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DOI:
10.1080/13287982.2017.1382045

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(Title contains 13 words)

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Submitted to
Australian Journal of Structural Engineering

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Manuscript Summary:

Total pages	37 (including one-page cover)
Number of figures	15
Number of tables	9

Comparison of structural design methods for railway composites and plastic sleepers and bearers

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Abstract: Railway sleepers are safety-critical and essential components in a ballasted railway track system. Sleepers could principally be made of different materials, such as, timber, steel, concrete, composite and plastic. The deterioration process of sleepers depends largely on the materials of which they are made. The most popular material for manufacturing sleepers nowadays is concrete. In very recent years, a new type of railway sleeper has been developed using composite and plastic materials. These plastic sleepers have been trialled as bridge transoms and, to a limited extent, as switch and crossing bearers. A limited application of composite (a combination of cement, steel and plastics) to bridge transoms can also be seen. At present, there is no unified design method or standard for these new plastic and composite sleepers and bearers. The lack of design information can compromise public safety. This paper thus highlights the design aspects for plastic and composite sleepers in comparison with traditional materials. It reveals that limit states design concept is the most optimal approach for sleeper design and manufacture. The insight will help rail asset owners and managers establish predictive and condition-based track design and maintenance.

Keywords: sleeper; crosstie; transom; plastic; composite; structural design; railway; track component

1 Introduction

Railway sleepers are significantly important components in ballasted railway track systems (Zhao, Chan, and Burrow 2007). Their main functions are to withstand static and dynamic loads imposed by the wheels and transfer them to the ballast and underlying formation, and to secure the rail gauge to allow trains to travel safely (Kaewunruen and Remennikov 2009). Another important function of the sleepers in a ballasted railway track system is to help provide lateral track resistance to improve the stability and stiffness of the track structure (Kumaran et al., 2003; Koike et al., 2014). Any damage to or poor conditions of sleepers could influence the quality of the railway track, resulting in impaired rail services. For example, if the sleepers cracked severely they would deform highly under the loads imposed by wheel–rail interaction. This large differential settlement accelerates the damage to other railway components, which in turn shortens the maintenance period of the railway track. In addition, if the lateral resistance of the track is insufficient to support lateral forces (i.e. because of loosened ballast or abraded sleepers), rail buckling may occur as shown in Fig. 1 (Kumaran et al., 2003).

In general, railway sleepers are made of concrete, timber, steel, plastic or a composite material (referred to hereinafter as 'composite'). Timber, concrete and in some cases steel are traditional materials used to manufacture railway sleepers. Figure 2 gives an actual breakdown (as of 2010) of different types of sleeper used in mainline railway tracks within European countries (UIC 2013). The deterioration process of sleepers depends substantially on the materials of which they are made. Hence, studies have attempted to determine the most suitable material for sleepers with regard to durability, strength and cost (Ticoalu et al., 2008). However, most sleepers deteriorate regardless of their material, thereby reducing their performance capacity. To ensure acceptable track performance, broken sleepers should be replaced by new ones (Manalo et al. 2010).

According to Hagaman and McAlphine (1991) and Goldgabr (2009), 14 million timber sleepers are replaced each year by the US railroad industry. McConnell (2008) also states that around 5% of timber sleepers are replaced annually in the US and Canada. In Germany, the railway industry must replace about 11 million timber sleepers in the future (Woidasky, 2008). In Australia, 25–35% of the costs of the railway industry are for maintenance, including sleeper replacement (Yun and Ferreira 2003). Therefore, the elevated maintenance costs of sleepers make it even more important to study railway sleeper materials and their design methods.

This paper presents a state-of-the-art review of the structural design of railway sleepers made of concrete, steel, timber, plastic or composite, and identifies essential factors such as their life cycle and deterioration process. However, the main focus is on the design concepts of plastic and composite sleepers. Because the use of such sleepers is relatively new in railway industry around the world, this review offers new useful information for the industry. There is a misconception that standard testing procedures (or laboratory type testing for manufacturing quality) could replace a design method. It is therefore important to highlight the necessity of reliable design methods to ensure that future track maintenance does not suffer from the lack of design information so that the service life of the structural and safety-critical component could be determined at a given time in adverse rail environments (Setsobhonkul et al., 2017; Binti Saadin et al., 2017). Commercially, plastic and composite sleepers are often manufactured and fabricated by small and medium-sized enterprises whose product line may not last as long as railway lines do (i.e. the average lifespan of a start-up company is about 5–8 years, whereas a railway line is normally built to last 50+ years). Knowledge of the engineering design principle is therefore crucial for enabling suitable repair, modification and retrofit of the track components in the future (Kaewunruen et al., 2014, 2015, 2016). In this paper, we evaluate and explain different design methods associated with plastic and composite sleepers. These insights will help railway engineers determine suitable engineering techniques and solutions for track construction and maintenance under future uncertainties.

2 Different types of sleeper

2.1 Materials

2.1.1 Timber

The most common material used to make railway sleepers is hardwood. Nowadays, about 2.5 billion sleepers in railway networks around the world are made of timber. The state of Queensland, in Australia, alone has 8 million timber sleepers in service (Manalo et al. 2010). In China, there are more than 13.8 million timber sleepers under revenue services. Each year, the European wood industry supplies around 390,000 m³ of wooden sleepers, part of which is exported out of Europe. Figure 3 shows the different species of wood purchased in Europe in 2010 (UIC 2013).

According to Zarembski (1993), high-quality hardwood timber sleepers perform reliably and capably for many years. However, as they deteriorate, they become less able to meet the performance requirements (Manalo et al. 2010). In the US, the railway industry replaces about 15 million timber sleepers each year (Lampo 2002). Such demand makes it necessary to develop an alternative to timber for the railway industry. The main advantage of timber sleepers is their versatility. They are easy to manage, simple to replace, light in weight, high in damping and require no complex equipment. Timber sleepers can also be used in every type of railway track. Therefore, they are attractive to the railway industries of countries in which high-quality hardwoods are accessible.

However, one of the main disadvantages of timber sleeper is their susceptibility to mechanical degradation and moisture. The combination of bearing-plate and ballast effects and the fracture of timber sleepers caused by stresses may advance their mechanical failure (Qiao et al., 1998). Because of material degeneration, it is very common for the ends of timber railway sleepers to split (Hibbeler, 2004). Another significant disadvantage of timber sleepers is fungal decay. In Queensland, for example, the most common cause for the failure of timber sleepers is fungal decay (Hagaman and McAlphine 1991). Both main types of failure of timber sleepers are shown in Fig. 4.

There are many ways to improve the performance of timber railway sleepers, not least timber preservatives given the high incidence of decay. In addition, dowels can be used to reduce the frequency of splitting (Qiao et al., 1998).

2.1.2 Steel

Because of the scarcity of timber, steel sleepers began to be used in railway networks around the 1880s and have advanced since; the original sleeper design has been replaced by the modern Y-shaped one (Ferdous et al., 2015). Australia is among the countries with the most steel railway sleepers, with 13% of its stock made of steel nowadays (Manalo et al., 2010). However, compared to timber sleepers, more care is required during the installation and tamping of steel sleepers because their inverted shape complicates the ballast-packing process. This aspect makes steel sleepers more expensive to manufacture and to maintain.

