American Journal of Mechanical and Industrial Engineering
2024, Vol. 9, No. 3, pp. 43-51
https://doi.org/10.11648/j.ajmie.20240903.11

Research Article

44 Years of FFU Synthetic Railway Sleeper

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Abstract

In the 1970s, FFU (Fibre Reinforced Foamed Urethane) was developed by Japanese Railways in collaboration with Sekisui Chemical Co. Ltd. This technical report provides an overview of the production process and summarizes various material performance tests conducted by technical universities in Europe. Additionally, it addresses the lateral track resistance of German Railways before ballast compression and after more than 20 million load tonnes had been applied, compacting the ballast. To implement this technology in Finland, a full-body performance test at minus 65 degrees Celsius was required by the client. Meanwhile, the city of Warsaw's public transport operator requested a test to simulate vandalism fire scenarios under bridges and FFU sleepers. In 2010, 30 years after the first installation, the Railway Technical Research Institute (RTRI) of Japan retrieved sleepers from test tracks to assess their performance. The results showed that the sleepers were still in excellent condition, prompting RTRI to inform Japanese Railways that the technology could safely be used for another 20 years, reaffirming the proposed 50-year lifespan. Furthermore, the Technical University of Graz in Austria conducted a life cycle cost analysis for various countries, focusing on the use of FFU sleepers on bridges with open steel decks. For Germany, the study calculated an effective domestic interest rate of 25% for German Railway bridges, indicating strong economic viability. From a safety perspective, TNO, a Dutch research institute, examined the effects of FFU dust during on-site operations such as sawing and drilling. The results confirmed that working with FFU materials poses less risk compared to traditional wood, making it a safer option for on-site workers. This compilation of test results and real-world performance data highlights the reliability, longevity, and safety advantages of FFU technology for railway applications.

Keywords

Composite railway Sleepers, Life Cycle Cost Analysis, Load-Deflection Lines, 30 Years Field Test. Lateral Resistance, Fire Test

1. Introduction: Why FFU Synthetic Wood

In the 1970s, the Japanese Railway identified that the life expectancy of the wooden sleepers used is very short, primarily because of exposure to weathering and the conditions around the sleepers created by this in the superstructure.

As a result, the Japanese Railway wanted to create railway sleepers with the same material properties as the wooden sleepers. These, though, had to be affected as little as possible by the effects of the weather in respect of their material properties and durability. Sekisui, together with the Japanese Railway, developed a technology that uses long, directionally

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Received: 8 August 2024; **Accepted:** 2 September 2024; **Published:** 20 September 2024

aligned glass fibres to mimic in principle the fibre structure of wood (Figure 1). The development of this new material, named Fibre-reinforced Foamed Urethane (FFU), was completed in 1978.

FFU synthetic wood railway sleepers are produced by a pultrusion process (Figure 2). In this, the base material of the sleeper is created by drawing the individual material components through a moulding casing.

Continuous surface-optimised glass fibres are drawn precisely into the moulding casing. A special polyurethane composite is added in the moulding channel which moves along with it. This saturates the very dense glass fibres completely and non-porously. The precisely controlled quantity of heat and the monitored draw speed guarantee very high and durable material quality.

The finished FFU strand is continuously extracted at the other end of the casing channel and monitored as it is cooled. It is then cut to the required length and checked again for its quality.

Figure 1. *50 percent by volume ratio of glass fibres in the cross section of the FFU- railway sleeper.*

