International Journal of Frontiers in Engineering Technology
ISSN 2706-655X Vol.4, Issue 9: 41-49, DOI: 10.25236/IJFET.2022.040908

A European Norms-Based Sleeper Design of Broad Gauge Railway in Bangladesh

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Abstract: *European Norms (EN) are internationally used railway design standards, mastering the design theory of EN is an important prerequisite for smoothly prompting international projects. This paper took a 1676mm broad gauge prestressed reinforced concrete sleeper on ballasted track of Bangladesh Railway as an example. Through the sleeper design method of EN, the tensile stress in concrete for serviceability limit state, the static load, the dynamic load and the fatigue load are analysed, and the feasibility of the design is verified by the acceptance criteria. The research results of this paper can provide design guidance for similar international projects.*

Keywords: *Bangladesh railway; Prestressed reinforced concrete; European Norms; Broad gauge; Acceptance criteria*

1. Introduction

India, Pakistan, Argentina, Chile mainly use 1676mm broad gauge; Russia uses 1520mm broad gauge; Japan's Tokaido, Shanyang Shinkansen and other Shinkansen use 1435mm standard gauge; China, the United States, Canada and most countries in Europe adopt the 1435mm standard gauge[1]. EN is the international standard widely recognized in the world railway system. Based on the Padma Bridge Railway Link Project in Bangladesh, this paper takes 1676mm broad gauge as an example to study the design method of broad gauge sleeper based on EN, so as to provide reference for similar engineering projects.

2. Design theory and methods

2.1. Calculation of sleeper bending moment

According to references [2]~[3]:Design of monoblock concrete sleepers, the design rail set load P_d is:

$$P_d = \frac{Q_0}{2}(1 + \gamma_P \gamma_v)\gamma_d \gamma_r \qquad (1)$$

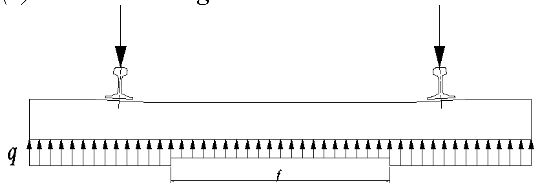
Where, Q_0 is the static component of vertical design load, its value is determined directly by the static axle load of the train;γ_p is the factor of apply to dynamic increment to reflect rail-pad attenuation, shown in Table1;γ_v is the normal service dynamic increment determining the effect of speed,γ_v=0.5 when speed V＜200km/h,γ_v =0.75 when speed V≥200km/h;γ_d is the factor to allow for load distribution between sleepers;γ_r is the partial factor to allow for variation in the sleeper reaction due to support faults.

Table 1: Value of factor of apply to dynamic increment to reflect rail-pad attenuation

Attenuation type	Attenuation	Value
Low	<15%	1.0
Medium	>15-30%	0.89
High	>30%	0.78

The key sections of the sleeper bending moment are at the rail seat and at the center of the sleeper is shown in Figure 1.

(a)Positive bending moment at the rail seat section



(b)Negative bending moment at the center section

Figure 1: Calculation model for sleeper bending moment

The positive bending moment at the rail seat can be derived from Figure1 (a), the counter acting force extends to the sleeper end at an equal distance on both sides of the center line of the rail seat.

The positive bending moment at rail seat M_{dr+} is calculated according to Formula (2):

$$M_{dr}+=\gamma_i\frac{P_d\lambda}{2} \tag{2}$$

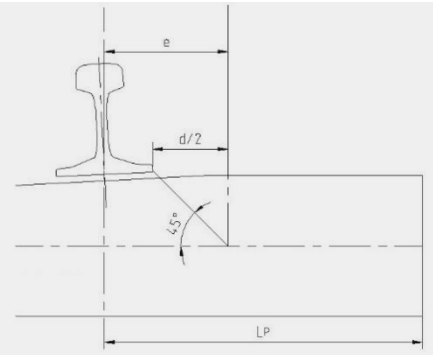


Figure 2: Assumed load distribution and lever arm derivation of bending moment at rail seat

$$\lambda=\frac{L_p-e}{2} \tag{3}$$

As shown in Figure 2, λ is the effective lever arm; L_p is the distance between the axis of the rail seat and the edge the sleeper (m); d is the sleeper thickness at the rail seat; e is the width of load distribution, for UIC60 rail, $e = 0.15/2 + d/2$.The negative bending moment in the center of sleeper of regular shaped is calculated according to Formula (4);

$$M_{dc-}=\gamma_{\mathrm{i}}\mathrm{P_d}\left(\frac{c}{2}-\frac{2L^2-f^2}{4(2L-f)}\right) \tag{4}$$

