Design of holes and web openings in railway prestressed concrete sleepers

Erosha Kahawatta Gamage
University of Birmingham

Sakdirat Kaewunruen
University of Birmingham, sakdirat@hotmail.com

Alex M. Remennikov
University of Wollongong, alexrem@uow.edu.au

Design of holes and web openings in railway prestressed concrete sleepers

Abstract

As the crosstie beam in railway track systems, the prestressed concrete sleepers (or railroad ties) are principally designed in order to carry wheel loads from the rails to the ground. Their design takes into account static and dynamic loading conditions. It is evident that prestressed concrete has played a significant role as to maintain the high endurance of the sleepers under low to moderate repeated impact loads. In spite of the most common use of the prestressed concrete sleepers in railway tracks, there have always been many demands from rail engineers to improve serviceability and functionality of concrete sleepers. For example, signalling, fibre optic, equipment cables are often damaged either by ballast corners or by tamping machine. There has been a need to re-design concrete sleeper to cater cables internally so that they would not experience detrimental or harsh environments. Accordingly, this study will investigate the design criteria and effects of holes and web openings on structural capacity of concrete sleepers under rail 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 enable the new design and calculation methods for prestressed concrete sleepers with holes and web opening that practically benefits civil, track and structural engineers in railway industry.

Disciplines

Engineering | Science and Technology Studies

Publication Details

DESIGN OF HOLES AND WEB OPENINGS IN RAILWAY PRESTRESSED CONCRETE SLEEPERS

Erosha Kahawatta Gamage[1], Sakdirat Kaewunruen[2] and Alex M. Remennikov[3]

[1] School of Civil Engineering
The University of Birmingham, Edgbaston, B15 2TT UK
e-mail: EBK415@student.bham.ac.uk

[2] Birmingham Centre for Railway Research and Education, School of Civil Engineering
The University of Birmingham, Edgbaston, B15 2TT UK
e-mail: s.kaewunruen@bham.ac.uk

[3] School of Civil, Mining, and Environmental Engineering
University of Wollongong, Northfield Ave, Wollongong, NSW 2522 Australia
e-mail: alexrem@uow.edu.au

KEYWORDS: Concrete sleeper, Crosstie, Design, Holes, Web opening, Railway infrastructure

ABSTRACT
As the crosstie beam in railway track systems, the prestressed concrete sleepers (or railroad ties) are principally designed in order to carry wheel loads from the rails to the ground. Their design takes into account static and dynamic loading conditions. It is evident that prestressed concrete has played a significant role as to maintain the high endurance of the sleepers under low to moderate repeated impact loads. In spite of the most common use of the prestressed concrete sleepers in railway tracks, there have always been many demands from rail engineers to improve serviceability and functionality of concrete sleepers. For example, signalling, fibre optic, equipment cables are often damaged either by ballast corners or by tamping machine. There has been a need to re-design concrete sleeper to cater cables internally so that they would not experience detrimental or harsh environments. Accordingly, this study will investigate the design criteria and effects of holes and web openings on structural capacity of concrete sleepers under rail 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 enable the new design and calculation methods for prestressed concrete sleepers with holes and web opening that practically benefits civil, track and structural engineers in railway industry.

INTRODUCTION
Prestressing in railway concrete sleepers yields endurance property under high-cycle fatigue. In practice, track engineers need to generate holes or web openings in concrete sleepers to enable the accommodation of cables and signalling equipment. This study aims to provide a principle understanding of the structural capacity and energy toughness of prestressed concrete sleepers without and with holes and web openings. It will investigate the design criteria and effects of holes and web openings on structural capacity of concrete sleepers under rail loading. The modified compression field theory and finite element modelling for ultimate strength design of concrete sleepers will be highlighted in this study.