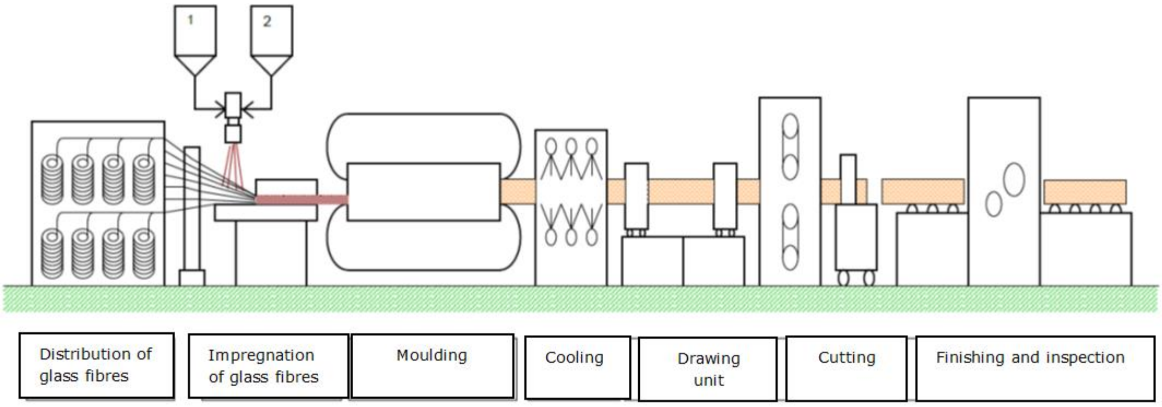

Figure 2. *FFU Synthetic Wood Railway Sleeper Manufacturing Process.*

This technology offers the advantage that nearly any sleeper shape that can be shown in a plan can be produced just as precisely. This applies, for example, to soleplates from a height of as little as a few millimetres up to actually produced and installed sleepers of length 16 m, 70 cm width and 35 cm height.

Special productions depending on the project, cambers in curve areas, milled grooves for support bearings, holes and much more are precision pre-manufactured in the factory according to customer requirements. The sleepers are numbered according to the plan, stamped with the production period and delivered to the construction site for installation.

Sleepers using this technology were first installed in two projects in 1980, in the form of field trials for the Japanese Railway. One of these was a bridge with an exposed track and the second was a tunnel with bi-block sleepers in a solid trackway.

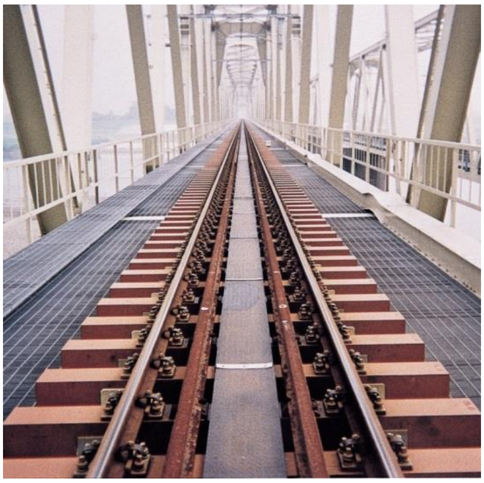

Figure 3. *FFU-Bridge sleepers on the Tokyo-Osaka-Shinkansen High Speed Line (270 km/h).*

FFU has been installed since 1985 as an approved regular sleeper in the Japanese railway network.

By 2024, more than 3.55 million FFU railway sleepers have already been installed around the world. This is equivalent to a track length of more than 2,100 km. It should be remembered that FFU is primarily used in the areas of bridges and points (Figure 3).

The Japanese Railway Technical Research Institute [RTRI] tested FFU synthetic wood sleepers before their first installation in 1980, after 5 years test operation after 10 years, after 16 years and after 30 years in operation. It will also remove and test sleepers in 2020, that is, over 40 years after their first installation.

These tests serve to investigate and document the long-term properties of FFU synthetic wood sleepers in daily railway operation.

The results of the tests after 30 years (2011) prompted RTRI to confirm in a letter to the Japanese Railway that the FFU synthetic wood sleepers could be used safely for the next 20 years, thereby confirming the forecast 50-year expected lifetime.

Table 1. *RTRI Test values (collapse) for FFU sleepers new, after 10, 15 and 30 years in use. the values are the material failure values [1]. Figures only to demonstrate the performance over years. Not for calculations!. Figures for calculations you must ask Sekisui to get calculation values.*

Tested values		Unit	Value as equivalent of 740 kg/m³ density after 10, 15, 30 years in use and new sleeper				Requirement JIS New sleeper	Requirement ISO 12856-1 Type A New sleeper
			30 years	15 years	10 years	New		
Material strength	Flexural strength	N/mm²	116,6	131,4	114,6	142	≥70	≥ 60
	E-Module	N/mm²	8.414	8.788	8.044	8.100	≥ 6,000	≥ 6,000
	Compressive strength longitudinal	N/mm²	60,3	63,2	75,7	58,0	≥ 40	≥ 40
Electrical values	AC failure voltage	kV	≥ 25	≥ 25	≥ 25	≥ 25	≥ 20	≥ 20
	Insulation resistance	MΩ	8,2 x 10^5	1,4 x 10^6	1,1 x 10^6	1,6 x 10^7	≥ 1 x 10^4	≥ 1 x 10^4

The values for material strength shown in Table 1 are the failure values for the material. The values used for the calculation of material properties in use on railway tracks are proven with a safety factor of 2.5 – 3.0 and can be obtained direct from Sekisui. The corresponding specified regulations of the railway operator concerned must of course always be considered.

