Experimental and numerical study on the mechanical behavior of Kunststof Lankhorst Product (KLP) sleepers

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Abstract

This paper studies the mechanical behavior of two types of Kunststof Lankhorst Product (KLP) sleeper, namely low-density polyethylene sleeper (LDPE-16) and high-density polyethylene sleeper (HDPE-25) with 16 mm and 25 mm steel bars diameter, respectively, in static, dynamic and longtime static three points bending moment tests. Therefore, HDPE-25 and LDPE-16 with six strain gauges mounted on their steel bars, were manufactured to assess their mechanical responses. Moreover, a finite element method (FEM) model is developed to perform a sensitivity analysis based on different diameters of steel bars for HDPE with 16 mm (HDPE-16) and LDPE with 25 mm (LDPE-25). The results show that steel bars of LDPE-16 yielded under 4 hours of 30 kN load, while, HDPE-25 shows significant resistance. Numerical results show that HDPE-25 is overdesigned and can be replaced by LDPE-25 which has lower weight and price. The natural frequencies of HDPE-25 are almost 16%, 19%, 16% and 33% higher than the three first bending frequencies and first torsion frequency of LDPE-25, respectively, that proves the better performance of LDPE-25 in case of preventing resonance. Moreover,

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the bending modulus HDPE-25 is almost 42%, 45% and 65% is higher than HDPE-16, LDPE-25 and LDPE-16, respectively.

**Key words:** Hybrid polymer plastic sleeper; KLP sleeper; Railway ballasted track; Dynamic loading; Finite element method; Three bending moment test; composite sleeper

### 1. Introduction

Railway track components have been modified over the years such as ballast particles, fastening system and sleepers [1–3]. Railway sleeper is one of the crucial elements of railway track infrastructures which has a significant rule to support rails, providing the adequate lateral and longitudinal strength and transferring the forces from the rails to the ballast bed [4]. There are several kinds of sleepers that the most popular ones are manufactured from timber, steel and concrete. Despite some disadvantages as the biological degradation (timber rotting), firing and insect attacks, timber sleepers has already a good market among track owners [5]. Steel sleeper was created as an alternative of timber sleeper, with lighter weight, lower installation cost, higher lateral resistance but corrosion and electrical isolation problems [6–8]. The concrete sleepers, as another alternative for railway tracks implementation, can offer greater strength against higher axle load and longer durability compared to timber sleepers. Jing et al. [9] suggested to add sensors embedded within concrete sleepers for tracking railway track dynamic behavior which cannot be provided for steel and timber sleepers. But this type of sleeper also has its own limitations in railway track operation such as relatively heavyweight, high initial cost, lower damping and ductility [10–12] and consuming natural resources of environment [13]. Ferdous et al. [14] performed a comprehensive study on composite railway sleepers. It was concluded that limited knowledge on the
long-term and mechanical performance of new composite sleepers and alternative materials to timber sleepers reduces their application.

The history of the application of timber sleeper goes back to more than 150 years ago [15]. Currently, about 2.5 billion timber sleepers are used in railway network, worldwide [16]. Timber sleepers have been used for a long time in the railway industry, especially in the US [17] and Australia [18]. There are several researches that assess dynamic and static performance of timber sleepers [19–21]. Sadeghi et al. [22] studied the performance of timber sleeper in a three bending test. It shows that the timber sleeper subjected to a load of 30kN at the middle of sleeper, has a deflection around 4.2 mm. Song et al. [23] investigated the pressure distribution of timber sleeper under cyclic loading. It was concluded that with approximately 40 kN cyclic load timber sleeper faced a maximum pressure around 0.13 MPa in the middle of sleeper. Ferdous et al. [24] presented several main failure causes for timber sleepers as fungal decay, end splitting and termite attacks. These damage causes has been treated with toxic chemicals to destroy harmful organisms in timber and installing plates at timber sleeper ends to minimize their separations. Fig. 1 shows some common defects in timber sleepers.

