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Time-dependent behaviour of composite beams with blind bolts under sustained loads

Huiyong Ban [a,b,*], Brian Uy [b], Sameera Wijesiri Pathirana [b], Ian Henderson [b], Olivia Mirza [c], Xinqun Zhu [c]

[a] Key Laboratory of Civil Engineering Safety and Durability of China Education Ministry, Department of Civil Engineering, Tsinghua University, Beijing 100084, PR China
[b] Centre for Infrastructure Engineering and Safety, School of Civil and Environmental Engineering, The University of New South Wales, Sydney, NSW 2052, Australia
[c] Institute for Infrastructure Engineering, University of Western Sydney, Penrith, NSW 2751, Australia

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ABSTRACT

The use of blind bolts in steel–concrete composite beams is beneficial for promoting sustainable design and for retrofitting existing steel structures. This paper presents an experimental study as well as finite element (FE) modelling analyses for the time-dependent behaviour of composite beams with blind bolts subjected to sustained loads. Four full-scale simply supported beams utilising different types of bolts and studs were tested under long-term static loads. The mid-span deflections were monitored for a period of over 260 days. Short-term push-out tests were also carried out on the connectors used in the composite beams, and their slip deformation was recorded for determining the initial stiffness. The experimental results were modelled by using a three-dimensional FE model, in which the creep of the concrete was simulated through defining a viscoelastic response and the shrinkage of concrete was incorporated by means of notional thermal expansion. The FE model was validated against the experimental results reported herein and other independent results of composite beams using conventional welded studs reported elsewhere, and it was subsequently applied to carry out parametric studies. An extensive body of parameters was considered to clarify their effects on the time-dependent behaviour of composite beams with blind bolts, including the mechanical properties and configuration details of shear connectors, the concrete strength, the loading conditions, the span-to-depth ratio and the reinforcement ratio. It was demonstrated that the time-dependent behaviour was sensitive to the stiffness and the bolt-to-hole clearance of connectors, and some other parameters also possessed effects with different degrees. The research findings implied that using blind bolts in composite beams was beneficial to the time-dependent response due to their relatively lower deflections resulting from the creep and shrinkage of the concrete over time. The outcome may provide an important basis and guidance for designing such composite beams when considering their long-term response with time effects.

1. Introduction

Using bolted shear connectors in steel–concrete composite beams has seen considerable interest of late in both research and practice due to the various benefits in terms of the sustainable design and the retrofit of existing steel structures. For instance, the use of blind bolts that can be installed and tightened from one side of a connection makes composite construction demountable and sustainable, because the blind bolts can also be unbolted from one side and therefore it's possible to demount the structure at the end of its service life for potential reuse or recycling of components, as well as to replace damaged structural members during the service life. With respect to the retrofit of existing steel structures, the blind bolts may be post-installed in non-composite beams with the concrete slab being core drilled and the top flange of the steel beam being cut with holes, and after the installation the holes within the concrete slab need to be filled with high strength structural grout [1,2]. In this way, the loading capacity of the existing non-composite steel structures would be highly improved and their service life may be significantly extended. Whilst conventional headed studs most widely utilised in contemporary composite structures as shear connectors cannot be effortlessly deconstructed at the end of their service life. Furthermore, in the case of rehabilitating old structures, it is unlikely for headed studs either being welded to steel beams or being embedded into the concrete slab, because the weldability of the steel must be known before the studs can be welded to the existing steel beams and furthermore welding studs to the existing steel beams requires relatively large pockets to be broken out of the concrete slab. From this viewpoint, the use of bolted shear connectors is an appropriate solution for these problems, because it requires much smaller pockets to be broken out of

* Corresponding author at: Key Laboratory of Civil Engineering Safety and Durability of China Education Ministry, Department of Civil Engineering, Tsinghua University, Beijing 100084, PR China. Tel./fax: +86 10 62782708.
E-mail address: banhy@tsinghua.edu.cn (H. Ban).

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the concrete slab through the core drilling and no welding is needed. In addition, using bolted shear connectors innovatively makes the composite beam system demountable during its service life, and its damaged components may be replaced by new ones; at the end of its service life, its components can be separated easily for subsequent reuse or recycling.