2. Recycling/Sustainability

Since the first sleepers were installed in 1980, they are still in safe use. There has therefore not yet been a need to recycle sleepers that are in use.

There is waste in the manufacturing process of the synthetic wood sleepers in the form of drilling waste, and dust and chippings from milling and sanding. One hundred percent of this waste is recycled. The manufacturer also guarantees that it will recycle synthetic wood sleepers at the end of their lifetime and create new products out of them. Thus, for example, FFU in the form of so-called K-FFU, made from manufacturing waste, has been used in projects in Austria as sole-plates in the area of bridge thrust-bearings with a constructive height if a few millimetres (Figure 4).

Figure 4. *Recycled FFU production waste (K-FFU) between FFU sleeper and thrust bearing.*

3. Technical Values

The FFU synthetic wood sleeper has been investigated and tested by many international technical universities and testing institutes. These include the Technical University of Munich, the Technical University of Milan, the Technical University of Tampere, the Technical University of Brunswick, the University of Southampton and of course the Railway Technical Research Institut in Japan, to name just a few.

If the technical limit values of synthetic wood are compared with those of oak wood sleepers, it can be roughly stated that the flexural strength of FFU 74 is about 80% and the compression strength about 50% higher.

the investigations also showed that the elasticity modulus is always in the range of over 7,000 N/mm^2.

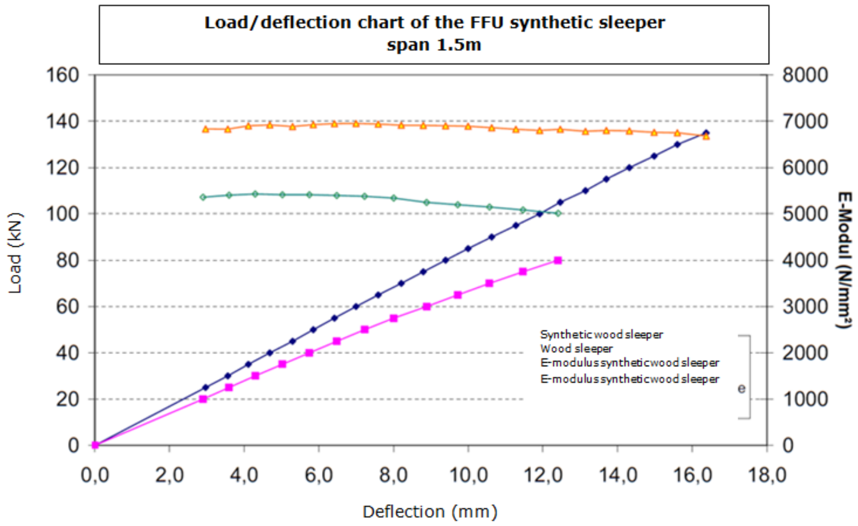

Figure 5. *Load deformation curve FFU 74 – Test TU Munich, 2008 [2].*

The load deformation curve (Figure 5) also shows that the material properties of the synthetic wood sleeper is linearly elastic over a very large range. that means deformations, such as occur when passing over points in the centre area, which then return to the zero position after the load is removed. This, combined with the E-modulus, the material-specific warping property under load and the low thermal expansion coefficient of 7.8 x 10^{-6} /°K leads to an absolute advantage for the railway operators in using them in the area of points.

Deutsche Bahn for example installed two points with FFU sleepers in Würzburg in 2012. In 2011 they also installed two points on concrete sleepers. In 2018, after six and seven years duration respectively, they carried out comparative investigations on these four points. The findings, to be reported in a following publication, were convincing.