According to several studies, there are many reasons why steel sleepers are not the preferred choice in railways networks. The main ones are their high corrosion rates, difficult ballast contact and appreciable electrical conductivity (Ferdous and Manalo 2014). They corrode because of salts in the ballast, soil and groundwater, as can be seen in Fig. 5. Given that steel sleepers are prone to corrosion, it is essential avoid bringing them into contact with salt-bearing materials (ETC-02-03 2009). Another problem with steel sleepers is fatigue cracking due to repeatedly imposed loads (Ferdous and Manalo 2014). These problems with corrosion and fatigue cracking mean that steel sleepers are not always the appropriate choice. In addition, according to Manalo et al. (2010), handling and installation are more difficult with steel sleepers, which also increase the maintenance costs.

2.1.3 Concrete

Nowadays, in railway networks around the world, about 500 million concrete sleepers are required every year, which is more than half the total demand. Concrete is the principal material used for sleepers in many countries around the world. The increasing use of concrete sleepers is due to the need of the railway industry to replace aging timber by more durable concrete (Ferdous et al., 2015).

Concrete sleepers present damage similar to that in concrete structures because they use the same material. Depending on the consequences to the sleepers, this damage can be classified into different types. One common type in concrete sleepers is longitudinal cracks (see Fig. 6), which usually start at the dowels and continue along the sleeper, even before loading occurs. The main causes of such cracks are incorrect placement of the dowel screws, the presence of sand in the dowels and dowels that rupture because of the expansion of frozen water (Rezaie, 2012a. 2016b).

In Australia, the first concrete sleepers were used in 1970, and currently mono-block prestressed concrete is the material of choice (Kaewunruen, 2010). Because concrete sleepers are effectively prestressed concrete beams, the pre-stressing force is one of the most important parameters to be considered in the structural design process. However, even if the tensile strength of concrete is low, longitudinal cracks may occur before traffic loading occurs. This is due to the high pre-stressing force that is applied to the concrete. Therefore, the tensile strength and pre-stressing force are the two most important parameters that determine the occurrence and propagation of longitudinal cracks (Rezaie et al., 2016). The negative point of using this type of sleeper is the high cost involved (Rezaie et al., 2016).

2.1.4 Plastic and composite

Plastic sleepers are now being used more by the railway industry, with composite also being useful in sleeper manufacturing. Different papers have different meanings for composite and plastic sleepers. In this paper, we consider plastic sleepers as being those made of recycled plastic or vehicle tyres (or something similar), with no (or barely any) fibre reinforcement. Meanwhile, we consider composite sleepers as being either those made of long-fibre composites or whose strength has been increased by adding long-fibre composites to the original ones.

Recent studies have been conducted globally to develop technologies for composite and plastic sleepers. These developments are aimed at reducing the number of timber sleepers in railway networks. Such composites try to imitate the behaviour and performance of timber while reducing maintenance costs and minimizing environmental impact (Ferdous et al. 2015).

Recycled rubber is added to some types of plastic sleeper. According to (Pattamaprom et al. 2005), natural rubber has better hardness and compressive modulus compared to other materials. However, engineered rubber has greater stiffness and inelasticity. Japan has recently developed synthetic sleepers made of glass fibre and hard polyurethane foam. This type of composite sleeper is designed to have a long lifespan and the same physical properties as timber ones. These synthetic sleepers have also been used in places where replacement is more difficult, for example in switches and girder bridges (Miura et al. 1998). Figure 7 shows an example of composite sleepers.

Another possibility is to use fibre composites to increase the strength of original sleepers (Manalo et al. 2010). Qiao et al. (1998) showed that the performance of timber sleepers improved appreciably when they were enveloped in grass-fibre-reinforced polymer (GFRP). These GFRP–timber sleepers were stiffer and could support greater imposed loads compared to the original timber sleepers. The treatment also reduced stresses and increased the surface resistance to ballast attrition. In addition, grass fibre improves the durability of timber sleepers (TTCI. 2005)..

2.2 Topological design aspects

Each sleeper has its own characteristic size, shape and dimensions according to its material, the type of railway in which it is used and the company that operates the railway. General design aspects are described in Table 1 for each sleeper material. Several aspects should be considered when determining the shape, size and dimensions of a sleeper. For example, the length of a sleeper depends on the track gauge. The choice of material is also an important factor when determining these design aspects because it will dictate the time and costs of manufacturing and maintenance, as well as the deterioration process.

3 Design aspects

3.1 Life cycle and deterioration process of sleepers

The life cycle of a sleeper depends directly on the material of which it is made and on the quality of that material. Other factors such as imposed load, temperature change and chemical elements present in the atmosphere also affect sleeper life cycle. The main causes of failure of each type of sleeper are listed in Table 2.

3.1.1 Timber sleepers

One of the most important issues with regard to timber sleepers is rotting. Wetting environments facilitate the biological degradation of timber sleepers by fungus because timber is an organic material. This issue is referred to in general as fungal decay (Ferdous and Manalo 2014). Another common problem with timber sleepers is end spitting, which is caused by the behaviour of the timber itself (Manalo et al. 2010). These two issues are the main reasons why timber sleepers fail (Ticoalu et al. 2008). Insect attack (e.g. from termites) is another common problem for timber sleepers (Ferdous et al. 2014a, 2015b).

3.1.2 Steel sleepers

The life cycle of steel sleepers is determined by the build-up of fatigue over time (ETC-02-03 2009). Fatigue cracking occurs because of train-induced movement in the fastening holes (Manalo et al. 2010). The rail-seat area is exposed to fatigue failure due to the repeated imposition of excessive loads on the rails (ETC-02-03, 2009; Ferdous and Manalo 2014). Steel sleepers are also susceptible to chemical harm and corrosion, mainly when they come into contact with salts in the ballast and other subgrade materials (ETC-02-03 2009; Ferdous and Manalo 2014).

3.1.3 Concrete sleepers

Rail-seat damage is the most serious cause of failure in concrete sleepers around the world. This issue can be caused by several factors, but rail-seat abrasion is the most harmful one (Ferdous and Manalo 2014). According to Kaewunruen and Remennikov (2009), cracks are common in concrete sleepers because of the inconstant and considerable loads due to irregular wheel imperfections.

Some problems associated with concrete sleepers are similar to those with other concrete structures, such as sulphate attack, alkali–aggregate reaction and acid attack. Sulphate salts are present in the soil, groundwater and aggregates, and may react with hydrated cement past to produce expansive products that cause the sleeper to crack (Neville 2011). According to (Shayan and Quick 1992), the alkali–aggregate reaction is responsible for longitudinal cracking parallel to the top of the sleeper and map cracking in its ends. Acid attack is common in concrete given that the constituent cement is not resistant to it and is consequently destroyed (Ferdous and Manalo 2014).

3.1.4 *Plastic and composite sleepers*

The process of manufacturing plastic and composite sleepers creates voids inside the materials that concentrate any applied load. This process is responsible for failures before the design lifetime (Ferdous et al. 2015). Another important issue with plastic and composite sleepers is the loosening of the fastening system caused by creep deformation, the extent of which depends on the magnitude and frequency of the applied loads (Nosker1998; Ferdous et al. 2015). Fatigue cracking is a serious problem in plastic and composite sleepers because they are made of heterogeneous and anisotropic material.