Recently, composite sleepers are increasingly being used due to lower weight, thermal and electrical conductivity, and higher corrosion resistance, damping ratio and durability [25–27]. Composite sleepers are mostly regarded as a substitution for timber sleepers according to their geometrical and mechanical properties, especially in critical areas such as turnouts [28], bridges [29,30], and tunnels that damping and ductility features are more needed [31]. Recently, the new generation of KLP sleeper type with steel bars is offered to the market which has sufficient mechanical properties against high train axle loads. These sleepers have a better elasticity, low ballast abrasion index respect to elastic
contact between sleeper-ballast particles, and higher lateral and longitudinal stability for railway tracks [32]. In addition, they provide higher durability, easier transportation and installation, and sustainability concerning solid waste plastic materials. These sleepers are dominated by the polymer matrix, and typically manufactured from recycled plastics, for which the notable available products are TieTek [33], Axion [34] and Kunststof Lankhorst Product (KLP) [35] (see Fig. 2).

This kind of sleepers still needs more investigation; however, there are some related researches has been done. ISO standard [36] categorized plastic sleepers into three material types of (A), (B) and (C), based on the track operational features such as train axle load and speed. Material type (A) provides properties equivalent to tropical hardwood sleepers for track without ballast and special railway track operation, with maximum axle load of 200 kN and 140 kN for train speed of 130 km/h and 300 km/h, respectively. Material type (B) is equivalent to timber sleepers for UIC 5/6 track categories, with maximum 225 kN axle load for train speed of 160 km/h, and material type (C) is equivalent to hardwood sleeper for heavy-haul track with maximum axle load of 350 kN for train speed of 80 km/h. In the following Table 1 [36], some mechanical properties of plastic sleeper for adoption in the industry are presented based on ISO standard.

Nosker et al. [37] discussed the requirement of KLP sleepers to be used in the US as an alternative to timber sleepers. A bending test was performed on HDPE sleeper with 25 mm steel bar, and it demonstrates that the ultimate strength of sleeper exceeds 31 MPa. In a research done by Transportation Technology Center [38], the effect of temperature on the track vertical stiffness with plastic sleeper was quantified. The measurement data showed that the vertical track modulus with plastic sleeper was comparable to that with
oak-wood sleeper and was not significantly affected by the change of temperature within
the range of 57 degrees in the environment and 88 degrees in center of sleeper [38]. The
Federal Railroad Administration (FRA) [39] conducted a series of tests addressing the
influence of temperature and fastening system to the cracking and impact performance
of plastic sleepers. It was found that during the low-temperature tests, the overall
stiffness of sleeper increased significantly more than tests conducted at ambient and
elevated temperatures. The test results showed that the fastening system could cause a
significant reduction of resistance of the sleeper. Vijay et al. [40] completed a study about
the mechanical property of glass fiber reinforced plastic sleeper (GFRP) manufactured
with thermoplastics and continuous glass fiber. In this research, fatigue test, spike pull-
out test and field tests were carried out. Results showed similar strength and fatigue
resistance of these sleepers with those of the timber sleeper. Lotfy et al. [41] conducted a
study of the behavior and the long-term performance of the entire rail system with high-
density polyethylene (HDPE) sleeper using static and cyclic test methods. The outcomes
of this study showed the behavior of HDPE sleeper under the fatigue loading with normal
wear and minimal degradation.

