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

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

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

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

1. Introduction

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

Notably, prestressed concrete sleepers have been widely used for more than 50 years [19-23]. Prestressed concrete sleepers would have an improved structural capacity and/or serviceability as compared to conventional reinforced concrete. Given their importance, it is crucial to ensure that concrete sleepers are always in excellent condition before and during operation. However, they are prone to deterioration issues as cracks may occur and expand. This may incur extra costs as concrete cannot be repaired and has to be replaced should it suffer considerable damage and fail over time. All static, quasi-static, and impact loads are very important in design and analysis of railway track and its components. Railway sleepers are often subjected to impact loading, which is a shock load applied over a short period. Impact loading is a possible source of damage which may induce cracking in sleepers. Impact loading is caused by the interaction with abnormalities in either wheel or rail, as well as the resonance produced among the track components [24]. Impact load, which varies roughly from 200kN to 750kN, would imply severe damage to the sleepers. In fact, many studies over a number of years show that statistically, up to 25% or more of dynamic loading conditions are of transience and high-intensity by the nature of wheel-rail interaction over irregularities [3-9, 15, 24]. This issue is further compounded considering that holes are often drilled into sleepers for signalling gears, cables, and additional train derailment protection, such as guard rails, check rails, earthquake protection rails, etc. [25-27]. With the introduction of these holes into sleepers, the structural integrity of the sleeper may be weakened and thus, more vulnerable to the adverse effects under impact loading. Not only will that mean a replacement of the sleeper is in order, there is likelihood that the signalling equipment may get affected as well. If that happens, signalling faults may result and cause disruption to the entire track operation. Based on the literature, although the effects of holes on the capacity reduction of concrete sleepers have been studied via compression field theory and experiments [28-31], performance and crack propagation prediction under impact loading corresponding to dynamic wheel load has not been fully investigated.

Hence, these evidences highlight the importance of studying the performance of these railway sleepers under impact loading. Finite element analysis (FEA), which is a common approach for solving engineering problems, is a numerical technique and used through a finite element software ABAQUS. Numerical modelling is an ideal tool to enable complex structural scenarios to be replicated and analysed, providing insights that would be beneficial for solving issues without using a huge amount of resources as traditional experimental methods would. Two different methods, the concrete damaged plasticity (CDP) model [32-35] and the brittle cracking model [36-37] are used to compare the results. The CDP model is designed based on two failure mechanisms, tensile cracking and compressive crushing. The brittle cracking model contains a failure criterion and allows the removal of elements during the analyses. The aim of this study is to investigate the failure modes of prestressed concrete sleepers with holes/web openings under impact loading considering two different finite element models: concrete damaged plasticity (CDP) and brittle cracking model, in order to compare the different from both models. The condition recommended by European Standard [10] to identify common failure modes of concrete sleepers is emphasised. The results show that the brittle cracking model demonstrates better results by illustrating crack propagation and removed elements until failure. The findings of this study can provide information to rail and track engineers in determining the best way to generate holes into sleepers without compromising the sleeper performance during operation. Consequently, this study will enhance structural safety and reliability of railway infrastructure.

2. Methodology

2.1 Finite element modelling

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

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

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

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

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

2.1.1 Element and mesh size

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

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

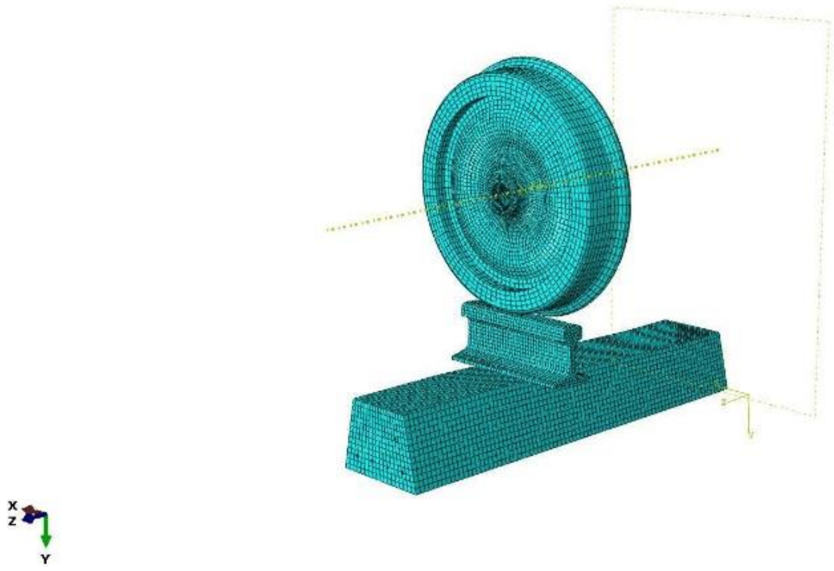


Fig. 1. Constructed mesh of sample model.