Sekisui Chemical Co.Ltd., the creator of FFU, can create the synthetic wood sleepers of different density. this primarily involved chaging the density of the polyurethane used, while the proportion of glass fibre remains almost the same. IN this way, the material can be optimised for special demands and uses by railway operators.

The Paris Metro RATP, for example, wanted a guaranteed extraction forcse of 120 kN per bolt for the bolts used by them. These requirement were met with with an FFU 100 sleeper (Table 2). These different FFU materials could also be combined. In that way, long timbers were produced from FFU 74 with 6cm of FFU 100 on the upper surface for Network Rail, a rail operator in the UK, for the Newark crossing project. in this way, the compression strength of the railway sleepers could be adjusted to the opertor's requirements.

Table 2. *Technical Values of FFU Synthetic Wood for Railway Sleepers [3, 4].*

Techn. Values	Unit	FFU 100 High strength	FFU 95 Soft	FFU 74 Standard	FFU 50 Light	RFFU Recycling
Density	kg/m^3	1,000	950	740	500	1,100
Flexural strength	N/mm^2	225	109	142	71	60
E-modulus	N/mm^2	16,400	10,490	10,600	7,450	5,000

Techn. Values	Unit	FFU 100 High strength	FFU 95 Soft	FFU 74 Standard	FFU 50 Light	RFFU Recycling
Compression strength lomgitudinal	N/mm^2	108	37	58	29	40
Water absorption	mg/cm^2	3	4	3	6	38
Electrical resistance	Ω	$1.0x10^{14}$		$1.6x10^{13}$	$1.0x10^{13}$	$7.6x10^{14}$
Thermal expansion coeff.	[1/°K]			$7.8x10^{-6}$		

All values are average values at which material failure occurs. Values are not guaranteed. Not for calculations! If you need figures for calculations you must ask Sekisui to get calculation values.

4. Lateral Shift Resistance on Ballast Base- LSR

Proof of the lateral shift resistance (LSR) was strictly specified to gain final EBA approval in Germany. This had to take place on a real track.

To do this, together with the TU Munich, Sekisui installed FFU synthetic wood in four different construction heights and designs in a new real Deutsche Bahn track in summer 2015. 45 of each type of sleeper were installed and every third one of these was tested [5]. To get a direct comparison with Deutsche Bahn wooden sleepers, 45 wooden sleepers were also installed and tested.

The dimensions of the wooden track sleepers investigated were W/H/L = 16/26/260 cm, the FFU Type 1 synthetic wood sleepers were W/B/L = 12/26/260 cm. the dimensions of the Type 2 FFU synthetic wood sleepers were as for Type 1, although shims each of height 6cm and length 15cm were attached to the underside at each end and the centre of the sleeper. Type 3 had dimensions of W/B/L = 16/26/260 cm. Type 4 was as Type 3, but with shims of height 2cm and 15 cm length on the underside at each end only.

The first measurement was made in an unconsolidated status, that is, after the insertion of the tracks and before any train traffic passed over the tracks. The second measurement took place in a consolidated condition in the summer of 2016, after a traffic load of 33.9 million tonnes had passed over the test section of track.

Results showed that the Type 3 synthetic wood sleeper of construction height 16 cm had an LSR 7.8% lower than that of a wooden sleeper in unconsolidated status. In the consolidated status, the LSR of the synthetic wood sleeper was 14.9 N/mm with a 2mm shift, that for the wooden sleeper was 14.8 N/mm (Figure 6). Apparently there was an increasing working into the ballast bed of the underside of the sleeper with the synthetic wood sleeper.

