Down Rail | Up Shore | 0.000 | 12.000 |
| 49 | Turnout Running Face Up Rail | Up Shore | 4.000 | 13.000 |
| 50 | Turnout Running Face Up Rail | Up Shore | 1.000 | 14.000 |
| 51 | Turnout Running Face Up Rail | Up Shore | 2.000 | 9.000 |
| 52 | Turnout Running Face Up Rail | Up Shore | 1.000 | 4.000 |
| 53 | Turnout Running Face Up Rail | Up Shore | 6.000 | 20.000 |
| 54 | Turnout Running Face Up Rail | Up Shore | 14.000 | 20.000 |
| 55 | Turnout Running Face Up Rail | Up Shore | 0.000 | 20.000 |
| 56 | Up Main, Running Face Down Rail | Up Main | 3.000 | 18.000 |
| 57 | Up Main, Running Face Down Rail | Up Main | 7.000 | 14.000 |
| 58 | Up Main, Running Face Down Rail | Up Main | 3.000 | 6.000 |
| 59 | Up Main, Running Face Down Rail | Up Main | 1.000 | 5.000 |

Continued-

Table 4 Survey data monitoring of double slips (Hornsby 521-523) – 10 June 2012, continued

| POINT | DESCRIPTION | TRACK | Pull (mm) | Lift (mm) |
|---|---|---|---|---|
| 60 | Up Main, Running Face Down Rail | Up Main | 11.000 | 14.000 |
| 61 | Up Main, Running Face Up Rail | Up Main | 4.000 | 5.000 |
| 62 | Up Main, Running Face Down Rail | Up Main | 2.000 | -8.000 |
| 63 | Up Main, Running Face Down Rail | Up Main | 16.000 | 24.000 |
| 64 | XOVER Running Face Down Rail | | 0 | 0 |
| 65 | XOVER Running Face Down Rail | | 0 | 0 |
| 66 | 521B Pts. RH Switch Tip | Down Main | 24.000 | -2.000 |
| 67 | Theoretical Xing Point (Top of Rail RL 181.103 ) | Down Main | 14.000 | 23.000 |
| 68 | Top of Rail adjac. to Theoretical Crossing Point | Down Main | 0.000 | 23.000 |
| 69 | Down Main, Running Face Up Rail | Down Main | 19.000 | 10.000 |
| 70 | Down Main, Running Face Down Rail | Down Main | 19.000 | 13.000 |
| 71 | Turnout Back Face (70mm O/S) Up Rail | Down Shore | 10.000 | -1.000 |
| 72 | Turnout Running Face Up Rail | Down Shore | 14.000 | 0.000 |
| 73 | Turnout Running Face Up Rail | Down Shore | 17.000 | 6.000 |
| 74 | Turnout Running Face Up Rail | Down Shore | 16.000 | 17.000 |
| 75 | Turnout Running Face Up Rail | Down Shore | 12.000 | 15.000 |
| 76 | Turnout Running Face Up Rail | Down Shore | 0.000 | 18.000 |
| 77 | Down Main, Running Face Down Rail | Down Main | 9.000 | -1.000 |
| 78 | Down Main, Running Face Down Rail | Down Main | 9.000 | 0.000 |
| 79 | Down Main, Running Face Down Rail | Down Main | 5.000 | 8.000 |
| 80 | Down Main, Running Face Down Rail | Down Main | 16.000 | 40.000 |
| 81 | Down Main, Running Face Down Rail | Down Main | 15.000 | 25.000 |

## 8. Monitoring & analysis of track/turnout settlement

Survey data were carried out by two independent private surveyors. The survey data before and right after construction (as-built) of the up and down main North were obtained and reviewed. It was reported by local maintainers that the as-built alignment of the double slips (Up Main North) was good in general. It should be noted that the construction tolerance allows +/-15 mm outside a design alignment, and the resurfacing capability is to adjust line (pull) no less than +/- 10 mm and to lift from over +/- 15 mm to +/- 50 mm.

Table 4 shows the survey data of the turnout after a year of revenue service. Fig. 16 shows the summary of survey locations on the double slips and turnouts in the area (Hornsby 521-523). It is found that the maximum lift (vertical to design) is 55 mm at a point for Down Shore line and 45 mm for Up Main. The maximum pull (lateral to design) is 24 mm for the Down Main and 16 mm for the Up Main.

Based on the survey data, it could be observed that the lateral global movement of the double slips after 1 year service is very little (an estimate to be varying from 0 to 5 mm at the double slips on the Up Main), and there is no sign of the diamond’s alignment skewing. Moreover, the overall vertical settlement of the double slips tends to be varying from 10 mm to 25 mm due to the un-compaction of ballast after re-construction.