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

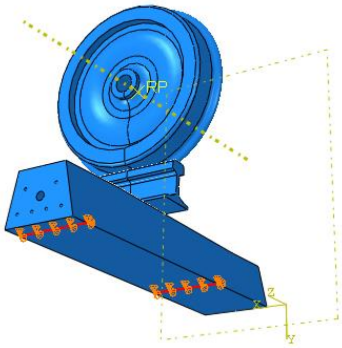
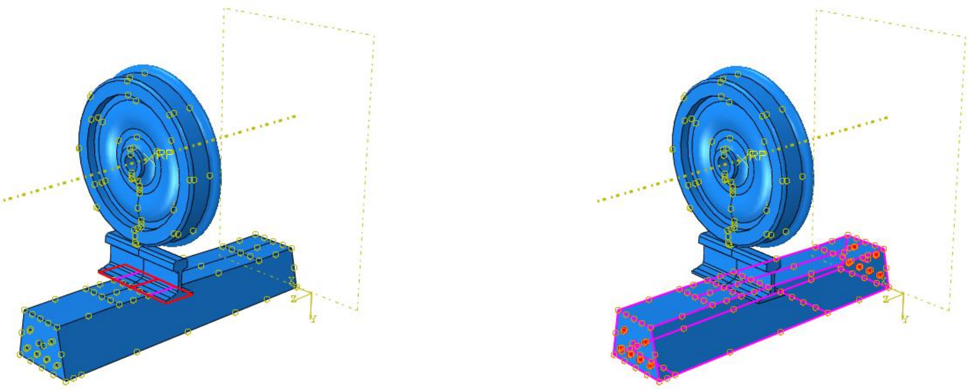


Fig. 2. Support boundary conditions.



(a) (b)

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

Table 2 Constraints definition.

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

2.2 Material properties

2.2.1 Concrete

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

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

2.2.2 Steel and prestressed steel tendon

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

Table 4 General properties of steel [12].

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

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

2.2.3 Concrete damaged plasticity (CDP) model

The two main failure mechanisms in CDP models are tensile cracking and compressive crushing of concrete. In this study, it was expected that the sleepers would fail at the bottom due to the tensile resistance concrete. Thus, tensile damage is presented as the damage mechanism in CDP model. The compressive (d_c) and tensile damages (d_t) proposed by Lubliner et al. [32] are defined as the cracking strain-total strain ratio. This mechanism is one of the most popular and has been widely used in ABAQUS to simulate realistic concrete behaviour. It was found that this mechanism can represent closely to the actual crack pattern as seen in previous studies [32-35]. The Eq. (1) shows the plastic strain calculation based on the stress strain relationship. The CDP model parameters used are listed in Table 6.

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

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

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

Where

ε^{P}, ε, $\acute{\varepsilon}^{e}_{cr}$, σ , and E_0 are plastic strain, total strain, concrete cracking strain, stress and elastic modulus of concrete, respectively.

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

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

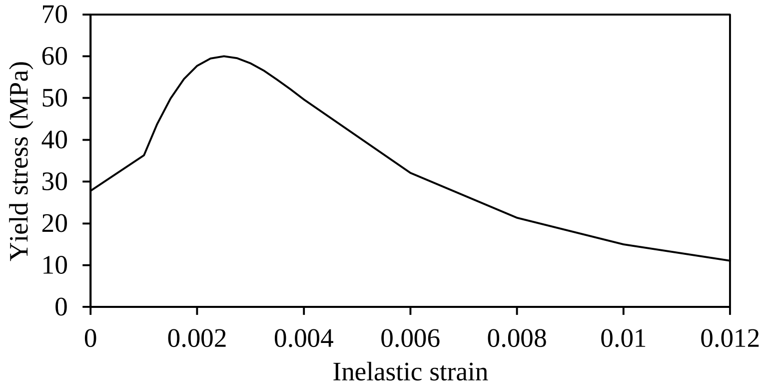


Fig. 4. Stress-strain relationship for compression of concrete for CDP model [12].