Considering low fatigue strength and environmental resistance and a sharp reduction in
forest resources, as well as low structural properties, timber sleepers cannot be an option
for tracks concerning the increasing trend in the axle load and train speeds, and other
railways with tough operation conditions. Therefore, according to the literature review,
no one has addressed the static and dynamic behavior of the new generation of KLP
sleepers with steel bars that are very important for widespread adoption in railway
tracks as well as their modal behavior. Furthermore, a FEM modeling of KLP sleepers is
needed for more investigation of this new type of sleepers. Therefore, two types of KLP
sleeper as HDPE-25 and LDPE-16 that are already used in railway tracks, are studied in three bending moment tests in mechanical laboratory of TU Delft. They were investigated using static, dynamic and longtime flexural tests. Six strain gauges were mounted inside of each of these two sleepers to study yield behavior of steel bars in longtime bending moment test. A sensitivity analysis has been done to check the other steel bar diameters for HDPE and LDPE, to meet an optimization in structural and economical aspects of these sleepers. Therefore, HDPE-16 and LDPE-25 are also considered for the further analysis of mechanical behavior.

2. Material properties of KLP sleepers

Lankhorst Moldings Sneek-Holland [42] has designed two reinforced plastic sleepers that are more durable, namely HDPE sleeper and LDPE sleeper with 25 mm and 16 mm diameter of reinforcing steel bars. There are some differences between the KLP sleepers of HDPE and LDPE type. The LDPE has four reinforcement steel bars with 16 mm diameter and is manufactured from low-density polyethylene recycled plastic. The HDPE has four reinforcement steel bars with 25 mm and is manufactured from high-density polyethylene recycled plastic. Both types are proposed to be used in railway tracks (Type B), considering that LDPE has lower price, weight and mechanical properties. The characteristics of these two types of KLP sleeper are presented in Table 2.

3. Experimental study

3.1. Bending moment test

One of the criteria for the assessment of sleepers is the maximum bearing loading level which produces the first crack identified by operators using portable microscopes [42]. This method is mostly used for concrete sleepers based on AS1085.14-2009 [43], AREMA
2017 [44], TB/T 1879-2002 [45] and UIC-713R [46]. In this research, bending test is performed based on the ISO standard for plastic sleepers [36]. Two sleepers of H/LDPE with six strain gauges mounted on the steel bars are manufactured to study their behavior in flexural strength [47]. There are static, dynamic and longtime static 3-point bending tests performed for both KLP sleepers. During the tests, a metal rod is installed as the reference of zero point, and the deflection is measured by the displacement of the center of the beam relative to the reference rod using a displacement sensor of the linear variable differential transformer (LVDT) as can be seen in Fig. 3. The actuator loaded at the center of sleeper around 1250 mm from the end and the sleeper resting on two supports at a distance of almost 1500 mm from each other.

Fig. 4 shows that the six strain gauges are mounted at 400 mm (1/6 sleeper length), 900 mm (1/3 sleeper length) and 1250 mm (the sleeper center) from the left side of the sleeper on the steel bars at the top and bottom of sleeper. The strain gauges were connected to a data logger through wires that can be seen in Fig. 4. Strain gauges were prepared from TML Company, the type suitable for use on steel material, and the data logger is TMR manufactured by TML Company.

3.1.1. Static bending moment test

Three static 3-point bending tests were performed for both H/LDPE sleepers with different loading speeds. The sleeper was loaded with a preload of 2 kN, and then the load was increased with three speeds of 0.5 kN/s, 1 kN/s and 2 kN/s. The load reached to maximum value at sleeper failure and then decreased to 2 kN loading level with the same loading speed. The maximum load of H/LDPE then is used in Equation 1 to calculate flexural strength (MPa) of sleepers ($\sigma_f$) and compare it with ISO standard (Table 1). The Equation 1 is as follows:
\[ \sigma_f = \frac{3FL}{2bh^2} \]  

where \( F \), \( L \), \( b \) and \( h \) indicate maximum applied load (N), span of supports (mm), sleeper width (mm) and sleeper height (mm), respectively.

3.1.2. Dynamic bending moment test

The dynamic 3-point bending tests were carried out for both H/LDPE sleepers. The dynamic loading had a cyclic load between 3 kN and 30 kN which were applied to the sleeper with the frequency of 5 Hz.

