Feasibility study of random fibre reinforced railway ballast using image-based deformation measurements

Étude de faisabilité du ballast ferroviaire aux fibres aléatoires renforcées utilisant des mesures de déformation basées sur images

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ABSTRACT The need to develop new means of optimizing the performance and minimizing maintenance requirements of railway ballast has become more pressing. This is due to the growing need for the development of resilient track materials (including ballast) capable of withstanding increasing train speed, load and frequency. In recent times, railway ballast has been reinforced mostly by the use of geogrids placed at strategic depths within the ballast layer. However, experience has shown that the presence of geogrids restricts the type of maintenance activity (tamping) that can be carried out on the reinforced track section. The addition of random fibre reinforcements in ballast has been proposed as an alternative reinforcement technique that can meet the reinforcement requirements of ballast without limiting future maintenance activities. Using novel digital-image based deformation measurement technique for triaxial tests, the deformational evolution of random fibre reinforced scaled ballast was investigated. The mechanism of reinforcement in the reinforced granular material is highlighted and the potential applications in railway ballast discussed.

RÉSUMÉ La nécessité de développer de nouveaux moyens d'optimisation des performances et des réductions d'exigences d'entretien du ballast des voies ferrées devient de plus en plus pressante. Cela est dû à un besoin croissant de développer des matériaux résilients adaptés aux les voies (ballast inclus), capables de résister à la vitesse, la charge et la fréquence grandissantes des trains sur les voies. Ces derniers temps, le ballast de chemin de fer a été renforcé principalement par l'utilisation de géogrilles placés à des profondeurs stratégiques dans les couches d'épaisseur du matériau. Cependant, le retour d'expérience a montré que la présence de géogrilles restreint le type d'activité de maintenance pouvant être effectué sur la section de voie renforcée (bourrage). L'ajout de renforts de fibres aléatoires au ballast a été proposée comme une technique de renforcement alternative qui peut répondre aux exigences de renforcement de ballast sans limiter les activités d'entretien futures. En utilisant une nouvelle technique de mesure de déformation à base d'images numériques pour les essais triaxiaux, l'évolution de déformation des fibres aléatoires renforcées ballast mise à l'échelle a pu être étudiée. Le mécanisme de renforcement dans le matériau granulaire renforcé a été observé et des applications potentielles dans les ballasts de voies ferrées sont en discussion.

1 INTRODUCTION

The ballast supporting a traditional railway track has attracted significant research interest in recent times, but there is considerable potential for optimizing its performance and minimizing maintenance requirements. The use of randomly orientated fibre reinforcements in sand has been shown by previous research to improve its mechanical properties. Similar benefits can be expected to be observed in ballast (which is also a granular material) if an in-depth scientific understanding of the mechanics involved is achieved.

The use of randomly orientated fibres to reinforce soil has been investigated by a number of researchers (e.g. Michalowski and Cermak, 2002; Lirer et al., 2011; Diambra et al., 2013). The mechanical behaviour of the mixture may be influenced by fibre properties, soil characteristics and reinforced soil characteristics. There is also a general consensus among researchers that the micromechanics of the fibre/particle interaction significantly influence its mechanical properties (e.g. Michalowski and Zhao, 1996; Diambra et al., 2013). These fibre/particle interaction mechanisms include the relative fibre/particle dimensions, fibre content etc. However, no attempt has been made to study the deformation of fibre reinforced granular materials at both the full field and local micro-scale level.

This paper reports the use of an image-based deformation measurement method developed by Bhandari et al. (2012) to study the local deformation of fibre reinforced triaxial specimens.

2 EXPERIMENTAL WORK

2.1 Materials

The granular material used in the experiments reported in this paper follows a grading parallel to that of standard Network Rail (NR) ballast at 1/5 scale (Figure 1). This offers an attractive and economical means of developing an understanding of the mechanics of full size ballast (D_{100} = 62 mm). Le Pen et al. (2013) demonstrated that although there is a measurable variation of form and roundness with particle size over a range of sieve intervals, these differences are slight and do not militate against the use of scaled material in investigating the factors influencing macro-mechanical behaviour.

The dimensions and the typical mechanical properties of the fibres used are presented in Table 1.

2.2 Laboratory Tests

The scaled ballast-fibre mixture used in the triaxial tests was prepared by mixing known masses of fibres and scaled ballast in a plastic container. The resulting mixture was random and homogeneous. The procedure for determining the maximum and minimum density of fibre reinforced granular are described in Ajayi et al. (2014).

