

Damage and failure modes of railway prestressed concrete sleepers with holes/web openings subject to impact loading conditions

Kaewunruen, Sakdirat; Ngamkhanong, Chayut; Lim, Chie Hong

DOI:

[10.1016/j.engstruct.2018.09.057](https://doi.org/10.1016/j.engstruct.2018.09.057)

License:

Creative Commons: Attribution-NonCommercial-NoDerivs (CC BY-NC-ND)

Document Version

Peer reviewed version

Citation for published version (Harvard):

Kaewunruen, S, Ngamkhanong, C & Lim, CH 2018, 'Damage and failure modes of railway prestressed concrete sleepers with holes/web openings subject to impact loading conditions', *Engineering Structures*, vol. 176, pp. 840-848. <https://doi.org/10.1016/j.engstruct.2018.09.057>

[Link to publication on Research at Birmingham portal](#)

Publisher Rights Statement:

<https://doi.org/10.1016/j.engstruct.2018.09.057>
checked for eligibility 8/1/19

General rights

Unless a licence is specified above, all rights (including copyright and moral rights) in this document are retained by the authors and/or the copyright holders. The express permission of the copyright holder must be obtained for any use of this material other than for purposes permitted by law.

- Users may freely distribute the URL that is used to identify this publication.
- Users may download and/or print one copy of the publication from the University of Birmingham research portal for the purpose of private study or non-commercial research.
- User may use extracts from the document in line with the concept of 'fair dealing' under the Copyright, Designs and Patents Act 1988 (?)
- Users may not further distribute the material nor use it for the purposes of commercial gain.

Where a licence is displayed above, please note the terms and conditions of the licence govern your use of this document.

When citing, please reference the published version.

Take down policy

While the University of Birmingham exercises care and attention in making items available there are rare occasions when an item has been uploaded in error or has been deemed to be commercially or otherwise sensitive.

If you believe that this is the case for this document, please contact UBIRA@lists.bham.ac.uk providing details and we will remove access to the work immediately and investigate.

1 **Damage and failure modes of railway prestressed concrete sleepers with**
2 **holes/web openings subject to impact loading conditions**

3
4
5 **Sakdirat Kaewunruen^{1,2}, Chayut Ngamkhanong^{1,2} and Chie Hong Lim¹**

6 ¹Department of Civil Engineering, School of Engineering, University of Birmingham, Birmingham

7 B152TT, United Kingdom

8 ²Birmingham Centre for Railway Research and Education, School of Engineering, University of

9 Birmingham, Birmingham B152TT, United Kingdom

10
11 **Abstract:** Prestressed concrete sleepers are essential to the structural integrity of railway track
12 structures, redistributing wheel loads from the rails to underlying ballast bed while securing rail
13 gauges for safe train traffics. In practice, drilled holes or web openings are usually generated ad hoc in
14 sleepers to enable signalling equipment and cables at a construction site. These holes and web
15 openings could however affect the structural integrity of sleepers, especially when they are exposed to
16 impact loading. In fact, statistically, 15 to 25% of dynamic loading conditions are of transience and
17 high-intensity by the nature of wheel-rail interaction over irregularities. This study is thus the first to
18 investigate the impact behaviours of railway sleepers with hole and web openings, which is critical to
19 railway safety and reliability. In this study, three-dimensional finite element modelling using
20 ABAQUS Explicit was used to design and analyse the behaviour of prestressed concrete sleepers with
21 various types of holes and web openings upon impact loading. Two different modelling techniques
22 including concrete damaged plasticity model and brittle cracking model are also exercised to aid in
23 this study. The results obtained show that the brittle cracking model provides better damage results as
24 it can illustrate crack propagation very well until reaching the failure mode under impact loading. The
25 findings illustrate a pathway to use brittle cracking model instead of concrete damaged plasticity
26 model for dynamic impact analysis. Moreover, the outcome of this study will provide a better insight
27 into the influences of holes and web openings on sleepers' failure modes under impact loading so that

28 appropriate guidance can be proposed to rail engineers in order to generate holes and web openings ad
29 hoc in prestressed concrete sleepers without compromising their structural performance.

30

31 **Keywords:** prestressed concrete; sleeper; impact loading; concrete damaged plasticity; brittle
32 cracking model; finite element analysis

33

34 **1. Introduction**

35 The railway sleeper plays a significant role in a railway track system, where it is responsible for
36 transferring and distributing vehicle loads from rail foot to the underlying ballast bed. It also helps
37 maintain track gauge and insulate the rails against electricity. It should be noted that railway sleepers
38 are a structural and safety-critical component in railway track systems experiencing aggressive
39 dynamic conditions [1-15]. Railway sleepers can be constructed of various materials such as timber,
40 concrete, steel, and other engineered materials [16-18]. It is important to note that an individual
41 failure of a sleeper will generally not cause disruption to rail operations but it will increase periodic
42 track maintenance costs, increase costs and effort for safety-related track inspection and monitoring,
43 and impair ride comfort of train passengers depending on the severity. For various exceptional cases,
44 the failure of a sleeper will significantly increase the risk of rail breaks at welds, joints, rail surface
45 defects, rail foot defects, turnouts (or called ‘switches and crossings’) [17-18], and will inevitably
46 create asymmetrical load balancing and redistribution [11]. These exceptional risks can lead to
47 detrimental train derailments causing not only financial penalties but also losses of lives [14-15].

48 Notably, prestressed concrete sleepers have been widely used for more than 50 years [19-23].
49 Prestressed concrete sleepers would have an improved structural capacity and/or serviceability as
50 compared to conventional reinforced concrete. Given their importance, it is crucial to ensure that
51 concrete sleepers are always in excellent condition before and during operation. However, they are
52 prone to deterioration issues as cracks may occur and expand. This may incur extra costs as concrete
53 cannot be repaired and has to be replaced should it suffer considerable damage and fail over time. All
54 static, quasi-static, and impact loads are very important in design and analysis of railway track and its
55 components. Railway sleepers are often subjected to impact loading, which is a shock load applied

56 over a short period. Impact loading is a possible source of damage which may induce cracking in
57 sleepers. Impact loading is caused by the interaction with abnormalities in either wheel or rail, as well
58 as the resonance produced among the track components [24]. Impact load, which varies roughly from
59 200kN to 750kN, would imply severe damage to the sleepers. In fact, many studies over a number of
60 years show that statistically, up to 25% or more of dynamic loading conditions are of transience and
61 high-intensity by the nature of wheel-rail interaction over irregularities [3-9, 15, 24]. This issue is
62 further compounded considering that holes are often drilled into sleepers for signalling gears, cables,
63 and additional train derailment protection, such as guard rails, check rails, earthquake protection rails,
64 etc. [25-27]. With the introduction of these holes into sleepers, the structural integrity of the sleeper
65 may be weakened and thus, more vulnerable to the adverse effects under impact loading. Not only
66 will that mean a replacement of the sleeper is in order, there is likelihood that the signalling
67 equipment may get affected as well. If that happens, signalling faults may result and cause disruption
68 to the entire track operation. Based on the literature, although the effects of holes on the capacity
69 reduction of concrete sleepers have been studied via compression field theory and experiments [28-
70 31], performance and crack propagation prediction under impact loading corresponding to dynamic
71 wheel load has not been fully investigated.