3.1.3. Longtime static bending moment test

A longtime static test was also performed for both H/LDPE sleepers. A load of 30 kN was applied for 4 hours. After 4 hours, the full load was removed, completely, and the measurement continued for another 12 hours. This measurement was recorded by a sampling frequency of 0.1 Hz.

3.1.4. Results and discussion

Fig. 5(A) shows that the minimum speed of loading has maximum deflection as 4.2 mm. Also, it can be seen that after unloading, the deflection of HDPE-25 returned back to the original position. However, a little plastic deformation remained about 0.3 mm. In Fig. 5(B), the 5 Hz cyclic load was applied in a 3-point bending test to the HDPE-25. A slight increase can be seen for the deflection from 3.2 mm at the beginning of the first cycle to 3.5 mm at the last cycle of loading. It can be seen that the deflection of sleeper with a little plastic deformation of 0.1 mm returned back to the first position. Fig 5(C) shows the results of the 4-hour static 3-point bending moment test of the HDPE-25. The deflection of the longtime test is considerably greater than the deflection of the static and dynamic
tests. It also has a higher value of plastic deformation of 0.5 mm after unloading, which reveals a lower strength against fatigue load compared to previous static and dynamic tests.

In Fig. 6, the strains of the HDPE-25 can be seen during the 4-hour static 3-point bending moment test. It shows that those strain gauges mounted closer to the loading zone of sleeper measured more strains. C1 strain gauge detected the maximum strain value of 1000 µε, which is followed by B1 with 600 µε. These strain gauges are located at the bottom of the loaded part of the sleeper where steel bars are under significant tensile stresses. Other strain gauges do not experience high tensile or compressive stresses due to high resistance of sleeper against the 30 kN loading level.

Fig. 7(A) shows the results of the static 3-point bending moment test of the LDPE-16. As it is expected, the lower speed of the loading (0.5 kN/s loading speed) results in higher deflection as 8.7 mm. Fig. 7(B) shows the 5 Hz dynamic 3-point bending moment test of the LDPE-16. As the cyclic loading time increases, the deflection of sleeper increases, slightly, from 6.8 mm at the first cycle to 7.2 mm at the last cycle. Fig. 7(C) shows the 4-hour static 3-point bending moment test of the LDPE-16 sleeper. It shows a much bigger deflection compared to that of HDPE-25 and two other static and dynamic tests, which means a lower strength of sleeper against fatigue loading.

In Fig. 8, the strains can be seen during the 4-hour static 3-point bending moment test of the LDPE-16. The strain gauge C1, which was located under the force, shows a larger strain than others. There is a peak in the strain of C1 from -2000 µε to -2500 µε; it shows that the steel bar yields due to the 30 kN loading level after around three and half hours of loading.
After calculation of flexural strength of two HDPE-25 and LDPE-16 as 28 MPa and 20 MPa, respectively, it can be concluded that the HDPE-25 and LDPE-16 both can be used for railway tracks based on standard (≥18 MPa); however, considering longtime static test, LDPE-16 is failed and cannot be used. When the LDPE-16 was loaded with 30 kN for a longtime (4-hour), the reinforcing steel bar yielded, therefore, the LDPE-16 does not meet the standard requirement. The comparison between flexural strengths of KLP sleepers and timber sleeper shows that timber sleeper made of hardwood – oak has middle flexural strength by 41 kN [22] which means almost 40% less than HDPE-25 and 15% more than LDPE-16.