Where, c is the distance between centers of rail seat (m); L is the length of the sleeper; f is the length of reducing reaction force in the center area shown in the Figure 1 (b);

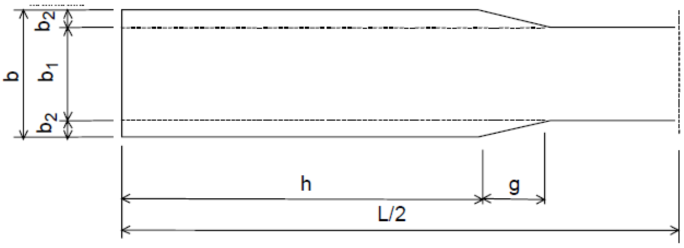


Figure 3: Plan of irregular sleeper

For irregular shaped sleeper, shown in Figure 3, the negative bending moment is calculated according to Formula (5).

$$M_{dc-} = \gamma_i P_d \left[\frac{c}{2} - \frac{L}{2} + \frac{b_1 . \frac{L^2}{8} + b_2 (h^2 + g.h + g^2/3)}{b_1 . \frac{L}{2} + b_2 (2h + g)} \right] \tag{5}$$

Where, c is the distance between center of rail seat (m);L is the length of the sleeper; b_1 is the waist width of sleeper; b_2 is the increased width of each side at the sleeper rail seat; h is the length of the wide segment at the end of the sleeper; g is the length of transition section.

Which derived that for the negative bending moment at rail seat:

$$M_{dr-} = 0.5 M_{dr+} \tag{6}$$

For negative bending moment at sleeper center:

$$M_{dc+} = 0.7 M_{dc-} \tag{7}$$

2.2. Checking of tensile stress in concrete for serviceability limit state

In the whole service process of sleeper, the maximum tensile stress of concrete should not exceed the flexural strength of concrete under fatigue load, and the corresponding tensile stress of sleeper concrete in normal use limit state should be checked and calculated.

Positive bending moment at the rail seat section:

$$\sigma_{ct,max,r,p} = -\frac{P_{m,t2}}{A_{r,c}} + \frac{P_{m,t2} e_{r,0}}{W_{r,bottom}} + \frac{M_{k,r,pos}}{W_{r,bottom}} \tag{8}$$

Negative bending moment at the rail seat section:

$$\sigma_{ct,max,r,n} = -\frac{P_{m,t2}}{A_{r,c}} + \frac{P_{m,t2} e_{r,0}}{W_{r,top}} + \frac{M_{k,r,neg}}{W_{r,top}} \tag{9}$$

Positive bending moment at the center section:

$$\sigma_{ct,max,c,p} = -\frac{P_{m,t2}}{A_{c,c}} + \frac{P_{m,t2} e_{c,0}}{W_{c,bottom}} + \frac{M_{k,c,pos}}{W_{c,top}} \tag{10}$$

Negative bending moment at the center section:

$$\sigma_{ct,max,c,n} = -\frac{P_{m,t2}}{A_{c,c}} + \frac{P_{m,t2} e_{c,0}}{W_{c,top}} + \frac{M_{k,c,neg}}{W_{c,top}} \tag{11}$$

Where, $\sigma_{ct,max,r,p}$is the maximum tensile stress in concrete at rail section; $P_{m,t2}$ Is the prestressing force after 50 years;$e_{r,0}$is the eccentricity of prestressing force at rail seat section;$A_{r,c}$ is the area of cross section of sleeper at rail seat section;$W_{r,bottom}$ is the modulus for bottom at rail seat section;$\sigma_{ct,max,r,n}$ is the maximum tensile stress in concrete at rail seat section;$W_{r,top}$ is the Modulus for top at rail seat section;$\sigma_{ct,max,c,p}$ is the maximum tensile stress in concrete at center section;$e_{c,0}$ is the eccentricity of prestressing force at center section;$A_{c,c}$ is the area of cross section of sleeper at center section;$W_{c,bottom}$ is the modulus for bottom at center section; $\sigma_{ct,max,c,n}$ is the maximum tensile stress in concrete at center section; $W_{c,top}$ is the modulus for top at center section.

