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Experimental and numerical investigations of flexural behaviour of composite bearers in railway switches and crossings

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Abstract

Composite bearers, which are the long crosstie beams, are safety-critical components in railway switches and crossings. Recent adoption of composites to replace aging timber bearers has raised the concern about their engineering performance and behaviour. Since the design and test standards for composite bearers are not existed, most performance evaluations are based on the flexural tests in accordance with the test standards for railway concrete sleepers. In this study, both numerical and experimental studies into the flexural behaviours of composite bearers have been conducted to improve the understanding into the resilience and robustness of the components under service load condition. The full-scale composite bearers are supplied by an industry partner. The full-scale tests have been conducted in structures laboratory at the University of Birmingham. 3D finite element modelling of the bearers has been developed using Strand7. The comparison between numerical and experimental results yields an excellent agreement with less than 3% discrepancy. The results exhibit that the composite bearers behave in the elastic region under service load condition. This implies that they can recover fully under the load, enhancing engineering resilience of the turnout systems.

1. Introduction

A novel composite material, 'fibre-reinforced foamed urethane (FFU)' has gained an important momentum for applications in railway industry. As railway bearers in switches and crossings, the FFU components acting as a beam are to redistribute the train forces (static and dynamic loads) onto track support (ballast). Also, they can secure the rail gauge to allow trains to travel safely [1-3]. Its structural performance must be instigated and assured at all time through inspection (safety-related assessment functions), monitoring (surveillance functions) and maintenance [4-6]. A further function of the structural elements in a ballasted railway track system is to aid lateral track protection to enhance the stability and stiffness of the track structure. Any structural deterioration or poor conditions of the elements could affect the reliability, safety, and quality of the railway line. This leads to impaired rail services, for example, if the bearers cracked dramatically, they would deform highly under the loads induced by wheel-rail interaction. This large differential settlement encourages the damage to other railway elements that in turn shortens the maintenance period of the railway line. However, if the bearers are more flexible (low elasticity), the track can dramatically deform and providing the outcome in a large differential local track surface (top smoothness) [7-12]. These cause higher dynamic loads, poor travelling comfort and extra train energy consumption [13-15]. Additionally, if the lateral resistance of the line is inadequate to support horizontal loads, (i.e. due to loosened ballast or abraded bearers), rail buckling may occur [16].

Railway urban turnout is a unique track system employed to divert a train from a particular direction or a particular line onto other lines or other directions. It is a structural grillage system which comprises of steel rails, crossing (uncommon line elements), points (well-known as switches), rubber pads, steel plates, insulators, screw spikes, fasteners, beam bearers (either polymer, concrete, steel, or timber), ballast, and formation as shown in Figure 1. Conventional turnout structural were typically supported by timber bearers. They allow the steelwork to be mounted directly on steel plates which are spiked or screwed into the bearers. Timber has an outstanding damping coefficient, whilst steel and concrete tend to have nearly no damping coefficient [17-20]. Concrete has proven to be a great counterpart to improve line and turnout stability – laterally, vertically [21-22]. Moreover, steel bearers perform well in a short period, anyway, having higher turnout settlement and ballast breakage during the long period [23-24].



Figure 1. Typical turnout geometry [25].

Material scarcity and environmental concern force researchers considering new materials capable of satisfying the railway system specifications. Developing new materials capable of satisfying the functional requirements including enhancing their recyclability. There is a constant search for a material that is durable, reasonably easy to produce and maintain, has attractive costs, and meets the expected requests effectively [26]. A crucial concern in the railway industry is the replacement of deteriorated and damaged bearers in existing lines [26]. Especially in special positions such as railways crossings and switches, railway bridges, and transition zones, the requirement for alternative materials to replace old timber components is undoubtedly important [27-28]. It is well known that common turnout generally imparts high impact actions on to structural members due to its blunt geometry and mechanical connections between closure rails and switch rails. This has boosted the importance of structural performance and failure modes of the elements employed in railway systems. Because the design method for composite bearers has not been standardized yet [1-4], most design concept for the composites is based on allowable stresses, which is slightly more conservative (more safety margin) compared with limit states design principle (Figure 2).



