An investigation on the stiffness of timber sleepers for the design of fibre composite sleepers

A. Ticoalu, T. Aravinthan & W. Karunasena
Centre of Excellence in Engineered Fibre Composites, Faculty of Engineering and Surveying, University of Southern Queensland, Toowoomba, Queensland, Australia.

ABSTRACT: This paper presents an experimental investigation on timber railway sleepers with a view to select a suitable stiffness and a modulus of elasticity for the design of a fibre composite railway sleeper. Eight full size timber sleepers were tested using a four point bending test arrangement. An overview of existing material for railway sleepers is also presented. Based on the tests, it is concluded that timber sleepers have significant variation in strength and stiffness as can be inferred from the modulus of elasticity ($E_{sleeper}$) which ranged between approximately 9520 MPa and 27600 MPa. It is desirable to develop a concept fibre composite sleeper within a similar range of modulus of elasticity. Based on the statistical analysis, it is proposed to use the lower tail value that is 12000 MPa as design modulus of elasticity for the fibre composite railway sleeper.

1 INTRODUCTION

1.1 *General*

Timber was the first material widely used for railway sleepers. Creosote saturated timber sleepers have been used since the early nineteenth century and were considered economic and appropriate at that time (Bonnett 1996) because timber was readily available. There is now a limited supply of timber and the existing timber sleepers are deteriorating with age.

Several investigations have been carried out in an attempt to decide the most durable, strong and cost-effective material for railway sleepers. Some early approaches were to optimise the use of existing resources of sleepers such as timber, steel, and concrete (Adam 1991, McLeod 1991). Another approach was to strengthen or combine the existing material with fibre composite materials (Davalos et al, 1999, Humphreys & Francey 2004). Further approaches focussed on the replacement of existing deteriorated sleepers using alternative materials such as polymer concrete (FCDD), rubber (Pattamaprom et al n.d) and fibre composite material (TieTek).

Fibre composites (FC) have been used mainly in the aircraft and automotive industries in previous decades. In recent years, they have been utilised in civil engineering applications to satisfy the growing need for higher strength and higher performance requirements. Fibre composites are basically a combination of engineered resin and fibre reinforcement. This combination determines many outstanding characteristics such as high durability, fire resistance and corrosion resistance. However, it is to be noted that the characteristics of fibre composite materials depend upon the properties of the component materials and the ways in which the fibres and resins are combined and manufactured. Several studies on FC (Ayers 2001, Grace 1998, Hakim 2002) have identified the potential of FC for structural applications. While fibre composites have a broad range of potential applications, this paper is devoted to the investigation of fibre composite railway sleepers. Successful development and implementation of a new material for sleepers will depend on the durability, performance, strength, and cost-effectiveness of manufacturing and installation.

1.2 *Background*

Railway is an important and popular means of transportation for people and freight in many parts of the world including European countries, India, Australia and America. However, some of the railway tracks were built hundreds of years ago and track components such as rails and sleepers need to be replaced or require extensive maintenance. One of the most important parts in the railway track is the sleepers. They constitute the railway track super-structure together with rails, ballast, sub-ballast, base and formation layer of the base (Profillidis 1995). Rails and sleepers are connected by a fastening system which utilises equipment to secure the rails into baseplates or sleepers (Ellis 2004) to maintain the track. Sleepers spread wheel loads to the ballast, hold rails to gauge and inclination, transmit forces, insulate rails electrically, and provide a base for rail seats and fastenings (Bonnett 1996, Cope & Ellis 2001).

As world timber resources dwindle, timber sleepers must be replaced by those of an alternative material. The alternative material should have at least the same properties as timber and be competitively priced. Steel and concrete sleepers have been extensively used in several railway tracks. Steel sleepers were found to be difficult to maintain, noisy and required special fastenings for electrical insulation. Concrete sleepers were heavy, relatively brittle, and stiff. Subsequently prestressed concrete was introduced and has been a popular material for sleepers although manufacturing cost is high.

One of the ways to reduce the cost of railway maintenance is to replace only the deteriorated sleepers in the rail track (spot replacement). In some locations in the existing railway systems, there are several timber sleepers which have to be replaced. Good quality sleepers with the same dimensions as the old timber sleepers are needed. If the dimensions are different, spacing will vary and the whole rail track might have to be rebuilt, thereby increasing costs. Timber sleepers can be drilled on-site and it would be highly desirable for the design of new fibre composite sleepers to incorporate that feature.