2.3. Prestress Loss calculation

2.3.1. Tensioning Stress of Prestressed Rebar

The tensioning stress of the prestressed rebar is:

$$\sigma_{p0} = \frac{F_0}{A_p} \tag{12}$$

Where, σ_{p0} is the tensioning stress of prestressed rebar;F_0 is the tensioning force of prestressed rebar; A_p is the gross Area of prestressed rebar.

The maximum tensioning stress of the prestressed rebar is:

$$\sigma_{\mathrm{p,max}} = min\{k_1 f_{pk}; k_2 f_{p0.1k}\} \tag{13}$$

Where k_1, k_2 are taken as 0.8, 0.9 respectively.

When$\sigma_{p0} < \sigma_{p,max}$, the tensioning stress of the prestressed rebar satisfies the requirement of the code.

2.3.2. Prestress Loss

(1) Prestress loss[4] due to anchorage deformation

$$\Delta\sigma_{sl} = \frac{\sigma}{L_t} E_P \tag{14}$$

After the anchor is applied to the prestressed rebar, the tensioning stress of the prestressed rebar σ_{pi} is:

$$\sigma_{pi} = \sigma_{p0} - \Delta\sigma_{sl} \tag{15}$$

(2) Prestress loss due to prestressed rebar relaxation before tensioning

The mean value of concrete cylinder compressive strength $f_{cm}$is:

$$f_{cm} = f_{ck} + 8 \tag{16}$$

Where, f_{ck} is the Characteristic compressive cylinder strength of concrete at 28 days.

Suppose that the prestressed rebar is tensioned at day t, a coefficient which depends on the age of the concrete $\beta_{cc}(\mathrm{t})$ is:

$$\beta_{cc}（\mathrm{t}） = exp\left\{s\left[1-\left(\frac{28}{t}\right)^{t/2}\right]\right\} \tag{17}$$

The mean concrete compressive strength at an age of t days $f_{cm}(\mathrm{t})$ is:

$$f_{cm}（\mathrm{t}） = \beta_{cc}(\mathrm{t}) f_{cm} \tag{18}$$

The prestress loss due to prestressed rebar relaxation before tensioning at an age of t days is calculated by Formula (19)-(20)

$$\frac{\Delta\sigma_{pr}}{\sigma_{pi}} = 0.66\rho_{1000} e^{9.1\mu} \left(\frac{t}{1000}\right)^{0.75(1-\mu)} 10^{-5} \tag{19}$$

Where, $\Delta\sigma_{pr}$ is the absolute value of relaxation losses of prestress; $\rho_{1000}$is the value of relaxation loss at 1000 hours after tensioning and at a mean temperature of 20°C. $\sigma_{pp}$is prestress of prestressed rebar with consideration of prestress loss due to anchorage deformation and prestressed rebar relaxation is:

$$\sigma_{pp} = \sigma_{pi} - \Delta\sigma_{pr} \tag{20}$$

(3) Prestress loss due to elastic deformation of concrete while tensioning

σ_c is the concrete stress with consideration of prestress loss due to anchorage deformation and prestressed rebar relaxation is;

$$\sigma_c = \frac{\sigma_{pp} A_P}{A_{r,0}} + \frac{\sigma_{pp} A_P e_{r,0} z_{cp}}{I_{r,0}} \tag{21}$$

$\Delta P_{el}$is the prestress loss due to elastic deformation of concrete while tensioning is

$$\Delta P_{el} = \frac{A_p \frac{E_p}{E_{cm}(t)} \sigma_c}{1 + \frac{E_p}{E_{cm}(t)} \frac{A_p}{A_{r,0}} \left(1 + \frac{A_{r,0} e_{r,0} z_{cp}}{I_{r,0}}\right)} \tag{22}$$

$P_{m0}$is the tensile force of prestressed rebar after tensioning is:

$$P_{m0} = \sigma_{pp} A_p - \Delta P_{el} \tag{23}$$

σ_{pm0} is the Maximum tensile stress of prestressed rebar after tensioning is:

$$\sigma_{pm0} = min\{k_7 f_{pk}; k_8 f_{p0.1k}\} \tag{24}$$

Where, $A_{r,0}$ is the area of transformed section of sleeper at rail seat section.