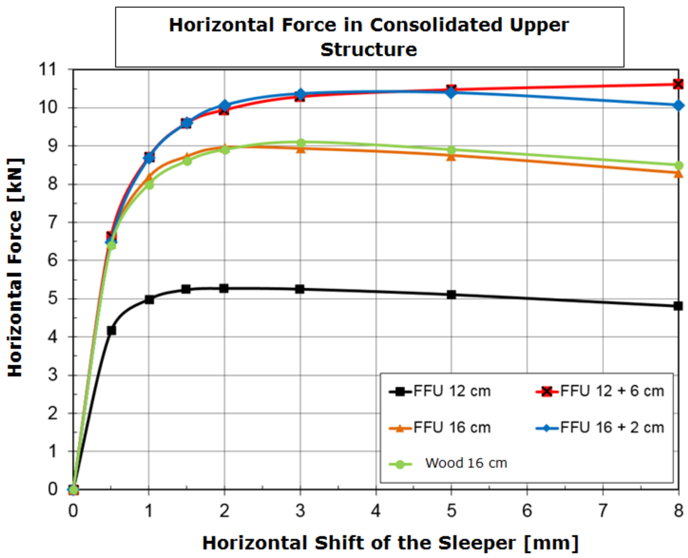

Figure 6. Lateral shift resistance of different FFU synthetic wood sleepers in consolidated upper structure Type 1 FFU H/W/L = 12/26/260cm, Type 2 FFU H/W/L = 12/26/260 plus 3 shims, each H/W/L = 6/26/15 cm, Type 3 = FFU H/W/L = 16/26/260 cm, Type 4 FFU H/W/L = 16/26/260 plus 3 shims, each H/W/L = 2/26/15 cm, wooden sleeper H/W/L = 16/26/260 cm.

5. Chemical Stability – Drinking Water Quality

Because of the closed cell structure, FFU railway sleepers absorb virtually no moisture. This technology maintains its full technical function, durability and safety vis-a-vis oils, lubricants and chemical substances used in railway operation, artificial fertilizers, salt and many other substances.

UV light has no effect on the technical quality of FFU synthetic wood. Uncoated surfaces with prolonged exposure to UV radiation only undergo discoloration of the upper surface, similar to natural wood.

The report OS57110607-1 was completed by "Japan Food Research Laboratories" [6] on 14th November 1994. This gave the chemical breakdown of the water quality test of FFU synthetic wood in relation to the regulation no. 69 of the Japanese Health Ministry. The result was that both the immersion test water and the control water comply with the standards for water quality and therefore the quality of the water was not affected.

6. Fire Properties

The smoke from FFU was classified by DMT GmbH & Co KG in 2009 as non-toxic and safe for use in enclosed installations or for rail infrastructure in Europe that runs underground according to DIN 5510-2:2009-05 [7]. The Institute for Construction Materials, Solid Construction and Fire Safety of the Technical University of Brunswick [8] classified FFU 74 and FFU 100 as B_{fl}-s1, i.e. with low flammability and low smoke production according to DIN 13501-1:2010.

Figure 7. Fire test on open steel beam construction (here: Fire on the upper surface of the bridge track).

The Institut Techniki Budowlanej in Poland tested FFU 74 in 2017 in respect of safety against fire that could be caused by vandalism on a railway bridge with open steel beams. This was done by starting a fire both on the upper surface of an exact replica of the trackway with steel beams, rails and grating and under the construction, which acted on the sleepers and the construction for 30 minutes. Wind was also simulated in the test. In each test, 20kg of wood was burned. The temperature on the top surface of the first FFU sleeper immediately adjacent to the one directly above the fire reached a maximum of 700° C. Over the course of the test, the fire only spread to the two directly neighbouring FFU sleepers. The three sleepers which has started to burn under this fire load extinguished simultaneously with the reduction of the artificially created fire (Figures 7 and 8).

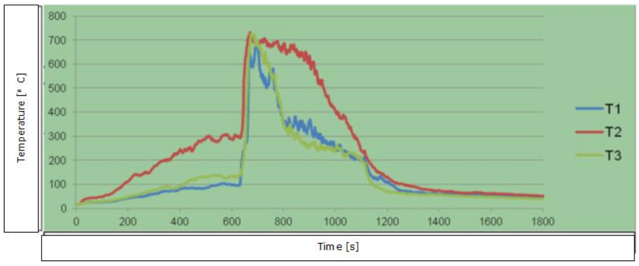

Figure 8. Temperature change on the side surface facing the fire of the sleeper to the left of the primarily affected FFU sleeper (at 3 measurement points).

T1 near the sleeper fixing pint on the bridge longitudinal beam left of the centre of the sleeper, T2 in the centre (vertical and horizontal) of the sleeper, T3 near the sleeper fixing pint on the bridge longitudinal beam right of the centre of the sleeper

As a result of the investigation, the laboratory issued a qualification certificate [12], certifying FFU74 as non-fire spreading, self-extinguishing and without any negative effects on the fire safety of this bridge construction as a building material.