72 Hence, these evidences highlight the importance of studying the performance of these railway
73 sleepers under impact loading. Finite element analysis (FEA), which is a common approach for
74 solving engineering problems, is a numerical technique and used through a finite element software
75 ABAQUS. Numerical modelling is an ideal tool to enable complex structural scenarios to be
76 replicated and analysed, providing insights that would be beneficial for solving issues without using a
77 huge amount of resources as traditional experimental methods would. Two different methods, the
78 concrete damaged plasticity (CDP) model [32-35] and the brittle cracking model [36-37] are used to
79 compare the results. The CDP model is designed based on two failure mechanisms, tensile cracking
80 and compressive crushing. The brittle cracking model contains a failure criterion and allows the
81 removal of elements during the analyses. The aim of this study is to investigate the failure modes of
82 prestressed concrete sleepers with holes/web openings under impact loading considering two different
83 finite element models: concrete damaged plasticity (CDP) and brittle cracking model, in order to

84 compare the different from both models. The condition recommended by European Standard [10] to
85 identify common failure modes of concrete sleepers is emphasised. The results show that the brittle
86 cracking model demonstrates better results by illustrating crack propagation and removed elements
87 until failure. The findings of this study can provide information to rail and track engineers in
88 determining the best way to generate holes into sleepers without compromising the sleeper
89 performance during operation. Consequently, this study will enhance structural safety and reliability
90 of railway infrastructure.

91

92 **2. Methodology**

93 **2.1 Finite element modelling**

94 The finite element software ABAQUS was used to establish the models for this study. Different type
95 of holes and web opening were demonstrated. It should be noted that the hole diameters considered
96 (32mm and 42mm) are practical options for drilling sleepers and have been cored in a similar manner
97 as in an actual construction. Two different types of models will be adopted, namely the Concrete
98 Damaged Plasticity (CDP) models and the Brittle Cracking models.

99 The CDP model is designed as a continuum and plasticity-based model, with the assumption of two
100 main failure mechanisms being tensile cracking and compressive crushing of concrete. The strain
101 hardening during compression, the stiffness recovery, and the sensitivity to the straining rate may be
102 controlled to allow the resemblance of the behaviour of concrete. However, it is impossible to conduct
103 a crack propagation analysis with the CDP models as the CDP concept does not employ a failure
104 criterion. The CDP is one of the most popular concrete models and has been used for concrete
105 behaviour simulation in ABAQUS as seen in the literature [32-35]. This model was theoretically
106 described by Lubliner et al. [32] and developed by Lee and Fenves [33]. The main assumptions of this
107 model are listed as follows.

- 108 • There are two damage mechanisms: tensile cracking and compressive crushing of concrete,
- 109 • Material stiffness is reduced by two damage parameters, separately for tension and
110 compression,

- 111 • The yield function is specified according to Lubliner et al.[32] and the flow potential is a
- 112 hyperbolic function,
- 113 • Non-associated potential plastic flow is assumed.

114 To enable the study of crack propagation of the sleeper models under impact loading, an alternative,
 115 the brittle cracking model, has been suggested [36-37]. The brittle cracking model contains a failure
 116 criterion and allows the removal of elements during the analyses. This method provides the capability
 117 for modelling brittle materials and is designed for structures which are dominated by tensile cracking
 118 such as concrete. It should be noted that the linear elastic is assumed in this method. This implies that
 119 the crack propagation of the sleeper can be thoroughly examined when it undergoes impact loading. It
 120 is noted that a vertical velocity of 1.94 m/s is applied at the centre of the wheel to generate the impact
 121 loading equivalent to the 600kg falling mass with the drop height of 0.2m which has been developed
 122 in previous experiments [38]. This velocity can generate the impact load associated with actual train
 123 load.

124 **2.1.1 Element and mesh size**

125 The four components used for the models are the concrete sleeper, the prestressed tendons, the wheel,
 126 and the rail. Their element sizes are 15mm, 35mm, 12mm and 10mm respectively. All components
 127 except the prestressed tendons are of C3D8R element type, while the prestressed tendons are of the
 128 C3D6 element type [39]. The C3D8R element is eight-node brick element with reduced integration
 129 whereas the C3D6 is a six-node wedge element. These element types and sizes were selected to
 130 reduce the computational time for contact analysis, without compromising the realism and accuracy of
 131 the results. It is important to note that these element size have reflected the accuracy results since the
 132 results started to converge to a particular value. Fig. 1 shows the constructed mesh of the model setup.
 133 The number of element and mesh density are shown in Table 1.

134 **Table 1** Element types and number of elements

Component	Element type	No. of nodes	No. of elements
Rail	C3D8R	5043	3600
Wheel	C3D8R	20398	16074
Sleeper	C3D8R	21588	18426
Tendon	C3D6	370	324

135

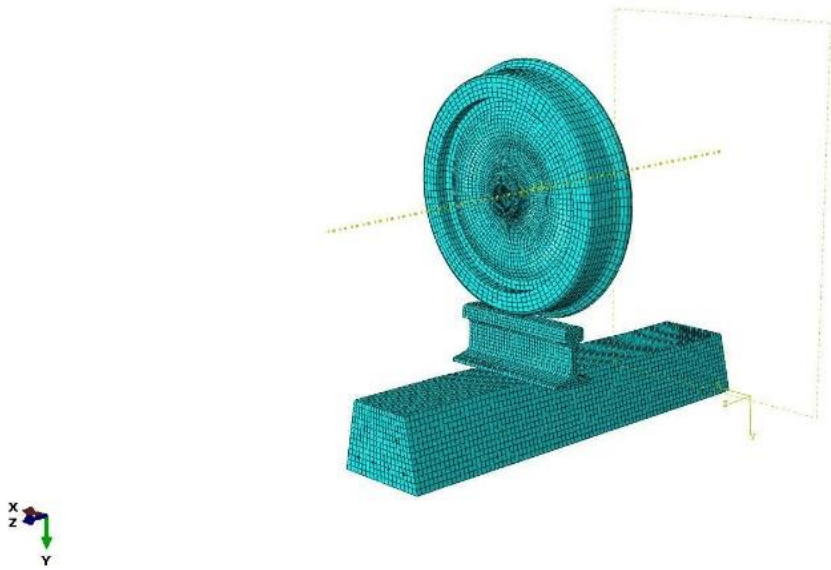


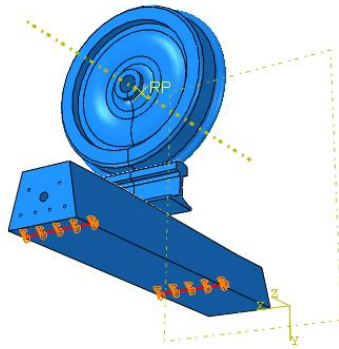
Fig. 1. Constructed mesh of sample model.

2.1.2 Contact and boundary conditions

The boundary conditions were assigned to replicate the real-life scenario of a sleeper under impact loading. A vertical velocity of 1.94 m/s was applied at the centre of the wheel and its DOF is constrained except for in the U2 direction [40-42] as shown in Fig. 2., which allows it to act as if it was a wheel imposing an impact load. It should be noted that this velocity can generate impact force equivalent to the 600kg falling mass with the drop height of 0.2m which has been developed in previous impact experiments [40, 41]. Equivalent train loads can be reversely predicted using multi-body simulations or any recommended unified codes (such as Australian Standard AS1085.14, European UIC 713, American AREMA Chapter 3) [2, 3, 4, 13]. The constraints of each component are shown in Table 2. In order to compare and validate with the three point bending tests [27], support boundary conditions are applied as rollers on the bottom of the sleeper as shown in Fig. 2. It should be noted that the aim of this study is to determine structural capacity and failure mode. The support condition in this study has been recommended by EN13230 (adopted throughout Europe) to determine common failure modes of the sleeper [43]. Thus, this support condition is suitable to identify the capacity and failure mode [27].