$z_{cp}$is the Distance between center of gravity of concrete section and prestressed rebar;

$e_{r,0}$is the Eccentricity of prestressing force;

$I_{r,0}$ is the second moment of area of concrete section; where k_7, k_8 are taken as 0.75, 0.85 respectively. When $P_{m0} \le \sigma_{pm0} A_p$, the tensile force of the prestressed rebar after tensioning satisfies the requirement of the code.

The compressive stress at top of concrete sleeper is

$$\sigma_{r,top} = P_{m0}\left(\frac{1}{A_{r,0}} + \frac{e_{r,0}(h_r - h_{r,d})}{I_{r,0}}\right) \tag{25}$$

Where, h_r is the height of sleeper section; $h_{r,d}$ is the distance between center of gravity of concrete section and bottom of concrete section.

When $\sigma_{r,top} < k_6 f_{ck} = 0.7 f_{ck}$ the compressive stress of sleeper concrete after tensioning satisfies the requirement of the code.

(4) Time dependent losses

1) Shrinkage strain

① Drying shrinkage strain

Suppose that 80% RH =80%, the coefficient depending on the relative humidity is

$$\beta_{RH} = 1.55\left\{1 - \left(\frac{RH}{RH_0}\right)^3\right\} \tag{26}$$

Where RH_0=100%.

The basic drying shrinkage strain is:

$$\varepsilon_{cd,0} = 0.85\left[(220 + 110\alpha_{ds1})exp\left(-\alpha_{ds2}\frac{f_{cm}}{f_{cm0}}\right)\right]10^{-6}\beta_{RH} \tag{27}$$

Where, α_{ds1}, α_{ds2} are the Coefficient which depends on type of cement.

Where, f_{cm0} is taken as 10MPa.

The notional size of sleeper section is

$$h_0 = \frac{2A_c}{u} \tag{28}$$

Where, A_c is the area of sleeper section; u is the perimeter of sleeper section in contact with atmosphere.

The final drying shrinkage strain is;

$$\varepsilon_{cd,\infty} = k_h \varepsilon_{cd,0} \tag{29}$$

Where, k_h is the coefficient depending on notional size.

② Autogenous shrinkage strain

The autogenous shrinkage strain is;

$$\varepsilon_{ca,\infty} = 2.5(f_{ck} - 10)10^{-6} \tag{30}$$

The total shrinkage strain is;

$$\varepsilon_{cs} = \varepsilon_{ca,\infty} + \varepsilon_{cd,\infty} \tag{31}$$

2) Creep coefficient

The Coefficients to consider the influence of the concrete strength are:

$$\alpha_1 = \left(\frac{35}{f_{cm}}\right)^{0.7} \tag{32}$$

$$\alpha_2 = \left(\frac{35}{f_{cm}}\right)^{0.2} \tag{33}$$

$$\alpha_3 = \left(\frac{35}{f_{cm}}\right)^{0.5} \tag{34}$$

The factor to allow for the effect of the relative humidity on the notional creep coefficient is:

$$\varphi_{RH} = \left(1 + \frac{1 - RH/100}{0.1\sqrt[3]{h_0}}\alpha_1\right)\alpha_2 \tag{35}$$

The factor to allow for the effect of concrete strength on the notional creep coefficient is:

$$\beta(f_{cm}) = \frac{16.8}{\sqrt{f_{cm}}} \tag{36}$$

The factor to allow for the effect of concrete age at loading on the notional creep coefficient is:

$$\beta(t_0) = \frac{1}{0.1+t_0^{0.2}} \tag{37}$$

For f_{cm}>35MP, the coefficient depending on the relative humidity and the notional size is:

$$\beta_H = 1.5[1 + (0.012RH)^{18}]h_0 + 250\alpha_3 \tag{38}$$

At the age of concrete in t days, the coefficient to describe the development of creep with time after loading is:

$$\beta_c(t, t_0) = \left(\frac{t-t_0}{\beta_H+t-t_0}\right)^{0.3} \tag{39}$$

Where, *t* is the age of concrete in days at the moment considered; t_0 is the age of concrete at loading in days.

The notional creep coefficient is

$$\varphi_0 = \varphi_{RH}\beta(f_{cm})\beta(t_0) \tag{40}$$

The creep coefficient is:

$$\varphi(t, t_0) = \varphi_0\beta_c(t, t_0) \tag{41}$$

3) Time dependent losses

The stress in the concrete adjacent to the prestressed rebar due to self-weight and initial stress and other quasi-permanent actions where relevant is

$$\sigma_{c,QP} = P_{m0}\left(\frac{1}{A_{r,0}} + \frac{e_{r,0}z_{cp}}{I_{r,0}}\right) \tag{42}$$

When $\sigma_{r,top} < 0.45f_{ck}$, the nonlinear creep is ignored.