2.2.1 Triaxial tests

Conventional monotonic triaxial tests on specimens 150 mm in diameter and 300 mm in height were carried out on fibre reinforced and unreinforced scaled ballast specimens. The fibre-reinforced scaled ballast mixture was prepared to achieve the densest state corresponding to the minimum void ratio at a given fibre content.

Table 1. Typical values of the basic properties of polyethylene fibres

	Polyethylene
Fibre length	58 mm
Fibre width	20 mm
Fibre thickness	0.5 mm
Specific gravity	0.92
Tensile strength	20.3 MPa[1], 11.2 MPa[2]
Softening temperature	85°C

[1] Longitudinal; [2] Transverse

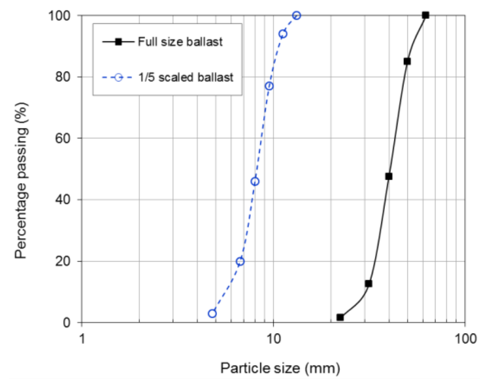

Figure 1. Particle size distribution of 1/5 scaled, and Network Rail standard ballast

The triaxial tests were carried out on dry specimens at a confining stress of 30 kPa to replicate the typically low confining stresses within ballast as reported in the literature (e.g. Indraratna et al., 2010; Sevi and Ge, 2012). The triaxial tests and the initial conditions of the specimen are summarised in Table 2.

The *void ratio*, *e* is defined as the ratio of the volume of voids (V_v) to the volume of grains (V_s). The *Volumetric fibre ratio*, V_{fr} is defined as the ratio of the volume of fibres (V_f) to the volume of solids.

2.2.2 Image-based deformation measurement technique

A digital image-based deformation measurement system for triaxial tests as described in Bhandari et al. (2012) was utilized to study the local deformation of the specimens. The triaxial setup consisted of two digital cameras placed along the radii of the transparent triaxial cell at an interval of about 120° when viewed in plan.

Table 2. Triaxial tests carried out

Specimen	e_o	Fibre content, V_{fr} (%)
1/5 SB	0.76	-
V_{fr} = 6.5%	0.98	6.5

In the image analysis, a resolution of 0.01 pixel was chosen for the sub-pixel interpolation, with a precision better than 0.0033 pixel for a 181 × 181 pixel subset based on the empirical equation given by White et al. (2003) is. The accuracy was found to be better than 0.10 pixels or 0.004 mm in the object-space at a nominal image scale of 0.04 mm/pixel at the centre of image (Bhandari et al., 2012).

3 DEFORMATION CHARACTERISTICS OF FIBRE REINFORCED TRIAXIAL SPECIMEN

The addition of fibres produces an increase in the peak stress ratio, q/p', of the mixture while suppressing its dilation (Figure 2). The effect of fibre reinforcements on the dilatancy (as defined in Eq. 1) of the specimen is further highlighted in Figure 3. Figure 3 indicates that the reinforced specimen is able to mobilise a higher mobilised strength at a given rate of dilation than the unreinforced specimen.

$$\delta = \frac{\delta\varepsilon_{vol}}{\delta\varepsilon_q} \qquad (1)$$

The results of the image analysis of the triaxial specimens during the pre-peak and post-peak deformation stages of the shearing process (as seen in Figure 2) are shown in Figures 4 and 5 respectively. The horizontal axis of each plot represents the circumferential distance of the specimen and the vertical axis represents the specimen height, both in millimetres. A reference vector is shown below the displacement vector field (Figure 4(a) and 5(a)) and the colour bar displayed to the right of the strain fields (i.e. Figure 4(b) and 5(b)) represents the corresponding strain in percentage. For comparison, the limits of the colour bar for each plot were kept constant.

During pre-peak deformation, a more nearly vertical deformation of the reinforced specimen was observed compared with the unreinforced specimen (Figure 4(a)). The unreinforced specimen exhibited higher shear strain over the pre-peak deformation stage than the reinforced specimen (Figure 4(b)).