In order to meet the objectives of this investigation, four approaches will be followed. Initial stages of the study involve a cross sectional analyses of concrete sleepers, which will be evaluated using, both modified compression field theory and finite element modelling. Then the analysis: the provisions of existing design guidelines will be used to calculate the capacity of the concrete sleepers. Next step involved lap testing where, five concrete sleepers obtained from our industry partner will be tested under a static bending load pattern. One sleeper will be a control sample, while the other four will be cored varying dimensions and locations. All sleepers will be subjected to static bending tests. The load-

deflection, stress-stress, and load-rotation curves will be plotted for comparison with analytical and numerical results. Finally the parametric studies using validated numerical model will be used to develop a practical design guideline for holes and web openings in railway concrete sleepers.

This paper will present the design criteria and effects of holes and web openings on structural capacity of concrete sleepers under rail loading. The modified compression field theory for ultimate strength design of concrete sleepers will be highlighted in this study. The effects of track environment including soft and hard tracks are also presented as to implement design guidance related to the ultimate limit state of concrete sleepers. The outcome of this study will enable the new design and calculation methods for prestressed concrete sleepers with holes and web opening that practically benefits civil, track and structural engineers in railway industry.

CONCRETE SLEEPERS

Sleepers are transverse beams laying on ballast and support. Wooden sleepers were utilized as a part of the past in light of the fact that timber was promptly accessible in the neighbourhood. Nevertheless, prestressed or reinforced concrete sleepers, and to a restricted degree steel sleepers, have been received in current railway tracks over the previous decades on account of their strength and long administration life [1-5]. Solid sleepers are depicted as either twin-square or mono-piece. Inside all these sorts, concrete sleepers are all the more generally utilized in light of the fact that they are not influenced all that much by either atmosphere or climate. Furthermore, it provides anchorage for the fastening system and limit longitudinal, parallel and vertical movement by implanting itself onto the substructures. Figure 1 below illustrates the two types of concrete sleepers [1-2].



Figure 1: Concrete sleepers (http://www.aboutcivil.org/types-of-railway-sleepers-advantages-disadvantages.html)

CROSS SECTIONAL PROPERTIES

All vital cross-sectional properties and measurements of the sleepers used in the investigation are represented below. These cross-sectional properties are used in order to calculate the moment of inertia, stress analysis of the rail seat utilizing the parallel axis theorem. Cross section 1 illustrates the sleeper with no web openings and cross section 2 illustrates a sleeper with a 50mm transverse hole.

FLEXURAL CAPACITY

The ultimate load capacity of the sleeper design will be resolved for comparative purposes. The nominal moment capacity will likewise show the real limit of the segment or potential store limit, which the section given is permissible to crack. Once separated into standard shapes the measurements are set into a spreadsheet, since this methodology will be rehashed for every segment and configuration cycle. However, the flexural calculations are done according to both ACI and Eurocode 2 [6]. A sample of the spreadsheet utilized for the estimation of cross-sectional properties is indicated in figure 2.
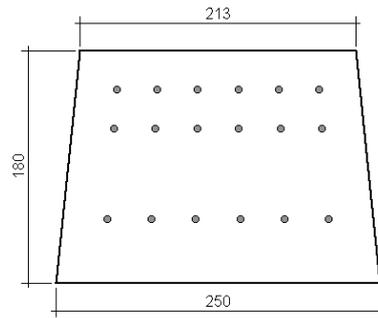
a) Cross section 1- Sleeper with no web opening
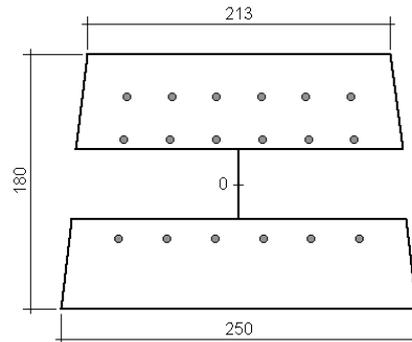
b) Cross section 2 - Sleeper with 50mm transverse hole