General contact was assigned for the entire model to ensure interaction and load transfers among the components. A friction coefficient of 0.3 was adopted for the interface between the structural

155 components as recommended by [44, 45]. The contact interfaces of each component are shown in Fig.
 156 3. As for the contact surface between rail and sleeper (Fig. 3a.), the interface was modelled as a tie
 157 constraint. Embedded interface was used as a contact between prestressed tendons and concrete
 158 sleeper (Fig. 3b.). It is noted that the master surface is for stiffer components, whilst the slave surface
 159 is for less stiff components.

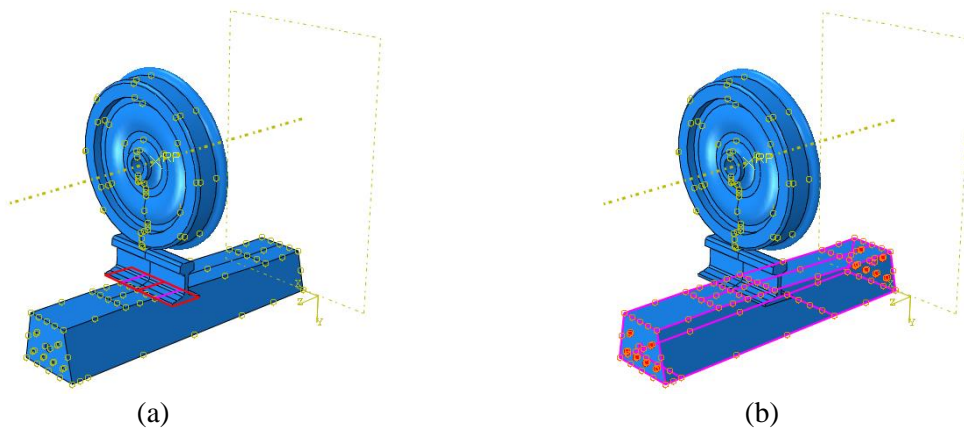


160

161

Fig. 2. Support boundary conditions.

162



163

Fig. 3. Contact interface between a) rail and sleeper b) prestressed tendon and concrete.

164

165

Table 2 Constraints definition.

Component	Constraint
Wheel	Rigid
Surface between rail bottom and sleeper top	Tie
Prestressed tendons and concrete sleeper	Embedded Region

166

167 **2.2 Material properties**

168 **2.2.1 Concrete**

169 The sleeper component is made of concrete and the typical properties of high-strength concrete are
170 listed in Table 3.

171 **Table 3** Typical properties of high-strength concrete C50/60 [12].

Density	2400 kg/m ³
Young's Modulus	36406 MPa
Poisson's Ratio	0.2
Compressive Strength	50 MPa
Tensile Strength	2.85 MPa
Fracture Energy	154 N/m

172

173 **2.2.2 Steel and prestressed steel tendon**

174 The general properties of the steel used for the wheel, rail and tendons are listed in Table 4 while the
175 plastic stress-strain relationship for the prestressed tendons is shown in Table 5. The prestressing steel
176 grade 270 ($f_{pu} = 1860$ MPa) is considered in this study.

177 **Table 4** General properties of steel [12].

Density	7.8 g/cm ³
Young's Modulus	200 GPa
Poisson's Ratio	0.3

178

179 **Table 5** Plastic stress-strain property for prestressed steel tendon [12].

Yield Stress (MPa)	Plastic Strain
1000	0
1703	0.0085
1750	0.0097
1797	0.0100
1860	0.0640

180

181 **2.2.3 Concrete damaged plasticity (CDP) model**

182 The two main failure mechanisms in CDP models are tensile cracking and compressive crushing of
183 concrete. In this study, it was expected that the sleepers would fail at the bottom due to the tensile
184 resistance concrete. Thus, tensile damage is presented as the damage mechanism in CDP model. The
185 compressive (d_c) and tensile damages (d_t) proposed by Lubliner et al. [32] are defined as the cracking

186 strain-total strain ratio. This mechanism is one of the most popular and has been widely used in
 187 ABAQUS to simulate realistic concrete behaviour. It was found that this mechanism can represent
 188 closely to the actual crack pattern as seen in previous studies [32-35]. The Eq. (1) shows the plastic
 189 strain calculation based on the stress strain relationship. The CDP model parameters used are listed in
 190 Table 6.

$$191 \quad \dot{\varepsilon}^p = \dot{\varepsilon} - \dot{\varepsilon}_{cr}^e = \dot{\varepsilon}^p - \frac{d}{1-d} \cdot \frac{\dot{\sigma}}{E_0} \quad (1)$$

192 Thus, the damage factor (d) can be defined as shown in Eq. (2).

$$193 \quad d = \frac{\varepsilon^p - (\varepsilon - \varepsilon_{cr}^e)}{\varepsilon^p - (\varepsilon - \varepsilon_{cr}^e) + \frac{\sigma}{E_0}} \quad (2)$$

194 Where

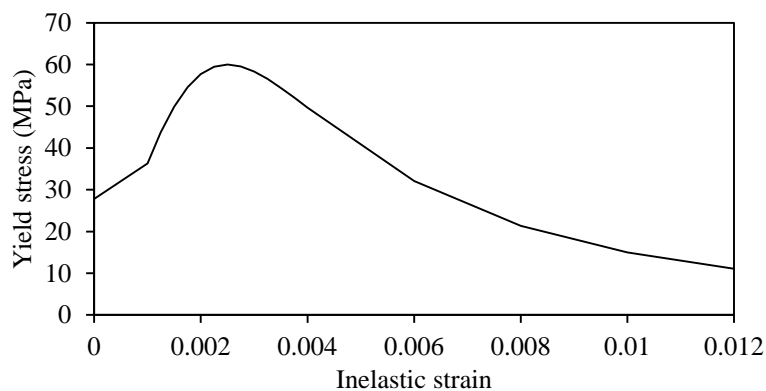
195 ε^p , ε , ε_{cr}^e , σ , and E_0 are plastic strain, total strain, concrete cracking strain, stress and elastic modulus
 196 of concrete, respectively.

197 **Table 6** Parameters inputted for CDP model [34].

Dilation Angle, Ψ	45
Flow potential eccentricity	0.1
Biaxial compressive yield stress to uniaxial compressive yield stress, F_{b0}/F_{c0}	1.16
Second stress invariant ratio, K	0.67
Viscosity parameter	0

198

199 Fig. 4. shows the compressive yield stress and inelastic strain curve while the tensile yield stress is set
 200 to be 2.56MPa.



201

202 **Fig. 4.** Stress-strain relationship for compression of concrete for CDP model [12].

203 **2.2.4 Brittle cracking model**

204 The elements will be removed when the local direct cracking strain reaches the failure value. The
 205 brittle cracking parameters are given in Table 7.