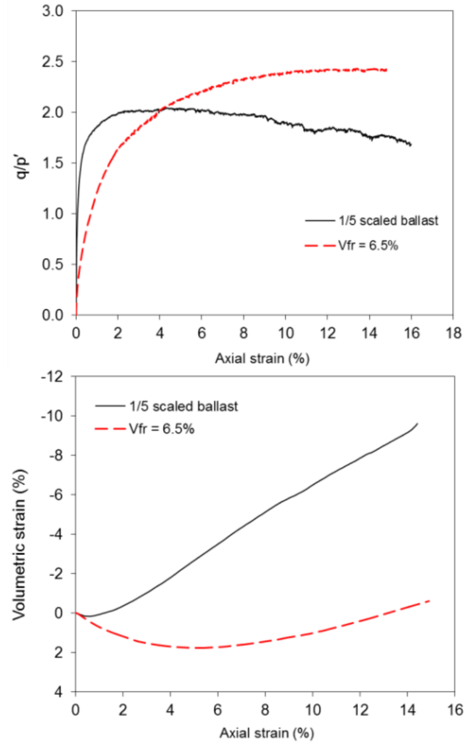

Figure 2. Effects of fibre reinforcements on the development of stress ratio, q/p' and volumetric strain with axial strain for scaled ballast

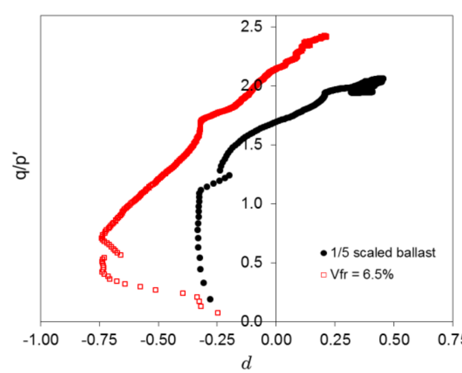

Figure 3. Effects of fibre reinforcements on the rate of dilation, d

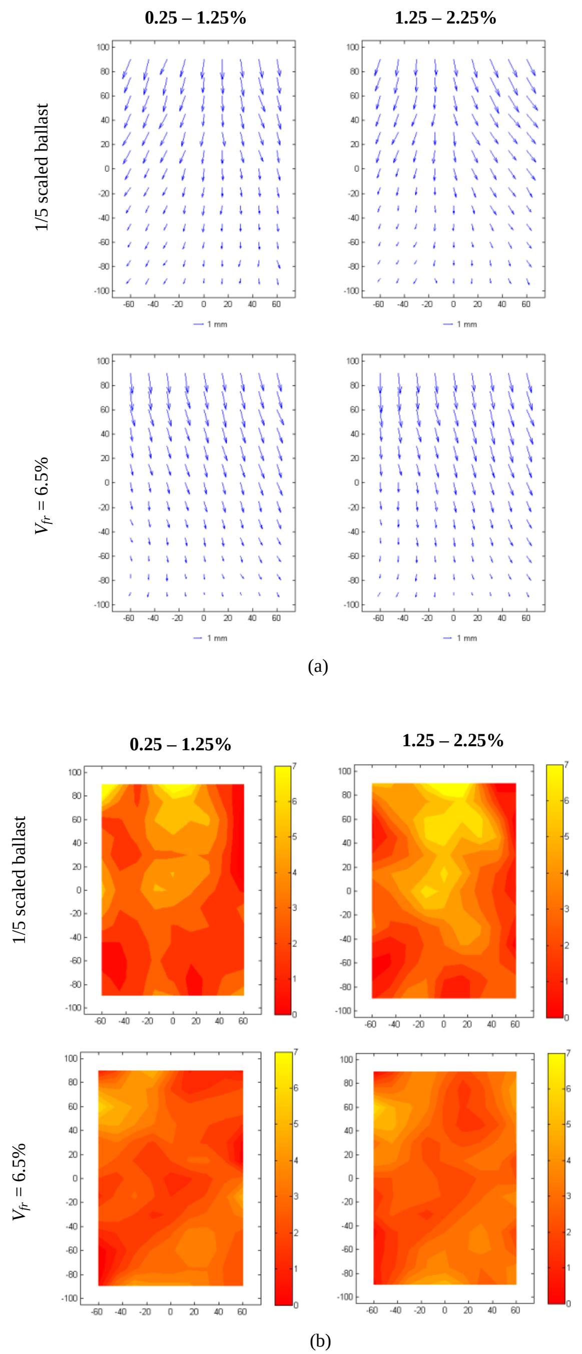

Figure 4. Pre-peak deformation characteristics of unreinforced and reinforced specimens (a) displacement vector (b) maximum shear strain fields