Figure 2. Schematics of allowable stress design concept for each material [29].

As a result, it is imperative that material reduction factors be identified based on the data recorded through experiments into failure mode and structural performance. These in-depth understandings would later help the railway owner or authority to verify the cost effectiveness and safety possibility of the composite bearers. This allowable stress design concept determines the maximum strength of constituent materials, which then cannot be exceeded in the component. Safety and serviceability aspects such as brittle fracture, bursting, fatigue failure, and allowable deflections are taken into account in this design method by the determination of safety factor values [30]. The cost effectiveness can then be evaluated using reliability indexes whether the component is either optimally, overly, or under designed.

There are many efforts towards improving the characteristics of the materials already utilized in the railway track engineering (wood, concrete, and steel) as applied to the polymer by itself or composite polymers, using primarily fibres [31]. For over 35 years, fibre reinforced foamed urethane (FFU) composites have been utilized in the construction of railway track systems. Sekisui Chemical & Co [32] is the principal producer of this material. Numerous researches using Japanese testing standards are conducted for this material in order to define its limits of use or validated them in specific and particular cases [32]. On the other hand, based on the significant review for composites [1], it is clear that there is no previous work to evaluate the failure mode, structural damage and structural design performance of the FFU composites. The aim of this study is to focus the flexural behaviours of FFU composite bearers obtained from numerical and experimental data to enhance the insight into the resilience and robustness of the components under service load condition. The main highlight is to underpin the design ideas of plastic and FFU composite bearers. This is because the use of such bearers is relatively new in railway industry across the world. Knowledge of the engineering design principle is therefore significant for enabling proper repair, adoption, and retrofit of the line components in the future. In this paper, the experimental and numerical investigation into the flexural modes connected with plastic and composite bearers are presented. These understandings will aid railway engineers to determine suitable engineering methods and solutions for track construction and maintenance under future uncertainties.

2. Materials and experiment of composite beams

An industry partner provided nine full-scale beams (160 mm depth x 250 mm width x 3200 mm length) using fibre reinforced foamed urethane composites (designed for railway track components). The experimental testing is based on the evaluation benchmark of EN 13230 (Test material specifications, support conditions, loading procedures, and some specific requirements for bending tests on railway track concrete sleepers). Some procedures are followed by these tests to prove the test information. On the other hand, EN 13230 has severe limitation in order to determine failure mode of flexible composites. For example, some test procedures are adjusted to investigate the structural damage and the failure mode of the full-scale FFU composite beams [33-35].

Positive and negative bending tests are needed at the rail seats support, based on EN 13230-2 bending testing. Since the FFU test specimens have the same positive and negative capacity (symmetry). In this paper, there is the only positive bending tests conducted to identify a resemble failure mode in a track system [26, 35-36]. The standard requires articulated support and must be 100 mm wide, made of steel with Brinell: HBW > 240. In the experiments, quasi-static load should be applied to the middle span of the beam for normal positive bending. Figure 3 demonstrates the layout of the bending load process. Additionally, it indicates the locations of many different non-destructive test (NDT) sensors. Linear variable differential transformers (LVDT) are placed at the mid-span location of the specimen to collect the deflection. Also, three acoustic emission (AE) devices are employed in each test. Four strain gauges are set up at the front and rear locations of each specimen to record stress changes.



Figure 3. Experimental setup of a full-scale FFU composite beam under flexural load.



Figure 4. Load-deflection behaviour of full-scale FFU composite beams under flexural load [29].