2.2.4 Brittle cracking model

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

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		

3. Results and discussions

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

3.1 Model validation

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

- Case 1 Sleeper with no hole
- Case 2.1 32mm longitudinal hole
- Case 2.2 42mm longitudinal hole
- Case 3.1 32mm transverse hole
- Case 3.2 42mm transverse hole
- Case 4.1 32mm vertical hole
- Case 4.2 42mm vertical hole

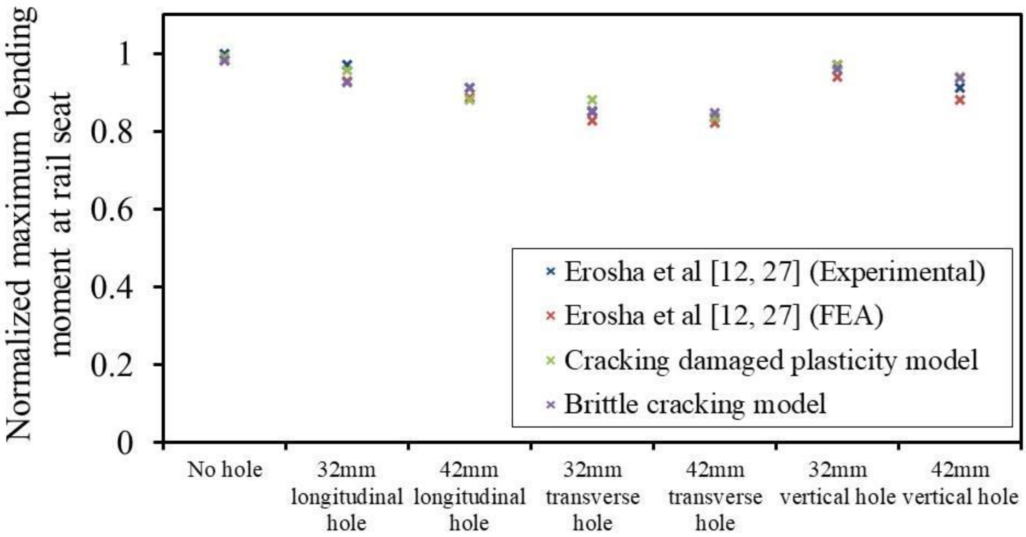


Fig. 5. Normalized maximum bending moment at rail seat (kNm) for model validation

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

3.2 Concrete Damaged Plasticity (CDP) models

It can generally be observed that the region that experiences the highest magnitude of vertical deflection is the bottom fibres located at the rail seat of the sleeper for every case. It should also be noted that the sleepers with larger holes experience higher deflections under impact loading than their respective counterparts. The von Mises stress distribution for the sleeper components of the CDP models are considered negligible considering the high magnitude of the impact loading imposed on the sleeper. The contour legend for the von Mises illustrated that there would be no obvious changes in the stress distribution in the models. This would imply that the CDP may not be an effective FE approach when assessing the von Mises stress distribution of the sleepers under impact loading.

However, the stresses in the prestressed tendon bars are well-represented in the CDP models. All the models have shown consistently high magnitudes of stresses in the tendon bars upon impact loading. This phenomenon is expected as the tendons are supposed to act as tensile resistants, when the concrete material is weaker against tension while having significantly stronger compressive strength. Furthermore, the sleeper is at its weakest against tensile forces in the bottom fibres and hence, the tensile forces carried by the tendons are assumed to be higher in those regions. The stresses sustained by the tendons for the sleepers with larger holes are also noted to be much higher than their counterparts.

