Impact capacity reduction in railway prestressed concrete sleepers with vertical holes

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Abstract. Railway prestressed concrete sleepers (or railroad ties) are principally designed in order to carry wheel loads from the rails to the ground as well as to secure rail gauge for dynamic safe movements of trains. In spite of the most common use of the prestressed concrete sleepers in railway tracks, the concrete sleepers are often modified on construction sites to fit in other systems such as cables, signalling gears, drainage pipes, etc. This is because those signalling, fibre optic, equipment cables are often damaged either by ballast corners or by tamping machine. It is thus necessary to modify concrete sleepers to cater cables internally so that the cables or drainage pipes would not experience detrimental or harsh environments. Accordingly, this study will extend from the previous study into the design criteria of holes and web openings. This paper will highlight structural capacity of concrete sleepers under dynamic transient loading. The modified compression field theory for ultimate strength design of concrete sleepers will be highlighted in this study. The outcome of this study will improve the understanding into dynamic behavior of prestressed concrete sleepers with vertical holes. The insight will enable predictive track maintenance regime in railway industry.

1. Introduction

Railway is one of the most efficient and effective modes of transportation, conveying cargo, passengers, minerals, grains, and so forth. Notably, railway prestressed concrete sleepers have been used in railway industry for over 50 years [1-5]. In general, railway sleepers (or called ‘railroad ties’ in North America) are a main part of railway track structures. The sleepers can be made of timber, concrete, steel or other engineered materials [6]. They have been systemically introduced to railway industry for many decades ago and currently are introduced in almost every railway network in the world. The main duties of sleepers are: (a) to transfer and distribute loads from the rail foot to the underlying ballast bed, (b) to hold the rails at the proper gauge through the rail fastening system, (c) to maintain rail inclination, and (d) to restrain longitudinal, lateral, and vertical movements of the rails and the rail gauge for safe passages of rolling stocks. It is important to note that railway sleepers are a structural and safety-critical component in railway track systems [7-15]. Therefore, the sleeper design and analysis must be ascertained to assure public safety and operational reliability. Critical performance criteria such as static capacity, dynamic strength and ultimate impact loading capacity should be evaluated as each property are mutually important and interconnected. Although the quasi-static capacity is often adopted in design process, the failure modes of the structural component must be known [16-17].
Railway track structures often experience impact loading conditions due to wheel/rail interactions associated with abnormalities in either a wheel or a rail [18]. All static, quasi-static, and impact loads are very important in design and analysis of railway track and its components. Generally, dynamic shock loading corresponds to the frequency range from 0 to 2000 Hz due to modern track vehicles. The shape of impact loading varies depending on various possible sources of such loading, e.g. wheel flats, out-of-round wheels, wheel corrugation, short and long wavelength rail corrugation, dipped welds and joints, pitting, and shelling. Wheel/rail irregularities induce high dynamic impact forces along the rails that may greatly exceed the static wheel load. In all cases, the impact forces are significantly dependent on the train speed. These impulses would occur repetitively during the roll. Loss of contact between wheel/rail, so-called “wheel fly”, will occur if the irregularity is large enough, or the speed is fast enough. However, the impact force could be simplified as a shock pulse acting after the static wheel load is removed. The typical magnitude of impact loads from the reviewed cases [4] varies roughly between 200 kN and up to 750 kN, depending on the causes and the traveling speed of train. The durations of such loads are quite similar, varying between 1 and 10 msec. However, the representative values of the first peak (P1) of the forces caused by dipped joints should be about 400 kN magnitude with 1 to 5 msec time duration. For the second peak (P2), the average values are about 80 kN magnitude and 5 to 12 msec time duration. Therefore, it should be taken into account that the typical duration of impact wheel forces varies widely between 1 and 12 msec [5-7]. Note that these actual loading conditions are different to the loading conditions specified in type testing methods of sleeper standards [1, 10]. This is because the type testing methods are commonly used for benchmarking purpose.

Currently, railway track components are often being modified at construction sites to fit with signaling gears, cables, and additional train derailment protections, such as guard rails, check rails, Earthquake protection rails, etc. [19-21]. The practical guideline for crosstie retrofit has not been well established and many attempts were carried out based on trials and errors. Despite a common task in construction site, the behavior of holes and web openings on concrete crossties has not been well documented in open literature. In this manner, it is important to ensure that concrete crossties can be retrofitted and modified for add-on fixture in practice. The emphasis of this study has been placed on the impact capacity of the crossties with vertical holes (e.g. for bolting and fixture of automatic train control system). The insight into these behaviors will not only improve safety and reliability of railway infrastructure, but will enhance the structural safety of other concrete structures.