3.2. Impact hammer test

An impact hammer test is performed for HDPE-25 as the mostly used plastic sleeper to present natural frequencies of this sleeper and also validate the results of numerical modeling for frequency analysis. This sleeper has been chosen because can pass all mechanical tests. Using the impact hammer test and ten accelerometers located on the HDPE-25 at a distance of 275 mm from each other, the natural frequencies are achieved [48]. Natural frequencies of sleeper are important to develop a realistic dynamic model of the railway track as well as the sleeper itself, which are capable to predict its dynamic responses. Impact hammer test is one of the popular methods for doing modal analysis of structures [49–51]. For preparing the free-free condition, the sleeper was placed on two wooden blocks at both ends. The impacts were applied in three places, as can be seen in Fig. 9. Impacts are applied five times at each location, in order to prevent errors in the measurement. The results were incorporated in the Matlab program [52]. Using Fast Fourier Transformer (FFT), the accelerations were converted to the frequency domain to obtain dominant frequencies of HDPE-25 [29].
Dominant frequencies of HDPE-25 are calculated in Fig. 10. It is shown that the first, second and third natural frequencies of HDPE-25 are almost 37.5 Hz, 156.3 Hz and 237.5 Hz, respectively. This results in the following sections will be used for validation of frequency analysis in FEM sensitivity analysis. Dominant frequencies of timber and HDPE sleeper are calculated in Fig. 10. It is shown that the first dominant frequency of HDPE as 37.5 Hz has almost 35% reduction compared to that of timber as 57.2 Hz. It should be considered that the amplitude of timber sleeper’s frequencies is about ten times of that of HDPE which shows the better performance of HDPE sleeper in damping of vibrations. Damping ratio of KLP sleeper is obtained as 0.34 based on modal analysis results which is almost 8% higher than that of timber sleeper as 0.31.

4. Sensitivity analysis

4.1. FEM model development

To analysis the behavior of H/LDPE sleepers, a numerical modeling is developed. The steel bars configurations can be seen in Fig. 11. There are four steel bars at the four corners of sleepers. The Hex mesh was chosen for the discretization of each instance. The mesh size of steel bars and sleepers are 50 cm and 10 cm, respectively. A mesh size analyze was performed to check the finer mesh sizes on the final results. A static load with a loading rate of 2 kN/s is applied to the sleepers at the middle point. The sleepers are rested as simply supported beam for boundary conditions. This section aims to categorize the application of four sleepers as HDPE-25, LDPE-16, HDPE-16 and LDPE-25 based on numerical study.

4.2. Model validation
To validate the numerical model with the experiment, the static bending test is considered as Fig. 12. The loading rate of numerical model has been selected as well as 2 kN/s loading speed in experimental study. As can be seen in Fig. 13, the deflections of H/LDPE sleepers in numerical modeling are almost identical to the maximum deflection values of the experiment results. The difference of the maximum deflections for HDPE and LDPE between numerical modeling and experiment are 4 % and 2 %, respectively.

4.3. Natural frequencies of KLP sleepers

To plot the mode shapes of the sleeper and compare it with the experimental results, a modal analysis is developed using numerical modeling. As can be seen from Table 3, the first, second and third natural frequencies of the numerical model and experiment for HDPE-25 are almost identical. It can prove the validation of HDPE-25 vibrational properties in the numerical model. A further frequency analysis was performed to compare the natural frequencies of H/LDPE-25 and L/HDPE-16. The results show that in first bending mode shape that steel bar is directly engaged in deforming, higher diameter of steel bar shows higher natural frequencies as the highest belongs to HDPE-25 as 37 Hz, which is followed by 31 Hz, 28.5 Hz and 24 Hz. From second to fifth mode shapes, also the higher frequencies belong to HDPE-25 & 16. In torsion mode shape just the material type are effective on the performance of sleeper because none of these sleepers have stirrup for bounding steel bars. As can be seen, HDPE-25 & 16 have higher frequencies than LDPE-16 & 25 due to higher mechanical properties. Considering the actuation frequencies of railway track due to dynamic loads which are mostly in the range of 200 Hz to 300 Hz [3,53], it is better that the sleeper keep the maximum distance with theses frequencies to avoid track resonance. Therefore, HDPE-25 shows the closest and LDPE-16 shows the furthest frequencies compared with other KLP sleepers.
4.4. Maximum stresses of KLP sleepers

ISO standard [36] provides guidelines for calculating reference test loads for plastic sleeper types. A three bending moment test is simulated, and the results are reported in the following sections. A static load with the loading speed rate of 2 kN/s is applied to the sleepers, and the corresponding stresses are presented. Table 4 shows the material properties used in the model. Sleeper is modeled as a simply supported beam by 1500 mm distance between supports.