Plastic sleepers can fail through fibre fissure, delamination, matrix fracture and fibre–matrix de-bonding (Degrieck and Paepegem 2001). Elevated temperature can also alter the performance of plastic sleepers, which expand if the temperature changes are excessive (Ferdous et al. 2015). Another disadvantage of plastic sleepers is material disintegration. Figure 8 shows an example of the failure of each type of sleeper.

3.2 Environmental effects

Environmental effects are important when choosing a sleeper material. The main environmental effects associated with each type of sleeper material are detailed in Table 3 in relation to manufacturing and maintenance.

3.3 Focus on plastic and composite sleepers

This paper highlights the disadvantages of the timber, concrete and steel sleepers that have been used by the rail industry throughout the years. Concrete and steel sleepers have now largely replaced the original timber ones, but concrete and steel themselves are not without their problems; sometimes it is actually better to replace old timber sleepers with new ones (Ferdous and Manalo 2014). Table 4 lists the properties of the various sleeper materials. The performance of plastic and composite sleepers is summarised in Table 5 (Ferdous et al. 2015; Kaewunruen and Remennikov, 2016; Kimani and Kaewunruen, 2017).

Recent studies around the world have looked for alternative materials in which the cited problems are less common and with which the maintenance costs should be reduced: plastics and composites are seen as such alternative materials. They do not corrode easily, are resistant to insect attack, and have high electrical resistance and low thermal conductivity (Ferdous et al. 2015). According to Lampo (2002), the manufacturing of recycled plastic sleepers is associated with a remarkable reduction in greenhouse gases. Furthermore, plastic sleepers can be manufactured in several different ways, which make railway industry hesitate to adopt a single method for design or type testing.

The number of companies investing in these recent technologies is increasing considerably (Manalo et al. 2010). Because of the recent growth in the use of plastic sleepers, research is required to assess their behaviour, limitations and environmental effects. The present review analyses the common design methods used for sleepers, with the aim of evaluating the reliability of composite and plastic sleepers.

4 Design concept for plastic sleepers

4.1 Design challenges

Because plastic is not an isotropic material, a specific drawback of plastic sleepers is that they have different strength in different directions. It is easier to design in concrete or steel because these materials have constant strength in all directions. Although timber is also an anisotropic material, it has been used in civil engineering for long time and designers are familiar with its behaviour. As yet, we do not have enough experience of using plastic in railway applications, and difficulties with designing plastic sleepers are intensified by their anisotropy, fragility, low tensile strength, light weight and the dependence of the properties of their topology. These issues increase the design complexity of composite and plastic sleepers; the design process must consider the sleeper material as well as its form and size (Awad et al. 2012).

Several standards and specifications cover the design of timber, steel and concrete sleepers because of their ubiquity. Timber sleepers are covered by RailCorp SPC 231 and AS 3818.2, steel ones by Australian Rail Track Corporation (ARTC) ETA-02-03 and AS 1085.17, and concrete ones by AS 1085.14 and RailCorp SPC 232. However, there is no specific design code for plastic sleepers, although the American Railway Engineering and Maintenance-of-Way Association (AREMA), the Chicago Transit Authority and the Union Pacific Railroad provide some specifications for their design (Ferdous et al. 2015). The absence of a consistent standard has resulted in non-uniformity in the manufacturing of plastic sleepers, which in turn creates uncertainty over using this material in long-term operation.

Most designs of composite and plastic sleepers are based on associated specific research outcome and guidelines. Experimental tests performed to benchmark structural capacity and manufacturing quality (i.e. type testing) using a certain number of sleepers and re-analysis are often chosen depending on the designer’s experience and the risk management plan taken by the railway organisation (though increased inspection and maintenance). For composite sleepers and bearers, any design method should consider the fibre layers, all dimensional aspects and structural functions of the sleepers and bearers (Kaewunruen, 2014a-c; Kaewunruen et al., 2017). Consequently, designers should use optimization methods after the experimental tests to seek an ideal solution in both aspects (Awad et al. 2012).

Numerical simulation is often used in the design of concrete, steel and timber sleepers, an example of which is shown in Fig. 9. Such numerical methods may be used to design composite and plastic structures as well, but the design process in that case is complicated by the uncertainty and variation in material quality, which depends on the process used to manufacture the composite or plastic sleepers. In contrast, it takes a long time to test several sleepers experimentally and requires the use of appropriate facilities. This difficulty also discourages the sufficient number of repeated tests since it increases the costs (Awad et al. 2012).

4.2 Design principles

4.2.1 Allowable-stress design

Allowable-stress design (also known as permissible-stress design) is a design concept used commonly to design traditional sleepers. Allowable-stress design is more conservative than limit states design because the former considers only quasi-static wheel loads (Kaewunruen et al. 2014), which need higher safety factors making the design method unsatisfactory. A quasi-static wheel load is usually multiplied by a dynamic factor of between 2.0 and 3.0 (AS1085.14 2003), (AREMA 2006). However, wheel–rail interactions can produce dynamic loads higher than those specified in the design codes. A recent studied showed that dynamic wheel loads can reach four to six times the static ones (Leong and Murray 2008). Figure 10 shows the static wheel loads that are considered in allowable-stress design.

The allowable-stress design concept is present in the concrete sleeper design standards used in Australia, Asia and North America. However, because this approach has to consider reductions in material strength, the resulting sleepers are over-designed (Kaewunruen, Remennikov, and Murray 2014), which is a concern for railway companies. Also, it omits the important factors in sleeper design, such as real dynamic load, ultimate material strength and risks associated with operation, maintenance and even failure (Kaewunruen et al. 2014). These are the main disadvantages of using this design principle.

As shown in Fig. 11, this design concept determines the maximum strength of some material, which then cannot be exceeded in the structure. Aspects such as buckling, brittle fracture, fatigue failure and allowable deflections are taken into account in this design method. In this concept, the limit strength of the material is reduced by factors associated with errors in material homogeneity, size and finishing (Mrema 2011) Examples of some reduced factor values are given in

Table 6 for each type of sleeper. The highest factor is for timber sleepers because timber is the least homogeneous of the materials.

4.2.2 Limit states design

Recently, limit states design has been used for concrete sleepers in Europe and South Australia. This concept takes into account the ultimate strength of materials by extensive analysis and experimentation, as shown in Fig. 12. Over the past 7–8 years, limit states design has replaced allowable-stress design because the former has many advantages such as less material waste and the implementation of new material technologies (Remennikov et al. 2012). These factors make limit states design superior to allowable-stress design because the former leads to much more optimal sleeper manufacturing.

Limit states design calculates the strength of a structure by multiplying its resistance by reduced factors (ϕ), which should be superior to multiplying the imposed loads by load factors (γ) (Remennikov et al. 2012). Therefore,

$$\Sigma\,(\gamma \text{ x imposed loads}) \leqslant (\phi \text{ x resistance}) \qquad (1)$$

or

$$\text{Design effects} \leqslant \text{Design capacity}, \qquad (2)$$

where the design effects taken into account are the shear forces, bending moments and axial forces imposed on the sleepers. These can be static or dynamic, depending on the analysis method (Remennikov et al. 2012).

