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New prediction model for the screw pull-out strength of polymer composite railway sleepers

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A R T I C L E I N F O

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A B S T R A C T

Estimation of the screw pull-out strength of composite railway sleepers is a complex problem due to the wide variability of their material properties and the availability of different screw geometries used to fasten the rail track. This study investigated the effect of screw geometry (screw diameter and embedded length) and sleeper material (timber, synthetic composites, recycled plastics and particulate filled resins) on the pull-out strength and developed a new prediction model for polymer composite railway sleepers. The two-way analysis of variance showed that the material shear strength has a higher influence than the screw geometries on the pull-out strength. Increasing the thread embedded length has a significant effect on all tested sleeper types due to the increased thread engaging area while the screw major diameter affects timber rather than composites owing to timber's continuously high shear strength. Based on the failure behaviour and type of fibre reinforcement, an analytical model was developed to estimate the pull-out resistance and was also verified by the results from the available literature and reports. The proposed model is found over 50% more reliable than other existing theoretical models.

1. Introduction

Composite railway sleepers have emerged as effective alternatives to timber sleepers owing to their superior durability, higher strength/weight ratio and lower environmental impact [1]. These new technologies are classified by Ferdous et al. [2] in three categories base on the amount, length and orientation of fibres. The Type-1 sleepers are generally made of recycled plastics with short (< 20 mm) or no fibre reinforcement [3–5]. Although this category of sleepers is easy to drill, durable, eco-friendly and reasonably priced, the low anchorage capability is one of their major issues especially in dynamic loading conditions due to the inherently low strength of the plastic material. Pull-out strength of 40 kN is required for the timber-replacement sleepers [6] while a relatively low pull-out resistance of 31.6–35.6 kN was reported for the plastic sleepers [2]. The plastic-composite sleeper tested by the Institute of Railway Technology (IRT) of Monash University [7] exhibited the pull-out force meeting the requirement of 22.2 kN specified by the American Railway Engineering and Maintenance-of-way Association (AREMA [8]) but failed to reach 40 kN required for timber sleepers as suggested in AS1085.18 [6]. A strong screw holding capacity reaching 65 kN was reported for the Type-2 sleepers with long fibre reinforcement in the longitudinal direction (represented by Fibre-reinforced Foamed Urethane, FFU) [9,10]. The Type-3 sleepers reinforced by fibres in both the longitudinal and transverse directions also showed a superior pull-out capacity of over 60 kN. The strong structural components of Type-3 sleepers can be due to the fibre-reinforced pultruded hollow section [11,12] and phenolic core sandwich beam [13,14] which are either provided confinement effect to the core material or contributed directly to the pull-out resistance. However, the pull-out performance of the above-mentioned sleeper technologies are difficult to compare directly as they were tested using different screws and geometries as required by current standards and specifications.

Various rail screws with different geometries were used in the pull-out test on composite sleepers according to the available literature and industry reports. The Ecotrax composite sleeper from Axion has a pull-out resistance of 31.6 kN using the Ø17.5 mm screw with the Ø14 mm diameter pilot hole [3] in accordance with ASTM D6117 [15]

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which nominates the Ø25 mm (in major diameter) screw. Other recycled plastic sleepers available in the US market mostly were tested following the AREMA specification [8]. Since spikes are extensively applied in the US railway industry rather than screws, the requirement for screw geometry is not stated in the test method. Lotfy et al. [16] measured the pull-out strength of the high-density polyethylene (HDPE) sleepers (44 kN averagely) adopting the Ø22 mm screw having 133 mm underhead length (76 mm effective thread length) and 12.7 mm pitch. Their study highlighted the effect of pre-drilling configuration, loading rate, and temperatures, but the influence of screw geometry was not within the scope. Unlike the US, rail screws are widely adopted in other countries (e.g., Japan, Australia, and European countries). Japanese Industrial Standard (JIS E 1023 [17]) recommends a screw diameter of 24 mm and a minimum pull-out strength of 30 kN is specified. The SS 8–140 sleeper screws with the same major diameter were pulled out from the Japanese SEKISUI FFU sleepers following the European Standard (DIN EN 13481–2 [18]) [19]. Even though Australian Standards recommends Ø24 mm screws with the pitch of 12.5 mm for timber sleepers (AS1085.18 [6]) and alternative material sleepers (AS1085.22 [20]), the Queensland Rail has been using the Ø16 mm screw with 125 mm of length in actual practice [21]. This type of screws was tested in an innovative composite railway sleeper developed by the University of Southern Queensland and an average of 74 kN was achieved in the pull-out test [22]. Qiu et al. [7] used Ø16 mm and Ø19 mm screws in the pull-out test on plastic sleepers under Australian Standards and highlighted that a higher pull-out force was achieved by the larger diameter screws rather than the smaller diameter. Due to the different test approaches, types of screws and screw geometries implemented by different researchers and industries, it seems difficult to straightforwardly estimate the pull-out resistance of composite-based sleepers, contributing to the low confidence in their usage and their wide application as timber replacement in the maintenance of railway track.

The pull-out performance of sleepers can vary significantly depending on the screw geometry while the understanding of how the screw geometry affect the pull-out behaviour is very limited. Moreover, the analytical model to predict the pull-out strength for railway sleepers is not currently available. This is probably the main reason why most available literature and industry test reports are limited to information on the level of the pull-out load based on the investigated sleeper material and type of screw used. The ultimate shear strength of the sleeper material is also known to have an effect when the pull-out failure mainly occurs in the hole [23–25] and the screw can be considered as a rigid body [26]. As a result, a variety of prediction models adopted the ultimate shear strength of the host material to estimate the pull-out strength. The fundamental thread stripping (FTS) model is a function of material shear strength and a cylindrical surface defined by the screw major diameter and thread embedded length. This basic model is developed from the assumption that the external threads of screw shear off the internal threads along the line "A" shown in Fig. 1 [27]. Alternatively, this function can also be transformed to express the average bond stress between the reinforcing bar [28,29] or rock bolt [30] or single fibre [31] and the host material. Additionally, ASTM (FED-STD-H28/2B) [32,33] modified the FTS model by considering the thread shape factor (TSF) which is the average product of pitch and thread depth [34]. Chapman et al. [24] indicated that TSF may decrease the predicted pull-out strength as this dimensionless value varied from 0.70 to 0.87 according to the type of the tested bone screws. The statistical significance of TSF was highlighted by Migliorati et al. [35] in defining the mechanical competency of orthodontic mini-screws. Tsai et al. [25] further modified the ASTM equation and focused on the integration of the pull-out force along the screw axis for conical and cylindrical screws. The Tsai's model describes the pull-out strength of bone screws as a function of squeezed bone strength, screw design, and pilot hole. In order to take these parameters into consideration, additional evaluation of the shear strength and material constant of the host material is required to conduct following ASTM F1839 [36], which

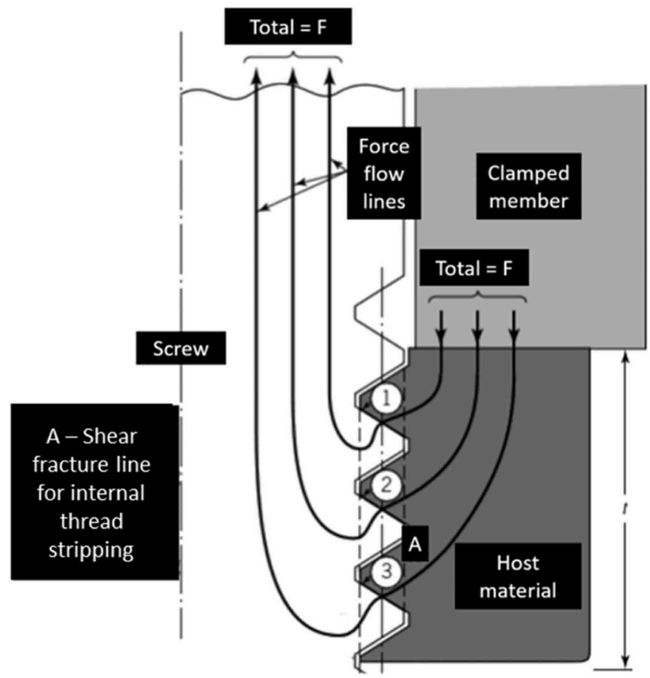


Fig. 1. Force flow for a fastener in pull-out [37].