The validated models based on the maximum deflection of sleepers are used for presenting the corresponding stresses of H/LDPE sleepers. As can be seen in Fig. 14, the maximum stresses for both H/LDPE sleepers appeared on steel bars which means the most stresses are transferred to steel bars that results in less stresses on the composite. Fig. 15 shows that the maximum stress in the HDPE-25 and LDPE-25 steel bars are 0.13 GPa and 0.19 GPa, respectively, with almost 30% difference; while the corresponding stresses in composite are around 5.22 MPa and 5.3 MPa with almost 1% difference. This difference show that the identical steel bars banned stresses to be transferred to composite, but LDPE-25 steel bars had to bear higher stresses. For HDPE-16 and LDPE-16, the maximum stress in composites are around 4 MPa and 3.3 MPa, respectively, with approximate 17% difference, and in steel bars, stresses are 0.2 GPa and 0.15 GPa with almost 25% difference. Due to lower diameter and resistance of 16 mm steel bars, there are some level of stresses transferred to the composite that may failure in high rates of loading and longtime service.

Fig. 16 shows the yield zone of steel bars for each sleeper. HDPE-25 has higher flexural strength around 68 kN that shows a little overdesigned and economically cannot be acceptable. LDPE-16 has the less flexural strength compared to the others with 35 kN.
Two other new designs as HDPE-16 and LDPE-25 that are studied based on sensitivity analysis show 33 kN and 63 kN flexural strength, respectively. Therefore, it can be concluded that LDPE-25 can be substitution for HDPE-25 in railway tracks with lower weight and price but almost the same flexural strength.

4.5. Bending modulus calculation

The bending modulus represents the ratio of stress to corresponding strain of the material within the elastic region. Stiff materials demonstrate a high modulus and ductile materials exhibit a low modulus. In this study bending modulus for all four designed sleepers has been calculated using FEM results and Equation 2 based on ASTM D790 standard [54]. Fig. 17 shows the bending modulus values of HDPE-25/16 and LDPE-25/16.

\[
E = \frac{L^3F}{4wh^3d}
\]

where \(w, h, L, d\) and \(F\) indicate the width and height of the sleeper, the distance between the two outer supports, and the deflection and the load applied at the middle of the sleeper.

As can be seen, HDPE-25 has maximum bending modulus with almost 0.6 MPa which is followed by HDPE-16, LDPE-25 and LDPE-16 with maximum bending modulus values of 0.32 MPa, 0.3 MPa and 0.2 MPa, respectively. The bending modulus HDPE-25 is almost 42%, 45% and 65% is higher than HDPE-16, LDPE-25 and LDPE-16, respectively.

5. Conclusions

Increasing axle loads and train speeds have motivated researchers and track owners to consider designing new types of sleepers. Recently, several composite sleepers have been
developed worldwide, but still, new designed types are proposed, such as KLP sleepers. Particularly with the development of railway track where timber sleepers are used, track components experience greater dynamic impacts and consequently experience accelerated degradation and shorter life span. Considering existing limitations of timber sleeper use, producing a new generation of KLP sleepers with steel bars that can provide more damping and higher mechanical properties is becoming essential. In this study, the mechanical behavior of HDPE-25 and LDPE-16 as two current KLP sleepers were studied and a numerical modeling is accordingly developed to analysis the behavior of HDPE-16 and LDPE-25. The highlighted results of the current study are presented as follows:

1. Both sleepers of HDPE-25 and LDPE-16 show less bending resistance against longtime static loading with bigger deflection around 5.75 mm and 11.7 mm, respectively, under a 4-hour load of 30kN. Strain results of steel bars in the middle of sleeper under loading zone show that the steel bars of LDPE-16 yielded under 30 kN loading in a longtime static test.