2. Prediction for ultimate moment capacity

2.1 Modified compression field theory
In this study, the moment curvature has been used to represent the capacity of prestressed concrete sleepers. The moment capacity are predicted by the modified compression field theory using Response-2000 [22]. This theory is capable of predicting the behaviour of reinforced concrete subjected to in-plane shear and normal stresses. The concrete stresses in principal directions along with prestressing steel are considered in only axial direction and uncracked portion will carry on to sustain a load in the analysis [23].

\[
\frac{f'_{c,dyn}}{f'_{c,cat}} = 1.49 + 0.268 \log_{10}\varepsilon + 0.035[\log_{10}\varepsilon]^2
\]  

(1)
Prestressing wires:

\[
\frac{f_{y,\text{dyn}}}{f'_{y,\text{st}}} = 10^{0.38\log_{10} \varepsilon - 0.258} + 0.993
\]  

(2)

Where \( f_{y,\text{dyn}} \) is the dynamic upper yield point stress, \( f'_{y,\text{st}} \) is the static upper yield point stress of prestressing wires (about 0.84 times proof stress), and \( \dot{\varepsilon} \) is the strain rate in tendon.

3. Material properties

In this study, there are 1 prestressed concrete sleeper with full cross section and 4 sleepers with a vertical hole, as shown in Figure 1. The position of the vertical hole is at the middle between the sleeper end and the edge of rail seat. It is interesting to note that the size of the vertical hole are varied from 20 mm to 50 mm.

![Figure 1. Prestressed concrete sleepers a) Full cross section b) with vertical hole.](image)

3.1 Static

The dimension and shape of prestressed concrete sleepers are shown in Figure 1. The high strength concrete was used with the design cylinder compressive strength of 55 MPa. The stress-strain curve of concrete derived by Vechio and Collin [23] was used in this study, as shown in Figure 2. The 22-prestressing steels used were the high ultimate strength with rupture ultimate strength of 1860 MPa, as shown in Figure . The initial elastic modulus of prestressing steel was 20000 MPa.

![Figure 2. Stress-strain curve of a) concrete b) steel.](image)

3.2 Dynamic

The prediction of moment capacity has been carried out using the data obtained from the previous experiments [25-26]. It should be noted that the average total duration of impact forces is about 4 ms.
In this study, the strain rate of concrete is varying from 2 ms to 8 ms. It is well known that the dynamic ultimate strain of prestressing steel is about $20 \times 10^3$, and the total duration of impact force influencing the steel fibre is roughly from 6 ms to 12 ms. This is because the impact stress wave delays during the stress propagation and will be impeded through concrete [24]. Using Equation. (1) and (2), the dynamic strength of materials can be obtained as the input for the sectional analysis. The 4 pairs of strain rates variations are used in this study, as shown in Table 1.

| Material          | A | B | C | D |
|-------------------|---|---|---|---|
| Concrete          | 2 | 4 | 6 | 8 |
| Prestressing wires | 6 | 8 | 10| 12|

### 4. Results and discussions

#### 4.1 Static analysis

In general, the first stage of the behavior of material is elastic range when there is no damage in the material and the applied external force is less than the proportional limit. Then, when the moment reaches the proportional yield point, the nonlinear behaviour takes place till the member reaches the ultimate capacity. After that, the curve drops rapidly due to the crushing and spalling of concrete.

The effect of vertical hole in the prestressed concrete sleepers is evaluated by the moment capacity. The obtained results indicate that the vertical hole in prestressed concrete sleepers can affect the moment capacity due to the reduction in cross sectional area. Figure 3 illustrates the moment curvature of prestressed concrete sleepers. It can be clearly seen that the ultimate moment capacity of prestressed concrete sleepers without a vertical hole is about 60 kNm which is more than the moment capacity of all sleepers with a vertical hole.

![Figure 3. Moment-Curvature comparison between 5 prestressed concrete sleepers.](image)

Table 2 displays the comparison of recorded moment capacity between the prestressed concrete sleepers with and without vertical hole. There are 2 conditions, crack and fail, can be determined from the modified compression field theory. It can be observed that the first crack of the sleepers is between 25-32 kNm and the fail condition is about 51-60 kNm. It can be clearly seen that when the vertical hole increase in diameter, reducing in width and cross sectional area, the moment capacity decrease.
Table 2. Moment capacities of prestressed concrete sleepers under static loading.

| Section   | Target conditions | Recorded moment capacity (kNm) |
|-----------|-------------------|--------------------------------|
| Full section | Crack             | 31.86                          |
|           | Fail              | 59.34                          |
| 20 mm hole | Crack             | 29.56                          |
|           | Fail              | 56.67                          |
| 30 mm hole | Crack             | 28.33                          |
|           | Fail              | 55.14                          |
| 40 mm hole | Crack             | 27.01                          |
|           | Fail              | 53.57                          |
| 50 mm hole | Crack             | 25.64                          |
|           | Fail              | 51.90                          |