seems to be necessary only for the conical thread pattern and meanwhile increases the practical efforts. On the other hand, the pull-out model due to thread bearing features the bearing area indicated as area 1–3 in Fig. 1 on threads and the thread number within the interacted depth [37]. Shih et al. [38] highlighted that the predicted values of the thread bearing (TB) model were generally lower than that of above-mentioned thread stripping models. This is because the bearing area could be considerably smaller than the cylindrical shear area if the screw with certain geometry (a small difference between the major and minor diameters or a small number of threads) was fully embedded. Sivapathasundaram and Mahendran [39] adopted the ASTM model and the TB model to predict the screw pull-out force of the connections in steel cladding system. Neither of these two equations reported accurate prediction as their pull-out failure modes are not well corresponding to the failure of steel roof battens and purlins. Predicting the pull-out strength of sleepers may face a similar challenge due to the much complex failures [40] (e.g., matrix splitting of synthetic composites, longitudinal grain shearing of hardwood timber, and global shear cracking of fibre-reinforced polymer matrix). It can be concluded that an accurate prediction of pull-out strength is greatly dependant on the influence of screw geometrical parameters and the pull-out failure mode, but current models are not likely to describe the pull-out behaviour of sleeper materials properly.

Based on a comprehensive review of the literature, no studies have been found that specifically investigate the effect of screw geometry (diameter and embedment length) on the pull-out behaviour of timber and timber-alternative composite sleeper products. The ultimate pull-out strength of the referenced sleeper types was measured in the screw pull-out test and analysed with the variance of thread embedded length and screw major diameter. The normalised stress on the screw was calculated to further determine the effect of the two investigated parameters. The two-way analysis of variance (ANOVA) was conducted to evaluate the influence level of the material shear strength and screw geometries. Based on the statistic results and the distinct failure modes of the tested sleeper materials, an analytical model is proposed to predict the pull-out resistance of railway sleepers and further compared with other existing theoretical equations. The novel findings of this research are expected to minimise the costly and time-consuming repeated pull-out test, to improve the limited understanding on the effect of screw geometries on the pull-out performance of composite railway sleepers, and to ensure the stability of railway track when alternative sleeper technologies are adopted for the maintenance strategy.

2. Methodology

2.1. Material characterisation and screw geometry

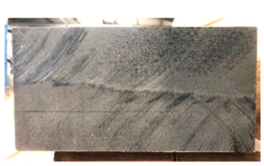
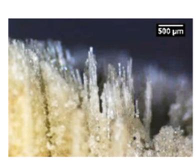
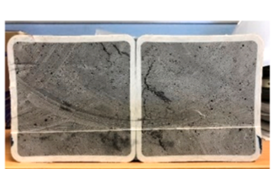
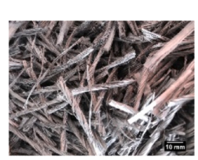
This study investigated hardwood timber railway sleepers and three types of timber alternative sleeper technologies including synthetic composites (SC) made from hard polyurethane foam reinforced with continuous glass fibre in the longitudinal direction, Ultra High Molecular Weight Polyethylene (UHMWPE) plastic sleepers and Particulate-Filled Resin (PFR) cored sleeper. The PFR core is reinforced with randomly dispersed short fibres (54 mm-long macro Polypropylene fibres) and inside the GFRP (Glass Fibre Reinforced Polymer) rectangular hollow pultruded sections. Table 1 presented the cross-sections, fibre reinforcement (if present), and the shear strength of the referenced sleeper materials. The ultimate shear strength is examined in this research owing to its highest correlation with the pull-out strength among other material properties [40]. In addition, the strength direction is perpendicular to grain/long fibre (directions defined in Fig. 2(e)) along the load direction as the sleeper hole is subjected to axial shear force due to the pull-out mechanism. The Asymmetrical Shear Beam test [41,42] was adopted to obtain the shear strength of the four tested sleeper types. It should be noted that this study does not consider the shear capacity of the GFRP section of the PFR sleeper due to PFR's significant effect on resisting screw pull-out, although the laminates impose restraint on the core.

GageLok rail screws made of Grade U3 steel [6] with a minimum 250 MPa yield strength and minimum 410 MPa tensile strength [43] are the fasteners used in this study. These screws are the type of screws used by Queensland Rail in Australia to fix rail directly to timber or composite sleepers or with plates and to prevent lateral and vertical movements between them [22]. Table 2 presents the parameters of the tested GageLok rail screws which have a thread angle of 60°. Fig. 2(a) illustrates these parameters including major diameter, minor diameter, pitch and thread angle which determine the screw profile configuration. The major diameter is the diameter of an imaginary cylinder formed by the crest of all external threads on the screw while the minor diameter is the lowest diameter measured from the thread root. Fig. 2(b) shows the Ø17.5 mm GageLok-11 rail screw. The shank of the screw can be noticed but its effect on the pull-out behaviour is not investigated in this study due to its main function of resisting the lateral shear force from the rail/plate rather than the uplift force. Thus, only the thread part was embedded in the sleeper material.

2.2. Screw pull-out test

Pilot holes were pre-drilled for screw installation to prepare the pull-out test. The size of the through-holes was close to 1.1 times the minor (root) diameter with no observation of timber splitting after installation complying with the requirements of AS1085.18 [6]. The timber-replacement sleepers were inserted in the holes of the same size. The last row of Table 2 presents the different sizes of pilot holes corresponding to the size of rail screws. The screws were then inserted in the rail-seat region of the sleeper at a distance of 100 mm in between and 50 mm from the edge using an 18 V brushless impact wrench. In order to investigate the effect of the thread embedded length, the GageLok-5 and GageLok-15 with the identical thread form (Ø16 mm) were inserted 35 mm, 50 mm and 65 mm deep in the rail-seat region of the sleeper samples. As presented in Table 2, the GageLok-5 and GageLok-15 have the same thread configurations but have different lengths. On the other hand, the GageLok-5, GageLok-13 (Ø17.5 mm) and GageLok-7 (Ø19 mm) were driven in the rail-seat region to the same depth of 50 mm to determine the effect of the major diameter of threads. Fig. 2(c) and (d) show the relevant screw installation diagrams. A universal test machine with 100 kN capacity was used to conduct the pull-out test following the AREMA specifications [8]. The Australian Standards AS 1085.22 [20] was mostly followed with some modifications in which the

Table 1
The tested railway sleepers.

Sleeper technology	Cross-section	Fibre reinforcement	Flexural strength (MPa)	Shear strength* (MPa)
Hardwood Timber		Timber grain in the longitudinal direction	136	9.0
UHMWPE Plastic		No fibre reinforcement	32.6	14.0
Synthetic Composite			137	7.0
PFR			45	10.6

* The shear strength is perpendicular to the grain/fibre direction along the load direction.