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

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

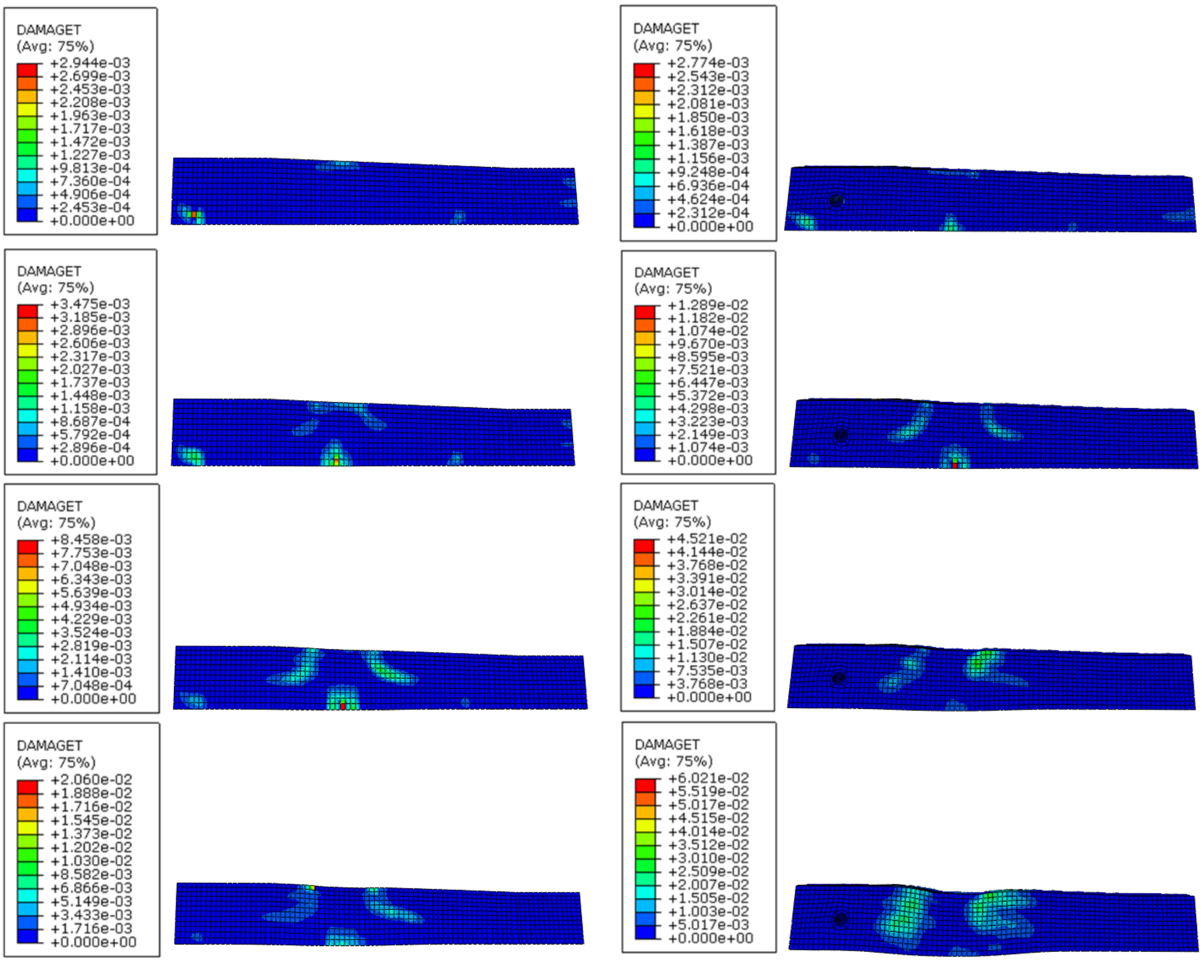


Fig. 6. Tensile damage contour in CDP models of concrete sleepers with a) no hole b) 42mm transverse hole

Table 9 shows that the maximum loads bored by each sleeper case, and the sleeper with 42mm transverse hole performed slightly worse than other cases at 241 kN. Although this may be consistent with the theory and previous experiments [12, 27] that it is the worst performing case under impact loading due to its high tensile damage value, it should be noted that the difference in maximum load is not significant. Furthermore, an attempt to obtain the load-deflection curve for all CDP models was made earlier but the results were not optimal as the sleepers tended to be failed very early during the loading process compared to the results obtained by brittle cracking model, despite the deflection experienced perhaps being a lot higher. This may yet again highlight the possibility that the CDP models may not be suitable for this study as the models were terminated earlier due to the convergence difficulties.