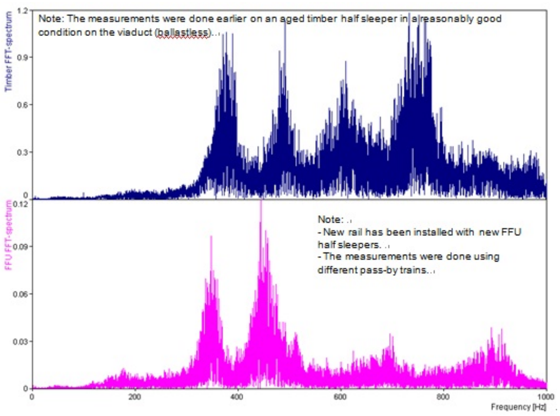



Fig. 15 Dynamic analysis of train pass-bys on Wooloomooloo Viaduct

## 9. Multi-disciplinary interface issues

It is important to note that special design and arrangement to reinforce lateral resistance of the turnouts had earlier been established. Extra depth of the FFU bearers has been adopted to provide extra weight to the turnout assembly and FFU material permits ballast to bite in so frictional resistance between FFU and ballast aggregates could be retained (Kaewunruen *et al*. 2011a, b, Xiao *et al*. 2011, Remennikov *et al*. 2012, Rama and Andrews 2013) as demonstrated in Fig. 17.

To maintain stable positioning of the turnout points where switch rails and signalling equipments require stringent precision, steel in-bearers were used with special ballast fill-in to stabilise the points.

In other applications of FFU bearers, other methods to further increase lateral resistance of turnouts have been implemented, such as:

- stiffening plates
- ballast glue/bond
- ballast shoulder and/or ballast wall.

Through inspections and maintenance tasks, it is important to note that construction and maintenance staff has appreciated the practical benefits of using FFU material, such as:

- ease in steel work adjustment;
- safe walking/working on the FFU with anti-slippery coated surface
- ease in cutting and drilling and other timber-like work (provided that the safety gears and protection equipment are used as per manufacturer's recommendation);
- dimensional stability: no warping of long bearers (compared with the problem frequently found on the timber bearers);
- no obvious failure of fastening or body of bearers.

From the dynamic behaviour results, the stiffness interface between FFU bearers and concrete sleepers needs a special attention (Remennikov *et al*. 2012, Kaewunruen and Remennikov 2013). Fig. 18 shows the actual dynamic effects on turnout systems, which previously were observed in the rail network. With the dynamic rigid body motion, the track superstructure will move/vibrate upward and downward against the substructure (ballast and formation). If stiffness transition is not established, rapid deterioration of substructure could incur, e.g., white ballast, large settlement, poor top, or pumping track etc. RailCorp standard ESC 230 (RailCorp 2012d) has suggested a treatment method of stiffness transition by replacing hard HDPE pads with softer SA-47 pads for 20 approaching concrete sleepers.

Interestingly, there is no major signalling problem at Hornsby junction over the year after the FFU installation, compared with a number of signalling problems reportedly in the past.