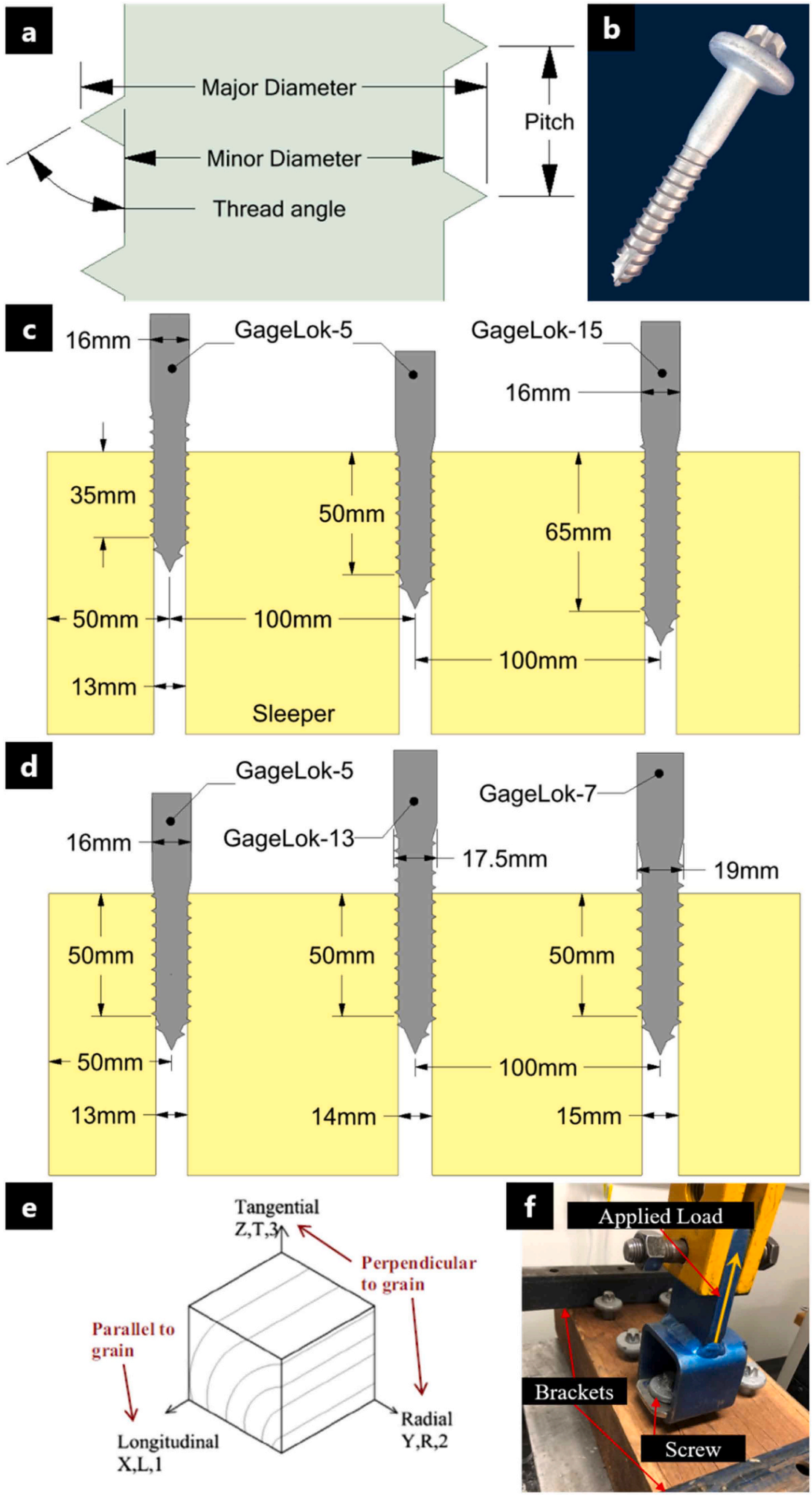


Fig. 2. a) Terminology of the screw profile, b) the GageLok-11 rail screw, c) screw installation diagram with varied thread embedded length, and d) screw installation diagram with varied major diameter, e) definition of material directions of orthotropic material, f) screw pull-out test setup.

Table 2
Screw geometry of GageLok rail screws.

Screw	GageLok-5	GageLok-15	GageLok-13	GageLok-7
Major Diameter	16	16	17.5	19
Minor Diameter	12	12	13.5	14.5
Pitch	6	6	6	7
Thread Length	70	90	99	90
Pilot hole diameter	13	13	14	15

Dimensions are in mm.

test load is increased to the maximum to measure the ultimate strength and to analyse the failure modes of the different sleepers instead of maintaining the load for 3 minutes. This load-maintaining requirement of AS 1085.22 seems to be suitable for a qualification test but not to understand the pull-out behaviour of sleeper technologies. Fig. 2(f) depicts the screw being lifted upward from the rail seat by a loading head and jig at a rate of 2 mm/min (suitable loading rate for pull-out test) until the maximum pull-out force was reached while the sleeper section was fixed to the test bench by two brackets at two ends.

2.3. Microscopic examination

The tested holes were cut in half to observe the cross-sections after the pull-out test. Both the longitudinal and transverse directions of the orthotropic sleepers including timber, SC and PFR are investigated. A Leica DMS 300 camera (Leica microsystems) was used to investigate the failure modes of different sleeper materials in terms of their pull-out behaviour. The microscopic photos were then analysed and the failure modes were used as the fundamental guide for predicting the pull-out behaviour in the development of the proposed new analytical models.

3. Results and discussion

3.1. Effects of the thread embedded length

Fig. 3 depicts the effect of the thread embedded length by varying from 35 mm to 65 mm (with an increment of 15 mm). The results showed that the pull-out load of all tested sleepers, i.e., hardwood timber (T), UHMWPE plastics (P), synthetic composites (SC), and PFR, increases linearly with increasing thread embedded length as illustrated in Fig. 3(a). This is due to the longer thread embedment length enabling more pitches of the screw engaging with the sleeper material and consequently generating higher pull-out resistance. Similarly, Cai et al. [44] reported better pull-out performance of rock bolts with increasing installing length as more rock mass were interacted and worked together. Maranan et al. [45] highlighted that the increased engaged surface generates higher mechanical interlock and greater friction resistance. Ren et al. [46] indicated the pull-out load continued to increase with the bond length even after the effective bond length was reached but at a slower rate. Nevertheless, different slopes are noticeable on the initial part of the pull-out load and embedment length relationship curve for different sleeper materials. By increasing embedded thread length from 35 to 65 mm, the PFR sleepers had a dramatic enhancement from 33.5±1.1 kN to 70.5±1.7 kN, and similarly, the pull-out strength of UHMWPE plastics increased from 23.9 ±2.8 kN to 56.2±0.4 kN. In comparison, timber and synthetic composite sleepers saw relatively small increases in the pull-out strength. The stiffer slope of PFR and plastic sleepers can be corresponding to their high shear strength as reported in Table 1. As shown in the theoretical equations, material shear strength is the most important factor affecting the pull-out performance when the same screw geometry is adopted. It can be thus concluded that the embedded length has a stronger positive effect on sleepers with high shear strength while it has a less effect on low shear strength sleeper materials.