Figure 2: Cross sections of concrete sleepers

f_{pe} = stress in prestressing at time of effective prestress, psi	=	173.07	Ksi
Eps - specifil modulus of elasticity of prestressing	=	28500	ksi
Ec = modulus of elasticity of concrete, psi	=	4769	Ksi
f'c = specified compressive strength of concrete(55Mpa)	=	5.118	in
d3- distance from top flange to the lower tedon from the top			
Ix_RS = Second moment area of the cross section	=	269.729	in^4
C (assumed)	=	2.835	in
Yt	=	3.622	in
Yb	=	3.465	in
Area of a tendon	=	0.044	in^2

fpk - prestressing stress	1648	Mpa
f'c - specified compressive strength of concrete	55	Mpa
Ep - modulus of elasticity of prestress	190000	Mpa
Ec - modulus of elasticity of concrete	38000	Mpa
P - Prestessing force	25	kN
Yp - partia factor of prestress	0.9	
ρ - loss ratio (20%)	0.8	
Ag - area of the gross cross section	41670	mm^2
Ap - Area of a tendon	28.274	mm^2
Ig- Secong moment area of the gross cross section	1.12E+08	mm^4
x - distance to neutral axis from top flange	92	mm

Figure 3: Cross sectional properties of concrete sleeper

CROSS SECTION ANALYSIS: NO WEB OPENING

A: American Concrete Institute (ACI) Method

A.1) Calculation of $\varepsilon_{d,max}$ (strain in concrete at furthest most layer of pre-stressing from extreme compression fiber at decompression condition)

$$\varepsilon_{d,max} = \frac{f_{pe\_RS}A_{ps}}{E_c}\left[\frac{1}{A_{c\_RS}} + \frac{(d_{max} - y_{t\_RS})^2}{I_{x\_RS}}\right]$$

$$[\ \varepsilon_{d,max} = \quad 0.000227722]$$

A.2) Finding the strain in the layers of pre-stressing corresponding to decompression

$$\varepsilon_{2\_1} = \frac{\varepsilon_{d,max}(y_{t\_RS} - d_1)}{d_{max} - y_{t\_RS}}$$

Layer 1

$\varepsilon_{2\_1} =$ 0.000371571 $[d_1 = \quad 1.181\text{in}]$

Layer 2

$\varepsilon_{2\_2} =$ 0.000191798

Layer 3

$\varepsilon_{2\_3} =$ 0.001330408 $[d_3 = \quad 5.118\text{in}]$

A.3) Finding the strain in concrete at layers of pre-stressing corresponding to ultimate ($\varepsilon 3$)

$$\varepsilon_{3\_1} = \varepsilon_{cu}\left(\frac{c - d_1}{c}\right)$$

$$[\varepsilon_{cu} = \quad 0.003\text{(according to ACI)}]$$

Layer 1

$\varepsilon_{3\_1} =$ 0.001750265

Layer 2

$\varepsilon_{3\_2} =$ 0.000500529

Layer 3

$\varepsilon_{3\_3} =$ 0.002415873

A.4) Finding the strain in pre-stressing layers (εps)

$$\varepsilon_{ps\_1} = \varepsilon_{1\_RS} - \varepsilon_{2_1} - \varepsilon_{3\_1}$$

$$[d_2 = \quad 2.362\text{in}]$$

Layer 1

$\varepsilon_{ps\_1} =$ 0.003948165

Layer 2

$\varepsilon_{ps\_2} =$ 0.005377673

Layer 3

$\varepsilon_{ps\_3} =$ 0.009816281

A.5) Finding the stress in pre-stressing layer at ultimate (fps)

$$f_{ps\_1} := \begin{vmatrix} E_{ps} \cdot \varepsilon_{ps\_1} & \text{if } \varepsilon_{ps\_1} \le 0.0076 \\[2ex] 250ksi - \dfrac{0.04ksi}{\varepsilon_{ps\_1} - 0.0064} & \text{if } \varepsilon_{ps\_1} > 0.00 \end{vmatrix} \qquad [\varepsilon_{1\_RS} = \quad 0.00607]$$