3. Finite-element model of composite beam

The finite-element model of an FFU beam under flexural load was developed to investigate its flexural behaviour. The sleeper model based on Timoshenko theory is the most agreeable approach for generating two-dimensional concrete sleepers [37-40]. Anyway, this model was modelled using 6,000 bricks with a trapezoidal cross-section in STRAND7 [41-42], as shown in Figure 5. Also, the finite element model consists of the brick components, which take into account flexural and shear deformations, in order to model the FFU beam model. The material and geometric properties of these bricks are presented in Table 1. These properties were chosen because they were identical to a particular type of bearers manufactured in the UK. A flexural mode shape was conducted to evaluate the quality of the finite element (FE) model. It was found that 6,000 bricks, representing a composite beam, can provide acceptable estimation of bearer's flexural behaviours under service load condition compared with the existing experimental measures.

Parameter lists	Value	Unit
Elastic modulus	7000	MPa
Poisson's ratio	0.25	-
Beam density	600	kg/m ³
Beam length	3.2	m
Beam cross-sectional area of a	0.042	m^2
rectangle $(0.16, \text{ depth } * 0.25,$		
width)		

Table 1. Engineering properties used in the modelling.



Figure 5. Finite element analysis for modelling and behaviour of an FFU composite beam under flexural condition.

In order to verify the model, the flexural bending mode shape of a beam under static load condition obtained from the FE model were compared with experimental data. Figure 6 shows a comparison between the finite-element analysis and experimental results of deflection. The outcomes are found to be in a very good agreement with around less than 3 percent, as given in Figure 6. However, this study shows the comparison between the FEA and experimental data in the only static linear analysis under flexural behaviour in first load condition.



Figure 6. Comparison the defection of Flexural behaviour between the numerical and experimental data under flexural load

4. Result and discussion

As shown in Figure 4, crack propagation has been collected and marked under the load increment. It is obvious that the first crack (fracture of internal fibres) occurs at 34 kN and composites failed at 132 kN. Figure 7 demonstrates the crack propagation appears. The fibre cracks can be observed longitudinally along the fibre orientation. Also, minor fractures can be noticed before the sudden failure of the composite beams. Figure 8 illustrates the failure mode of the composite beams in laboratory. Obviously, first cracks or localized fibre failure is relative low, compared with the ultimate failure load. The rapid rupture can be seen through the delamination of fibres along with the beams. In fact, the brittle failure mode of the composites controls as the consideration of the load deflection given Figure 4. In addition, when larger fibre breaks are seen, the composites behave nonlinearly towards the failure point. While the linearization of structural behaviour is true only when the small fibre breaks occur.



Figure 7. Crack behaviour of full-scale FFU composite beams under flexural load [29].



Figure 8. Failure mode of full-scale FFU composite beams under flexural load [29].

5. Conclusion

Flexural behaviours of Fibre-reinforced foamed urethane (FFU) bearers in railway system are crucial for improving the understanding into the resilience and robustness of the components under service load condition. The flexural behaviours of an FFU composite model were studied using the finite element approach. Whilst, FFU beam specimens used in the experimental test were conducted employing a three-point bending test. The experimental investigations into the failure modes of FFU composites. The new insight into the load defection, crack propagation, and failure mode will aid the rail industry to produce a better decision for proper adoption of composites in railway infrastructure. The three-dimensional modelling has been verified and found in very good agreements with the experimental data with less than 3% difference, as given in Figure 6. According to the use of standard test approaches, it is confirmed that existing standard cannot be acceptable for the composite materials. Obviously, the results of flexural behaviours between numerical and experimental data cannot be validated without better understandings of in-track behaviours, failure modes, and science-based design approach for the materials. Additionally, this paper identifies that the composites are likely to have brittle failure modes. This means that a more safety factor should be applied for the element approach. The rupture cannot literally be observed from the progression of cracks appeared on the surface of the element. The development of condition monitoring implement is essentiality before wide-spread use of composites in railway industry. This model has been very useful and has led to further research on structural behaviours of the railway FFU bearers in the track structure system or as well known 'the insitu railway FFU bearer'. Also, a numerical analysis under failure condition should be conducted to absolutely verify the experimental data.

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