206 **Table 7** Brittle cracking parameters [44]

	Direct stress after cracking	Direct cracking strain	Field 1
Brittle cracking	3.17	0	0.5
	0	0.0008	0.5
	4.50	0	1.5
	0	0.0008	1.5
	Shear retention factor	Crack opening strain	
Brittle shear	1	0	
	0	0.08	
	1	0	
	0	0.09	
Brittle failure (Failure criteria: Unidirectional)	Direct cracking failure strain or displacement		
	0.045		

207

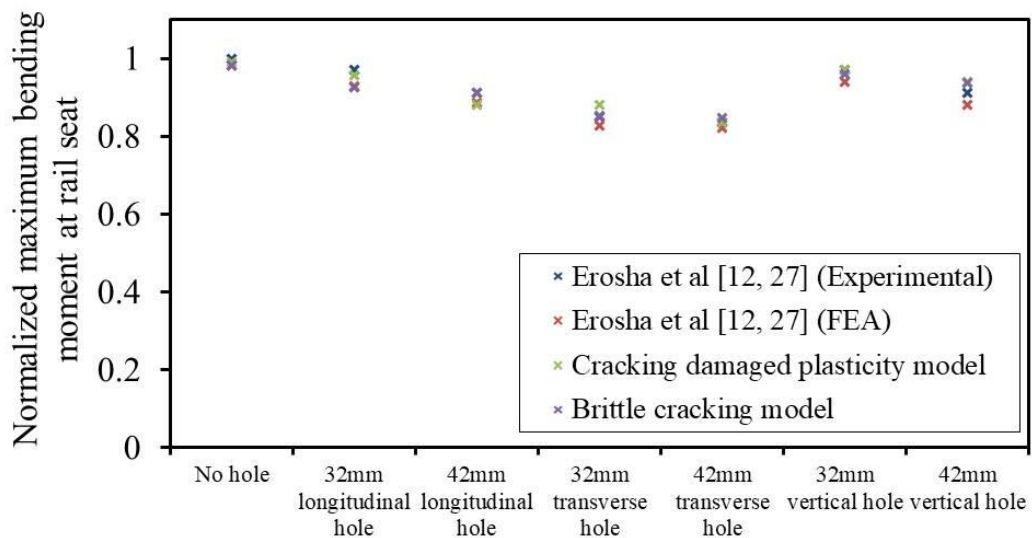
208 **3. Results and discussions**

209 The results for each case are presented in this section, where they are divided mainly into two
 210 different models – Concrete Damaged Plasticity (CDP) models and Brittle Cracking models. The
 211 finite element models are validated with previous studies [12, 27] under static loading. The results of
 212 the CDP models were presented in terms of tensile damage. As CDP models do not have a failure
 213 criterion, it is impossible for the models to display any cracking phenomenon. Instead the tensile
 214 damage suffered by the models is presented, where it is specified as a function of cracking
 215 displacement. The results of the brittle cracking models are then presented, where it explores the von
 216 Mises stress distributions and crack propagations of each case.

217 **3.1 Model validation**

218 To ensure the legitimacy of the models and their results, it is a necessity to validate the models. The
 219 finite element models using ABAQUS have been validated against the previous experimental and
 220 numerical results [12, 27]. To accomplish this, the ultimate bending moments at railseat for the
 221 developed models were compared in Fig. 5. As Eroscha et al’s study [12, 27] is based on sleeper
 222 models under impact loading, the boundary conditions of the developed models were adjusted to the
 223 same static loading conditions. There are a number of cases used in this study as follows.

- 224 • Case 1 Sleeper with no hole
- 225 • Case 2.1 32mm longitudinal hole
- 226 • Case 2.2 42mm longitudinal hole
- 227 • Case 3.1 32mm transverse hole
- 228 • Case 3.2 42mm transverse hole
- 229 • Case 4.1 32mm vertical hole
- 230 • Case 4.2 42mm vertical hole



231

232 **Fig. 5.** Normalized maximum bending moment at rail seat (kNm) for model validation

233 As observed from Fig. 5., it can be seen that there are positive correlations between the results of
 234 both cracking damaged plasticity model, brittle cracking model and the data obtained from Eroscha
 235 et.al. [12, 27].

236 **3.2 Concrete Damaged Plasticity (CDP) models**

237 It can generally be observed that the region that experiences the highest magnitude of vertical
 238 deflection is the bottom fibres located at the rail seat of the sleeper for every case. It should also be
 239 noted that the sleepers with larger holes experience higher deflections under impact loading than their
 240 respective counterparts. The von Mises stress distribution for the sleeper components of the CDP
 241 models are considered negligible considering the high magnitude of the impact loading imposed on
 242 the sleeper. The contour legend for the von Mises illustrated that there would be no obvious changes

243 in the stress distribution in the models. This would imply that the CDP may not be an effective FE
 244 approach when assessing the von Mises stress distribution of the sleepers under impact loading.
 245 However, the stresses in the prestressed tendon bars are well-represented in the CDP models. All the
 246 models have shown consistently high magnitudes of stresses in the tendon bars upon impact loading.
 247 This phenomenon is expected as the tendons are supposed to act as tensile resistants, when the
 248 concrete material is weaker against tension while having significantly stronger compressive strength.
 249 Furthermore, the sleeper is at its weakest against tensile forces in the bottom fibres and hence, the
 250 tensile forces carried by the tendons are assumed to be higher in those regions. The stresses sustained
 251 by the tendons for the sleepers with larger holes are also noted to be much higher than their
 252 counterparts.

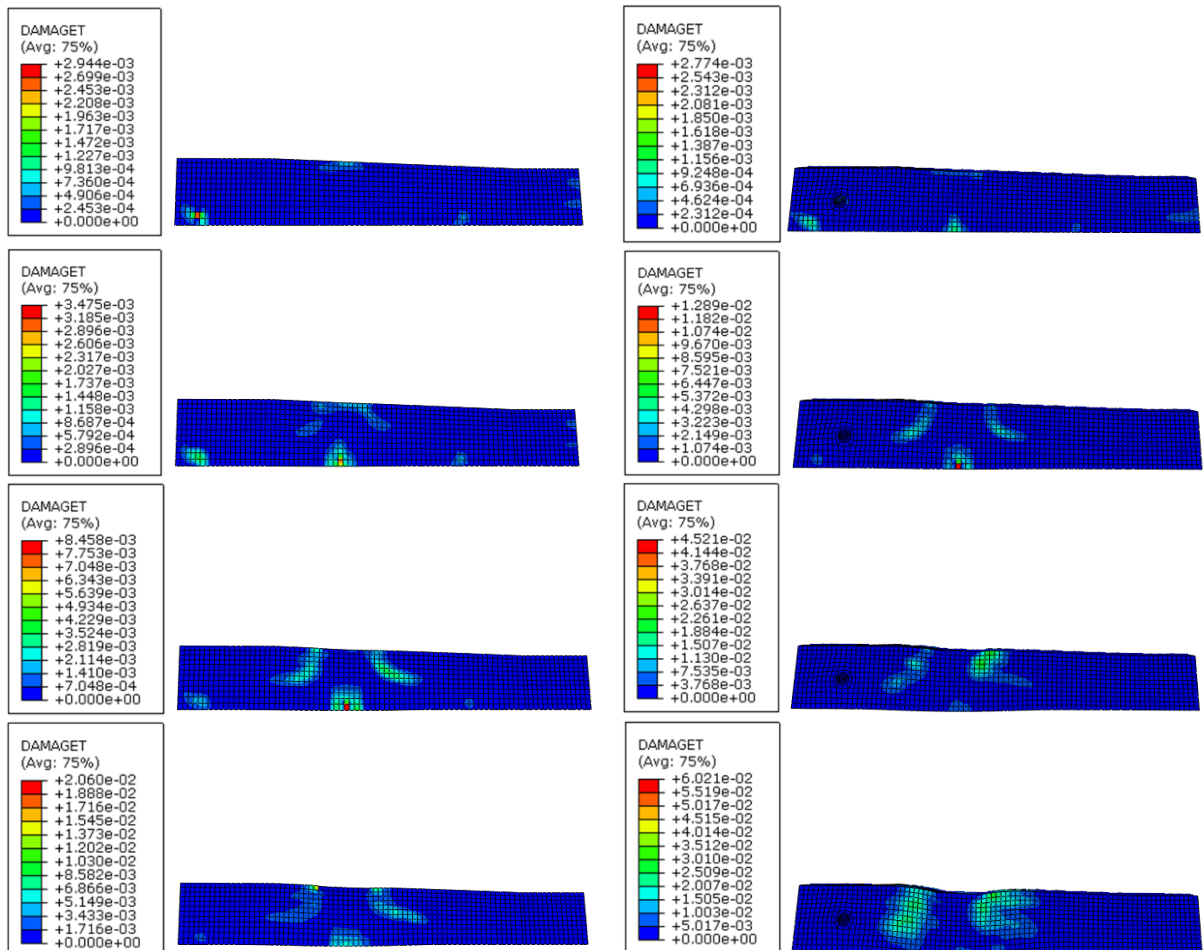
253 Tensile damage, which depends on the cracking strain, is presented in this model. The tensile damage
 254 can compare with the cracking patterns from experiment or brittle cracking model [34, 46]. It is
 255 discovered that the sleeper with 42mm transverse hole sustained the highest tensile damage. On a
 256 value between 0 and 1 (with 1 being the most severe), the sleeper with 42mm transverse hole has the
 257 highest value at 0.06 among all the sleeper cases. This may imply that it is the worst performing
 258 sleeper under impact loading. The tensile damages of concrete sleepers with no hole and with 42mm
 259 transverse hole under impact loading are shown in Table 8. Fig. 6a-b. show tensile damage contours
 260 which represent crack propagation of sleepers with no hole and 42mm transverse hole under impact
 261 loading at different steps. However, it should be noted that these results are the maximum tensile
 262 damage at the step before the convergence issue which show the large deformation at the unrealistic
 263 locations.

