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Non-linear hybrid homogenization method for steel-reinforced resin

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HIGHLIGHTS

- A prediction method for mechanical behaviour of steel-reinforced resin is derived.
- Steel-reinforced resins are superior to conventional resins in terms of stiffness.
- Body-centred cubic sphere packing is representative for random sphere disposition.
- Positive influences due to confinement effects depend mainly on Poisson ratio.

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ABSTRACT

Injected bolted connections have been used in the Netherlands since the 1970s, initially to replace riveted connections of steel railway bridges. More recently, structural components with different geometrical tolerances have also been connected using injection bolts and oversize holes. The natural confinement of a bolted connection provides support to the injected epoxy resin so that it can withstand bearing stresses that are significantly higher than its uniaxial compressive strength. A recent innovation in the field of injected bolted connections is the development of steel-reinforced resin, which consists of a skeleton of steel particles and a conventional epoxy resin (polymer). In previous research, the steel-reinforced resin has shown to increase the connection stiffness and decrease creep deformation significantly. In this paper, a hybrid analytical-numerical homogenization method, which can consider the plasticity of steel and resin, is proposed to determine the stress-strain relationship of steel-reinforced resins. The results of the hybrid homogenization method are validated against experimental data of small-scale specimen, subjected to compression in unconfined and confined conditions. Proposed hybrid homogenization method is an alternative to complex multi-scaling methods and allows for quick but accurate determination of mechanical properties of steel-reinforced resins.

1. Introduction

Injected bolted connections (IBCs) are conventional bolted connections of which the remaining bolt-to-hole clearance is injected with an epoxy resin through a standardized, modified bolt, as illustrated through Fig. 1. IBCs have been used in the Netherlands since the 1970s, initially to replace riveted connections of steel railway bridges. Two main reasons for the use of IBCs were:

- riveting was no longer common practice;
- determination of the actual slip factor of the faying surfaces in case of refitting with preloaded bolts is not possible.

Recently, a paper published by de Oliveira Correia et al. [1] addressed the application of IBCs in renovation of bridges, provided statistical analysis of fatigue experiments and identified needs for furthers studies related to fatigue classification.

Injected bolted connections can be used for two main types of applications: either to obtain a slip-resistant steel-to-steel connection (e.g. as an alternative to preloaded connections) [2] or to obtain a stiff connection between components with different geometrical deviations (e.g. steel and concrete) [3]. In the latter application, oversize holes are used to allow for greater positioning tolerances.

The epoxy resin system that is generally used in injected bolted connections (IBCs) is the commercially available RenGel SW 404 + HY 2404. Recent research of Koper [4] on steel-to-steel IBCs has indicated that this epoxy resin system performs best in comparison to a selection of alternative resins. Wedekamper [5] investigated the mechanical properties of this resin in detail through a series

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Nomenclature

d	diameter
D	damage variable
E_1	Young's Modulus of particles
E_2	Young's Modulus of matrix
$E_{c,lower}$	lower bound for Young's Modulus of composite material
$E_{c,upper}$	upper bound for Young's Modulus of composite material
E_r	Young's Modulus of resin matrix
E_s	Young's Modulus of steel particle
E_{s+r}	Young's Modulus of steel-reinforced resin
$h_r(x_i, y_j)$	total height of resin matrix in element (x_i, y_j)
$h_s(x_i, y_j)$	total height of steel particles in element (x_i, y_j)
$h_{s,p}(x_i, y_j)$	height of the p-th steel particle in element (x_i, y_j)
$k_{eq}(x_i, y_j)$	equivalent spring stiffness of element (x_i, y_j)
$k_r(x_i, y_j)$	spring stiffness of matrix component of element (x_i, y_j)
$k_s(x_i, y_j)$	spring stiffness of steel component of element (x_i, y_j)
l	length
m	mass
n	number of discrete elements within unit cell along x and y axes
q	number of spheres in unit cell
r	sphere radius
u_0	imposed longitudinal contraction of unit cell
$u_r(x_i, y_j)$	longitudinal contraction of resin spring in element (x_i, y_j)
$u_s(x_i, y_j)$	longitudinal contraction of steel spring in element (x_i, y_j)
V	volume
V_f	volume fraction of particles
X	parameter