Layer 1

$f_{ps\_1} =$ 112.52   ksi

Layer 2

$f_{ps\_2} =$ 153.26   ksi

Layer 3

$f_{ps\_3} =$ 238.29   ksi

A.6) The force of pre-stressing layers

$T_1 = A_{ps\_1}.f_{ps\_1}$

Layer 1

$T_1 =$ 29.71   kip

Layer 2

$T_2 =$ 40.46   kip

Layer 3

$T_3 =$ 62.91   kip

A.7) The moment produces by the layer of pre-stressing steel

$$M_{n1} := -T_1 \cdot (y_{t\_RS} - d_1)$$

Layer 1

$M_{n1} =$ -72.51   kip.in

Layer 2

$M_{n2} =$ -50.98   kip.in

Layer 3

$M_{n3} =$ 94.11   kip.in

A.8) Estimation of the depth of the compression stress block (to ACI)

$$\beta_1 := \begin{vmatrix} 0.85 - 0.05 \cdot \left(\dfrac{f_c - 4000\text{psi}}{1000 \cdot \text{psi}} \right) & \text{if } f_c \le 8000\text{psi} \\ 0.65 & \text{otherwise} \end{vmatrix}$$

$\beta_1 = 0.65$
$A_c = 16.35 \text{ in}^2$

Therefore,

$a = \beta_1.c$

d' =	3085 in
d"	60 mm

A.9) Finding the total area of the concrete in compression

$$A_c = \frac{2 * 9.13 + 0.00897(a - 0.6)}{2} \cdot (a - 0.6) + 5.92$$

A.10) The resultant force of the concrete in compression zone

$C = 110.89 \text{ kip}$

$C = 0.85 f'_c.A_c$

A.10) Flexural Capacity

$M_n = M_{n1} + M_{n2} + M_{n3} + C(Y_t - a/2)$

$M_n = 269.91$ kip.in
$= 31$ kNm

B: Eurocode 2 (EC2) Method

B.1) Calculation of strain in concrete due to prestress

$$\varepsilon_{ce} = \frac{1}{Ec} \left(\frac{\gamma_p * \rho * P}{Ag} + \frac{\gamma_p * \rho * M_p * e}{Ig} \right)$$

$\varepsilon_{ce} = 2.759 \text{x} 10^{-5}$

B.2) Calculation of tendon strain due to prestress

$$-\frac{\gamma_p * \rho * P *}{A_p * E_p}$$
(= - 0.0005584)

B.3) Calculation of strain in the layers at prestressing corresponding to decompression

$$\varepsilon_{ct} = -\frac{0.0035(d - x)}{x}$$

Layer 1

$\varepsilon_{ct\_1} =$ 0.00236

d =   130   mm

Layer 2

$\varepsilon_{ct\_2} =$ 0.00122

$f_c =$ 488,234.34 N

Layer 3

$\varepsilon_{ct\_3} =$ -0.00145

B.4) Calculation of tendon strain in each layer

$$\varepsilon_{pu} = -\frac{\gamma_p * \rho * P *}{\Lambda_p * E_p} + \varepsilon_{ct} - \varepsilon_{ce}$$

Layer 1

$\varepsilon_{pu\_1} =$ 0.00177

Layer 2

$\varepsilon_{pu\_2} =$ 0.0006314

Layer 3

$\varepsilon_{pu\_3} =$ -0.0020317

B.5) Forces at prestressing layer

$$f_p = \Lambda_p E_p \varepsilon_{pu}$$

Layer 1

$f_{p\_1} =$ 57,137.165N

Layer 2

$f_{p\_2} =$ 20,350.233N

Layer 3

$f_{p\_2} =$ -65,485.943N

B.6) Force in the compression zone

$f_c = 0.453.x.b.f_{ck}$

B.7) Ultimate Moment capacity (Mu)

$$M_u = -F_{p_1}(x - d') - F_{p2}(x - d'') + (F_c * 0.8x) + F_{p3}(x - d)$$

$M_u =$ 34,228,801.57 Nmm

$=$ 34 kNm

CROSS SECTION ANALYSIS: 50MM TRANSVERSE HOLE (WEB OPENNING)
In this case, only change is the resultant force in the compressive zone due to the opening where other variables remain constant. Therefore it follows a similar process shown in the above calculations.