4.2 Dynamic analysis

Figure 4 and Table 3 illustrate the moment curvature of the prestressed concrete sleepers under impact loading. It can be clearly seen that the trend of moment-curvature relationship under impact loading are similar to static loading but it is interesting that the ultimate moment capacity is more higher. Apart from that, it is observed that strain rate play a significant role in impact loading and moment capacity. It can be seen that when the strain rate increase, the moment capacity also increase.

Figure 4. Moment-Curvature of prestressed concrete sleepers between 4 differences strain rate
a) Case A b) Case B c) Case C d) Case D.
Table 3. Moment capacities of prestressed concrete sleepers under impact loading.

| Section       | Target conditions | A   | B   | C   | D   |
|---------------|-------------------|-----|-----|-----|-----|
| Full section  | Crack             | 31.98 | 32.572 | 32.92 | 33.17 |
|               | Fail              | 69.79 | 70.89 | 71.50 | 72.02 |
| 20 mm hole    | Crack             | 29.64 | 30.26 | 30.59 | 30.84 |
|               | Fail              | 67.63 | 68.69 | 69.49 | 69.96 |
| 30 mm hole    | Crack             | 28.36 | 28.97 | 29.33 | 29.58 |
|               | Fail              | 66.32 | 67.59 | 68.17 | 68.78 |
| 40 mm hole    | Crack             | 26.70 | 27.61 | 27.97 | 28.24 |
|               | Fail              | 65.03 | 66.30 | 67.04 | 67.48 |
| 50 mm hole    | Crack             | 25.63 | 26.21 | 26.56 | 26.81 |
|               | Fail              | 63.61 | 64.83 | 65.61 | 66.20 |

Figure 5 illustrates the relationship between percentage of ultimate moment capacities reduction of prestressed concrete sleepers and percentage of area reduction. Ultimate capacities reduction can be calculated from Eq.(3).

\[
\text{Ultimate moment reduction (\%)} = \left( \frac{M_{\text{full cross section}} - M_{\text{with vertical hole}}}{M_{\text{full cross section}}} \right) \times 100
\]  

Figure 5. The ultimate moment reduction-area reduction relationship.

The moment capacities reduction show a linear upward trend when the cross sectional area are reduced. This indicates about nearly 10% reduction of moment capacities by about 20% reduction in cross sectional area. Moreover, it is interesting to note that, at the same percentage of area reduction, the moment capacity of sleepers with the lower strain rate is greater than that with higher strain rate.

5. Conclusions
This study is the world first to investigate the effect of vertical holes on the impact capacity of railway prestressed concrete sleepers. It exhibits that the vertical holes undermine strength and impact capacity of railway concrete sleepers. Therefore, it is essentially important for track and rail engineers to assure that the modification or retrofitting of concrete sleepers at construction sites is carried out in a proper manner. By the results obtained from these unprecedented studies, the vertical hole can reduce almost 10% of dynamic load bearing capacity of the sleepers and such the hole also results in significant reduction of moment-curvature area, resulting in impaired structural ductility. The insight into the impact behavior of the concrete sleepers with vertical holes will enable safer built environments in
railway corridor, especially for concrete sleepers whose structural inspection is very difficult in practice.

Acknowledgements
The authors would also like to thank British Department of Transport (DfT) for Transport - Technology Research Innovations Grant Scheme, Project No. RCS15/0233; and the BRIDGE Grant (provided by University of Birmingham and the University of Illinois at Urbana Champaign). The first author would like to express his gratitude for the PhD scholarship provided from the Birmingham Centre for Railway Research and Education and the School of Engineering at the University of Birmingham. The last author gratefully acknowledges the Japan Society for the Promotion of Science (JSPS) for his JSPS Invitational Research Fellowship (Long-term), Grant No L15701, at Track Dynamics Laboratory, Railway Technical Research Institute and at Concrete Laboratory, the University of Tokyo, Tokyo, Japan. The authors are sincerely grateful to European Commission for the financial sponsorship of the H2020-RISE Project No. 691135 “RISEN: Rail Infrastructure Systems Engineering Network,” which enables a global research network that tackles the grand challenge in railway infrastructure resilience and advanced sensing in extreme environments (www.risen2rail.eu). We would also like to acknowledge the support from European Cooperation in Science and Technology (EU-COST) Action: TU1404 Towards the next generation of standards for service life of cement-based materials and structures.

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