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

3.3 Brittle cracking models

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

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

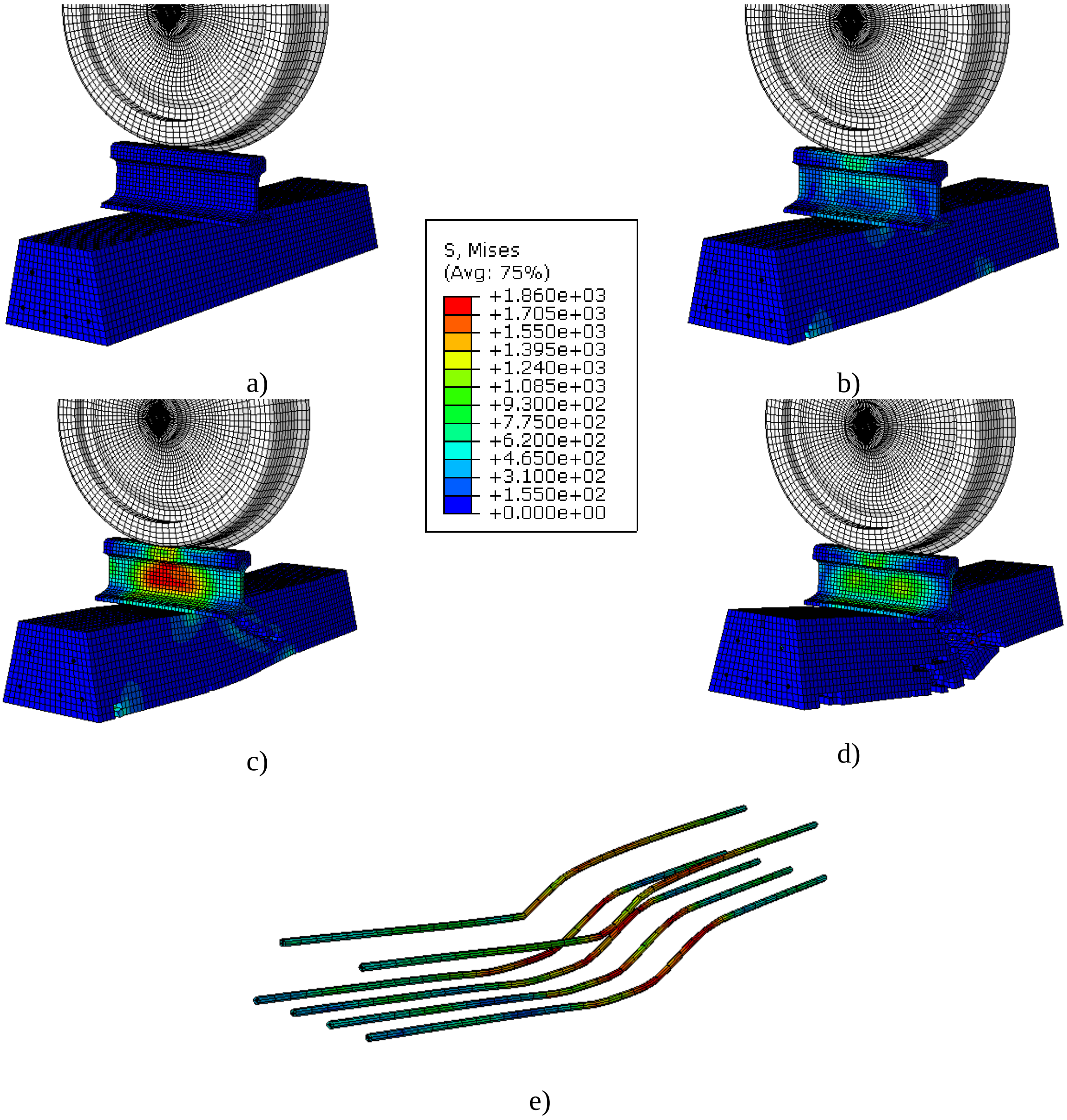


Fig. 7. Von Mises Stress distribution and crack propagation: of sleeper at a) 0.000 b) 0.001 c) 0.0015 d) 0.0025; e) steel tendon at 0.0025