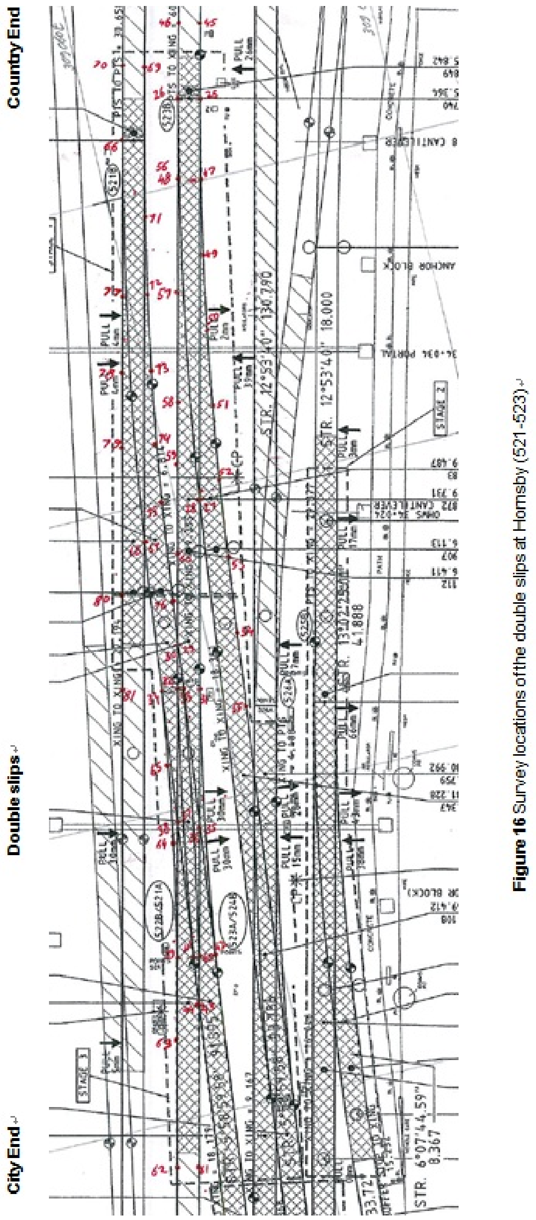


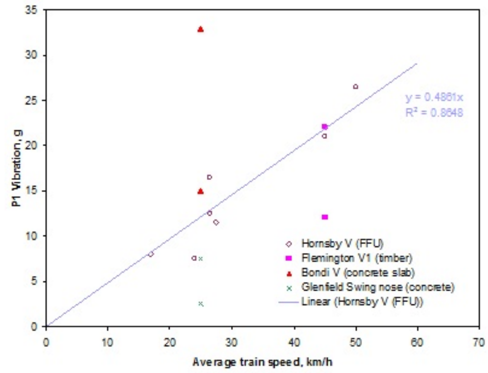

Fig. 16 Survey locations of the double slips at Hornsby (521-523)

Fig. 17 Allowance of FFU material to improve the lateral friction/stability of turnout system

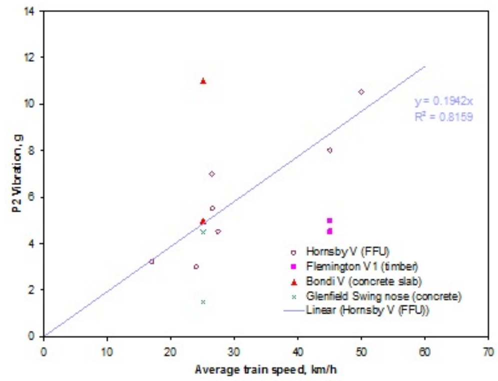
(a) pulverised ballast and broken concrete sleeper due to poor energy dissipation of material

(b) pulverised ballast and track pumping at the interface between timber and concrete sleepers due to the change in track stiffness

Fig. 18 Dynamic effects on turnout systems




(a) P1 vibration amplitude vs average train speed




(b) P2 vibration amplitude vs average train speed

Fig. 19 Performance benchmarking of v-crossings [13-15]

## 10. Conclusions

An application of fibre-reinforced foamed urethane (FFU) material to railway turnout structures has been highlighted in this paper. Design and analysis of the FFU material indicates a high level of safety. This study is aimed at evaluating the in-situ systems performance and effectiveness of FFU material in order to cater existing operations at complex turnout crossings. Data analyses of AK Car records, survey alignment data, and inspection data were conducted in conjunction with visual inspection at the double slips at Hornsby. The survey alignment data shows that there is a vertical settlement of track after a year of service, requiring a resurfacing work (vertical lift). On the other hand, the lateral global displacement of the double slips tends to be quite small over this period. Note that the as-built alignment was reportedly good in general. Overall there is no major issue with surface and line conditions of the double slips. Some vertical variations are mainly related to initial tamping and short-term un-settlement or un-compaction of ballast, which is very usual for any new railway turnouts.

Based on the condition inspection and vibration measurements, it can be considered that FFU material has equivalent static and dynamic performance relatively to timber bearers while lasting longer. Also, FFU bearers perform well in high-frequency region but not very well in low-frequency band. This is because the impact excitation in P1/P2 frequency band could excite the resonant behaviour of FFU bearers. However, FFU bearers exhibit relatively remarkable vibration suppression characteristics considering the high-frequency excitations at crossings. The high damping characteristics of FFU material were demonstrated in the frequency analyses. It is important to note that the stiffness transition at the interface between FFU and concrete sleepers must be established to suppress rigid body vibration damaging substructure components. At present, there is no problem associated with dynamic effects on the FFU turnouts at Hornsby Junction, whist comparatively certain problems (ballast pulverisation, broken bearer and fasteners, pumping track, etc) have already incurred on a number of concrete bearer turnouts after a short period of time. Good vibration suppression performance of FFU bearers can be evidenced when benchmarking with other turnout systems, as illustrated in Fig. 19.

Routine visual inspections in conjunction with the review of the examination sheet also confirm the findings. The double slips are stable and in good condition after over a year under mixed traffics. There is no major issue with lateral movement of the double slips. On this ground, FFU material, which lasts more than three times of timber's service life and is recyclable, can be a strategic material choice in railway industry that has a potential to reduce environmental impacts and maintenance costs. Notably, the carbon emissions from repetitive renewal construction activities and from the embodied carbon released during life cycles of timber can be diminished.

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