7. Investigation at Minus 65 Degrees Celsius

The University of Tampere in Finland tested FFU synthetic wood sleepers at very low temperatures that can arise in Finland [9]. The initial target temperature was at least minus 40 degrees Celsius, but the cooling apparatus lead to even lower temperatures. All load tests were load-controlled and carried out according to European Standard EN 13230-2, which describes the load test for concrete sleepers. In this, a static load is applied to the centre of a sleeper. The distance between the support points was 1,600 mm, the supports were 100 mm wide. Two vertical deformation gauges were installed directly above the support points and two more deformation gauges directly below the point of application of the load.

The temperature of the sleepers was measured at three points during the application of the load. One point was embedded about 80mm deep within the sleeper, the second point about 30 mm deep within the sleeper and the third temperature sensor measured the temperature of the sleeper surface.

A total of five FFU sleepers with dimensions H/W/L = 160 x 260 x 2,600 mm were tested. One of the sleepers was stored at room temperature (20° C), four were cooled with dry ice in an insulated box for at least 24 hours. This cooled the sleepers to temperatures of -65 to -70° C. The sleepers were not cooled during the tests, so that the surface of the sleepers warmed by the end of the test to nearly 20°, by about 10° at 30mm depth and at 80 mm depth by less than 1°.

All the load deformation curves are shown in figure 9; the maximum load was 250 kN. The results of the bending tests demonstrate very high flexural strength. The rigidity of the material increased slightly at low temperatures. The differences between the individual tests were negligible.

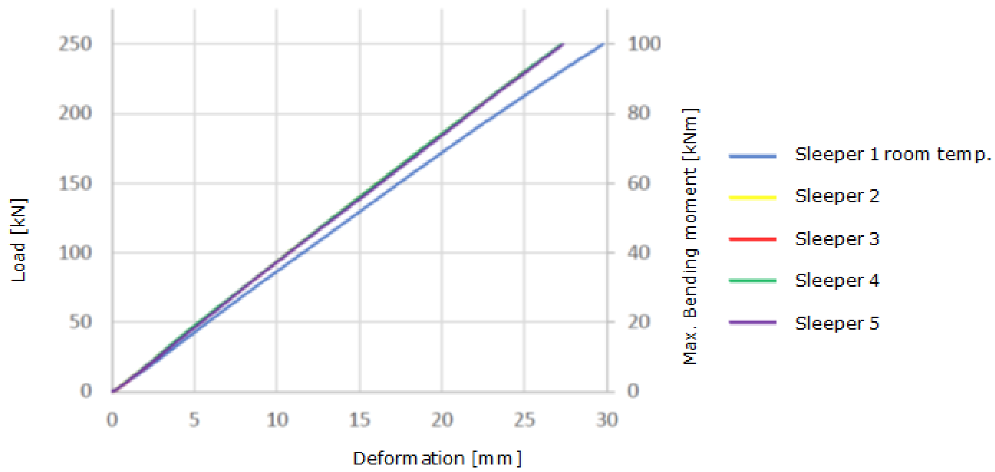

Figure 9. *Load-deformation curves for FFU sleepers in the low temperature test.*

All the FFU sleepers were visually inspected after the tests. No cracks were identified in the bending force area on the surface of the sleepers. An average e-modulus of 8,933 Mpa was determined for the 5 tested sleepers.

A comparison of the synthetic wood sleepers with wooden sleepers shows that the average breaking load of a new wooden sleeper in similar static tests (temperature +20°C) is 80 to 100 kN. The elasticity modulus of new wooden sleepers of dimensions B/W/L = 240/160/2,700 mm is about 7,300 MPa.

The tests showed both that the FFU sleepers can carry high loads and that they are also elastic. Very low temperatures cause the sleepers to become a little more rigid but there was no effect on the quality of the sleepers such that the FF sleepers can safely carry the loads of the Finnish railways rolling stock.

8. LCC Bridges

The Life Cycle Cost Analysis "LCC Bridges"[10] is concerned with bridge timbers fastened directly to exposed steel bridge beams in the Deutsche Bahn network.