The time dependent losses are,

$$\Delta P_{c+s+r} = A_p\Delta\sigma_{p,c+s+r} = A_p\frac{\varepsilon_{cs}E_p+0.8\Delta\sigma_{pr}+\frac{E_p}{E_{cm}}\varphi(t,t_0)\sigma_{c,QP}}{1+\frac{E_p}{E_{cm}}\frac{A_p}{A_{r,0}}\left(1+\frac{A_{r,0}}{I_{r,0}}z_{cp}^2\right)[1+0.8\varphi(t,t_0)]} \tag{43}$$

Where,$\Delta\sigma_{p,c+s+r}$Absolute value of variation of stress in prestressed rebar due to creep, shrinkage and relaxation.

The prestressing force of prestressed rebar with consideration of all kinds of prestress losses is.

$$P_{mt} = P_{m0} - \Delta P_{c+s+r} \tag{44}$$

2.4. Test Loads and Acceptance Criteria

In EN13230-2:2009[5] specified that the acceptance criteria of sleeper design acceptance test namely static test, dynamic test and fatigue test.

2.4.1. Test load

The initial reference test load $Fr0$ is calculated according to EN13230-2:2009[5].

$$F_{r0} = \frac{4M_{k,r,pos}}{L_r-0.1} \tag{45}$$

Where, design distance between articulated support center lines for test arrangement at rail seat section.

Testing bending moment for formation of first crack:

$$M_{t,r,pos} = M_{k,r,pos} + \left[(f_{ct,fl,t=28days} - f_{ct,fl,fat}) + (\Delta\sigma_{c,c+s+r,t=50years} - \Delta\sigma_{c,c+s+r,t=28days})\right] \times W_{r,bottom} = k_t \times M_{k,r,pos} \tag{46}$$

Where, $f_{ct,fl,t=28days}$ concrete flexural tensile strength under static load at age of 28 days;$f_{ct,fl,fat}$is flexural strength of concrete under fatigue loads;$\Delta\sigma_{c,c+s+r,t=50years}$is loss of prestress in concrete after 50 years;$\Delta\sigma_{c,c+s+r,t=28days}$ is loss of prestress in concrete after 28 days.

$$\Delta\sigma_{c,c+s+r,t=50years} - \Delta\sigma_{c,c+s+r,t=28days} = (P_{m,t2} - P_{m,t1})(\frac{1}{A_{r,c}} - \frac{e_{r,0}}{W_{r,bottom}}) \quad (47)$$

$$k_t = \frac{M_{t,r,pos}}{M_{k,r,pos}} \quad (48)$$

2.4.2. Calculation of the design acceptance criteria

(1) Static test

Formation of the first crack:

$$Fr_r > F_{r0} \quad (49)$$

Remaining crack width 0.05mm:

$$Fr_{0.05} > k_{1s}F_{r0} \quad (50)$$

Where, k_{1s} equals to 1.8×0.5/k_d.

Maximum test load:

$$Fr_B > k_{2s}F_{r0} \quad (51)$$

Where, k_{2s} equals to 2.5×0.5/k_d.

(2) Dynamic test

Remaining crack width 0.05mm:

$$Fr_{0.05} > k_{1d}F_{r0} \quad (52)$$

Where, k_{1d} equals to 1.5×0.5/k_d.

Remaining crack width 0.5mm:

$$Fr_{0.5} > k_{2d}F_{r0} \quad (53)$$

Where, k_{2d} is 2.2.

Maximum test load:

$$Fr_B > k_{2d}F_{r0} \quad (54)$$

Where, k_{2d} equals to 2.2×0.5/ k_d.

(3) Fatigue test

Maximum test load:

$$Fr_B > k_3F_{r0} \quad (55)$$

Where, k_3 equals to 3.

3. Sleeper design

3.1. Design parameter

The dimension of the PSC sleeper BG with UIC 60kg running rail shown in Figure 4, and the main parameters of the sleeper shown in Table2.