1.3 *Objective*

The main objective of this research is to investigate the stiffness and modulus of elasticity properties of the existing timber sleepers with experimental testing to generate a design value for the development of fibre composite railway sleepers.

2 OVERVIEW OF EXISTING MATERIALS FOR RAILWAY SLEEPERS

There has been a considerable amount of research and development into sleeper materials since railway was introduced. The most common material for sleepers, timber, is a rapidly diminishing resource. Steel sleepers were introduced and although steel is a high strength material which presented stability, corrosion and electrical conductivity remains to be the constraints. Prestressed concrete sleepers were introduced after unsuccessful attempts at using pure concrete and reinforced concrete.

Timber sleepers were readily available, and easy to handle and transport. Other advantages of timber sleepers are good resilience, adaptability to non-standard situations and good electrical insulation (Bonnett 1996). Also they can be drilled easily after installation onsite. However, the declining availability of hardwood such as ironbark and jarrah has made it difficult for the railway industry to rely on timber sleepers. Fungal decay and end splitting contribute to the failure of timber sleepers (Hagaman & McAlpine1991). An inadequate sleeper needs to be replaced as it will cause problems to the overall track.

Although they are not widely used, steel sleepers have been utilised in some countries due to their high strength to weight ratio. However, steel's susceptibility to corrosion, resulting in higher maintenance costs, detracts from its overall performance.

Reinforced concrete sleepers were not well accepted due to their high stiffness and weight. Prestressed concrete sleepers have been more widely accepted because they provide longer service life despite the high initial cost of manufacturing.

Recent trend has been to exploit advanced fibre composite material for railway sleepers. Although early works in fibre composite development was largely in the aircraft industries, its outstanding characteristics of strength and durability makes it attractive for civil engineering applications such as bridge (Van Erp 2006), beam reinforcement (Hakim 2002), railway sleeper (Hoger 2000) and structural slab (Huang 2004).

Research into the use of fibre composite material in a structural beam inspired the investigation of the use of this material for railway sleepers. Davalos et al (1999) have examined the use of glass fibre-reinforced plastic (GFRP) as a thin wrap to reinforce timber sleepers with filament winding process method. Their experiment includes four-point beam bending test and finite element (FE) modelling. Their results show that using 1.78 mm-thick layer of GFRP has increased the stiffness and strength of the sleepers. Similarly, Humphreys & Francey (2004) investigated the possibility of carbon fibre/epoxy laminates as an external reinforcement to strengthen timber railway sleepers. The experiment used four point bending test for sleepers with a length of 2012 mm. According to their manual calculations, it is possible to increase the load carrying capacity of timber sleepers using this method. However, their experimental results showed failure due to delamination.

In USA, thermoplastic composite sleepers (TieTek^{TM}sleepers) have been developed using recycled polyolefins, crumbed tire rubber and reinforcing parts. The sleepers were claimed to have beneficial properties such as resistance to water and insect, non toxic, reduced vibration, longer service life, utilising existing installation equipment and fastening systems, non-conductive, recyclable and economically viable. Namura et al. (2005) reported that in Japan, hard polyurethane foam and glass fibre have been used in railway sleepers which have physical properties similar to timber sleepers and are designed for more than 60 years service life.

Pattamaprom et al (n.d) have investigated the possibility of using a natural rubber composite in railway sleepers. The mechanical properties of natural rubber were engineered and resulted in better compressive modulus and hardness. However, their experimental results show high stiffness and inelasticity. Hoger (2000) investigated the use of bulk recycled plastic as a core material for railway sleepers. His study concluded that composite material increases the strength of railway sleepers but may not be competitive in terms of cost effectiveness. Nevertheless, the term cost-effective is a relative index in determining the acceptance of a product.

Existing studies (Hoger 2000, Davalos et al. 1999, and Humphreys & Francey 2004) have confirmed the feasibility of using fibre composites in railway sleepers. Despite many types of materials used for sleepers, there is still a need to find a reliable and better performing material. The conventional timber sleeper was actually ideal because timber was a readily-available resource that provides flexibility in installation and fastening, and has good resilience property. Therefore, it is preferred that the development of a new material for railway sleepers incorporate the same flexibility and resilience property.