The results of the economic efficiency calculation can be summarised as follows:

If the (remaining) life expectancy of the bridge beams exceeds that of the wooden sleeper by even one year, then it is economically expedient to use FFU sleepers.

For long (remaining)lifetimes of the bridge, there is a high potential saving from using FFU sleepers. The domestic interest rate with a bridge lifetime of 120 years is a very high 25%.

The base scenario shows a cost saving for FFU sleepers if the remaining lifetime of the bridge exceeds the lifetime of the wooden sleepers; the annuity of the wooden sleepers is about double that of the FFU sleepers (Figure 10). Pu another way, even if wooden sleepers only have to be replaced once, FFU sleepers are the more economical option.

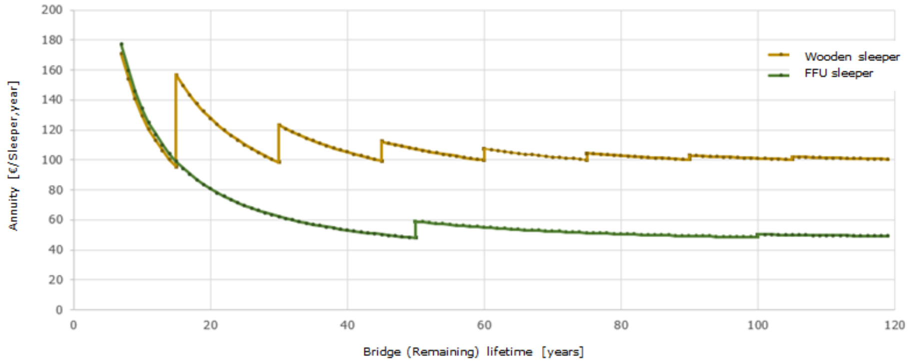

Figure 10. *Annuities of bridge timbers against bridge lifetime.*

The lifetime of wooden bridge timbers will fall with the ban on the impregnation materials normally used up to now. An investigation of this with a reduced lifetime of the wooden sleepers of 8 years 8 shows that the annuity for wooden sleepers is about three times as high as that for FFU sleepers (Figure 11). The amortisation duration for FFU synthetic wood sleepers falls to 9 years.

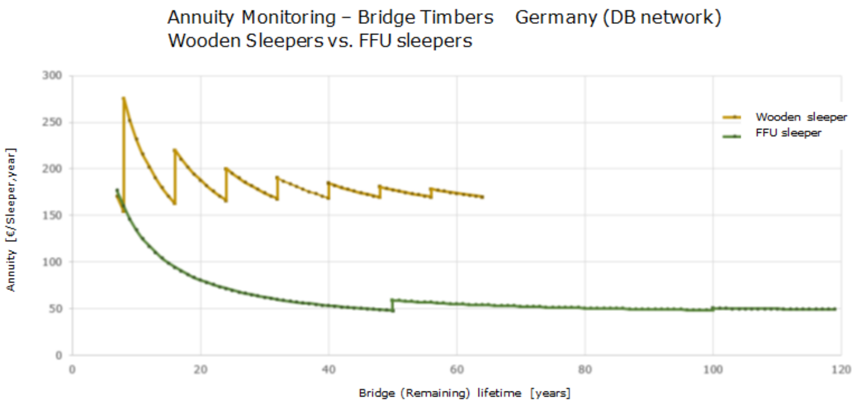

Figure 11. *Annuities of bridge timbers against bridge lifetime – reduced wooden sleeper lifetime 8 years.*

9. Work Safety - TNO - Investigation

The TNO (Dutch Organisation for Applied Scientific Research) carried out investigations in 2017 in respect of the effects of fine dust produced in working on the sleepers with reference to the legal specifications [11].

Sekisui Chemical Co. Ltd. Produces FFU synthetic wood from fibre-reinforced polyurethane. During mechanical working of FFU synthetic wood on site, harmful substances could be released which constitute a possible exposure risk to employees. The substances possible released include respirable und inhalable dust, glass fibres, diisocyanates and products of the thermal decomposition of diisocyanates.

Realistic "worst case" simulation measurements were made under standardised conditions. The investigations were made in two different ways:

With emission-reducing according to the working guidelines for FFU synthetic wood.