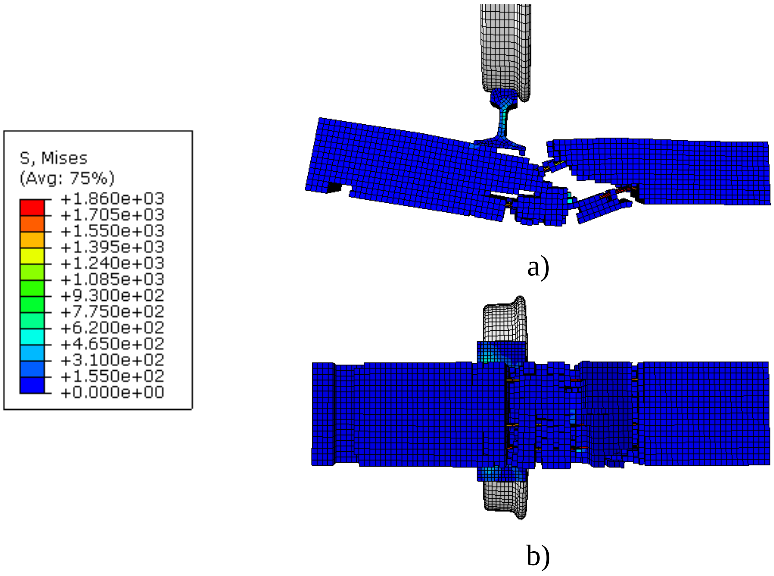


Fig. 8. Crack pattern of sleeper with no hole at a) rail seat b) bottom

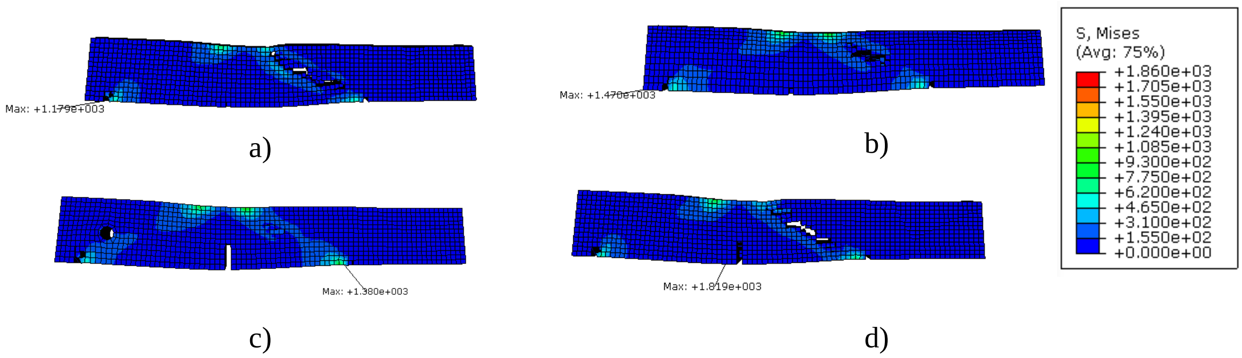
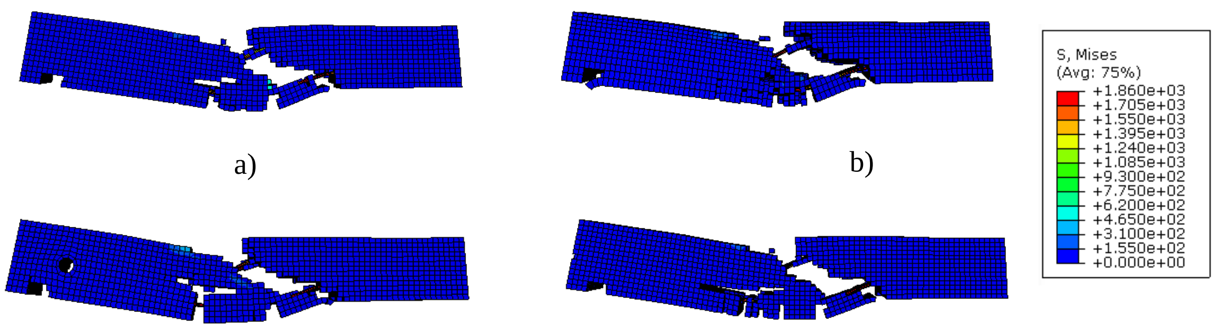


Fig. 9. Von Mises Stress distribution and crack propagation at the time step of 0.015 of sleeper with a) no hole b) 42mm longitudinal hole c) 42mm transverse hole d) 42mm vertical hole



c) d)

Fig. 10. Von Mises Stress distribution and crack propagation at the time step of 0.025 of sleeper with a) no hole b) 42mm longitudinal hole c) 42mm transverse hole d) 42mm vertical hole

Although cracks were initially detected at the supports, it is the diagonal shear cracking that has dominated throughout the process and ultimately resulted in the failure of the sleeper, as seen in Fig. 9. This implies that the sleeper has inadequate shear resistance in every case. Another observation that was made for every sleeper case was the slight cracking that appeared at the top fibres of the sleeper where the rail seat lies (Fig. 9.), and this did not form until the sleeper was close to failure. The cracks occurred as the compressive forces at the top fibres exceed the compressive strength of the concrete, and this delayed response can only be explained by the high compressive strength of concrete.