3 IDENTIFICATION OF STRENGTH AND STIFFNESS OF SAMPLE TIMBER SLEEPERS

3.1 *General*

For use as railway sleepers, timber needs to satisfy specific requirements such as strength, durability and stiffness properties. In Australia, it has to meet the standard for railway track timber (AS 3818.2-1998). In reality, due to the fact that timber is easily affected by moisture and the environment, the mechanical properties of timber sleepers may vary. Therefore, it was considered essential to conduct testing of timber sleepers, since stiffness (EI) is one of the major issues in the design of fibre composite sleepers

The objectives of this testing is to determine the strength, stiffness and the extent of variation of existing timber sleepers. It is intended as initial comparisons for the design of fibre composite sleepers. The data extracted from this test will be the maximum load (P_{ult}), maximum deflection (δ_{ult}), and modulus of elasticity (E).

3.2 *Testing of timber sleepers*

Eight timber sleepers were prepared for a four point bending test in order to get load data and deflection. From the load and deflection data, the modulus of elasticity was calculated. The beams were tested to failure. The diagram for the four-point bending test can be seen in Figure 1 while Figure 2 shows the set-up in the laboratory and Figure 3 shows the cross section of the tested timber sleepers

The testing was conducted in the Structures Laboratory of the Faculty of Engineering and Surveying at University of Southern Queensland. An Instron test rig with a load capacity of 250 kN was used to generate the loading. To measure and record load increment data and midspan deflection, a System 5000 data recorder with LVDT was used. Table 1 summarises the dimensions and testing span of the sleepers.

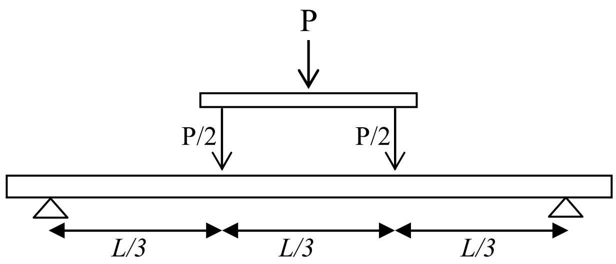
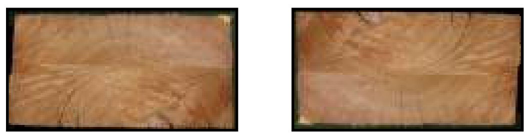


Figure 1. Four point bending test setup diagram

Figure 2. Four point bending test setup in laboratory



(a) T1 (b) T2

Figure 3. Cross sections of T1 and T2 when tested

Table 1. Dimensions and testing span of timber sleeper specimens

Beam No	Overall length	Width, b	Depth, D	Testing span, L
	mm	mm	mm	mm
T1	4118.0	230.0	120.0	3600
T2	4136.0	230.0	120.0	3600
T3	3202.0	212.7	115.7	2700
T4	3223.3	232.3	115.3	2700
T5	3220.0	231.3	111.0	2700
T6	3260.7	223.3	123.3	2700
T7	3344.7	228.3	112.3	2700
T8	3326.3	218.7	109.7	2700

In this test, the sleepers exhibited failure with P_{ult} and δ_{ult} at midspan and cracked at the midspan tension zone. The results of the ultimate loads and corresponding deflections are presented in Table 2.

Table 2. Ultimate load and corresponding deflection

Beam No	Span, L	P_{ult}	δ_{ult}
	mm	N	mm
T1	3600	113640	130.00
T2	3600	72730	160.14
T3	2700	61640	98.44
T4	2700	89700	81.97
T5	2700	105830	98.81
T6	2700	121310	64.33
T7	2700	84370	116.31
T8	2700	42940	88.38

Even though T1 and T2 have similar dimensions, there is a difference in ultimate load (P_{ult}) reached and the deflection. T1 has approximately 36% higher value of P_{ult} than T2. Graph in Figure 4 shows that the two specimens exhibit different strength and stiffness. T1 is stronger than T2. The difference may be due to the difference of moisture content at the time of testing and different timber type. However, factors such as different grain composition and different cross section when tested may also affect the variation.