The mechanical performance of composite beams using bolted shear connectors is logically characterised as being different from those with conventional headed studs because of the varied slip responses of connectors in terms of the stiffness and the slip plateau [3,4]. The initial stiffness of bolted shear connectors is normally lower when compared with welded studs in accordance with previous research outcomes [4]; and due to the existence of the bolt-to-hole clearance, there may be a slip plateau in the slip response of bolted shear connectors until the bolt bears against the hole [3]. There have been a few investigations on the short-term behaviour of composite beams with bolted shear connectors. The push-out tests and composite beam tests with high-strength (HS) bolted shear connectors undertaken by Dallam and Harpster in 1968 [5–7] appear to be the first reported research work on the use of bolts in composite beams, in which the bolts were embedded in the concrete slab at casting. Marshall et al. [8] conducted an experimental study on composite beams using high-strength friction-grip bolts (HSFGBs) as shear connectors in 1971, and it was demonstrated that HSFGBs could be utilised as an efficient connector in composite construction, with the coefficient of friction at the service load as well as the ultimate load of the composite beams being evaluated. In 1984 Dedic and Klaiber [9] presented two methods of utilising HS bolts as shear connectors in the rehabilitation of composite structures, and compared their performance with conventional welded connectors by means of push-out tests. Commencing in the 2010s, the use of bolted shear connectors in composite construction attracted more attention, and more relevant research was undertaken. Kwon et al. [10] experimentally investigated the static and fatigue behaviour of three types of post-installed shear connectors (including the double nut bolt, HSFGB and adhesive anchor) with design equations being proposed, and markedly higher fatigue strength of these bolted connectors was indicated compared with conventional welded shear studs. Kwon et al. [1, 11] also carried out large-scale tests and parametric analyses of composite beams retrofitted by using post-installed shear connectors, with excellent ductility being observed and good predictions of the strength and stiffness provided by current design approaches being demonstrated. Pathirana et al. [12] reported an experimental study on full-scale composite beams, in which two specimens were fabricated by using blind bolts. It was demonstrated that blind bolts were capable of providing the composite action, and they could be unbolted after a load of 40% of the designed ultimate load was applied. Lam and Saveri [13] tested the shear capacity of demountable connectors machined from conventional studs with threads, which could produce similar strength and relatively higher ductility compared with welded studs. Very recently Rowe and Bradford [14] presented an analytical formulation for modelling the shear connection with HSFGBs in terms of three stages, including the full interaction with the interface shear being resisted by the friction produced by the pretension of bolts, the slip condition within the bolt-to-hole clearance, and the eventual contact status after the bolt bears against the hole; and Liu and Bradford [3] further developed a finite element (FE) model for more detailed research on the behaviour of HSFGBs as shear connectors, and proposed a load–slip relationship in algebraic form for this innovative connection. Pavlović et al. [4,15] undertook a series of push-out tests with grouped bolted shear connectors (with a single embedded nut) and prefabricated slabs within which openings were left for subsequent assembly of connectors, and developed a fine-mesh FE model for parametric analyses. The basic mechanical properties of bolted shear connectors including the shear resistance, stiffness, ductility, and failure modes were experimentally and numerically analysed in detail, with a reduction factor for the shear resistance being proposed. Moynihan and Allwood [16] tested three composite beams constructed with bolts as demountable shear connectors, and found that they possessed higher strengths than predicted in accordance with Eurocode 4 (EC4). Chen et al. [17] presented ten push-out tests with through-bolts as shear connectors and various parameters relating to the diameter and pretension of bolts and interface contact properties were involved. Low initial slip loads and comparable ductility and ultimate loads were observed compared with welded studs, and an analytical model as well as a FE model were developed for predicting the loading capacity of such bolted connections and bridge girders, respectively.

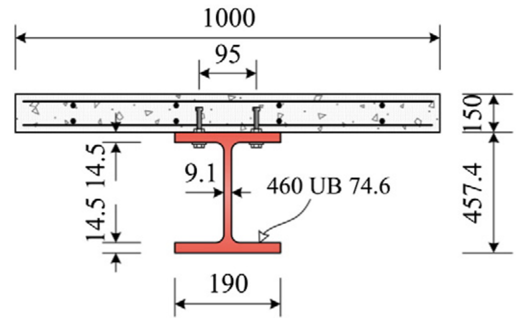

Fig. 1. Cross-sectional geometry (unit: mm).

Based on the afore-mentioned literature review, it was indicated that previous research of composite beams using bolted shear connectors was focused on the short-term behaviour. Whilst with respect to the long-term behaviour of such innovative composite beams, surprisingly few studies could be found in the open literature despite extensive investigations on the time-dependent behaviour of composite beams with conventional welded studs being undertaken [18–27]. With the aim of understanding the time-dependent behaviour of composite beams with bolted shear connectors and of providing benchmark data for further relevant research, four full-scale tests of simply supported composite beams with either blind bolts or conventional studs subjected to sustained loads for over 260 days are presented herein, of which the variation of the mid-span deflection with time is analysed. A three-dimensional FE model allowing for the creep and shrinkage behaviour of the concrete is developed, and subsequently validated against the test results reported in this paper as well as independent test results provided elsewhere. Extensive parametric analyses are conducted by using the calibrated FE model, with various parameters relating to the mechanical properties and construction configurations of shear connectors, the concrete strength, the loading conditions, the span-to-depth ratio and the reinforcement ratio being involved. Based on this work, the time-dependent behaviour of composite beams with blind bolts can be better understood, and their application in practice may be promoted for sustainable design.

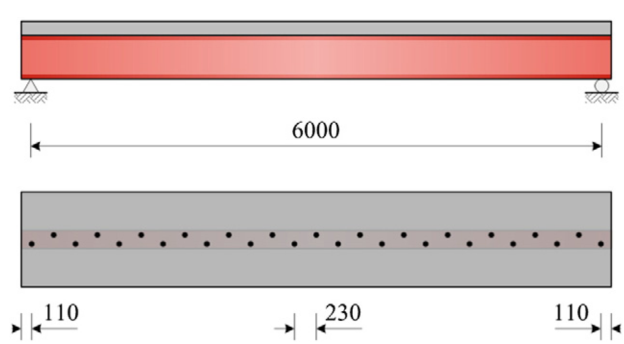

Fig. 2. Longitudinal geometry and shear connector arrangement (unit: mm).