The effect of thread engaged length is further investigated when a constant stress distribution is assumed along the screw embedment during pull-out. Eq. (1) is transformed from the FTS model [27] to calculate this normalised shear stress τ as demonstrated in Fig. 3(b).

$$\tau = \frac{F_{pull-out}}{\pi D_{major} L} \tag{1}$$

where $F_{pull-out}$ is the pull-out force, D_{major} is the major diameter of the screw, and L is the thread embedded length. It is observed that the normalised stress on each type of the tested sleepers is almost the same with increasing thread length. These experimental results were further analysed in Section 3.4 using Tukey's honest significant difference (HSD) Post Hoc multiple comparisons. Table 3 presents the significance of difference ranging from 0.845 to 0.996 (with 95% confidence interval) which indicates a minor statistical difference of the normalised stress. During pull-out testing, the failure of sleeper materials rather than screws is necessary to gain an understanding of the relationship between normalised stress and shear strength. The unnoticeable change in stress implies that the sleepers' shear strength was fully utilised as the failure generally occurred within the sleeper material rather than the screw. Thus, the normalised stress can correspond to sleepers' shear strength. Similarly, it is reported that the bond strength of rock bolts increases with the increasing shear strength of the grouting material during pull-out [30]. However, a distinct effect of embedded length was found in the research of composite reinforcing bar pull-out [28] that the shear stress decreases with the increasing length due to its nonlinear distribution (the stress gap between the loaded end and the unloaded end). Even though the nonlinear stress distribution was also proposed by Lotfy et al. [16] for the mechanics of rail screw pull-out, the stress gap seems relatively small, as the embedded length (35–65 mm) of rail screws is much less than the rebar embedded length (63–300 mm) [28].

3.2. Effect of the thread major diameter

The major diameter of the screw is extensively regarded as one of the dominant factors of the predicted pull-out force [24,26,27,47,48] while the variation of the minor diameter did not show a statistically significant difference [49] nor the pitch [26]. Theoretically, it corresponds to the thread stripping failure in which the external threads on screws shear off the internal threads on the host material. However, Fig. 3(c) illustrates the minor effect of the increasing screw major diameter (16–19 mm) on the pull-out performance of the tested sleepers except for the hardwood timber. In the pull-out mechanism, the increase in major diameter is able to interact with the sleeper material in a larger area but the total increment of 3 mm (from 16 mm to 19 mm) in diameter seems limited compared to the ten times larger increase (30 mm) of embedded length. To be specific, the 19% increment in diameter can be correlated to the improved pull-out strength of PFR (17%) and UHMWPE plastics (15%) while it did not affect the pull-out performance of SC sleepers due to its significantly low shear strength. The SC sleepers are weak in shear as subjected to in-plane shear cracking due to the matrix failure in the fibre direction [40]. On the other hand, the increase of major diameter immediately enlarges the thread bearing area (on thread surface) and strongly affects the pull-out strength of timber which has superior load-bearing capacity. This capacity is dependent on the continuously high shear strength of timber as a natural orthotropic material. In the authors' previous work [40], shear failure longitudinal to the grain direction and hole lifting was observed in the pull-out failure of the timber sleeper, which implies that the hardwood timber is strong in shear in the screw axial direction and continuously along the full length of the sleeper. Hence, its 57% increase in the pull-out strength can be explained.

Similar to the effect of embedded length, various researchers reported that increasing bar diameter decreases the bond stress due to non-linear stress distribution [28,50,51], Poisson effect [29], or shear lag effect [52]. However, Fig. 3(d) depicts that the normalised stress of

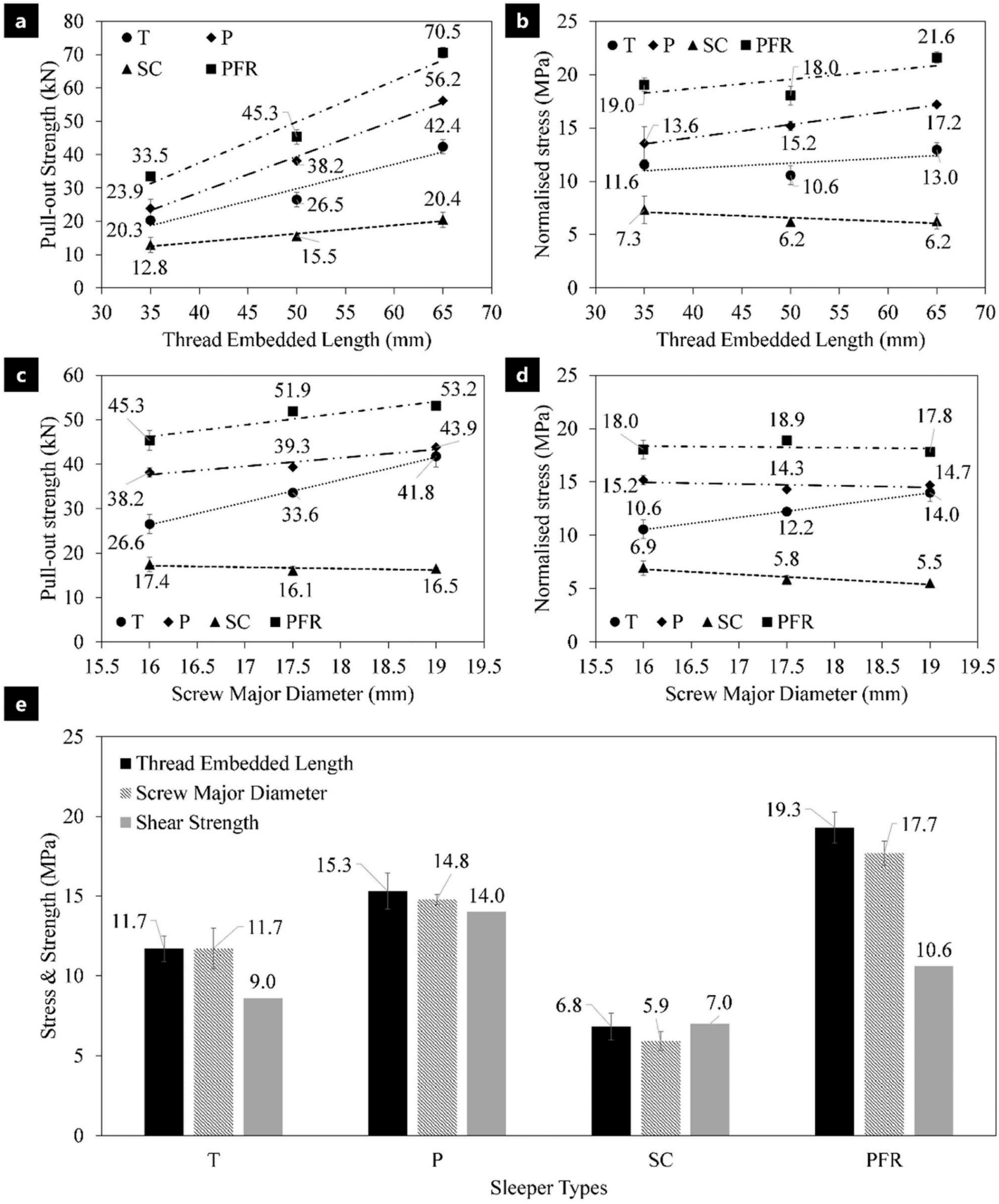


Fig. 3. Increasing thread length (mm) plotted against a) pull-out strength (kN) and b) normalised stress (MPa); increasing screw major diameter (mm, discussed in Section 3.2) plotted against c) pull-out strength and d) normalised stress of timber (T), synthetic composites (SC), UHMWPE plastics (P), and PFR; e) average normalised stress compared to the sleepers' shear strength (MPa).

the composite sleepers is hardly affected by the screw major diameter. In comparison to the bar's pull-out, the non-linear stress distribution can be ignored possibly owing to the relatively shorter embedded length of rail screws. Besides, it seems the Poisson's ratio or the shear lag showed no influence on the screw behaviour as the deformation on the screw can be neglected due to its considerably higher strength than the sleeper materials. Table 3 further verifies the minor significance of difference (>0.95) in the normalised stress of different major diameters using Tukey's HSD multiple comparisons. Additionally, the timber samples see a noticeable increase in normalised stress exceeding the material

Table 3
Tukey's HSD Post Hoc multiple comparisons on normalised stress (in MPa) of reference sleeper technologies.