Similarly, for specimens T3 to T8, despite having similar dimensions and test span, the ultimate load (P_{ult}) reached and the deflection show significant variation.

To calculate the properties of the tested timber sleepers, the following formulae were used:

$$I = \frac{bD^3}{12} \quad (1)$$

$$\delta = \frac{23(P/2)L^3}{648EI} = \frac{23L^3}{1296EI} \quad (2)$$

$$EI = \frac{23L^3}{1296}\frac{P}{\delta} = \frac{23L^3}{1296}m \quad (3)$$

$$M = \frac{PL}{6} \quad (4)$$

where M = bending moment ; I = moment of inertia; EI = stiffness; m = slope.

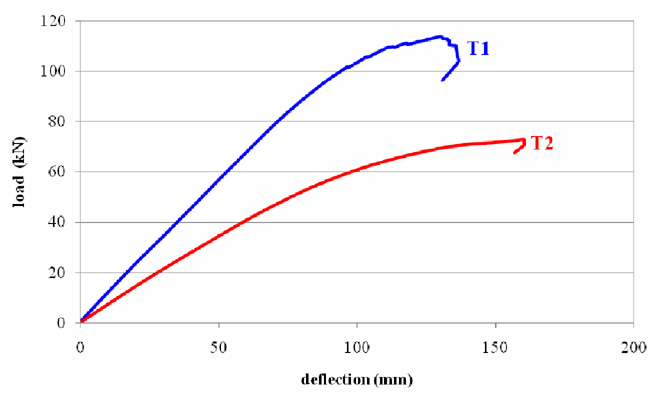


Figure 4. Load vs deflection plot for L = 3600 mm

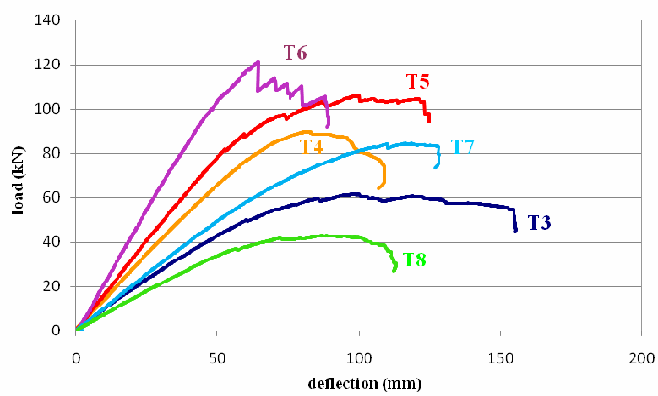


Figure 5. Load vs deflection plot for L = 2700 mm

Figure 5 confirms the difference of T3 to T8 where T6 has the highest P_{ult} (121310 N) and T8 the lowest (42940 N). As can be seen from the varied slope in the graph, these sleepers also have significant variation in modulus of elasticity.

From Figure 4 and Figure 5, the failure modes of the tested timber sleepers' exhibit similar trend with large deflection before failed, except for T6 which had lower deflection but higher load capacity.

3.3 *Data Analysis*

A statistical analysis was carried out to identify the difference in stiffness value (Table 3). It was found that the stiffness and modulus of elasticity have averages of 5.03E+11 Nmm^2 and 16607 MPa, respectively. The variation in the values of EI and E, which are relatively wide, are shown by the calculated standard deviation.

Table 3. Stiffness and modulus of elasticity from testing

Beam No.	L mm	I mm^4	EI Nmm^2	E MPa
T1	3600	33120000.00	9.14E+11	27600.00
T2	3600	33120000.00	5.28E+11	15950.00
T3	2700	27424760.16	2.85E+11	10393.49
T4	2700	29702623.45	4.47E+11	15053.22
T5	2700	26364886.50	5.45E+11	20681.93
T6	2700	34915133.74	7.46E+11	21379.86
T7	2700	26972053.30	3.31E+11	12277.46
T8	2700	24033956.36	2.29E+11	9519.85
		mean, m	5.03E+11	16606.98
		standard deviation, s	2.35E+11	6218.15
		95% confidence level -- a =	0.05	0.05
		standard error	8.30E+10	2198.45
		Upper	6.40E+11	20223.42
		Lower	3.67E+11	12990.53

Table 4 summarises the stiffness (EI), modulus of elasticity (E) and bending moment (M). The stiffness varies between 2.29E+11 Nmm^2 and 9.14E+11 Nmm^2 and the modulus of elasticity varies between 9520 MPa and 27600 MPa. Therefore, it can be inferred, based on the attained modulus of elasticity, that the specimens tested have a range of timber grade between F8 (E = 9100 MPa) and F34 (E = 21500 MPa) as per AS 1720.1-1997.