This concept is based on a deterministic model. However, the resistance and loads factors are based on a probabilistic model, which means a reliable statistical distribution of loads and resistance (Kaewunruen et al. 2012). Figure 13 shows an example of a statistical probability distribution. Failure will happen in the area of the curves in Fig. 13 in which the distribution of load effects reaches that of the capacity. In limit states design codes, the probability of failure relates p_t to the reliability index or safety index β through

$$\phi(-\beta) = p_{t,} \quad (3)$$

where the factor ϕ is a cumulative distribution curve (AS5104 2005) Figure 14 shows how the safety factors and probability of failure are related. The limit state can be divided into the following limit states.

The ultimate limit state is associated with one event that can cause a sleeper to fail because of the imposed loads. The analysis is probabilistic, which means it is based on the results of experiments involving loading over a period of time (usually more than one year); a statistical analysis takes into account the importance of the train and operational data (Ferdous et al 2015). Failure is common at the midspan and the rail seat. This limit state is more common in concrete sleeper design (Kaewunruen 2007).

The fatigue (damageability) limit state considers the accumulated damage caused by the loads over a long period of time. Therefore, the sleeper lifetime is determined by the design service time to support repeated loads; the design service time should be longer than the actual life of the sleeper (Kaewunruen et al. 2014).

Finally, the serviceability limit state is the limit state that defines when problems incur during revenue services (such as displacement, ride quality, gauge and rail cant, etc.). Failure of a significant number of sleepers may reduce its operational capacity. Currently, this limit state is used in the replacement of sleepers made of different materials based on track stiffness (Kaewunruen et al. 2014).

4.3 Application of design principles to plastic and composite sleepers

4.3.1 General design aspects

Currently, the design of composite and plastic sleepers is based on allowable-stress design. To guarantee better reliability, static and dynamic loads should be considered in the design (Ferdous et al 2015). According to (Remennikov, Kaewunruen 2007), a quasi-static wheel load is about 1.4–1.6 times a static one, when the track is well maintained to a very good condition. Because this concept does not take dynamic loads into account, the load factor used is usually taken as 1.5 times of rail-seat loads. However, calculation of the real dynamic loads is important to guarantee better analysis of sleeper performance, rather than merely some estimates. Therefore, the effects of real dynamic loads should be considered and included in sleeper design standards to increase the design reliability (Ferdous et al 2015).

In addition, the design of fibre composite sleepers is usually based on the allowable deflection limit (Awad et al. 2012). The serviceability deflection limit permitted by the EUROCOMP design code is between L/150 and L/400 for composites structures, where L is the span (Clarke 1996). In the absence of standards for fibre composite structures, civil engineers use various methods to design these structures, such as optimization and finite-element analysis (FEA). Both methods can be used to design these structures according to their serviceability limits (Awad et al. 2012).

In the design of fibre composite sleepers, FEA is important for determining in which areas the stresses are higher, and consequently where the fibres should be placed. This is an intuitive and iterative method that can also determine in which areas the stresses are lower and so material can be removed. This addition and removal of polymers and fibres should happen until the sleepers have the strength required by the serviceability conditions and the costs are the lowest possible (Ferdous et al 2015). By optimizing the material distribution, this method is very useful for designing composite sleepers. It avoids material waste by reducing the height and weight of the sleepers, thereby reducing manufacturing costs appreciably.

Another way to design fibre-reinforced polymer composite sleepers is via optimization. Awad et al. (2012) demonstrated several different optimization methods, such as design sensitivity analysis, genetic algorithms and simulating annealing. However, the method most used is the finite-element method, which can be applied to various composite structures (Prochazka, Dolezel., and Lok 2009). All these methods have the same objective: to optimize the sleeper design, thereby reducing material waste and manufacturing costs, among others.

Despite the absence of design standards for composite sleepers, AREMA (2006) currently require plastic sleepers to satisfy minimum criteria for mechanical and physical performance. In addition, the Japanese code JIS 2101 (Takai et al., 2006) and Koller (2015) also specify certain properties required of FFU (fibre-reinforced formed polyurethane). However, these design codes are currently limited in practice, and the behaviour of composite sleepers requires further research (Ferdous et al 2015; Kaewunruen, 2014b). The lack of standards limits the ability to retrofit or maintain such sleepers during the service life.

4.3.2 Comparison and application of methods

The design of prestressed concrete sleepers is usually done by allowable-stress design, which is the preferred approach in standards such as AS 1085.14 (2003). However, allowable-stress design is more conservative than limit states design. Therefore, using allowable-state design, the effectiveness of the sleepers is reduced and their cost is increased (Kaewunruen 2007). The same happens with the design of composite sleepers, so limit states design should be researched further for composite and plastic sleepers to guarantee acceptable values for the reduction factors and partial-load factors (Ferdous et al 2015) and to further optimize the design. A comparison between the allowable-stress and limit states design methods is given in Table 7.

There are several companies around the world that are producing different types of plastic and composite sleepers, each of which uses a different methodology to design its own products; some companies known to be active in the railway field are listed in Table 8. Allowable-stress design is preferred in different parts of the world for designing plastic sleepers. However, the absence of a consolidated standard has spawned several different sets of guidelines for designing plastic and composite sleepers.

As mentioned before, allowable-stress design is a conservative approach that usually results in over-designed sleepers. The performance benchmarking is in fact based on timber and its performance, but it is found that not all behaviours are mapped. The reduced factors consider only

40–50% of the real material strength, which shows how moderate this method is. Many researchers around the world are working on the limit states design method for railway sleepers, trying to reduce the amount of material used and consequently the manufacturing costs.

Van and Mckay (2013) state that transoms (large sleepers used on railway bridges) have higher strength requirements than those of commonly used sleepers because the latter are supported by ballast. The design requirements for common transoms are given in Table 9; the method used to design these transoms is once again allowable-stress design. According to Table 6, the maximum bending moment required is 60 kN m, which corresponds to roughly half the real bending moment. Therefore, the value of the reduced factor is 0.5, which is a typical value for plastic sleepers. This is a real example of how allowable-stress design works for transoms.

The CarbonLoc company has promoted a new technology of a hybrid plastic transom with steel bars inside a plastic sleeper. In 2007, the ARTC used several of these transoms on a railway bridge in Hunter Valley, Australia (Van Erp and Mckay 2013), some of which are shown in Fig. 15.

As mentioned before, the reduction of 40–50% in the material strength makes allowable-stress design inappropriate for designing plastic sleepers because this reduction does not consider plastic behaviour such as fatigue or dynamic dumping. This method merely reduces the total strength of the material without a complex analysis of the real behaviour of plastic and composite sleepers.

The fact that there are few available standards to guide the design of composite and plastic sleepers restricts their use and application in railways networks (Ferdous et al. 2015; Kaewunruen, 2015). To increase the number of composite sleepers used, further research should be undertaken to guarantee better knowledge about these sleepers.

5 Conclusions

The use of plastic and composite sleepers and bearers has increased by degrees in rail networks around the world, but their structural design is yet to be thoroughly determined. The disadvantages of timber, concrete and steel sleepers have inspired research into this new technology of plastic and composite sleepers. These could be made of recycled plastic so that less carbon dioxide is emitted into the atmosphere. These materials have many suitable properties, such as durability, lightness and high damping. However, some disadvantages of plastic sleepers are their low stiffness, low strength, light weight (for track stability) and high plastic deformations due to elevated temperatures.