Greek letters

Δu_{max}	maximum difference between imposed and actual contraction of unit cell
$\varepsilon_r(x_i, y_j)$	resin strain in element (x_i, y_j)
$\varepsilon_s(x_i, y_j)$	steel strain in element (x_i, y_j)
ε_{thr}	threshold strain after which damage develops
ν_{s+r}	Poisson ratio of steel-reinforced resin
ρ_r	density of resin matrix
ρ_s	density of steel particle
σ_D	stress in damaged element
σ_{s+r}	stress in steel-reinforced resin

a) b)

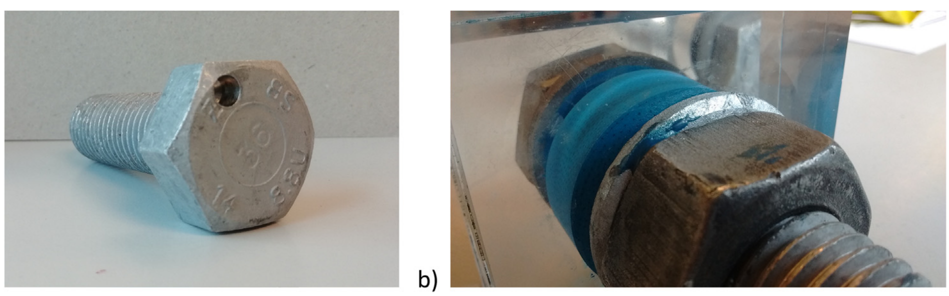

Fig. 1. (a) M20 × 50 mm ISO4017 8.8U bolt with an injection channel in the bolt head. (b) Resin-injected bolted connection with transparent plate package. The resin (blue) is injected through a hole in the bolt head. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

of compression, tension, shear and pull-out tests. Nijgh [6] has suggested reinforcing commercially available resins using steel particles in order to increase connection stiffness and to decrease creep deformation. In this perspective, steel shot has a good potential as the reinforcing material, given that this product is widely available on the market because of its application in steel blasting.

The material behaviour of reinforced resin depends on the type of resin, type of the reinforcing material and the volume fraction thereof. It is important to adopt a multi-scale analysis to determine the mechanical properties of the steel-reinforced resin. Generally, multi-scale homogenization methods are subdivided into analytical and numerical methods. After decades of effort, several analytical methods of continuum micromechanics have been developed, including Voigt's model [7], Reuss' model [8], Vanishing Fiber Diameter (VFD) model [9], Composite Cylinder Assemblage (CCA) model [10,11], Hashin-Shtrikman Bounds [12,13], Self-Consistent Schemes [14,15] and the Mori-Tanaka Method [16,17]. The unit cell complexity and non-linear behaviour of the constituent materials make the analytical micromechanics methods cumbersome for non-linear predictions. Compared with analytical micromechanics formulations, numerical homogenization simulations can accurately consider the geometry and spatial distribution of the phases, and can also accurately estimate the propagation of damage to predict the failure strength [18]. Macroscopic material properties of the composites can be determined by means of numerical modelling of deformation and failure of the assumed microstructural model, which is considered through a representative volume element (RVE). A downside of numerical homogenization methods is that they are computationally expensive, as frequently reported in the literature [19,20,21]. A combination of analytical micromechanics methods and numerical homogenization methods is expected to consider the complexity of constituent materials and spatial distribution of phases in a unit cell, at little computational cost.

The goal of this paper is to demonstrate a hybrid analytical-numerical homogenization method, which is less mathematically strict compared to traditional homogenization methods, but can be effectively used to determine the compressive stress-strain relationship of steel-reinforced resins. The hybrid homogenization model is validated against experimental data obtained from a small-scale specimen, subjected to compression in confined and unconfined conditions. In addition, an analytical method is derived to determine the degree of confinement and it is investigated which parameters have the largest influence on the apparent longitudinal Young's Modulus. Finally, conclusions are drawn on the effectiveness of the reinforcing particles through a parameter study on the effects of the steel volume fraction on the Young's Modulus of the composite material.