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Derailment-resistant performance of modular composite rail track slabs

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ABSTRACT

Railway transportation, comprising freight and passenger transport, is the lifeblood of the social economy of a country today, especially for developing countries. Despite over a decade of operations, derailment accidents are among the most frequent accidents for railway transportation and may cause fatally or severe injury to passengers, loss of property and damage to the railway track. Hence, this study focuses predominantly on the structural response and performance evaluation of composite rail track slabs through 3D finite element analysis using ABAQUS. The response and performance of composite track slab subjected to derailment actions has been observed. Material strain-rate properties and impact loads have been introduced to the numerical simulation in order to investigate impact behaviours of composite slabs subjected to derailment loading in explicit dynamic analysis. Based on obtained results, it was found that 45 km/h in the direction of gravity is the limit impact velocity for the designed composite rail track slab. The outcome of this study will improve the design standard and calculation of composite rail track slabs subjected to derailment actions.

1. Introduction

Nowadays, railway transportation, including freight and passenger transport, plays a significant role in the economic development of a region or even a whole country. It is apparent that there are many irreplaceable merits of rail transportation. First, the rail sector performs better financially compared with air or road transportation, which is crucial for developing countries. Second, it can shorten transit time dramatically compared to shipping. Finally, it is adaptable to most geographical situations, so the transport route can be more flexible. However, unexpected train derailment accidents have become a substantial issue. Train derailment is common for both freight and passenger train accidents and it always has disastrous consequences due to its heavy weight and rapid speed [1–4].

According to the *Rail Accident Report: Derailment at Grayrigg* [5], an express passenger train, which was a nine-car, electric, multiple unit, travelling from London Euston to Glasgow, derailed near Grayrigg bridge in Cumbria at the speed of 95 mph (153 km/h) on 23 February 2007 as shown in Fig. 1. This event caused severe damage to the train and injuries to the passengers and driver. One passenger was fatally injured; 28 passengers, the train driver and one other crew member received serious injuries and 58 passengers received minor injuries.

Table 1 shows the numbers of unexpected derailment accidents in the USA between 2007 and 2016. It can be clearly seen that more than 1000 events were observed every year between 2007 and 2016 [6]. As a result, government and related industries should do more to control the risk of train derailments through the design and operation phase, informed by a full understanding of every previous accident. Kaewunruen and Remennikov [7–9] suggested that the impact loading, which has an extremely high magnitude over a short time period, should be considered in the limit states design method.

Jafarian and Rezvani [10] used a persuasive method called ‘fuzzy fault tree analysis’ to look for the basic reasons for train derailments. They found that broken rails and lots of technical faults are the main hazards in derailment accidents. Cao et al. [11] suggested that government and related industries should pay particular attention to some specific factors when train derailments occur on bridges rather than on other lines. At present, a new modular composite track slab has been designed to change the conventional structures on railway bridge transoms [12]. Oehlers and Bradford [13,14] revealed that an ideal composite construction involves a combination of concrete with a high compressive strength and high tensile strength steel. Currently, most railway bridge transoms are made up of different kinds of timber. However, there are some shortcomings in timber railway sleepers/transoms, evidenced by their high replacement frequency and rapid deterioration from chemical attack [15]. Manalo et al. also tried to find an alternative material, such as fibre composites, to replace timber. However, the fibre composites material is still in trial stage.

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Fig. 1. Aerial view of the derailed train from the Grayrigg derailment [5].

Based on a critical literature review, the derailment resistant capacity of railway track slabs has not been investigated. In particular, the composite track slabs installed over bridge girders are prone to failure under derailment impacts [6,11,16]. Thus, this paper aims to establish a 3D finite element modeling in ABAQUS, in order to improve a numerical simulation of a modular composite rail track slab. In this study, sensitivity analysis is also performed in order to evaluate structural capacity considering strain rate effect of composite track slabs under derailment impacts. This is a world first in highlighting the performance of composite rail track slabs under train derailments by considering the effect of strain rate. The insight from this study will improve the design standards and calculations relating to composite rail track slabs, for a better performance and capacity to prevent damage from dynamic load caused by train derailment.

2. Design methodology

2.1. Design loading

2.1.1. Dead load

The thickness of a panel for a railway is restricted to 0.18 m and the density of concrete is taken as 2400 kg/m^3. In addition, the thickness of the steel sheeting profile bondek section is negligible compared to concrete part and acceleration of gravity (g) is taken as 9.81 m/s^2 [15].