Table 4. Calculated stiffness (EI), modulus of elasticity (E) and bending moment (M)

Beam No	EI Nmm^2	E MPa	P N	M Nmm
T1	9.14E+11	27600.00	113640	68184000
T2	5.28E+11	15950.00	72730	43638000
T3	2.85E+11	10393.49	61640	27738000
T4	4.47E+11	15053.22	89700	40365000
T5	5.45E+11	20681.93	105830	47623500
T6	7.46E+11	21379.86	121310	54589500
T7	3.31E+11	12277.46	84370	37966500
T8	2.29E+11	9519.85	42940	19323000

3.4 *Discussion*

The variation in timber properties is affected by the type of timber, moisture content, grain direction, and environment effect. For sleepers, it understood that in practice, it is possible to use timber from strength group SD1 to SD5 (seasoned) or S1 to S4 (unseasoned) as per AS 3818.2-1998. This explains the big variation in the properties of the tested timber sleepers.

The results of the four-point bending test of eight specimens demonstrated that timber sleepers vary significantly in strength and stiffness. A statistical analysis showed that the stiffness averaged 5.03E+11 Nmm^2 with a standard deviation of 2.35E+11 Nmm^2, indicating a large variation of timber stiffness.

The modulus of elasticity of the sleepers varied between 9520 MPa and 27600 MPa which corresponds to the range of timber grade between F8 (E = 9100 MPa) and F34 (E = 21500 MPa).

4 CONCLUSIONS

In terms of strength and stiffness, timber sleepers are still adequate for use. However, timber's decreasing supply, susceptibility to rot and its performance cannot be well predicted have become a major issue. The testing of existing timber sleepers confirmed that there is a significant variation in timber's mechanical properties, particularly in modulus of elasticity and stiffness. From eight timber sleepers tested, the $E_{sleeper}$ values ranged from approximately 9520 MPa and 27600MPa.

In order to design a dimensionally stable sleeper having similar stiffness and elasticity, it is desirable that the new concept fibre composite sleepers have a similar range of modulus of elasticity with the tested timber sleepers. However, due to significant variation in the results from testing of timber sleepers, it is intended that new concept fibre composite sleepers have a modulus of elasticity of approximately 12000 MPa, which corresponds to the lower tail value (12990 MPa) from the statistical analysis. The lower end of the spectrum is used considering the cost of FC sleepers.

In a fibre composites system, fibre reinforcement is used as the main part which sustains the load because of its high strength. However, fibre reinforcement such as glass fibre is relatively brittle, has low stiffness and costly. Therefore, using higher value of design modulus of elasticity is not necessary in this stage because targeting a higher value of E and EI for FC sleeper design will require more laminates whereas the strength requirement has been exceeded. More material means higher cost to spend for material.

Targeting on a specific value of E that is 12000 MPa is beneficial in designing the cross section of fibre composite sleeper and predicting the behaviour of the design sleeper.

Further investigation is necessary on the effect of sleeper stiffness on the stiffness of ballast materials. If substantial difference is not found in the bending moments and shear forces, selecting a lower stiffness would result in a fibre composite sleeper that is cost competitive.

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6 REFERENCES

Adams, J.C.B. 1991. *Cost effective strategy for track stability and extended asset life through planned timber sleeper retention*, *Railway Engineering Conference, Adelaide*: 145-152.

Ayers, S.R. 2001. *Material foundations for the application of fibre composite materials in civil and structural engineering*. Toowoomba: University of Southern Queensland:

Bonnett, C.F. 1996. *Practical Railway Engineering*. London: Imperial College Press.

Cope, D.L. & Ellis, J.B. 2001. *Plain line maintenance*. British Railway Track. England: The Permanent Way Institution.