Multiple Comparisons – Tukey HSD							
Dependant Variable: Normalised Stress (MPa)							
Factor (I & J)	(I)	(J)	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval Lower Bound	Upper Bound
Thread Embedded Length (mm)	35	50	.18000	2.07267	.996	-4.9133	5.2733
		65	-.99644	2.11925	.886	-6.2042	4.2113
	50	35	-1.8000	2.07267	.996	-5.2733	4.9133
		65	-1.17644	2.11925	.845	-6.3842	4.0313
	65	35	.99644	2.11925	.886	-4.2113	6.2042
		50	1.17644	2.11925	.845	-4.0313	6.3842
Screw Major Diameter (mm)	16	17.5	.60447	2.03446	.953	-4.3950	5.6039
		19	.09333	1.98974	.999	-4.7962	4.9829
	17.5	16	-.60447	2.03446	.953	-5.6039	4.3950
		19	-.51114	2.03446	.966	-5.5106	4.4883
	19	16	-.09333	1.98974	.999	-4.9829	4.7962
		17.5	.51114	2.03446	.966	-4.4883	5.5106

shear strength, which indicates Eq. (1) is not suitable to predict the normalised stress in timber sleepers due to its different failure behaviour. Specifically, since the rail screw interacts with more timber material in thread bearing failure than thread stripping, the relevant stress area is larger as illustrated in Section 4.3. This is corresponding to the failure of the timber hole being lifted during screw pull-out [40]. Therefore, the stress area on threads mainly defined by the major diameter greatly affects the pull-out performance of timber.

3.3. Relationship between normalised stress and shear strength of sleepers

The pull-out failure generally occurs on sleeper materials instead of screws. This suggests that the normalised shear stress have a strong relationship with the sleepers' ultimate shear strength. Fig. 3(e) compares the shear strength of the tested sleeper technologies with the average normalised stress with varied embedded lengths and major diameters. Synthetic composites and UHMWPE plastics show a minor difference which implies the effectiveness of Eq. (1) and the basic pull-out model [27] in predicting the pull-out strength of thread stripping failure. In this failure mode, the stress component equals the ultimate shear strength of the sleeper materials. In comparison, the shear strength of hardwood timber and PFR sleepers is noticeably lower than their normalised stress. This result implies that the theoretical model for thread stripping failure is not suitable to estimate the pull-out performance of these two types of railway sleepers as the screw geometrical parameters may have a distinct effect on the thread bearing failure of timber and global shear cracking of PFR observed in [40]. Timber sleeper showed grain longitudinal shearing accompanied by inclining shear cracking in the transverse direction while the global shear cracking due to the load transfer function of short fibres dominated the pull-out failure of the PFR sleeper. Compared to the simple thread stripping failure, these two complex failure modes indicate that more sleeper materials were engaged with screw uplifting, and therefore, the relevant stress area can be larger. Hence, a new analytical model is required to incorporate the effect of screw geometry on the pull-out capacity of different sleeper technologies.

3.4. Statistical analysis of pull-out results

The pull-out results were analysed with IBM Statistical Package for the Social Science (SPSS) Statistics 26 [53] to compare the significance of the difference at a 95% confidence interval. The one-way analysis of variance (ANOVA) [54–56] was conducted to determine whether there was any significant difference between the mean and the standard deviation of the calculated normalised stress. In Table 3, Tukey's honest significant difference (HSD) Post Hoc multiple comparisons show the minor difference of the normalised stress despite the increasing thread embedded length or screw major diameter. On the other hand, the univariate analysis of two-way ANOVA [57] was applied in Table 4 to evaluate the influence of sleepers' shear strength, embedded length and major diameter over the pull-out performance of all the tested sleeper technologies while the effects of the last two parameters on each sleeper type were also investigated. The p-value represents the significance level and demonstrates that the pull-out strength is remarkably influenced by all the three parameters indicated by the p-value below 0.05 except the screw major diameter for the SC sleeper (0.979). The limited effect of major diameter indicates that SC failed immediately instead of bearing the axial pull-out force, which corresponds to the progressive load drops observed in both this study and in [40]. The partial eta squared reflects the influence level of different parameters on the pull-out strength. Table 4 highlights that the shear strength (0.938) and embedded length (0.882) has approximately two times greater influence than the major diameter (0.463) for all tested sleeper types. In the conditions considering each sleeper technology separately, thread embedded length is more likely to affect the pull-out strength than major diameter. However, it is noticeable that the effect of major diameter is much higher on hardwood timber (0.739) than other sleeper types but minor on synthetic composites (0.003). The statistical results are discussed with different pull-out failure modes to develop a new analytical model for sleeper technologies.

Table 4
Two-way ANOVA determining the influence effect of parameters.

Dependant variable	Sleeper technologies	Independent variable	F-value	p-value	Partial eta squared
Pull-out strength	All	Shear Strength	237.2	.000	.938
		Embedded Length	175.4	.000	.882
		Major Diameter	20.3	.000	.463
	T	Embedded Length	31.1	.000	.827
		Major Diameter	18.4	.000	.739
	P	Embedded Length	121.2	.000	.949
		Major Diameter	5.1	.024	.438
	SC	Embedded Length	4.7	.030	.418
		Major Diameter	.02	.979	.003
	PFR	Embedded Length	137.4	.000	.955
		Major Diameter	9.9	.002	.603

4. Analytical models for screw pull-out strength based on failure modes

The ultimate shear strength of sleeper materials is found to be the most significant parameter for the pull-out behaviour compared to the screw geometrical parameters. Likewise, screw diameter and embedded length show different levels of importance in the prediction equations of different failure modes. The thread embedded length has considerably greater influence in the thread stripping model while major diameter affects the thread bearing model more. According to the effects of the parameters discussed above, this section reviewed currently existing pull-out models and proposed a new analytical model based on the observed three failure modes to predict the pull-out strength of the railway sleepers.

4.1. Review of existing pull-out models

The fundamental thread stripping (FTS) model expressed in Eq. (2) is extensively applied to formulate the pull-out strength in various research areas (e.g., rebar [28], rock bolt [30], bone screw [27] and single fibre pull-out [31]) when the internal thread/bond of host materials is stripped off.

$$F_{pull-out} = S\pi D_{major}L \tag{2}$$

where $F_{pull-out}$ is the pull-out strength, S is the material ultimate shear strength, D_{major} is the major diameter of the threads (mm), L is the thread embedded length (mm). Since the thread stripping failure is assumed, the pull-out strength is determined by the material shear strength (S) and cylindrical shear area ($\pi \times D_{major} \times L$) of the threads. Another pull-out model is the ASTM function [32] featuring the thread shape factor (TSF) as presented in Eq. (3).

$$F_{pull-out} = S\pi D_{major}L \times TSF \tag{3}$$

TSF (dimensionless) is defined by $(0.5 + 0.57735 \times \frac{d}{p})$, where d is the thread depth ($(D_{major} - D_{minor})/2$, D_{minor} is the minor (root) diameter of the threads, all dimensions in mm) and p is the thread pitch (mm). Since Tsai's model [25] is more suitable for conical screws rather than cylindrical rail screws, it is not included in this section. The two pull-out models of thread stripping clearly explain the linear relationship between the embedded length/major diameter and the pull-out strength. These two parameters show positive contributions to the pull-out force, but their influence can be largely affected by the low shear strength of sleeper materials (e.g., the synthetic composite sleeper) especially when the increment of the parameter is small. This result suggests that the prediction equations developed based on the thread stripping failure seem to be suitable for the sleeper technologies exhibiting similar failures. On the other hand, Eq. (4) shows the prediction equation for the thread bearing failure [37].

$$F_{pull-out} = S\frac{\pi}{4}({D_{major}}^2 - {D_{minor}}^2)\frac{L}{p} \tag{4}$$

where D_{minor} is the minor diameter (mm) of the screw. The pull-out force is a product of material shear strength, the number of threads, and the difference in the cross-sectional area of the major and minor diameter. It is noticeable that only two failure modes (thread stripping and thread bearing) are described in the existing models, but the timber and composite sleeper materials seem to have distinct pull-out failures. Hence, a new analytical model consisting of three equations is developed from the distinct pull-out failure mechanics in the following sections and each equation corresponds to a specific failure mode.