264

265 **Table 8** Tensile damage in CDP models

Sleeper cases		Tensile damage
No hole/web opening		0.021
Longitudinal hole	32 mm	0.027
	42 mm	0.031
Transverse hole	32 mm	0.028
	42 mm	0.060
Vertical hole	32 mm	0.020
	42 mm	0.032

266
 267
 268
 269
 270



271 **Fig. 6.** Tensile damage contour in CDP models of concrete sleepers with a) no hole b) 42mm
 272 transverse hole

273 Table 9 shows that the maximum loads bored by each sleeper case, and the sleeper with 42mm
 274 transverse hole performed slightly worse than other cases at 241 kN. Although this may be consistent
 275 with the theory and previous experiments [12, 27] that it is the worst performing case under impact
 276 loading due to its high tensile damage value, it should be noted that the difference in maximum load is
 277 not significant. Furthermore, an attempt to obtain the load-deflection curve for all CDP models was
 278 made earlier but the results were not optimal as the sleepers tended to be failed very early during the

279 loading process compared to the results obtained by brittle cracking model, despite the deflection
 280 experienced perhaps being a lot higher. This may yet again highlight the possibility that the CDP
 281 models may not be suitable for this study as the models were terminated earlier due to the
 282 convergence difficulties.

283 **Table 9** Maximum load for CDP models

Sleeper cases		Maximum Load (kN)
No hole/web opening		243
Longitudinal hole	32 mm	243
	42 mm	243
Transverse hole	32 mm	244
	42 mm	241
Vertical hole	32 mm	244
	42 mm	243

284

285 **3.3 Brittle cracking models**

286 The von Mises stress distribution and crack propagation of sleepers are shown in Fig. 7. Depicts the
 287 changes in von Mises stress distributions and crack propagations undergone by the brittle cracking
 288 models. It has been observed that every sleeper displayed quite similar behaviours under impact
 289 loading. The general behaviour of the sleeper for every case can be described in the following. The
 290 sleeper is initially un-deformed and does not experience any stresses throughout the structure prior to
 291 impact loading (Fig. 7a). Stresses can then be observed developing at the supports and the rail seat
 292 position, as the sleeper is subjected to impact loading. The stresses then intensify in these locations
 293 and can be seen advancing in a diagonal direction between the rail seat and one of the supports.

294 The modes of failure in the sleeper component for every sleeper case are determined to be a
 295 combination of shear and flexural failure as shown in Fig. 8a. Cracks are initially detected at the
 296 supports for every sleeper case, and this is followed by the appearance of diagonal cracks at the
 297 middle height of the sleeper at approximately 45° near one of the supports as clearly seen in Fig. 8b.
 298 Transverse cracks start forming at the bottom fibres of the sleeper at its mid-span, suggesting that
 299 flexural cracking has begun as the tension of the bottom fibres exceeds its tensile strength. The
 300 diagonal shear cracks, which initiate at the support, continue to propagate towards the rail seat while
 301 the flexural cracks extend upwards, and a longitudinal crack begins to form at the reinforcement level

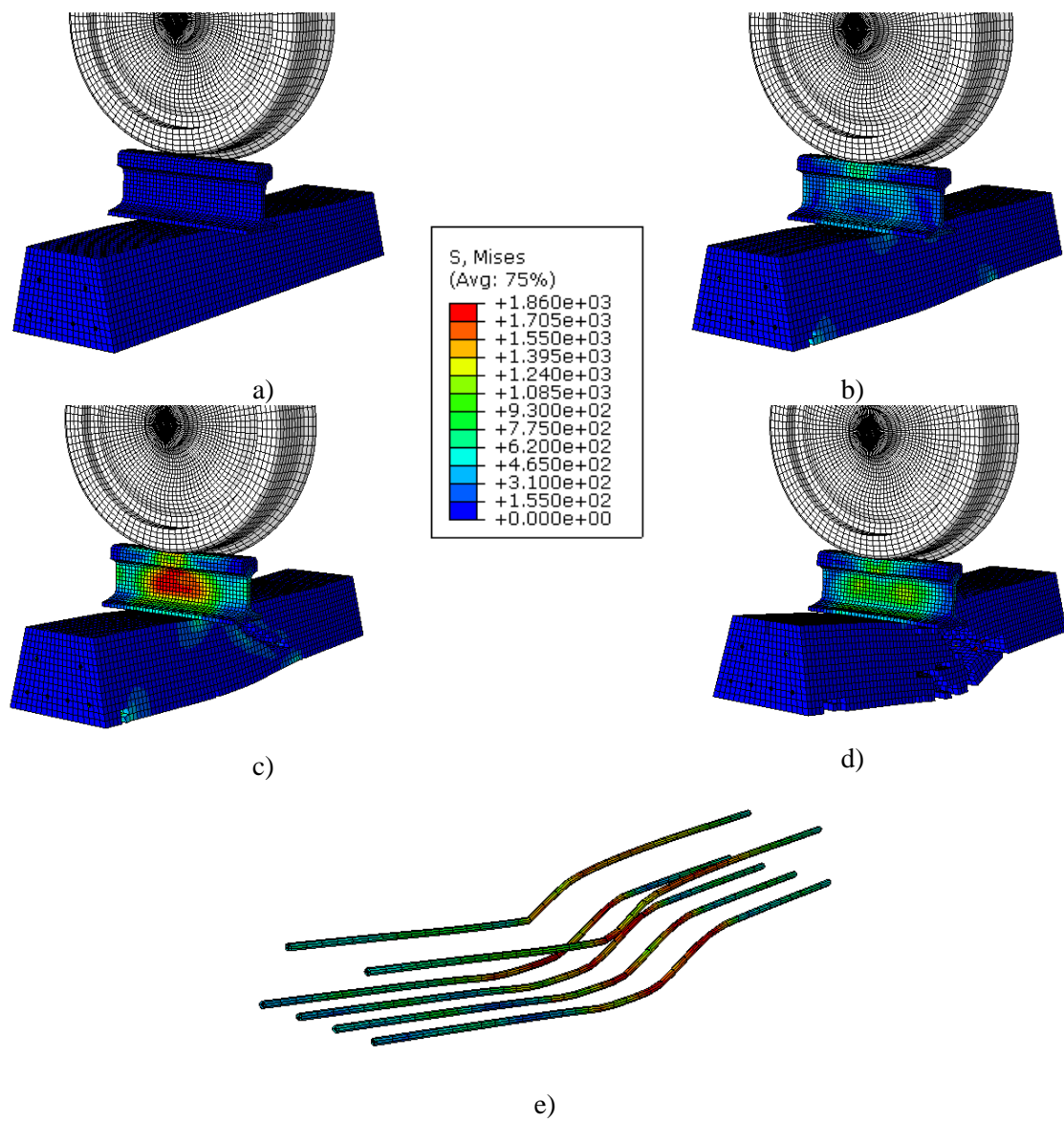
302 as the shear bearing capacity of the concrete ligament is transferred to the tendons prior to failure.