2. The higher natural frequencies belong to HDPE-25 as 37 Hz, 155.8 Hz, 236 Hz and 60.23 Hz. Considering the actuation frequencies of train wheels in the range of 200 Hz to 300 Hz, LDPE-25 has the furthest natural frequencies as 31 Hz, 125.67 Hz, 169.92 Hz and 40.31 Hz from actuation frequencies.

3. According to numerical bending test results, HDPE-25 has higher flexural strength around 68 kN. LDPE-16 has the less flexural strength compared to the others with 35 kN. Two other new designs of HDPE-16 and LDPE-25 that are studied based on sensitivity analysis show 33 kN and 63 kN flexural strengths, respectively. Therefore, it can be concluded that HDPE-25 can be substituted by LDPE-25 in railway tracks with lower weight and price, but almost identical flexural strength.
4. The maximum stress in the HDPE-25 and LDPE-25 steel bars are 0.13 GPa and 0.19 GPa, respectively, with almost 30% difference; while the corresponding stresses in composite are around 5.22 MPa and 5.3 MPa with almost 1% difference. This difference show that the identical steel bars banned stresses to be transferred to composite, but LDPE-25 steel bars had to bear higher stresses. For HDPE-16 and LDPE-16, the maximum stress in composites are around 4 MPa and 3.3 MPa, respectively, with approximate 17% difference, and in steel bars, stresses are 0.2 GPa and 0.15 GPa with almost 25% difference. Due to lower diameter and resistance of 16 mm steel bars, there are some level of stresses transferred to the composite that shows this 16 mm diameter of steel bar is not suitable for KLP sleepers for type (B) railway tracks.

5. HDPE-25 has maximum bending modulus with almost 0.6 MPa which is followed by HDPE-16, LDPE-25 and LDPE-16 with maximum bending modulus values of 0.32 MPa, 0.3 MPa and 0.2 MPa, respectively. The bending modulus HDPE-25 is almost 42%, 45% and 65% is higher than HDPE-16, LDPE-25 and LDPE-16, respectively.

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Conflict of interest

None.

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Figure captions:

Fig. 1. The timber sleepers’ defects that mostly are seen in the field due to the environmental effects (A) and (B) overloading (Photo credit: G. Jing).

Fig. 2. Cross section of KLP sleepers (HDPE) (A) without steel bar and (B) with steel bars and (C & D) Tietek sleeper used in China (Photo credit: G. Jing).

Fig. 3. An overview of experimental test, including (A) Placement of sleeper and (B) LVDT location.

Fig. 4. Location of strain gauges in sleepers body and unit (cm).

Fig. 5. (A) Static, (B) dynamic and (C) longtime static bending tests of HDPE-25.

Fig. 6. Strains of longtime static 3-point bending test for HDPE-25.

Fig. 7. (A) Static, (B) dynamic, and (C) longtime static bending tests of LDPE-16.

Fig. 8. Strains of longtime static 3-point bending test for LDPE-16.

Fig. 9. Configuration of sensors and impacts on the HDPE-25 sleeper.

Fig. 10. Dominant frequencies of (A) HDPE-25 and (B) timber sleeper in free vibration analysis.

Fig. 11. Steel bars configuration for KLP sleepers; (A) H/LDPE-25 and (B) L/HDPE-16.

Fig. 12. An overview of three bending moment test of KLP sleepers.

Fig. 13. Validation of FEM results with bending moment test of sleepers; (A) HDPE and (B) LDPE

Fig. 14. Stress distribution (Pa) of the center bending test of sleepers and steel bars for HDPE-25; LDPE-16; HDPE-16; and LDPE-25.

Fig. 15. (A) Maximum stress of KLP sleepers in composite, and (B) maximum stress of KLP sleepers in steel bars.

Fig. 16. Load-center displacement relationship for KLP sleepers.