Figure 12. *Drilling the holes for sleeper bolts.*

Worst case simulation without emission-reducing measures. The following equipment and emission-reducing measures were used:

1. Drill – with and without extraction
2. Hand chainsaw – without extraction
3. Electric planer - with and without extraction
4. Belt grinder / manual grinding- without extraction

As the FFU technology represents an alternative to the conventional oak railway sleepers, the measured dust concentrations were also compared with the dust emission data in the corresponding processes for hardwood, to show the results by comparison.

The extensive study made by the TNO showed that in general the concentrations of respirable dust are lower wit FFU synthetic wood than with hardwood. Working with FFU synthetic wood meets the corresponding regulations of Germany and Sweden, which have the most demanding working regulations in Europe.

10. Conclusion

FFU synthetic sleeper technology is already in use since more than 40 years. Many Universities tested this technology along different standards and regulations. It always showed that it performs better than soft wood (beach, oak), has a similar elastic behaviour. In comparison to soft wood (beach, oak) as well hard wood (Ekki), it is linear elastic and not influenced from the weather.

Since the year 2024 an ISO 12856 standard is existing, regulation how test for composite railway sleeper technologies must be performed. In comparison to the ISO 12856 standard from 2014 this standard does not offer the client what technical performance he should expect in real values from composite materials for the railways.

It also doesn't collect any water. Considering this it was already discussed to use it in the field of coast protection. For those tests like abrasion from geological material of the sea could be researched in the future.

Abbreviations

FFU	Fibre Reinforced Foamed Urethane
FFU 74	Fibre Reinforced Foamed Urethane with a Density of 740 kg/m^3
LCC	Life Cycle Costs Analysis
RTRI	Railway Technical Research Institute
K-FFU	Is a 100% Recycled FFU material. It will Be Produced from Small Parts Collected During the Milling of the Surface of the FFU Technology During the Production
RATP	Public Transport in Paris and Île-de-France
LSR	Lateral Shift Resistance, Criteria What Load Is Needed to Move the sleEper 2 mm in Lateral Direction
TU	Technical University
UV	Ultra Violet
DIN	German Industry Standard
ISO	International Organisation for Standardization
TNO	Dutch Organisation for Applied Scientific Research

Conflicts of Interest

The authors declare no conflicts of interest.

References

[1] Railway Technical Research Institute, Track Structure Dept., Track Technology Div., Follow-up Survey on FFU Synthetic Sleepers after 30 Years in Service, June 2011.

[2] TU Munich, Research Report Nr. 2466 f 19.9.2008, Univ. Prof. S. Freudenstein, Dipl. Ing N. Maleki, Dr.-Ing. Ch. Simon.

[3] Sekisui GmbH, technical specifications FFU, 2016.

[4] Monash Institute of Railway Technology, Report No. Monash/RT/2020/1500, Cong Qiu, Siva Naidoo, Rob Lambert.

[5] TU Munich, Research Report 3484, Lateral Shift Resistance of FFU synthetic wood in consolidated ballast surface, Univ. Prof. S. Freudenstein, Dr.-Ing. K Geißler, Dipl.-Phys. J. Mack, 24.11.2016.

[6] Japan Food Research Laboratories, Test Report No. OS57110607-1, 14.12.1994.

[7] DMT GmbH & Co KG, Report on the Fire Technology Test according to DIN EN ISO 5659-2 and classification of the toxicity of the smoke according to DIN 5510-2: 2009-05, 20613024b, GS-BS/Püs, 2009.

[8] TU Brunswick, Institute of Construction Materials, Solid Construction and Fire Safety, Material Test Institute for the Building Industry, Classification Report K-3522/798/11-MPA BS, Dr.-Ing Blume, B. Müller, 2012.

[9] Tampereen yliopisto, FFU sleeper bending test at low temperature, Dipl.-Ing. Dr.-techn. H. Luomala, M.Sc. R. Varis, M.Sc. T. Rantala, March 2020.

[10] TU Graz, LCC Bridge Beams, Economic Use of FFU Bridge Beams, Univ. Prof. P. Veit, Dipl.-Ing. Dr. techn. S. Marschnig, 2019.

[11] TNO (*Toegepast-Natuurwetenschappelijk Onderzoek)*, Evaluation of Exposure While Working with FFU Synthetic Wood Railway Sleepers, P. C. Tromp, June 2019.