According to ACI:

Finding the total area of the concrete in compression

Ac =   13.651 in^2

Flexural Capacity

Mn =   220.44 kip.in
    =   25kNm

According to Eurocode 2

Force in the compression zone

f_c = 488234.34 N

Ultimate Moment capacity (M_u)

M_u =   24,464,114.77 Nmm
    =   25 kNm

SECTIONAL ANALYSIS USING COMPRESSION FIELD THEOTRY (RESPONSE-2000)
The sectional capacity plays a major role in the analysis of prestressed or reinforced concrete components in bending. The sectional limit considers the flexural moment and stress and strain relationship into account. This study makes utilization of a PC program for sectional analysis (Response 2000), which is in view of the modified compression field hypothesis. The results from the Response 2000, were used to compare the results with the hand calculations demonstrated the section earlier in the study [7-8]. However there seem to be an error in the software when analysing the sleepers with web openings. Nevertheless, the results obtain as follows.
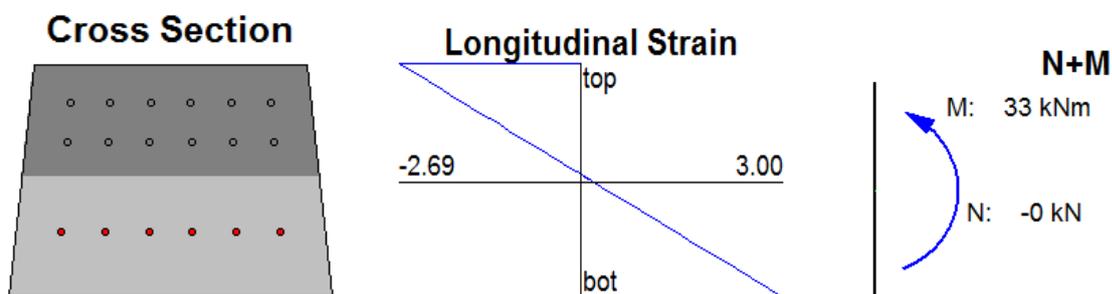

Figure 4: Response 2000 results for cross section 1: full section
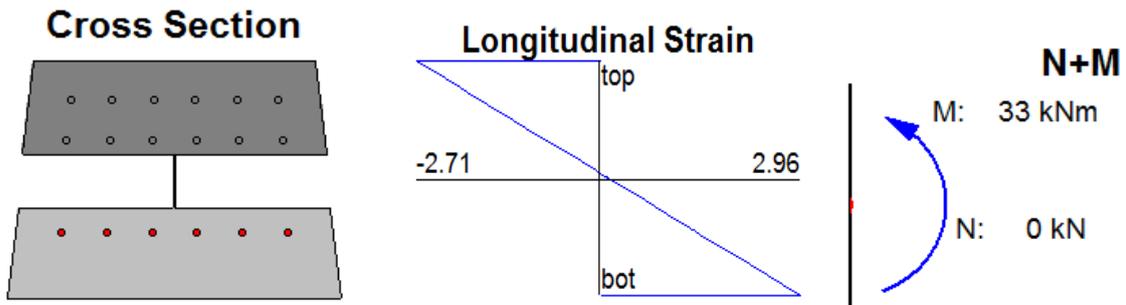
Figure 5: Response 2000 results for cross section 2 Cross section 2 - Sleeper with 50mm transverse hole