At present, there are only several guidelines that are used inconsistently to design and manufacture plastic and composite sleepers/bearers. It is important to note that there are no specific structural standard or method for the design of plastic and composite sleepers/bearers. This could lead to serious safety risks over their service life. This review has highlighted the necessity for further research into the design of plastic and composite sleepers/bearers to ascertain public safety and operational reliability over time.

Based on the comparison of structural design methods for railway composites and plastic sleepers, it could be found that allowable-stress design is a conservative approach. The information about material-strength reduction of composites and plastics does not justify the use of such a design principle. That is why more research should be undertaken to underpin the reliability and safety of the process of designing such sleepers. This state-of-the-art review has also revealed that different design guidelines use different values of reduced-strength factors in the allowable-stress design method. Thus, railway authorities should pay special attention to the use of plastic and composite sleepers and ensure that high-quality track maintenance is always planned as required during the service life of the sleepers. In addition, it was found that limit states design takes into account the ultimate strength of the material and other important failure-mode and serviceability considerations. This makes that approach more suitable than allowable-stress design for plastic and composite sleepers’ design and manufacture. Since, the field experience of composites and plastics sleepers are rather limited, it is recommended that future work be focussed on the unified limit states design method of plastic and composite sleepers and bearers in order to ensure the railway’s safety, stability and durability.

Acknowledgements

EAS would like to thank Brazil's Sciences without Borders for her scholarship at the University of Birmingham, UK. DP would like to acknowledge the support of the Erasmus+ program. RY is grateful to the China Academy of Railway Sciences for visiting fellowships at the University of Birmingham, UK. SK wishes to thank the Australian Academy of Science and the Japan Society for the Promotion of Sciences for his Invitation Research Fellowship (Long-term) at the Railway Technical Research Institute and The University of Tokyo, Japan. The authors wish to gratefully acknowledge the financial support from the European Commission for H2020-MSCA-RISE Project No. 691135 'RISEN: Rail Infrastructure Systems Engineering Network', which enables a global research network that tackles grand challenges (Kaewunruen et al., 2016) in railway infrastructure resilience and advanced sensing in extreme events (www.risen2rail.eu); and from H2020-S2R Project No. 730849 "S-CODE: Switch and Crossing Optimal Design and Evaluation."

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Table 1 . Topological design aspects for each type of sleepers

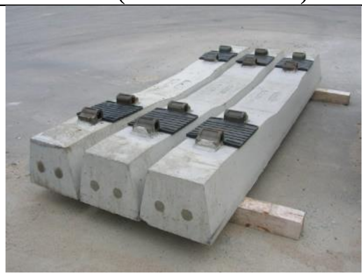
Material	Outside design aspects	Images
Timber	The timber sleepers are usually rectangular due the difficulty of designing different shapes in timber bodies. The Australian Standard (ARTC) recommends the following dimensions with their correspondent tolerances: length (standard gauge) = 2440+75mm; length (broad and mixes gauge) = 2600+50mm; width = 230+25mm and depth = 130+10mm.	 (Rail News 2015)
Steel	Recent railways have used ‘Y-steel-sleepers’ instead the orthogonal steel ones (Hibbeler.2004). These modern sleepers have more resistance to support cross movements due to the ballast between the parts of the ‘Y’. However, these ‘Y-shape’ are indicated to areas with reduced radius because the contact area is limited (Rail News 2015).	 (Manalo et al.2010)
Concrete	Several concrete sleepers have a complex shape because concrete is easily workable. Hernandez, Koch, and Barrera (2007) shows, for example, the dimensions of the used concrete sleepers. However, the University of Queensland design a rectangular pre-stressed concrete sleeper appropriate to replace timber ones (EFRTC 2007) .	 (Allbiz)
Plastic and Composite	Fibre composites sleepers may be manufactured with similar dimensions to timber ones (Ticoalu, Aravinthan, and Karunasena 2008). However, the shape, size and dimensions of polymer sleepers depend on the company which produce them and the type of plastic used (Ferdous et al 2015).	 (Lankhorst)

Table 2. Life cycle and failure causes of each type of sleepers

Material	Life Cycle	Failure Causes
Timber	* Hardwood – 20-30 years * Softwood – 20 years (Manalo et al.2010)	▪ Fungal decay ▪ End splitting ▪ Insect attack
Steel	50 years (Manalo et al.2010)	▪ Fatigue cracking ▪ Corrosion
Concrete	50-60 years (SPC 232 2012)	▪ Rail-seat corrosion ▪ High impact loading ▪ Sulphate attack ▪ Alkali-aggregate reaction ▪ Acid attack
Plastic and Composite	50 for fibre-reinforced Foamed Urethane (Manalo et al.2010),and 60 or more for glass fibre-reinforced hard polyethylene foam (Ferdous, Manalo 2014)	▪ Voids ▪ Wear & tear ▪ Decomposition ▪ Permanent deformations ▪ Fatigue cracking ▪ Elevated temperature

Table 3. Environmental effects of material used in sleepers

Material	Environmental effects
Timber	▪ A considerable amount of tree are cut to timber sleepers manufacturing (Ferdous et al 2015). ▪ The emission of carbon dioxide during operation. ▪ The use of chemical substances to reduce the decay rate may affect expressively the environment (Thierfelder, Sandström 2008).
Steel	▪ The steel industry produces a large amount of carbon dioxide during its production (Ferdous et al 2015). However, during the operation, the emission is insignificant. ▪ The high corrosion rates reduce the time for replacement, which generate more waste.
Concrete	▪ The concrete industry also produces a large amount of carbon dioxide during its production (Ferdous et al 2015), and the emission is reduced significantly in operation period. ▪ The high replacement rate due sulphate and acid attack, and alkali-aggregate reaction. ▪ The concrete wasted during the production.
Plastic and Composites	▪ Plastic is not a bio-degradable material, and, if not recycled, it will be discharged in the environment unsustainably. ▪ The plastic, which is not recycled, is made of petroleum which makes it unsustainable. Therefore, recycled plastics are the preferable ones.

Table 4. Summary of properties of different materials sleepers (Manalo et al.2010)

Properties	Hardwood	Softwood	Concrete	Steel	Plastic/composite
Adaptability	Easy	Difficult	Difficult	Difficult	Easy
Workability	Easy	Easy	Difficult	Difficult	Difficult
Handling and installation	Easy	Easy	Difficult	Difficult	Easy
Durability	Low	Low	High	Low	High
Maintenance	High	High	Low	High	Low
Replacement	Easy	Easy	Difficult	Difficult	Easy
Availability	Low	High	High	High	Low
Cost	High	Low	Very high	Very high	Low
Fasteners	Good	Poor	Very good	Poor	Good
Tie ballast interaction	Very good	Good	Very good	Poor	Good
Electric conductivity	Low	Low	High	Very high	Low
Impact	High	High	Low	Medium	Low
Weight (kg)	60-70	60-70	285	70-80	45-75
Service life (years)	20-30	20	60	50	60

Table 5 Comparison of the performance of composite sleeper (Ferdous et al 2015)