4.2. Prediction model for Failure Mode 1

Failure Mode 1 can be regarded as the traditional thread stripping failure in which the internal threads in the sleeper hole are sheared off due to the screw's axial shear force. This type of failure is common in the composite sleepers with no [16] or one-directional (normally longitudinal) fibre reinforcement [40] for which the matrix dominates the shear strength in the pull-out direction. Although synthetic composites and UHMWPE plastics exhibited noticeably different shear capacities as well as the pull-out performance, their failure modes are similar and categorized to the same failure mode in Table 5 (a). The localised failures were observed in the cross-sections of both sleeper types and the sleeper material between threads was partly stripped in the plastics while that in SC was mostly deformed due to abrasion. Due to the flexibility of the synthetic composite and plastic material, the internal threads were not completely stripped off similar to rock bolting failure [58] or bone chips peeling [25,38]. However, this type of failure can be considered as the localised damage along the shear fracture line (shown in Table 5 (b)) same to the thread stripping. Therefore, Eq. (2) is directly applied to predict the pull-out strength of SC and P based on the material shear strength and screw geometry. Table 5 (c) illustrates the pull-out strength of SC and P from experiments is plotted against the predicted values from Eq. (2). The coefficient of determination (R^2) reaches 0.90 indicating the 90% of the total variation of the data can be explained by the model while the root mean square error (RMSE) has a value of 4.75 demonstrating the actual difference between the experimental results and the predicted values.

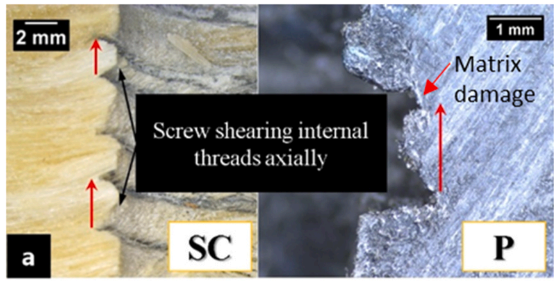
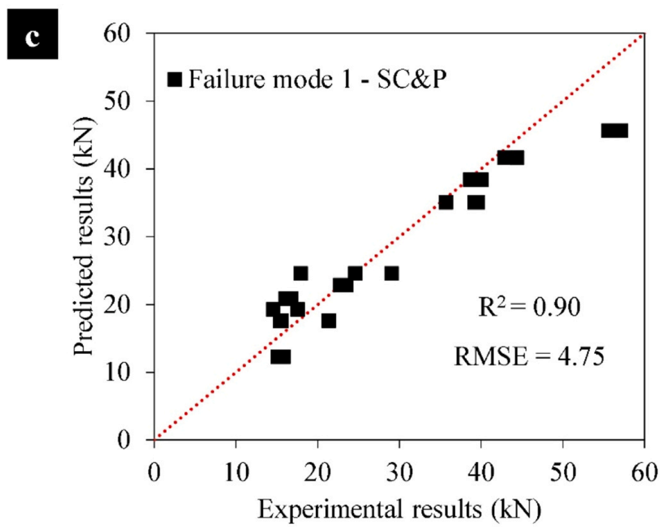
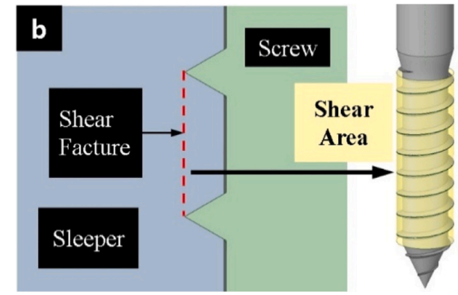
4.3. Prediction model for Failure Mode 2

Failure Mode 2 features thread bearing in timber holes as shown in Table 5 (d). This unique type of failure is only observed in hardwood timber rather than other polymer composite sleepers [40] because timber has a strong shear capacity in the screw pull-out direction and continuously along the full length of the sleeper. As illustrated in Table 5 (d), the load-bearing capacity of hardwood timber is revealed by the grain longitudinal shearing during screw pull-out while the entire hole being lifted implies that timber's shear strength was fully utilised along the shear fracture line. Although brittle shear cracks were observed in [40], the grain shearing dominates the pull-out failure in timber sleepers. This is due to the hardwood material has a high shear strength (9 MPa) perpendicular to grain along the load direction [59]. Additionally, the significant role of load-bearing is corresponding to the greater effect of thread major diameter on the pull-out strength of timber than other sleeper technologies. According to the pull-out mechanics of timber sleepers shown in Table 5 (e), Eq. (4) for thread bearing is combined with Eq. (2) for thread stripping to predict the pull-out strength of hardwood timber sleepers as presented in Equation (5). Equation (6) shows the proposed prediction equation, which matches reasonably well with the experimental pull-out strength having a coefficient of determination of 0.73 and the RMSE being 5.15 as depicted in Table 5 (f).

4.4. Prediction model for Failure Mode 3

Failure Mode 3 of the PFR sleepers is dominated by global shear cracking accompanied by thread partly stripping, as the sleeper material is reinforced by fibres in multi-directions. Table 5 (g) depicts that the inclined cracks occurred owing to fibres' load transferring function while the short fibres also bridged the cracking at thread root and prevented thread stripping. Hence, the existing theoretical models seem unsuitable to describe Failure Mode 3. As revealed in Section 3 that the non-linear stress distribution has a minor effect on the screw pull-out mechanism despite the increasing major diameter, the normalised stress method is used to simplify the matrix global cracking by increasing the projected shear area. It is possible because the global shear cracking [40] in the core indicates more PFR material has radially interacted with the short fibres and thus generated a shear cylindrical area (formed by projected shear fractures shown in Table 5 (h)) larger

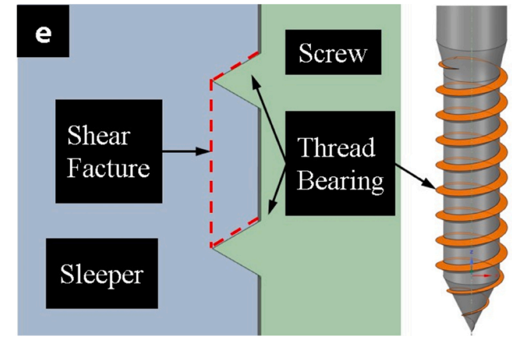
Table 5
Analytical models developed based on failure analysis.