As seen from Figs. 9-10, flexural cracks have been identified at the bottom fibres of every sleeper and they progressed upwards to the neutral axis of the sleeper. These flexural cracks occurred due to the brittle nature of concrete, as well as the high tensile forces in this region which have exceeded the tensile strength of concrete. In cases of transverse hole (Fig. 9c., 10c.), flexural cracks can be seen more clearly than other cases. However, the flexural cracks have not progressed beyond the neutral axis due to the longitudinal tendons providing resistance against the tensile forces. By comparing these to the results obtained by the CDP model, it is clearly seen that the brittle cracking model has better results under impact loading as the CDP model can provide only the early stage before failure due to the convergence difficulties.

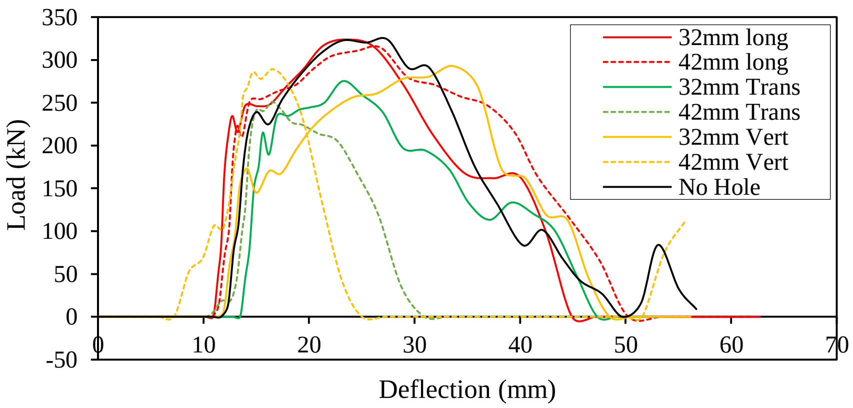


Fig. 11. Load-deflection curve of sleeper using the Brittle Cracking Model.

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

4. Conclusion

This study investigates the performance of railway sleepers with holes/web openings under impact loading using finite element analysis software ABAQUS. It is noted that the modification or retrofitting of concrete crossties at construction sites through holes and web openings undermines the strength of railway concrete sleeper. It is important to ensure that concrete crossties can be retrofitted and modified for add-on fixtures in practice. The performance of railway sleepers with holes/web openings have not been fully investigated in recent studies. In this study, the three-dimensional finite element model has been developed and validated. It has adopted two different types of models, concrete damaged plasticity and brittle cracking models for seven different sleeper cases, each with a different hole size and the direction generated in. The damage of sleepers is represented by tensile damage in the CDP model and crack propagation in the brittle cracking model. The aim and scope of this study is to identify impact damage and failure mode of sleepers with holes and web openings. The effectiveness of advanced numerical modelling techniques has also been investigated. The results obtained from both methods show that the sleeper with 42mm transverse hole has the worst performance among all sleeper cases. However, the stress distribution and load-deflection relationship from the CDP model may however be regarded as inconclusive due to the insignificant differences shown during the analyses. Moreover, although crack propagation can be represented by tensile damage contours, the CDP models were terminated before failure due to the convergence difficulties. Thus, the maximum loads occurred are less than those in the brittle cracking model. Whilst the brittle model shows better results as it still retains high magnitude stresses after the sleeper component has failed so that the maximum load is higher than that in the CDP model. Furthermore, the crack propagations are shown properly in this model. It is apparent that failure mechanism of sleepers under impact load is mixed bending-shear failure. It can be concluded that the brittle cracking model is more suitable for dynamic analysis. The insight into the performance of railway prestressed concrete sleepers with holes and web openings will help improve the design standard and will enable safer built environments in railway infrastructure especially with concrete sleepers.

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