Construction and Building Materials 38 (2013) 582–593

Contents lists available at SciVerse ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

# Comparison of behaviour between channel and angle shear connectors under monotonic and fully reversed cyclic loading

Mahdi Shariati *, N.H. Ramli Sulong, Meldi Suhatril, Ali Shariati, M.M. Arabnejad Khanouki, Hamid Sinaei

*Department of Civil Engineering, University of Malaya, 50603 Kuala Lumpur, Malaysia*

## HIGHLIGHTS

- ▶ Angle connectors showed 7.5–36.4% less strength in monotonic and 23.6–49.2% in cyclic loading than channels.
- ▶ Failure of connector fracture was experienced for both channel and angle connectors.
- ▶ After the failure, more cracking was observed in slabs with channels than with angles.
- ▶ All channel connectors have sufficient ductility but angle connectors showed less.
- ▶ Angles showed good behaviour in ultimate shear capacity but not in ductility.

## ARTICLE INFO

*Article history:*
Received 8 December 2011
Received in revised form 12 June 2012
Accepted 21 July 2012
Available online 23 October 2012

*Keywords:*
Shear connector
Composite
Channel
Angle
Cyclic loading
Push-out test
Monotonic loading

## ABSTRACT

Channel shear connectors are used to transfer longitudinal shear forces through the steel–concrete interface in composite beams. Angle shear connectors without bottom flange compared to channel shear connectors could be cheaper and more economic by saving more steel material. This paper presents an experimental evaluation for comparison of the behaviour of channel and angel shear connectors under monotonic and fully reserved cyclic loading based on 16 push-out tests. The connection shear resistance, ductility and failure modes are presented and discussed. By comparing the channel and angle shear connectors, it was concluded that angle shear connectors showed 7.5–36.4% less shear strength than channel shear connectors under monotonic loading and 23.6–49.2% under fully reversed cyclic loading. Connector's fracture type of failure was experienced for both channel and angle connectors. After the failure, more cracking was observed in slabs with channels compared to slabs with angles. Furthermore, in despite of sufficient ductility for all channel connectors, angle connectors showed less ductility. The results indicate that the angle shear connector gave good behaviour in terms of the ultimate shear capacity; however, this type of connector cannot satisfy the ductility criteria imposed by some codes. In the end, the shear load capacities obtained from the experiments are compared with those suggested by the design codes.

## 1. Introduction

Steel–concrete composite constructions have been used in buildings and bridges since the early 1920s [1]. The component that assures the shear transfer between the steel profile and the concrete slab is the shear connector. The shear connector enables a composite action to contribute to the shear transfer and prevents uplift. The strength and stiffness of a composite section depend on the degree of composite action between the concrete and steel components. The degree of composite action is related to the geometrical and mechanical properties of the shear connectors and the concrete slab.

The desire for a good solution for composite action with minimum cost encourages the development of new products. As it is widely known, there are many different types of shear connectors. The ones which are quoted as the most common types in use are the headed studs, Perfobond and C-shaped sections. Due largely to the high degree of automation both in workshops and on sites, the headed studs are widely used throughout the world; nevertheless, their limitations cannot be ignored since they need high power generators as well as specific welding equipment on site and they have some limitations in structures subjected to fatigue [2]. Initiation of fatigue crack under cyclic loading, which is induced by welds, is another shortcoming of headed studs [3].

Perfobond shear connectors are designed to fulfil the need of a connector that could mobilize elastic deformations for service loads. Despite the advantages of Perfobond shear connectors, the

---

* Corresponding author. Tel.: +60 17 243 4142.
*E-mail addresses:* shariati@siswa.um.edu.my, shariatimehdi@yahoo.com (M. Shariati).

0950-0618/$ - see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.conbuildmat.2012.07.050

main disadvantage of Perfobond connectors is the difficulty to position the lower reinforcement in the slab, particularly when the steel bars have to cross the connector openings [4].

To overcome the limitations and disadvantages of headed studs and Profobond shear connectors, C-shaped shear connectors may be a preferred alternative. Higher load carrying capacity and no need for some inspections like bending test are among the advantages of C-shaped shear connectors. In addition, there may be less difficulty in positioning the slab's lower reinforcement through the use of C-shaped shear connectors rather than by using Perfobond shear connectors.

Furthermore, the C-shaped profiles are widely available and the cost of the product is much cheaper than other types, hence, these types of shear connector are popular in composite beams, especially in developing countries. Channel and angle shear connectors, known as C-shaped shear connectors, are the topic of interest in this study.

Although channel shear connectors, as one of the popular C-shaped shear connectors, are used more in structures because of their accepted well-behaved performance, angle shear connectors without bottom flange could be cheaper and more economic than channel shear connectors by saving more steel material in composite beams. The convenient welding process of angle connectors compared to channel connectors is a further advantage.