It is likely that the results for the sleeper with the transverse holes seem to have an error in the software (Response 2000). In this case, the package Response 2000 was used to analyse 3 cases of web opening in the sleeper, which are longitudinal, transverse and vertical hole. Figure 6 shows the relationship between the maximum moment capacity and diameter for 5 different diameters ranging from 0mm to 50mm holes for all 3 cases. Clearly, systemic error within the software can be identified from the analyses of transverse web opening (TH) and longitudinal holes (LH).
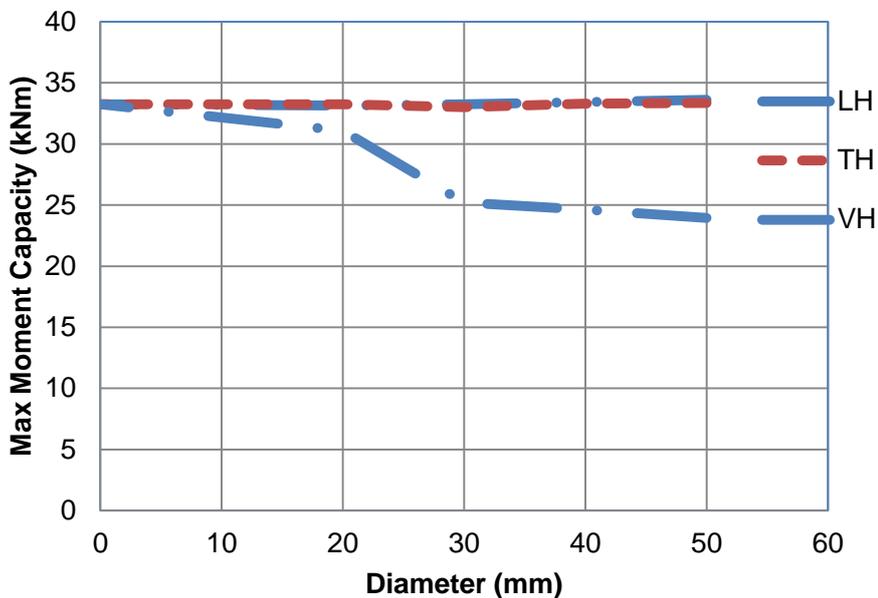

Figure 6: Moment capacity - diameter for all the 3 cases using Response 2000

Due to the error occurred, manual calculations were obtained for both ACI and Eurocode to give a fair value to show the relationship between the moment capacity vs diameter for 5 different diameters ranging from 0mm to 50mm holes for transverse hole (TH) is illustrated in Figure 7:
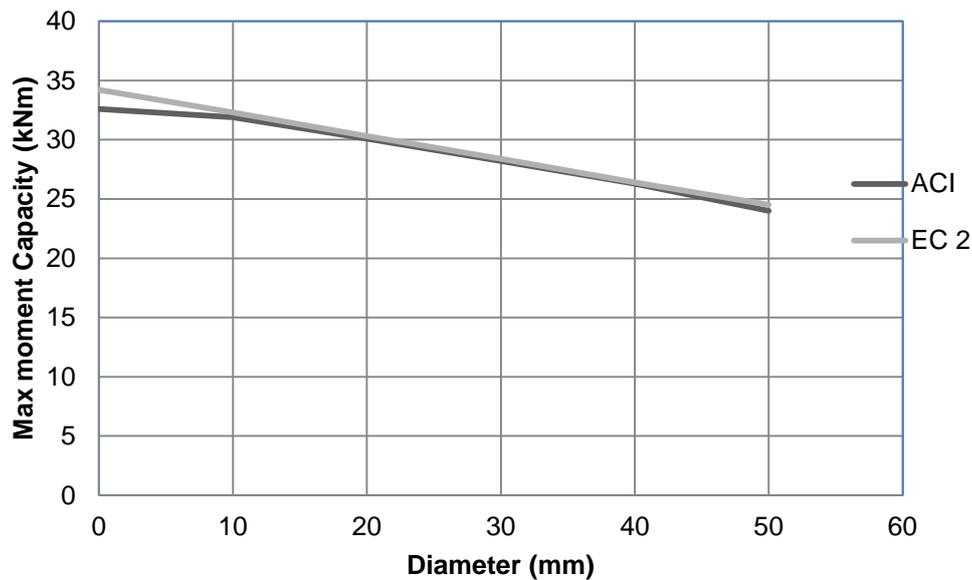
Figure 7: Moment capacity - diameters for transverse hole using manual calculations

DISCUSSIONS
Table 1 shows comparison of the numerical and analytical results of the flexural capacity of sleeper with no web openings and 50mm transverse hole.