Properties \ Types of sleeper	Timber	FFU	TieTek	Axion	InegriCo	Wood core	Glue laminated
Density, (kg/m^3)	1085	670-820	1153	849-897	1121	993	-
Modulus of Elasticity, (MPa)	16000	8100	＞1724	1724	1655	1517	5190
Modulus of Rupture, (MPa)	65	142	＞18.6	20.6	18.6	17.2	103
Compressive MOE, (MPa)	-	-	269	176.5	262	241	-
Rail-Seat Compression, (MPa)	60	58	16.5	20.6	15.9	15.2	-
Screw Pullout Force, (kN)	40	65	35.6	31.6	73.4	-	63.8
Thermal Expansion, (cm/cm/℃)	-	-	1.35×10^{-4}	0.74×10^{-4}	1.26×10^{-4}	0.2×10^{-4}	-
Electrical Impedance (wet), (Ω)	-	140×10^{6}	500×10^{6}	-	-	-	-
Flammability	-	-	No@20s	-	-	-	-
Impact bending strength, (MPa)	-	41	-	-	-	-	-

Table 6 Reduced factors values in allowable stress design

Members	Reduced factor	Source
Prestressed concrete sleeper – at operational performance level	0.50	AS 1085.14
Prestressed concrete sleeper – at fully operational performance level	0.45	AS 1085.14
Steel sleeper	0.40-0.60	AS 1085.14
Timber sleeper – permissible tension stress	0.60	BS 5268
Composites sleeper – at service at top and bottom of centre of sleeper, and at top of rail seat	0.40	Rajendran and Tensing (Rajendran, and Tensing 2015)

Table 7 Comparison of allowable stress design method and limit state design method (You, R., Silva 2017)

Items	Allowable stress design	Limit state design
Basic principle	working stress ≤ permissible stress≈ ultimate stress/SF	Σ (γ x imposed loads) ⩽ (ϕ x resistance)
Filled status	Excess the permissible stress	Divide into ultimate limit state serviceability limit state etc.
Load	Use dynamic factor	Combine the loads that multiplied by a load factor
Material strength	Ultimate stress/SF	Based on the degree of reliability
Reliability index	Not take into account	Use reliability index or safety index
Structure importance factor	Not take into account	Depend on the category
Common sleeper material	Concrete, timber, steel, plastics, composite	Concrete, steel

Table 8 Different sleepers' technologies and their design method

Name	Material	Country	Design Method	Source	Images
AXION	100% recycled plastics	USA	AREMA	Railway-technology	
TieTek	85% recycled materials (plastic, rubber, fiberglass)	USA	AREMA	TieTek web-site	
IntegriCo	Landfill-bound recycled plastics	USA	AREMA	IntegriCo web-site	
Wood core	Plastic mixture reinforced by wooden beam	USA	AREMA	Southwest RV and Marina	
I-plas	100% recycled plastic	UK	Network Rail	Greener Business	
Ecotrax	High density polyethylene and polypropylene plastic recycled.	New Zealand	AREMA and ASTM	SICUT	
KLP	100% recycled plastics	Netherlands	French national railroad company SNCF	Lankhorst	
MPW	Mixed Plastic wastes and glass fibre waste	Germany	WO 9808896 A1 (UPS), WO 2000044828 A1 (Polywood), US 639 1456 B1, among others	Fraunhofer ICT (2010)	
FFU	Fibre-reinforced Foamed Urethane	Japan	JIS E1203	SEKISUI web-site	

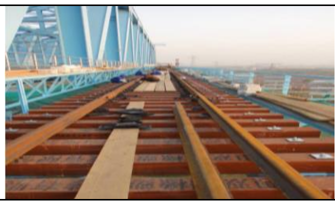
		China	CJ/T 399	Xssunrui web-site	

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Table 9 Requirements for a typical transom (Kaewunruen 2008a, 2014b, 2017c; Wu 2017)

Limit State Action Effect	**Axle Load (tonne)**	**Distance rail to girder web**	**Limit State Design Requirement**
Strength Limit State Bending Moment	30	250 mm	60 kNm
Strength Limit State Shear Force	30	n/a	200 kN
Fatigue Limit State Bending Moment	30	250 mm	18.75 kNm
Fatigue Limit State Shear Force	30	n/a	75 kN

Figure 1. Rail buckling due to lateral movements of sleepers, commonly found in timber and steel sleepered tracks (Kumaran, Devdasand Krishnan 2003)

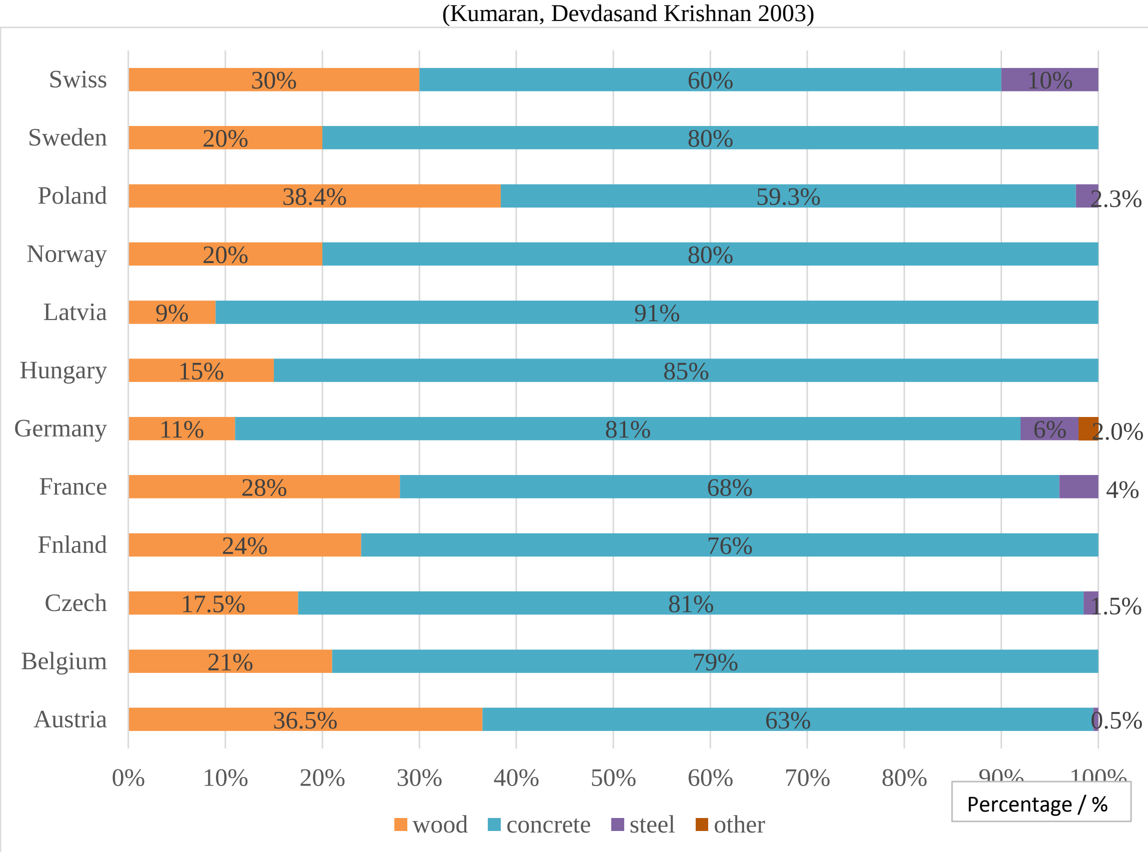


Figure 2. Different kinds of sleepers used in main tracks of European countries (UIC 2013)