	Failure Mode	Failure Mechanism
Failure Mode 1	 $F_{pull-out} = F_{stripping} = S\pi D_{major}L$ (2) 	

(*continued on next page*)

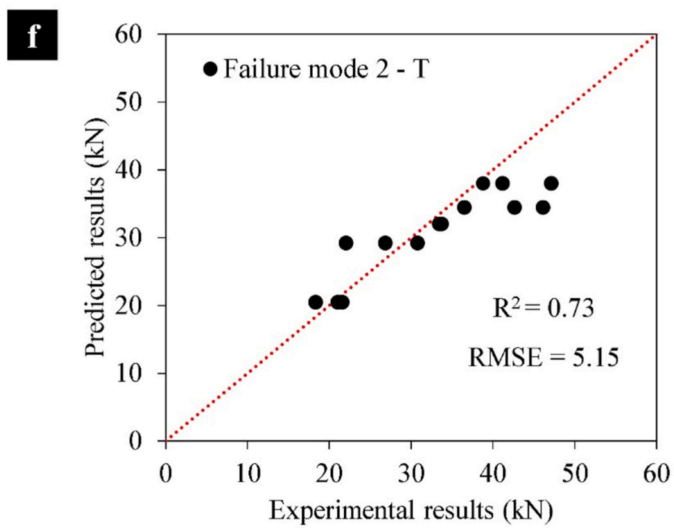
Table 5 (*continued*)

	Failure Mode	Failure Mechanism
Failure Mode 2		



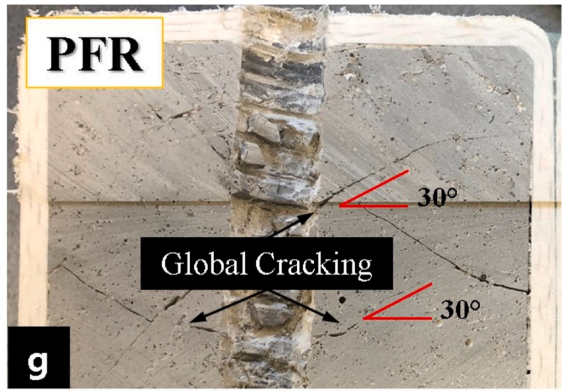
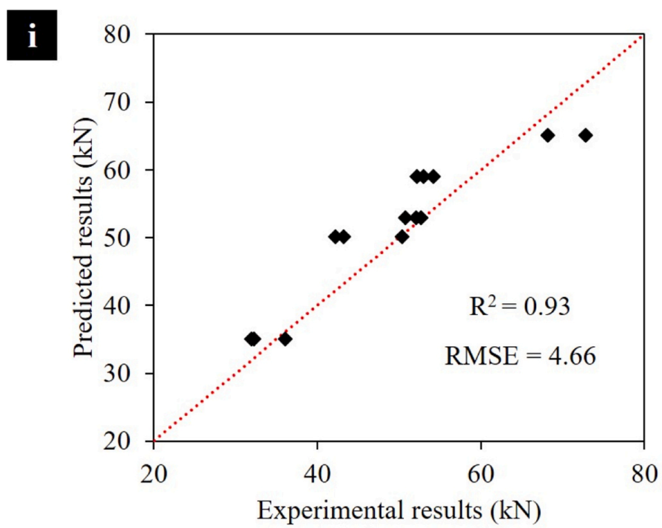
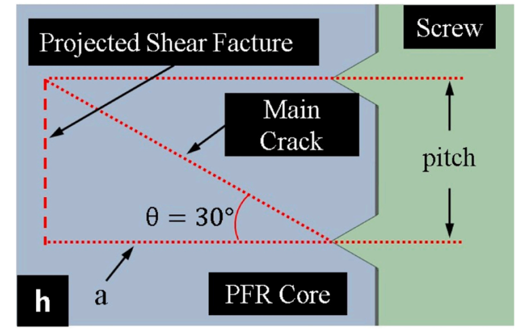
$F_{pull-out} = F_{stripping} + F_{bearing}$ (5)

$F_{pull-out} = S\pi D_{major}L + \frac{\pi}{4}(D_{major}{}^2 - D_{minor}{}^2)S\frac{L}{p}$ (6)



(*continued on next page*)

Table 5 (*continued*)

	Failure Mode	Failure Mechanism
Failure Mode 3	 $F_{pull-out} = S\pi(D_{major} + \frac{p}{\tan\theta})L$ (8) 	 $F_{pull-out} = S \times A_{projected}$ (7)

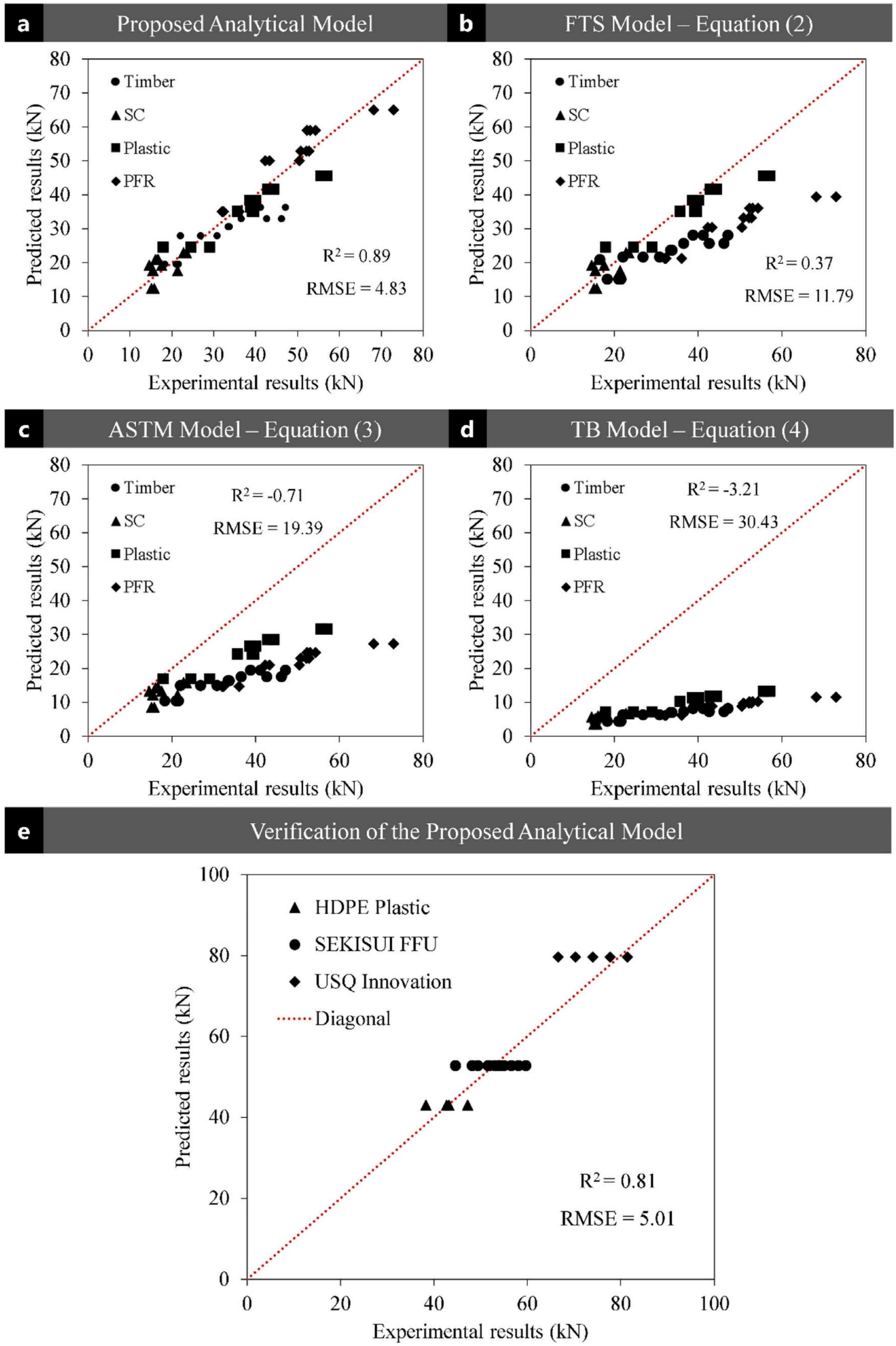


Fig. 4. Comparison between the a) proposed model and b) - d) existing prediction models, e) verification with the data from literature.