Fig. 17. Bending modulus values based on FEM results for HDPE-25&16 and LDPE-25&16 sleepers.

Table captions:

Table 1. Mechanical properties plastic sleepers according to ISO standard [36].

Table 2. Characteristics of KLP sleepers, including H/LDPE.

Table 3. Natural frequencies and mode shapes of four different KLP sleepers.
Table 4. Material properties of H/LDPE sleepers used in FEM modeling of bending moment test.

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<table>
<thead>
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<th>EN ISO Standard</th>
<th>Bending Strength (MPa)</th>
<th>Flexural Modulus (MPa)</th>
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Table 2. Characteristics of KLP sleepers, including H/LDPE.

<table>
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<th>Bending modulus</th>
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</tbody>
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Fig. 5. (A) Static, (B) dynamic and (C) longtime static bending tests of HDPE-25.

Fig. 6. Strains of longtime static 3-point bending test for HDPE-25.

Fig. 7. (A) Static, (B) dynamic, and (C) longtime static bending tests of LDPE-16.
Fig. 8. Strains of longtime static 3-point bending test for LDPE-16.

Fig. 9. Configuration of sensors and impacts on the HDPE-25 sleeper.

Fig. 10. Dominant frequencies of (A) HDPE-25 and (B) timber sleeper in free vibration analysis.
Fig. 11. Steel bars configuration for KLP sleepers; (A) H/LDPE-25 and (B) L/HDPE-16.

Fig. 12. An overview of three bending moment test of KLP sleepers.

Fig. 13. Validation of FEM results with bending moment test of sleepers; (A) HDPE and (B) LDPE
Table 3. Natural frequencies and mode shapes of four different KLP sleepers.

<table>
<thead>
<tr>
<th>Mode shape No.</th>
<th>Natural frequencies (Hz)</th>
<th>Mode shapes</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>HDPE-25</td>
<td>LDPE-16</td>
</tr>
<tr>
<td>1st bending mode shape</td>
<td>37</td>
<td>24</td>
</tr>
<tr>
<td>2nd bending mode shape</td>
<td>155.8 Hz</td>
<td>122.14</td>
</tr>
<tr>
<td>3rd bending mode shape</td>
<td>236 Hz</td>
<td>193.42</td>
</tr>
<tr>
<td>4th bending mode shape</td>
<td>366</td>
<td>323</td>
</tr>
<tr>
<td>5th bending mode shape</td>
<td>469</td>
<td>426</td>
</tr>
<tr>
<td>1st torsion mode shape</td>
<td>60.23</td>
<td>44.4</td>
</tr>
</tbody>
</table>

Table 4. Material properties of H/LDPE sleepers used in FEM modeling of bending moment test.

<table>
<thead>
<tr>
<th>Sleeper properties</th>
<th>Density (kg/m²)</th>
<th>Elastic modulus (MPa)</th>
<th>Poisson's ratio</th>
<th>Plasticity modulus (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Composite</td>
<td>HDPE 870</td>
<td>800</td>
<td>0.4</td>
<td></td>
</tr>
<tr>
<td></td>
<td>LDPE 870</td>
<td>325</td>
<td>0.4</td>
<td></td>
</tr>
<tr>
<td>Steel bars</td>
<td>7850</td>
<td>210000</td>
<td>0.3</td>
<td>235</td>
</tr>
</tbody>
</table>
HDPE-25 mm

LDPE-16 mm

HDPE-16 mm
Fig. 14. Stress distribution (Pa) of the center bending test of sleepers and steel bars for HDPE-25; LDPE-16; HDPE-16; and LDPE-25.

Fig. 15. (A) Maximum stress of KLP sleepers in composite, and (B) maximum stress of KLP sleepers in steel bars.
Fig. 16. Load-center displacement relationship for KLP sleepers.

Fig. 17. Bending modulus values based on FEM results for HDPE-25&16 and LDPE-25&16 sleepers.

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