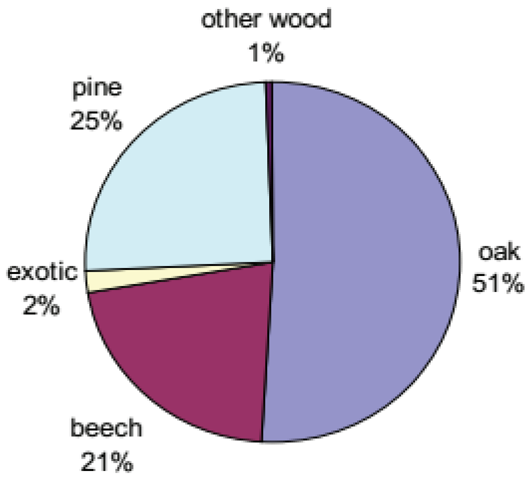


Figure 3. The different species of wood purchased in Europe, in 2010 (UIC 2013)

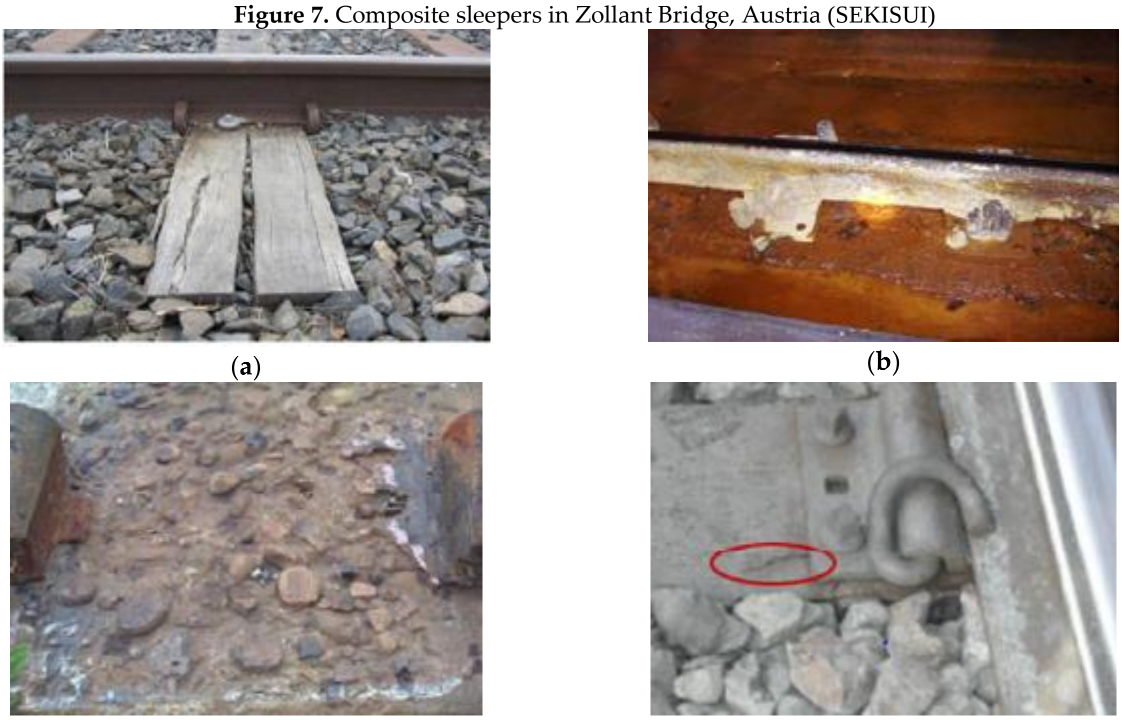
(**a**) (**b**)

Figure 4. Types of timber sleeper failure. (a) Fungal degradation, (b) end splitting (Manalo et al.2010)

Figure 5. Corrosion in steel sleepers due salt deposits (Hernandez, Koch, and Barrera 2007)

Figure 6. Longitudinal cracks in concrete sleepers (Rezaie, Bayat, and Farnam 2016)

Figure 7. Composite sleepers in Zollant Bridge, Austria (SEKISUI)



(**a**) (**b**)

(**c**) (**d**)

Figure 8. Failures of each type of sleepers a) Timber sleepers: end splitting, b) Steel sleepers: corrosion, c) Concrete sleepers: rail-seat abrasion, d) Plastic sleepers: cracking at fasteners (Hernandez 2007; Ferdous 2014a,2015b)

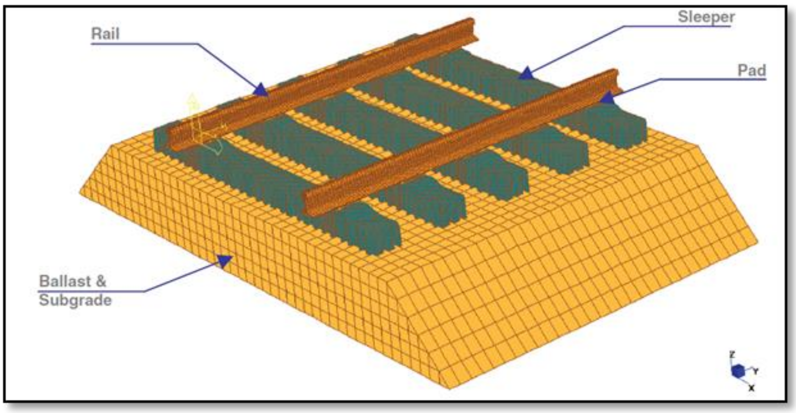


Figure 9 Components of railway tracks in a numerical simulation (Kaewunruen, Remennikov, and Murray 2014)

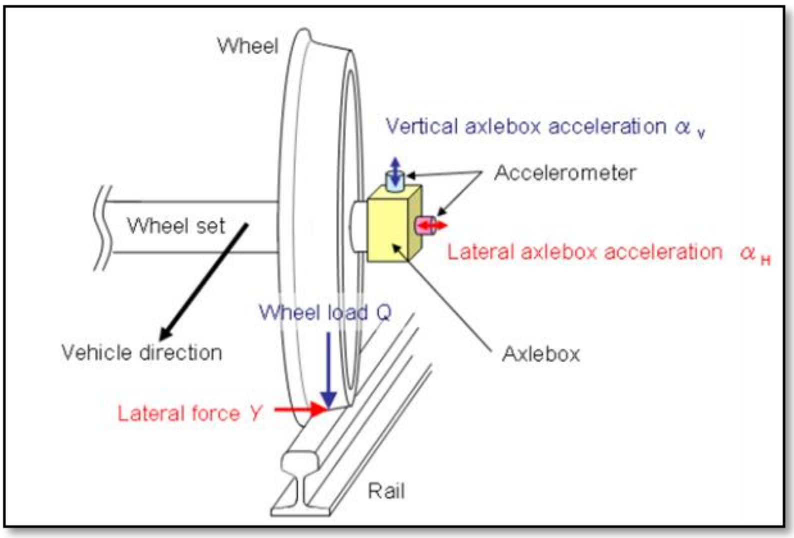


Figure 10. Static wheel loads (Tanaka, Furukawa 2008)