Table 6
Referenced sleeper technologies.

Sleeper Type	Fibre Reinforcement	Assumed Failure Mode	Shear Strength (MPa)	*Thread Embedded Length (mm)	Major Diameter (mm)
HDPE Plastic	No fibre	Failure Mode 1	8.1	76	22
Sekisui FFU	Longitudinally one-directional	Failure Mode 1	10.0	70	24
USQ	Multi-directional	Failure Mode 3	16.0	60	16

*The thread embedded length does not include the length of shank and conical area of the screw due to their minor contribution to pull-out.

than the thread stripping failure. The engaged area of sleeper material is assumed based on the observed crack path. As the mechanism of Failure Mode 3 demonstrated in Table 5(h), the main crack initiated from thread tips, propagated at approximately 30° (along the lower surface of external threads), and was assumed to stop at the horizontal level of the next thread tip. Hence, the diameter of the new projected shear area can be calculated as the sum of the screw's major diameter and the length of 'a' in the Failure Mode 3 mechanics in Table 5. The length of 'a' equals to $\tan\theta$ multiplied by the pitch of the screw. Equation (7) is modified from Eq. (2) by adopting the new projected shear fracture line. Equation (8) presents the full prediction equation for Failure Mode 3. The relation between the experimental and predicted values are provided in Table 5 (i). The R squared value for the prediction model is 0.93 while the RMSE is 4.66.

4.5. Verification and comparison with other models

This section compares the proposed analytical model for three failure modes of railway sleeper technologies with other existing models. The predicted results for the tested sleeper types are plotted against the experimental results measured in this work. The diagonal line in red is also plotted to provide a good understanding of the accuracy of each prediction model. Fig. 4(a) depicts the overall performance of the proposed analytical model. It is noticeable that the plotted points are well aligned with the diagonal line showing an R-squared value of 0.89 and RMSE of 4.83. In Fig. 4(b), Eq. (2) based on thread stripping failure did not show a good correlation with the experimental results, especially for timber and PFR. This is due to these two sleeper types have different pull-out failure modes other than thread stripping. Adopting the thread stripping model generally neglects the fact that more sleeper materials of timber and PFR were engaged in the pull-out behaviour resulting in larger axial shear resistance. It is noticeable that neither Fig. 4(c) illustrates that the predicted values from Eq. (3) are generally lower than the experimental results due to the effect of TSF (Thread Shape Factor). Rail screws generally have a low value of TSF due to relatively long pitch and thus a small number of threads [6,16,40]. In this study, the TSF ranges from 0.64 to 0.67 which largely decreases the predicted values, and thus, is not suitable for the prediction of rail screw pull-out. Compared to the prediction models discussed above, the thread bearing model (Eq. 4) not only exhibits the lowest predicted results but also shows almost no difference between different sleeper technologies. This is due to the fact that this model considers the thread bearing area, which is dependent on the thread number, to be the dominant factor instead of thread embedded length. In comparison, Eq. 4 seems to be more suitable for the prediction with a smaller pitch, hence a larger number of threads [27,38,39,60]. It can be concluded that the existing theoretical models provide less accurate results as these equations only consider the individual contribution of either the shear strength of the sleeper materials or the geometry of the screw. It is noticeable that the overall performance of the new prediction model is over 50% more reliable than the existing models. This highlights the need for a new theoretical prediction equation that can appropriately describe the pull-out behaviour of railway sleeper materials.

The overall prediction performance of the proposed model is further verified by the pull-out results measured by other researchers to enhance its reliability and applicability. To apply the new analytical model, the failure mode of the target sleeper technology needs to be determined to select the most suitable prediction equation. Eq. (1) was applied to predict the pull-out strength of the HDPE plastic and Sekisui FFU sleepers according to their fibre reinforcement as shown in Table 6. Lofty et al. [16] inserted the Ø22 mm rail screw with an effective thread length of 76 mm into the HDPE plastic sleeper having the shear strength of 8.1 MPa while Sekisui tested the pull-out strength of their FFU sleepers (10 MPa in shear) using the Ss 8–140 screw (24 mm of major diameter and 70 mm of thread embedded length) [33]. Additionally, Equation (8) was adopted to estimate the pull-out performance of the innovative composite sleeper developed by USQ [22] as the core material of this type of sleeper failed in a similar manner as the short-fibre-reinforced PFR. The inclining shear cracks were observed in the shear failure of both the phenolic sandwich beam [14] and the polymer bonding material [61]. The Ø16 mm rail screws having 6 mm pitch were installed in the rail-seat region with 60 mm-long threads embedded. Fig. 4(f) illustrates that the predicted strength is well aligned with the measured results from the literature. The proposed model shows an R squared value of 0.81 and a low RMSE of 5.01, which demonstrates that the capability of this new model to estimate the screw pull-out performance of current fibre-reinforced composite sleeper technologies.

5. Conclusions

This study experimentally investigated the effect of screw geometry on the screw pull-out behaviour in the rail-seat region of timber and composite railway sleepers. An analytical model based on pull-out failure modes was proposed to well predict the pull-out strength of different sleeper materials. Based on the results, the following conclusions are made:

- Increasing thread embedded length has a significant effect on the pull-out strength of timber and timber alternative sleepers, but has a very minimal effect on the normalised stress on the screw. This result indicates the sleepers' shear strength is fully utilised during pull-out. The higher shear strength the sleeper material exhibits, the greater influence the embedded length has.
- The increase in major screw diameter has a greater effect on the pull-out performance of hardwood timber than other sleeper technologies, same to the normalised stress. This is due to the timber's high axial shear resistance on the thread surface accompanied by the hole being lifted. The size of thread surface defined mainly by the major diameter thus has an important influence on timber's pull-out capacity.
- The two-way ANOVA demonstrates the greatest influence of material shear strength in the screw pull-out behaviour, closely followed by the effect of thread embedded length which is approximately two times higher than that of thread major diameter. The influence level of the shear strength is at 0.938 while the embedded length is at 0.882. The influence level of the major diameter is generally low on the composite sleepers but relatively high on timber.
- New analytical models considering the material shear strength, thread embedded length, screw major diameter and the failure mode were developed to predict the screw pull-out resistance of railway sleepers. The proposed model shows a relatively well agreement with

the experimentally tested sleeper types ($R^2 = 0.89$, RMSE = 4.83) and the referenced sleeper technologies from literature ($R^2 = 0.81$, RMSE = 5.01).

The above conclusions are drawn from the investigation on the effect of screw geometry on the pull-out behaviour of timber and timber-replacement composite sleeper technologies of this study. Researchers and design engineers are encouraged to conduct finite element analysis for a particular type of sleeper without building different models. Nevertheless, the experimental results and proposed analytical model could improve the understanding of screw pull-out behaviour of timber and alternative composite sleepers to facilitate their wide adoption in the maintenance of deteriorating railway tracks.

CRediT authorship contribution statement

Peng Yu: Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Tom Heyer:** Writing – review & editing, Funding acquisition. **Peter Schubel:** Writing – review & editing, Supervision, Funding acquisition. **Allan Manalo:** Writing – review & editing, Supervision, Methodology, Funding acquisition, Conceptualization. **Wahid Ferdous:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Choman Salih:** Writing – review & editing, Methodology. **Rajab Abousnina:** Writing – review & editing, Methodology.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Data will be made available on request.

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