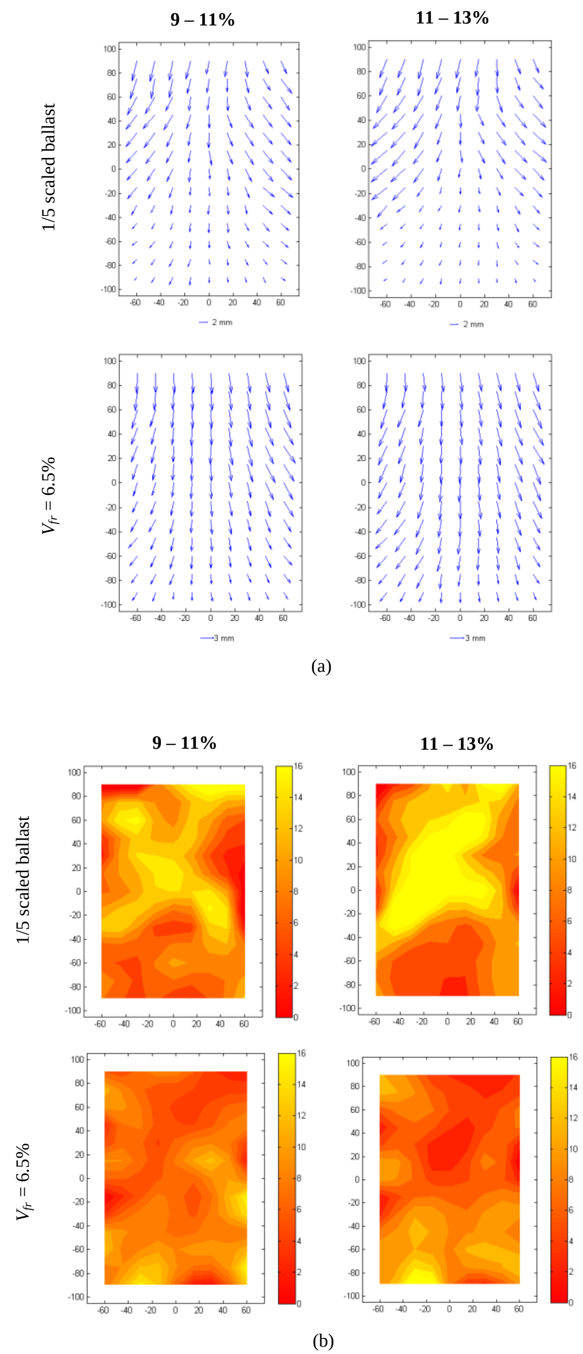

Figure 5. Post-peak deformation characteristics of unreinforced and reinforced specimens (a) displacement vector (b) maximum shear strain fields

During post-peak deformation, the reinforced specimen exhibited more nearly vertical deformation than the unreinforced specimen (Figure 5(a)). A more-homogeneous distribution of shear strains is also observed in the reinforced specimen.

4 DISCUSSION

At large strains, fibres in granular materials are believed to be undergoing significant stretching thereby mobilising their tensile forces. This in turn creates an apparent confinement of the granular matrix (Diambra et al., 2013) and thus a reduced shear strain distribution.

This suggests that fibre reinforcements in railway ballast can potentially reduce shear deformation (evident through reduced lateral spread) while increasing the mobilised strength of the composite. In addition, the more uniform distribution of strains as observed in the reinforced scaled ballast specimen can potentially lead to a re-distribution of stresses (vertical and horizontal) within the reinforced ballast layer.

5 CONCLUSIONS

An image-based deformation measurement technique was used to investigate the deformation characteristics of unreinforced and reinforced 1/5 scaled ballast specimens. Fibre reinforcements in scaled ballast produced an increase in the mobilised strength of the mixture while suppressing dilation. At large strains, the addition of fibres to scaled ballast produced a more uniform distribution of shear strains owing to the apparent confinement provided by the tensile resistance of the fibres.

ACKNOWLEDGEMENT

This research was supported by the UK Engineering and Physical Sciences Research Council (EPSRC) through the TRACK21 Programme Grant (EP/H044949). The first author further acknowledges the support of the University of Southampton.

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