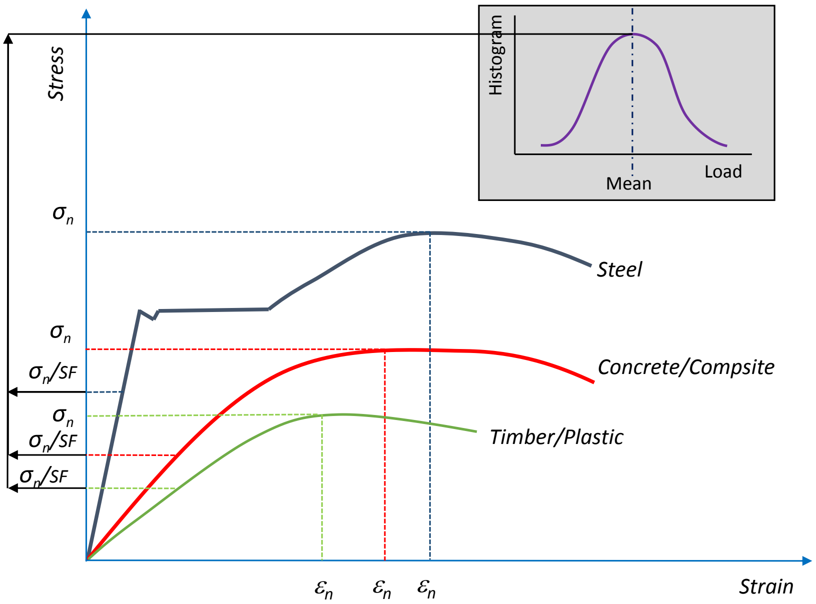


Figure 11. Allowable stress of materials (SF is safe factor)

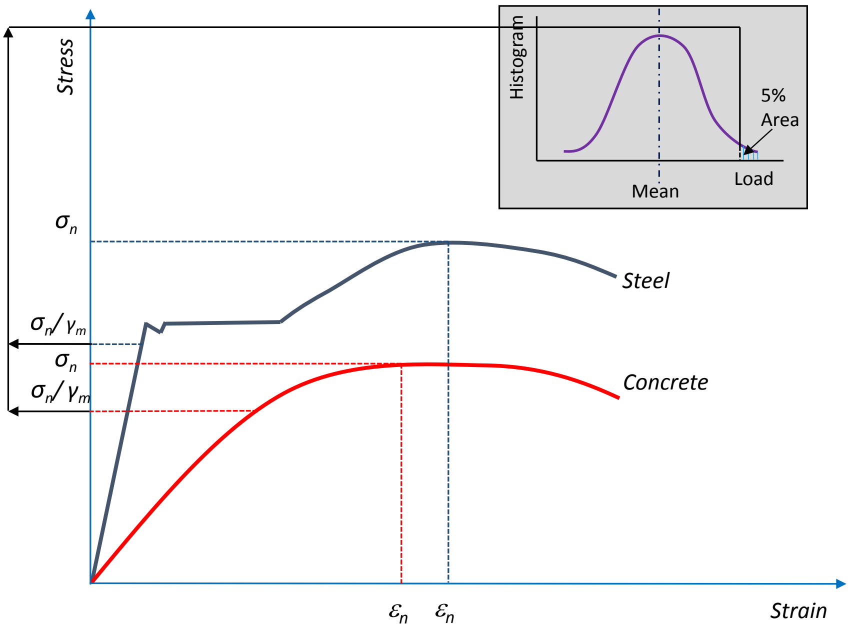


Figure 12. Ultimate limit states of materials (γ_m is material strength reduction factor)

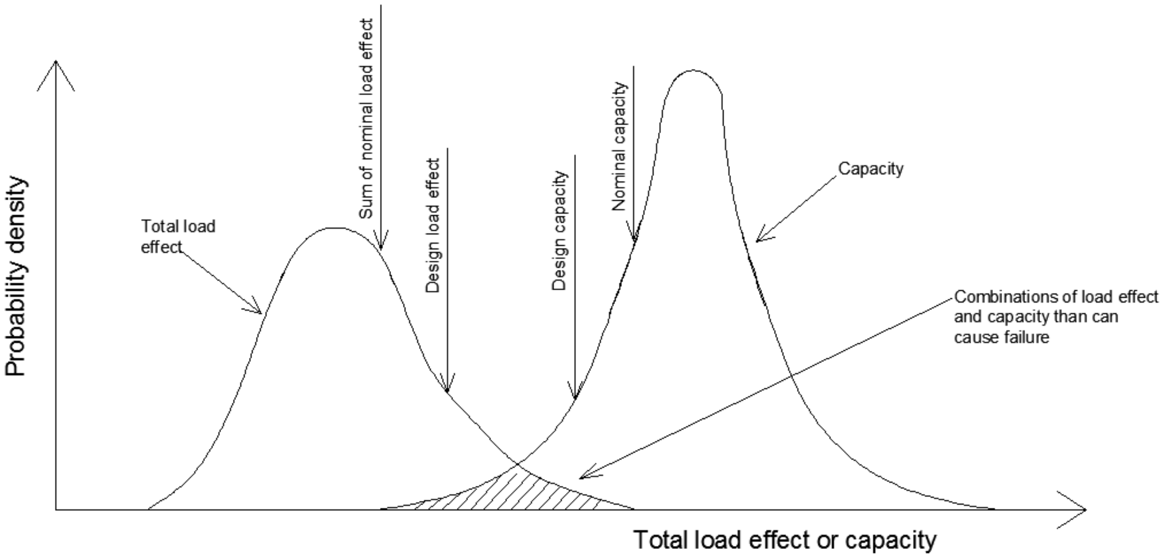


Figure 13. Model of probability density function

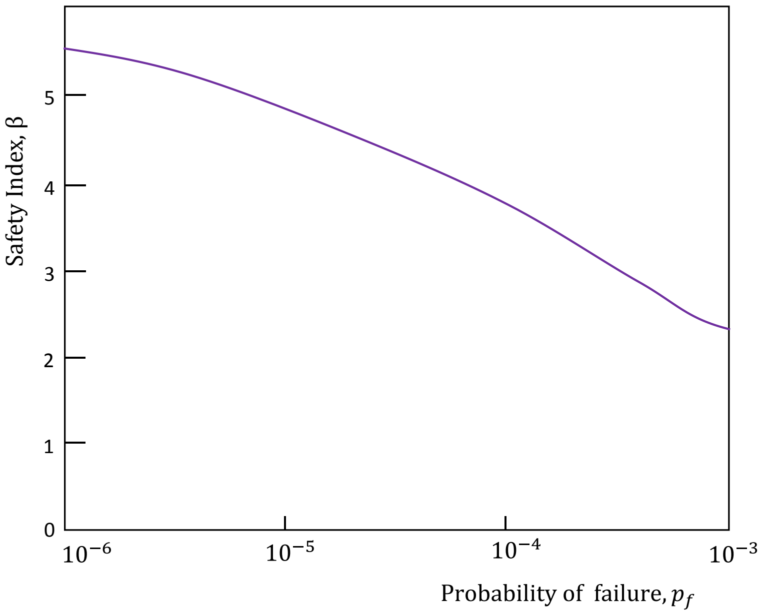


Figure 14. Graph: Safety Index (β) x Probability of failure (p_f) (AS5104 2005)

Figure 15. Hybrid polymer transoms (Van, Mckay 2013)