303 Finally, the sleeper fails and the cracking process stops.

304

305

306



307

308 **Fig. 7.** Von Mises Stress distribution and crack propagation: of sleeper at a) 0.000 b) 0.001 c) 0.0015

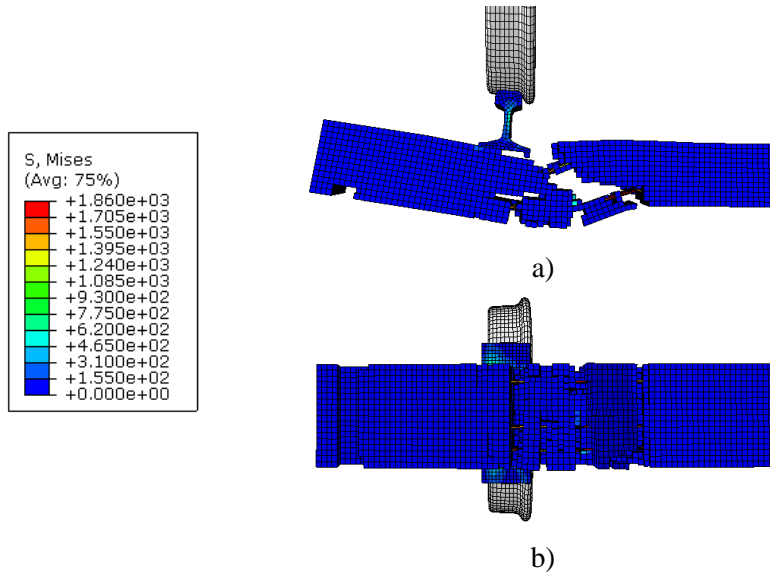
309

d) 0.0025; e) steel tendon at 0.0025

310

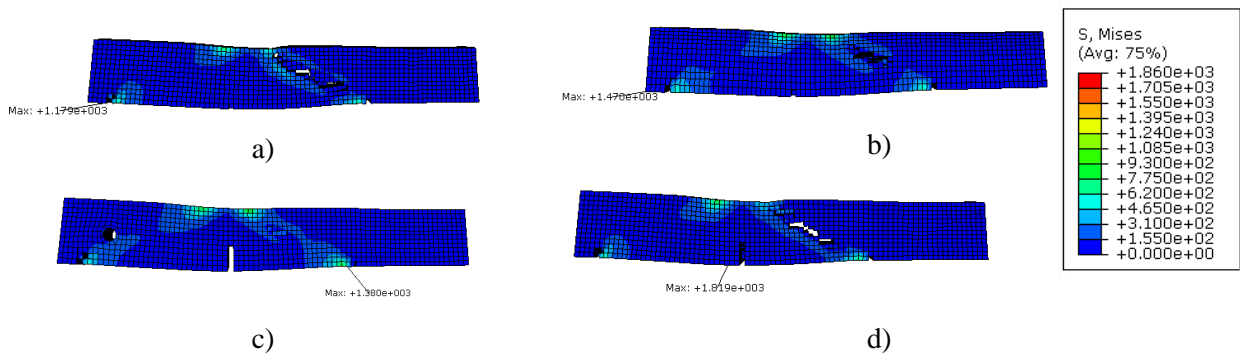
311

312
313
314



315
316

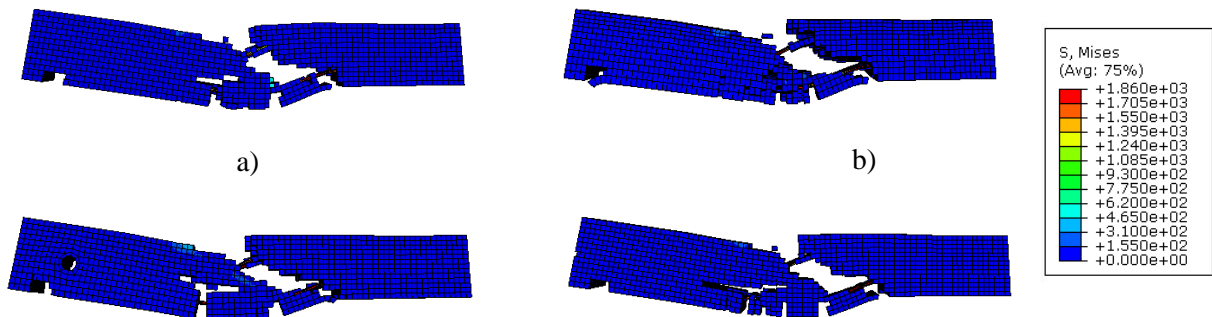
Fig. 8. Crack pattern of sleeper with no hole at a) rail seat b) bottom



317
318
319

Fig. 9. Von Mises Stress distribution and crack propagation at the time step of 0.015 of sleeper with

a) no hole b) 42mm longitudinal hole c) 42mm transverse hole d) 42mm vertical hole



c)

d)

320

321 **Fig. 10.** Von Mises Stress distribution and crack propagation at the time step of 0.025 of sleeper with

322 a) no hole b) 42mm longitudinal hole c) 42mm transverse hole d) 42mm vertical hole

323

324 Although cracks were initially detected at the supports, it is the diagonal shear cracking that has

325 dominated throughout the process and ultimately resulted in the failure of the sleeper, as seen in Fig.

326 9. This implies that the sleeper has inadequate shear resistance in every case. Another observation that

327 was made for every sleeper case was the slight cracking that appeared at the top fibres of the sleeper

328 where the rail seat lies (Fig. 9.), and this did not form until the sleeper was close to failure. The cracks

329 occurred as the compressive forces at the top fibres exceed the compressive strength of the concrete,

330 and this delayed response can only be explained by the high compressive strength of concrete.