Channel shear connectors were used in the scale-model of composite bridges and initially tested at the University of Illinois by Viest et al. [5]. The test results of a preliminary study of channel shear connectors were presented by Slutter and Driscoll [6] and Pashan [7] to identify their behaviour and assess the possibility of using this steel profile as a shear connector. From the above studies, some equations were derived for achieving the shear capacity of channel shear connectors in a solid concrete slab. Those equations were adopted from building codes, such as the National Building Code of Canada (NBC) [8] of Canada and the American Institute of Steel Construction (AISC) [9].

In order to calculate the nominal strength, $Q_n$, for a channel shear connector (Fig. 1), embedded in a concrete slab, the following equation has been provided by the current American Standard (AISC 2005) [9].

$$Q_n = 0.3(t_f + 0.5t_w)L_c\sqrt{f_c' E_c} \tag{1}$$

where $Q_n$ is the nominal strength of one channel shear connector (N); $E_C$ is the modulus of elasticity of concrete (MPa); $t_f$ is the flange thickness of channel shear connector (mm); $t_w$ is the web thickness of channel shear connector (mm); $L_C$ is the length of channel shear connector (mm); and $f_c'$ is the compressive cylinder strength of concrete (MPa).

Meanwhile, the National Building Code (NBC) [8] of Canada suggests the following equation which can be implemented for calculating the shear strength of a channel shear connector embedded in a solid concrete slab,

$$Q_n = 36.5(t_f + 0.5t_w)L_c\sqrt{F_c} \tag{2}$$

where $Q_n$ is the nominal strength of one channel shear connector (N); $t_f$ is the flange thickness of channel shear connector (mm); $t_w$ is the web thickness of channel shear connector (mm); $L_c$ is the length of channel shear connector (mm); and $f_c$ is the specified compressive strength of concrete (MPa).

Recently, push-out tests on channel connectors under monotonic and low cycle fatigue loading have been conducted by Maleki et al. [10,11] in which the channel connectors were embedded in plain concrete, reinforced concrete (RC), fibre reinforced concrete (FRC) and engineered cementitious composite (ECC). Other similar push-out tests have been performed by Shariati et al. [12] for channel connectors after being embedded in high strength concrete (HSC).

In addition, modified equations for the prediction of the shear capacity of channel shear connectors embedded in polypropylene (PP) concrete were suggested by Maleki and Mahoutian [11]. Other than that, a modified equation for the prediction of the channel shear connectors' capacity after being embedded in light weight aggregate concrete (LWAC) was suggested by Shariati et al. [13,14]. Pashan and Hosain [15] proposed two equations for the capacity of channel connectors in solid and metal deck slabs as well.

However, there has been limited study on the behaviour of angle shear connectors in composite beams. Choi et al. [16,17] investigated the fatigue strength of welded joints between angle shear connectors and the bottom plate in steel–concrete composite slabs through fatigue tests. The research confirmed that the stress level at the welded joint was small and much lesser than the fatigue limit. Shariati et al. [18] also performed a research on shear behaviour of angle shear connectors under monotonic and fully reversed cyclic loading.

Empirical equations were developed by Kiyomiya et al. [19], Yamada and Kiyomiya [20] that predict the load-carrying capacity of shaped shear connectors including of angle connectors (Fig. 1).

$$P = 65\sqrt{t_w}L_c\sqrt{F_c} \tag{3}$$

$P$ is the load carrying capacity of connector (kgf); $t_w$ is the web thickness of connector (cm); $L_c$ is the length of connector (cm); and $f_c$ is the concrete compressive strength (kgf/cm$^2$).

Another equation was also proposed by Ros [21] that can predicts the ultimate shear capacity of angle shear connectors based on either the connector failure or concrete crush.

$$V_u = k \times \sqrt{f_c} \times L_c \times h \qquad k = 63 \times \left(\frac{t_w}{h}\right) + 1.60 \tag{4}$$

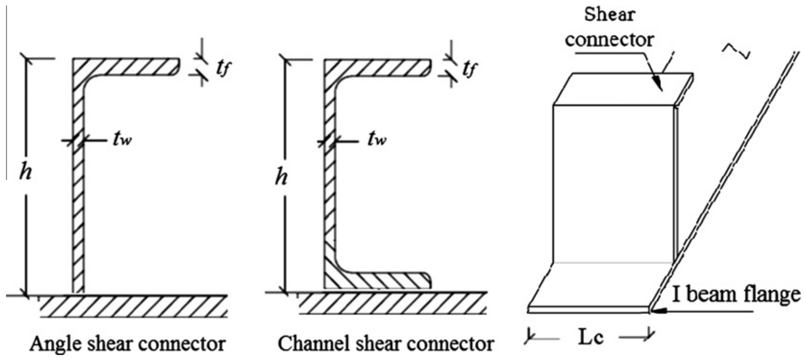

Fig. 1. Details of connectors' specifications.