Cases	Hand Calculations		Response 2000	Difference	
	ACI	**ECU2**		**ACI**	**ECU2**
Cross section 1 with no web opening	**32.6kNm**	**34.2kNm**	**33kNm**	**-0.4kNm**	**1.2kNm**
Cross section 2 with 50mm transverse hole	**24kNm**	**24.5kNm**	**33kNm**	**-9kNm**	**-8.5kNm**

Table 1: Comparison of analytical and numerical results

It is clear that ACI and ECU2 methods are consistent in many cases of web opening (transverse hole: TH). However, there is a need to include vertical and longitudinal holes. It is important to note that these holes are located symmetrically around neutral axis. The variation of the location will be investigated in the future, together with numerical and experimental studies.

It is also noted that it is very likely that Response 2000 is incapable of accurately calculating sectional analysis. The results presented in this paper are important lessons learnt to practical engineers, who will design holes and opening in prestressed concrete members using commercial available software. The design results should always be benchmarked by independent methodology.

CONCLUSIONS
As the flexural support members in railway track systems, the prestressed concrete sleepers (or railroad ties) are principally designed in order to carry wheel loads from the rails to the ground. Their design takes into account static and dynamic loading conditions. At present, there is a practical need to investigate the effect of coring concrete sleepers to generate holes and web opening to accommodate services cables, signalling gears and other necessary equipment.

Web openings that are round, square, or almost square fit as a fiddle may be considered as small openings given that the depth (or diameter) of the opening is in a sensible extent to the sleeper size, say, about 40% of the general sleeper depth. In such a case, sleeper performance may be expected to prevail.

Accordingly, investigation and configuration of a sleeper with holes and web openings may take after the comparative strategy as that of a prestressed concrete beam. The procurement of openings, on the other hand, produces discontinuities or unsettling influences in the ordinary stream of burdens, therefore prompting anxiety focus and early breaking around the opening district. Like any irregularity, unique support, encasing the opening near to its edges. The lessons learnt and the outcome of this study will enable the new design and calculation methods for prestressed concrete sleepers with holes and web opening that practically benefits civil, track and structural engineers in railway industry.

FUTURE WORK

Static bending test will be attempted in this examination keeping in mind the end goal to contrast the logical and numerical results and the got load-redirection, anxiety stretch, and burden turn bends plotted from the test outcomes. The area of estimations will be at the centre line of rail seat. In this test, inclinometers will be likewise introduced at the simply supported edges. The experimental setup of rail-seat positive moment test will be conducted in accordance with European Standard for Concrete Sleepers (BS EN 13230-2).

REFERENCES

1) Kaewunruen, S. 2007. Experimental and numerical studies for evaluating dynamic behaviour of prestressed concrete sleepers subject to severe impact loading. *PhD Thesis*, School of Civil, Mining, and Environmental Engineering, University of Wollongong, Australia.

2) Web access, 2015, Access Online [URL http://www.aboutcivil.org/types-of-railway-sleepers-advantages-disadvantages.html]

3) Kaewunruen, S and Remennikov, AM, (2006) "Post-failure mechanism and residual load-carrying capacity of railway prestressed concrete sleeper under hogging moment", *Proceedings of the International Conference on Structural Integrity and Failure (SIF-2006)*, Sydney, Australia, September 27-29, pp. 331-336.

4) Bian, J., (2012). ULTIMATE FLEXURAL LIMIT STATES ANALYSIS OF PRESTRESSED CONCRETE SLEEPER. *PhD Thesis*, School of Urban Development, Queensland University of Technology, Australia

5) Kaewunruen, S. and Remennikov, A.M., (2013), "On the residual energy toughness of prestressed concrete sleepers in railway track structures subjected to repeated impact loads." *Electronic Journal of Structural Engineering*, 13(1): 41-61 (invited).

6) M. A. Mansur & Kiang-Hwee Tan. (1999). *Concrete Beams with Openings: Analysis and Design*. Google Book, USA.

7) Remennikov, A.M., Murray, M.H. and Kaewunruen, S., (2012), "Reliability based conversion of a structural design code for prestressed concrete sleepers." *Proceedings of IMechE Part F Journal of Rail and Rapid Transit*, 226(2): 155-173

8) Kaewunruen, S., Remennikov, A.M. and Murray, M.H., (2011), "Limit states design of concrete sleepers." *ICE Transport*, 165(TR2): 81-85