331 As seen from Figs. 9-10, flexural cracks have been identified at the bottom fibres of every sleeper and

332 they progressed upwards to the neutral axis of the sleeper. These flexural cracks occurred due to the

333 brittle nature of concrete, as well as the high tensile forces in this region which have exceeded the

334 tensile strength of concrete. In cases of transverse hole (Fig. 9c., 10c.), flexural cracks can be seen

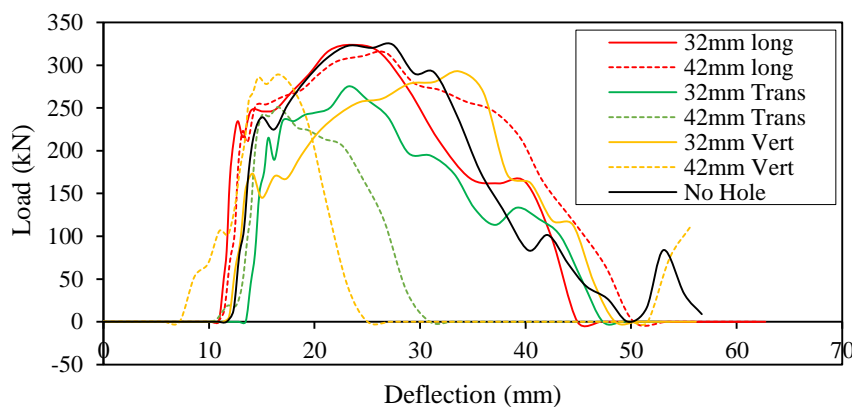
335 more clearly than other cases. However, the flexural cracks have not progressed beyond the neutral

336 axis due to the longitudinal tendons providing resistance against the tensile forces. By comparing

337 these to the results obtained by the CDP model, it is clearly seen that the brittle cracking model has

338 better results under impact loading as the CDP model can provide only the early stage before failure

339 due to the convergence difficulties.



340

341 **Fig. 11.** Load-deflection curve of sleeper using the Brittle Cracking Model.

342 However, a load-deflection curve was obtained for the brittle cracking models in Fig 11. This shows
343 the load-deflection curves of every brittle cracking model and it was later realized that the sleeper
344 with the 42mm transverse hole has the worst performance under impact loading. The load at failure
345 for the sleeper with 42mm transverse hole was the lowest, at approximately 251kN with a deflection
346 of 16.5mm. It is also concluded that the results obtained by the brittle cracking model show a better
347 agreement compared to previous studies than CDP model as the maximum loads are higher than those
348 in the CDP model. These results are related to the tensile damage which only shows the earlier stage
349 before failure.

350

351 **4. Conclusion**

352 This study investigates the performance of railway sleepers with holes/web openings under impact
353 loading using finite element analysis software ABAQUS. It is noted that the modification or
354 retrofitting of concrete crossties at construction sites through holes and web openings undermines the
355 strength of railway concrete sleeper. It is important to ensure that concrete crossties can be retrofitted
356 and modified for add-on fixtures in practice. The performance of railway sleepers with holes/web
357 openings have not been fully investigated in recent studies. In this study, the three-dimensional finite
358 element model has been developed and validated. It has adopted two different types of models,
359 concrete damaged plasticity and brittle cracking models for seven different sleeper cases, each with a
360 different hole size and the direction generated in. The damage of sleepers is represented by tensile
361 damage in the CDP model and crack propagation in the brittle cracking model. The aim and scope of
362 this study is to identify impact damage and failure mode of sleepers with holes and web openings. The
363 effectiveness of advanced numerical modelling techniques has also been investigated. The results
364 obtained from both methods show that the sleeper with 42mm transverse hole has the worst
365 performance among all sleeper cases. However, the stress distribution and load-deflection relationship
366 from the CDP model may however be regarded as inconclusive due to the insignificant differences
367 shown during the analyses. Moreover, although crack propagation can be represented by tensile
368 damage contours, the CDP models were terminated before failure due to the convergence difficulties.
369 Thus, the maximum loads occurred are less than those in the brittle cracking model. Whilst the brittle

370 model shows better results as it still retains high magnitude stresses after the sleeper component has
371 failed so that the maximum load is higher than that in the CDP model. Furthermore, the crack
372 propagations are shown properly in this model. It is apparent that failure mechanism of sleepers under
373 impact load is mixed bending-shear failure. It can be concluded that the brittle cracking model is more
374 suitable for dynamic analysis. The insight into the performance of railway prestressed concrete
375 sleepers with holes and web openings will help improve the design standard and will enable safer
376 built environments in railway infrastructure especially with concrete sleepers.

377

378 **Acknowledgements**

379 The authors are sincerely grateful to the European Commission for the financial sponsorship of
380 the H2020-RISE Project No. 691135 “RISEN: Rail Infrastructure Systems Engineering Network”,
381 which enables a global research network that tackles the grand challenge of railway infrastructure
382 resilience and advanced sensing in extreme environments (www.risen2rail.eu) [47].

383

384 **References**

- 385 [1] Kaewunruen S, Remennikov AM. On the residual energy toughness of prestressed concrete
386 sleepers in railway track structures subjected to repeated impact loads. *Electronic Journal of*
387 *Structural Engineering* 2013; 13(1): 41-61.
- 388 [2] Remennikov AM, Murray MH, Kaewunruen S. Conversion of AS1085.14 for railway
389 prestressed concrete sleeper to limit states design format. *Proc. CD-Rom Conf. AusRAIL Plus*
390 *(Sydney); 2007.*
- 391 [3] Remennikov AM, Murray MH, Kaewunruen S. Reliability based conversion of a structural
392 design code for prestressed concrete sleepers *Proceedings of the Institution of Mechanical*
393 *Engineers: Part F Journal of Rail and Rapid Transit* 2012; 226(2): 155-73.
- 394 [4] Wakui H, Okuda H. A study on limit-state design for prestressed concrete sleepers. *Concrete*
395 *Library of JSCE*, 1999. 33: 1-25.
- 396 [5] Wang N. Resistance of concrete railroad ties to impact loading, PhD Thesis, University of
397 British Columbia, Canada, 1996.

- 398 [6] Gustavson R. Structural behaviour of concrete railway sleepers. PhD Thesis, Department of
399 Structural Engineering, Chalmers University of Technology, Sweden, 2002.
- 400 [7] Stevens NJ, Dux PF. A method of designing a concrete railway sleeper, International Patent No
401 WO 2004/019772 A1, Publication Date 4 March 2004, World Intellectual Property
402 Organisation, International Bureau, 2004.
- 403 [8] Lilja J, Preliminaries for probabilistic railway sleeper design, Licentiate Thesis, Chalmers
404 Applied Mechanics, Chalmers University of Technology, Gothenburg, 2006, 70pp.
- 405 [9] Leong J. Development of a limit state design methodology for railway track. Master of
406 Engineering Thesis, Queensland University of Technology, QLD, Australia, 2007.
- 407 [10] British Standards Institution. BS EN 13230-2:2009. Railway applications. Track. Concrete
408 sleepers and bearers. Prestressed monoblock sleepers; 2009.
- 409 [11] Fryba L. Dynamics of railway bridges, Thomas Telford Ltd; 1996.
- 410 [12] Gamage EK, Kaewunruen S, Remennikov AM. Design of holes and web openings in railway
411 prestressed concrete sleepers, Railway Engineering Conference, June 28-July 2, 2015,
412 Edinburgh, UK.
- 413 [13] Remennikov AM, Kaewunruen S. Reliability-based design of railway prestressed concrete
414 sleepers. In G. I. Hayworth (Eds.), Reliability Engineering Advances. USA: Nova Science
415 Publishers; 2009, p. 65-93.
- 416 [14] Kaewunruen S, Remennikov AM. Structural safety of railway prestressed concrete Sleepers.
417 Aust J Struct Eng 2009; 9(2): 129–140. doi: 10.1080/13287982.2009.11465016
- 418 [15] Kaewunruen S, Remennikov AM, Murray MH. Limit states design of railway concrete sleepers
419 Proc. of ICE Transport Journal 2012; 164(TR1). doi: 10.1680/tran.9.00050
- 420 [16] Standards Australia, “Railway track material - Part 14: Prestressed concrete sleepers,”
421 Australian Standard AS1085; 2003.
- 422 [17] Kaewunruen S, You R, Ishida M. Composites for Timber-Replacement Bearers in Railway
423 Switches and Crossings. Infrastructures, 2017, 2, 13. doi:10.3390/infrastructures2040013