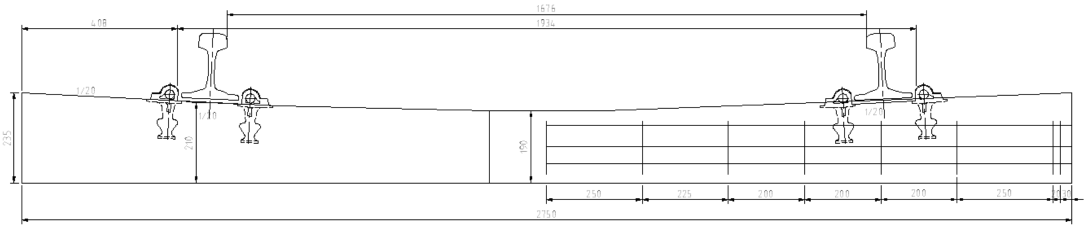
Table 2: Section size of PSC sleeper (mm)

Item	At the rail seat section	At the center section
height	210	190
Top width	150	150
Bottom width	236.4	220

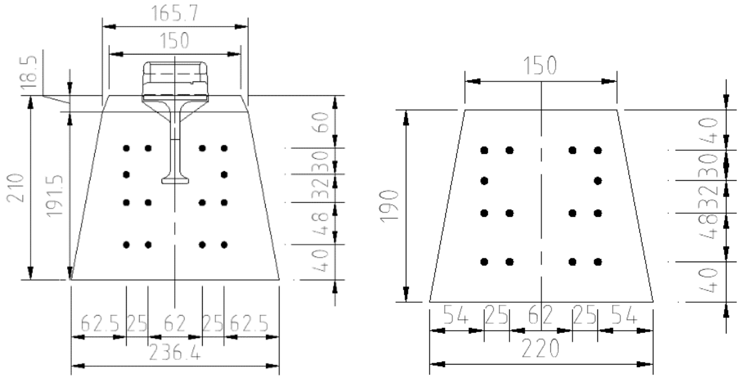
Prestressed rebar: 14Φ 6.25mm helical rib rebar. Tension force: 498kN±5kN. Stirrup: 15Φ 6mm ordinary hot rolled plain round rebar of HPB300. Release demolding strength: 45MPa.

Table 3: Design input data

Item	Value	Item	Value
Axle load	250kN	Gauge	1676mm
Design speed	120km/h	Rail type	UIC60
Sleeper spacing	600mm	Fastener	e-clip



(a)Vertical



(b)Cross section of rail seat and center

Figure 4: Dimension of sleeper

According to EN and design input data in Table3, the design rail set load P_d is 112.59kN and the bending moment of sleeper in different section is shown in Table4.

Table 4: Sleeper bending moment

Type	Value
Positive bending moment at rail seat	13.72kN.m
Negative bending moment at rail seat	-6.86kN.m
Positive bending moment at center section	11.44kN.m
Negative bending moment at center section	-16.34kN.m

3.2. Checking of Tensile Stress in Concrete for Serviceability Limit State

The concrete grade of sleeper adopts C60, Flexural strength of concrete under fatigue loads $f_{ct,fl,fat}$=3MPa. According to formula (8) ~(10), the results shown in Table5.

Table 5: Checking Results of Tensile Stress in Concrete for Serviceability Limit State

Section bending moment	Results	Criteria
Positive bending moment at rail seat section	-0.18	3
Negative bending moment at rail seat section	-3.67	3
Positive bending moment at center section	1.70	3
Negative bending moment at center section	2.59	3

3.3. Test load and acceptance criteria

Test load value was shown Table 6.

Table 6: Test load value

Item		Value(Rail seat section)
Static test	Formation of the first crack	109.76kN
	Remaining crack width 0.05mm	197.57kN
	Maximum test load	329.28kN
Dynamic test	Remaining crack width 0.05mm	164.64kN
	Remaining crack width 0.5mm	241.47 kN
	Maximum test load	241.47 kN
Fatigue test	Maximum test load	329.28kN

4. Conclusions

The following conclusions can be drawn by check on design of PSC sleeper BG in Bangladesh Railway based on the EN. In calculation of vertical load, the rail-pad attenuation, speed, load distribution between sleepers and support faults were taken into account by EN. The positive and negative bending moment of rail seat section and center section in the calculation of design loads and tensile stress in concrete for serviceability limit state. The prestress of sleeper mainly token anchorage deformation, relaxation losses of prestress before anchor applied, the prestress loss caused by elastic deformation of concrete during tensioning and time dependent losses into account.

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