Davalos, J.F. Zipfel M. G., & Qiao P. 1999. Feasibility Study of Prototype GFRP-Reinforced Wood Railroad Crosstie, *Journal of Composites for Construction*: 92-99. viewed 13 June 2006, <http://link.aip.org/link/?QCC/3/92/1>

Doyle, N.F. 1980, *Railway track design: a review of current practice*, Bureau of Transport Economics, Canberra: Australian Government Publishing Service.

Ellis, D.C. 2001, *British railway track: Plain line maintenance* (Vol. 4). England: The Permanent Way Institution.

Ellis, I.W. 2004. *Track Terminology*. British Railway Track. England: The Permanent Way Institution.

FCDD (Fibre composite design and development), Centre of Excellence in Engineered Fibre Composites USQ, 2006, 'Railway sleeper', viewed 20 April 2006, http://www.fcdd.com.au/Projects%20&%20or%20Products/Railway%20Sleepers/Railway%20Sleepers.htm

Grace, N.F., Soliman A.K., Abdel-Sayed G., & Saleh K.R., 1998. Behaviour and Ductility of Simple and Continuous FRP Reinforced Beams. *Journal of Composites for Construction*: 186-194.

Hagaman, B.R. & McAlpine, R.J.A. 1991, ROA Timber Sleeper Development Project, *Railway Engineering Conference*, *Adelaide*: 233-237.

Hakim, M.F. 2002. *Fibre composite reinforced timber beam design*. Toowoomba: University of Southern Queensland,

Hoger, D.I. 2000. *Fibre composite railway sleeper*. Toowoomba: University of Southern Queensland.

Huang, D. 2004. *Structural behaviour of two-way fibre reinforced composite slabs*, Toowoomba: University of Southern Queensland, PhD dissertation.

Humphreys, M.F. & Francey, K.L. 2004. An investigation into the rehabilitation of timber structures with fibre composite materials. *Proceedings Developments in Mechanics of Structures and Materials.* Perth, Western Australia: 1317-1322.

Kohoutek, R. & Campbell, K.D. 1989. Analysis of spot replacement sleepers. *The Fourth International Heavy Haul Railway Conference 1989*, Brisbane, Australia: Institution of Engineers.

McLeod, W.D. 1991. P.T.C Sleeper Management Strategies. *Railway Engineering Conference*. *Adelaide*: 233-237.

Miura, S., Takai H., Uchida M. & Fukada Y. 1998. *Railway Technology Today 2: The mechanism of railway tracks*, Japan Railway & Transport Review, EJRCF: 38-45

Namura, A., Kohata Y. & Miura S. 2005. Study on the optimum size of railway sleeper for ballasted track. *Structural Eng./Earthquake Eng. JSCE*: 245-255.

Pattamaprom, C., Dechojarassri D., Sirisinha C. & Kanok-Nukulchai W., n.d, *Natural Rubber Composites for Railway Sleepers: A Feasibility Study*, viewed 13 June 2006, http://www.rtg.ait.ac.th/abstract/rtg_0312.pdf

Profillidis, V.A. 1995. *Railway Engineering*. England: Avebury Technical.

Qiao, P., Davalos, J.F. & Zipfel, M.G. 1998. Modeling and optimal design of composite-reinforced wood railroad crosstie, *Composite Structures*: 87-96.

Standards Australia AS 1085.14-2003, Australian standard™, *Railway track material, part 14: prestressed concrete sleeper*, viewed 17 March 2006, <http://www.saiglobal.com/online/autologin.asp>

Standards Australia AS 3818.2-1998, Australian standard™, *Railway track timber,* viewed 17 March 2006, <http://www.saiglobal.com/online/autologin.asp>

Standards Australia AS AS 1720.1-1997, Australian standard™, *Timber Structures, part 1: design methods*, viewed 17 March 2006, http://www.saiglobal.com/online/autologin.asp

TieTek-Composite Railway Sleepers, Railway-Technology, <http://www.railway-technology.com/contractors/rail/tietek/>

Van Erp, G. 2006. *Future materials: The use of fibre composites in civil engineering*, <www.mainroads.qld.gov.au/MRWEB/prod/CONTENT.NSF/0/9220b8ce438ba0244a2571db001e1fe6/$FILE/03.pdf>