2.1.2. Live load

A series of general rules of design calculation, such as dynamic effects, centrifugal forces, nosing force and braking force, have been determined in *Part 2: Traffic loads on bridges of BS* EN 1991-2:2003 [18]. This report also introduces some load models to represent distinct train loadings. A model named 'Load Model 71' is adopted in this study, which displays a normal static effect of vertical rail traffic loads on mainline railways. Fig. 2 shows characteristic values for vertical loads for Load Model 71. These values shall be multiplied by a factor "α", which can be either higher or lower than normal traffic, depending on the actions. The characteristic vertical load multiplied by factor α can be called as "Classified vertical load". In summary, the concentrated 26 force Q_{vk} and the distributed load q_{vk} for Load Model 71 shall be taken as 250 kN and 80 kN/m respectively [18].

2.1.3. Derailment actions

Derailment accidents have always been accompanied by huge property damages and casualties. Consequently, derailment action calculations should be adopted in the design phase "as an Accidental Design Situation" [18] in order to minimize the damage to the structure.

There are two specific design situations relating to derailment action on railway bridges that shall be taken into account. Fig. 3a represents the design situation I, where derailed vehicles are still in the track area, due to the adjacent rail or the containment wall and are preventing the main part failure of the whole structure, is the top priority for designers [18]. Design load Q_{A1d} and q_{A1d} here should be taken as α × 0.7 × LM 71, where LM 71 is 250 kN [18]. Similarly, design Situation II shows another circumstance where derailed vehicles are not in the track area but are on the edge of a bridge, with wheels on one side [18], as shown in Fig. 3b. Designers should pay close attention to the trend of the whole structure overturning or collapsing within Design Situation II. Some local damage is allowed in this circumstance. The equivalent load q_{A2d} shall be taken as α × 1.4 × LM 71 for Design Situation II. For both cases, the characteristic vertical load shall be multiplied by the factor α of 1.1 in terms of derailment action for accidental design situations [19].

2.2. Finite element modeling

Nowadays, finite element analysis (FEA) is a common approach to simulate the behaviour and response of a structural body and to solve many reality problems in the area of engineering. It can reduce engineers' workload significantly. ABAQUS has been used for this study. The proposed modular panel designs have been carried out and a half model of the whole structure has been introduced for the derailment analysis [11,20]. In this study, finite element models for a composite rail track slab sitting on bridge girders (stringers) have been developed using ABAQUS and validated against experimental and field data [20,21]. Fig. 4 clearly displays all six parts of the rail track model: concrete, profiled steel sheet, bridge stringer, shear studs, reinforcing steel and wheel [22–26]. The dimensions for the track slab, comprised of concrete and steel parts, are 1619 mm in length, 600 mm in width and 180 mm in height. Similarly, the dimensions for the bridge stringer are 1000 mm in length, 260 mm in width for the top segment and 500 mm in height. There are six shear studs, which have a height of 100 mm, in the model that connect the top concrete, profiled steel sheet and bridge stringer as a whole. In addition, four steel reinforcements are used in the concrete to take the tension force and a wheel (modelled as a rigid body) is used in dynamic analysis only. Table 2 displays the boundary conditions of each component.

2.3. Contact and boundary condition

In term of contact between each component, it is interesting to note that material stiffness is necessary when defining constraint, in order to designate a master surface and a slave surface. The interface types between each element are shown in Fig. 5. It should be noted that the stiffer material is defined as the master surface, whilst the less stiff component is defined as the slave surface. Embedded technique is used as a contact between concrete and reinforced steel, while the contact between the concrete and steel sheet is modelled as a surface to surface with finite sliding, hard contact in the normal direction and a coefficient of friction of 0.5 in the tangential direction [30]. As for the shear studs in the concrete, the interface was modelled as a tie constraint. Tie constraints are considered to be an interface of a shear stud welded to bondek II and bondek II welded to stringer (located below shear studs). Where there is contact between bondek II and stringer outside the shear stud area, surface to surface contact techniques are employed with finite sliding, hard contact in the normal direction and a frictionless

Table 1
Derailments statistics in USA between 2007 and 2016 [6].

Year	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
Derailment	1789	1370	1333	1470	1294	1312	1312	1321	1351	1149