- 424 [18] Silva É. A, Pokropski D, You R. and Kaewunruen, S., Comparison of structural design methods
425 for railway composites and plastic sleepers and bearers, *Australian Journal of Structural*
426 *Engineering*, 18:3, 160-177, 2017. doi:10.1080/13287982.2017.1382045
- 427 [19] Kaewunruen S, Remennikov AM, “Sensitivity analysis of free vibration characteristics of an in-
428 situ railway concrete sleeper to variations of rail pad parameters,” *Journal of Sound and*
429 *Vibration* 2006; 298(1): 453-461.
- 430 [20] Kaewunruen S, Remennikov AM, “Investigation of free vibrations of voided concrete sleepers
431 in railway track system,” *Proceedings of the Institution of Mechanical Engineers Part F: Journal*
432 *of Rail and Rapid Transit* 2007; 221(4): 495-507.
- 433 [21] Kaewunruen S, Minoura S, Watanabe T, Remennikov AM. Remaining service life of railway
434 prestressed concrete sleepers. *Proceedings of International RILEM Conference on Materials,*
435 *Systems and Structures in Civil Engineering (22-24 August 2016, Technical University of*
436 *Denmark, Lyngby, Denmark), 2016.*
- 437 [22] Kaewunruen S, and Chamniprasart K, Dynamic responses of interspersed railway tracks to
438 moving train loads. *International Journal of Structural Stability and Dynamics* 18 (01),
439 1850011, 2018. doi: 10.1142/S0219455418500116
- 440 [23] Esveld C. *Modern Railway Track* (Delft University of Technology), 2001.
- 441 [24] Remennikov AM, Kaewunruen S. A review on loading conditions for railway track structures
442 due to wheel and rail vertical interactions. *Structural Control and Health Monitoring* 2008;
443 15(2): 207-34.
- 444 [25] Kaewunruen S, Gamage EK, Remennikov AM. Structural behaviours of railway prestressed
445 concrete sleepers (crossties) with hole and web openings *Procedia Engineering* 2016;
446 161:1247-1253
- 447 [26] Kaewunruen S, Gamage EK, Remennikov AM. Modelling railway prestressed concrete
448 sleepers (crossties) with holes and web openings. *Procedia Engineering* 2016; 161: 1240-1246.
- 449 [27] Gamage EK, Kaewunruen S, Remennikov AM. Toughness of Railway Concrete Crossties with
450 Holes and Web Openings. *Infrastructures* 2017; 2(1): 3. doi:10.3390/infrastructures2010003

- 451 [28] Gamage EK, Kaewunruen S, Remennikov AM, Ishida T. Reply to Giannakos, K. Comment on:
452 Toughness of Railroad Concrete Crossties with Holes and Web Openings. *Infrastructures* 2017,
453 2, 3. *Infrastructures* 2017, 2, 5. doi:10.3390/infrastructures2020005
- 454 [29] Ngamkhanong C, Li D, Kaewunruen S. Impact Capacity Reduction in Railway Prestressed
455 Concrete Sleepers with Surface Abrasions. *IOP Conference Series: Materials Science and*
456 *Engineering* 2017, 245(3).
- 457 [30] Ngamkhanong C, Kaewunruen S, Remennikov AM. Static and dynamic behaviours of railway
458 prestressed concrete sleepers with longitudinal through hole. *IOP Conference Series: Materials*
459 *Science and Engineering* 2017, 251(1).
- 460 [31] Ngamkhanong C, Li D, Kaewunruen S. Impact capacity reduction in railway prestressed
461 concrete sleepers with vertical holes. *IOP Conference Series: Materials Science and*
462 *Engineering* 2017, 236(1).
- 463 [32] Lubliner J, Oliver J, Oller S, Onate E. A plastic-damage model for concrete. *Int J Solids*
464 *Structures* 1989; 25(3): 299-326.
- 465 [33] Lee J, Fenves GL. Plastic-Damage Model for Cyclic Loading of Concrete Structures. *J Eng*
466 *Mech* 1998; 124(8): 892-900.
- 467 [34] Jankowiak T, Odygowski T. Identification of Parameters of Concrete Damage Plasticity
468 Constitutive Model. *Foundations of Civil and Environmental Engineering* 2005; 6: 53-69.
- 469 [35] Kral P, Hradil P, Kala J, Hokes F, Husek M, Identification of the Parameters of a Concrete
470 Damage Material Model. *Procedia Engineering* 2017; 172: 578-5
- 471 [36] Khan AJ, Iqbal N, Saeed HA, Tarar WA. Development of material model for assessment of
472 brittle cracking behavior of Plexiglas. *IOP Conf. Ser.: Mater. Sci. Eng.* 2016; 146.
- 473 [37] Ahmed A. Modelling of a reinforced concrete beam subjected to impact vibration using
474 ABAQUS. *International Journal of Civil and Structural Engineering* 2014; 4(3): 227-236.
- 475 [38] Kaewunruen S, Remennikov AM. Resistance of railway concrete sleepers to impact loading.
476 *Proceedings of the 7th International Conference on Shock and Impact Loads on Structures,*
477 *Beijing, China, 17-19 October 2007, 489-496.*

- 478 [39] Kaewunruen S, Wang Y, Ngamkhanong C. Derailment-resistant performance of modular
479 composite rail track slabs, *Engineering Structures* 160, 1-11, 2018. doi:
480 10.1016/j.engstruct.2018.01.047
- 481 [40] Kaewunruen S, Remennikov AM. Dynamic crack propagations of prestressed concrete sleepers
482 in railway track systems subjected to severe impact loads. *J. Struct. Eng.* 2010; 136: 749–754.
- 483 [41] Kaewunruen S, Remennikov AM, Progressive failure of prestressed concrete sleepers under
484 multiple high-intensity impact loads. *Eng. Struct.* 2007; 31: 2460–2473.
- 485 [42] Kaewunruen S. Experimental and numerical studies for evaluating dynamic behaviour of
486 prestressed concrete sleepers subject to severe impact loading. Ph.D. thesis. Australia: School
487 of Civil, Mining, and Environmental Engineering, University of Wollongong; 2007
- 488 [43] BS EN 13230-2:2009 Railway applications - Track – Concrete sleepers and bearers - Part 2:
489 Prestressed monoblock sleepers, 2009.
- 490 [44] Abaqus Benchmarks Guide, <http://abaqus.software.polimi.it/v6.14/books/bmk/default.htm>.
491 2014.
- 492 [45] Mirza O., Kaewunruen S. Influence of shear bolt connections on modular precast steel-concrete
493 composites for track support structures, *Steel and Composite Structures*. 2018; 27 (5), 647-659.
- 494 [46] Ngamkhanong C., Li D., Remennikov, A.M., Kaewunruen, S. Dynamic capacity reduction of
495 railway prestressed concrete sleepers due to surface abrasions considering the effects of strain
496 rate and prestressing losses, *International Journal of Structural Stability and Dynamics*. 2018; in
497 press. <https://doi.org/10.1142/S0219455419400017>
- 498 [47] Kaewunruen S, Sussman JM, Matsumoto A. Grand challenges in transportation and transit
499 systems. *Front Built Environ* 2016; 2(4).