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Comparative performance of channel and angle shear connectors in high strength concrete composites: An experimental study

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HIGHLIGHTS

- Channel and angle connectors in high strength concrete composites are studied.
- Connectors shear behaviors are tested under static (S) and cyclic (C) loads.
- Channel connectors are more ductile and more affected by crack than those of angle.
- 6.8–30% and 0–18.5% less strength are seen in angles under S and C loads respectively.
- Greater load is taken by higher connector; more concrete crack is seen in that longer.

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ABSTRACT

Structural performance of steel-concrete composite structures relies deeply on the characteristics of the shear connectors. Recently, great attention has been focused on the implementation of C-shaped connectors due to numerous advantages when used in composite beams. However, very little information is available in regard to the response of such connectors when embedded in the high strength concrete (HSC). To address this research gap, sixteen experiments on push-out specimens were conducted to compare the performance of channel and angle shear connectors embedded in HSC. The shear resistance and ductility of the connectors were primarily investigated by applying static and cyclic loadings. Results were also compared with the cases when using normal reinforced concrete. Furthermore, the evaluation of the available equations suggested by the American and Canadian codes for estimating these connectors' capacities when using HSC was carried out. In general, channel connectors exhibited 6.8–30.1% more shear strength than those of angle under monotonic loading, and up to 18.5% more when subjected to cyclic loading. Angle connectors were also less ductile than channel connectors and did not satisfy the ductility criteria specified in the codes' requirements. Connector fracture mode of failure was recorded for both connector types.

1. Introduction

Composite structures are well-recognized worldwide because of their high strength and reliable structural behavior. The benefits and versatility of composite beams have attracted and encouraged designers to use these structures in numerous skyscrapers in modern-day high-rise constructions. In detail, the strength and ductility of shear connectors play a vital role in the composite beam design. The successful design of shear connectors requires a careful estimation of the relationship between the transfer of shear force and slope provided at the steel and concrete boundary.

Many types of shear connectors are available commercially [1]. Headed studs [2,3], Perfobond [4–8], and C-shaped sections [9–13] are the most commonly used. Headed studs provide relatively high automation in the workplace. Popular use of headed shear connectors comes from their performance and ease of installation by means of welding gun. Even though headed shear studs are popular, their application and installation come with reliability problems. Unless great care is given to the installation process, welding strength and performance can be affected substantially by the weather, coating material of the steel and surface conditions. Because of their small load capacity, headed shear connectors are commonly installed in a large amount. This creates a crowded and unsafe working environment. The disadvantage of using headed studs continues with their comparatively poor

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performance under fatigue loading. Moreover, these connectors demand high energy consumption and a particular welding arrangement during installation [14]. This specific weld type can easily initiate crack development under fatigue loading [15], which leads to a girder design with partial interaction [16]. In addition, when reinforcement bars have to pass the connector openings, providing a good arrangement of the bottom reinforcement in the slab may infer further difficulty [17]. Due to these drawbacks, researchers and construction companies are continuously in pursuit of other better performing shear connectors.

In comparison, C-shaped or channel shear connectors are in many aspects exceeding the headed studs' performance. While studs need special equipment like welding guns, conventional welding equipment is enough for channel shear connectors. Conventional welding has a proven performance and is more reliable than the welding gun used to install the headed studs. Channel shear connector's load carrying capacity is at least twice that of the headed shear studs. This results in the use of fewer shear connectors. Fewer shear connectors means a substantial decrease in the labor time, offering a safer work environment as well. Also, conventional welding and channel connectors are more robust so that rough handling can be better tolerated.

The principal disadvantage of Perfobond shear connector lies in the placement of the slab transversal bottom reinforcement, which is often laborious and difficult. This drawback is efficiently overcome by C-shaped connectors, attributed to their higher constructability advantages. The bottom reinforcement is also relatively easy to adjust in the slab. Moreover, these shear connectors are commercially available in different sizes and necessitate only little cutting of steel sections into C-shaped profiles to make them ready for use. This relatively reduces expenditures and the manufacturing time. Given these advantages, C-shaped connectors are popularly utilized in composite beams in developing countries.

This study aims to examine and compare the performance of channel and angle shear connectors when embedded in high strength concrete (HSC). The profiles of the angle and channel shear connectors are shown in Fig. 1. The angle connectors differ from those of channel in that they do not have a bottom flange, such that they consume less steel material and require little welding process. Thus, these connectors provide a more cost-effective solution for composite beam design.

In predicting the strength of shear connectors, Slutter et al. [2], Pashan [18], and Viest et al. [19] performed different tests to estimate the performance quality of C-shaped shear connectors. These researchers proposed different equations to calculate the strength of the channel shear connectors [20]. Maleki and Bagheri [21,22] investigated the strength of the channel connectors used in different concrete types under different load types. Maleki and Mahoutian [23] tested the channel connectors implanted in polypropylene concrete. Two different equations that determine the strength of channel connectors in metal and solid deck slabs were introduced by Pashan and Hosain [24]. Baran and Topkaya [25] proposed a new equation that predicts the strength of C-shaped connectors, which improves the previous equations provided by different standards.

The American Institute of Steel Construction (AISC) [20] suggests that the nominal strength of a channel connector surrounded in concrete slab can be determined by the following:

$$Q_n = 0.3(t_f + 0.5t_w)L_c\sqrt{(f'_c E_c)} \quad (1)$$

where Q_n is the nominal strength (N), t_f and t_w are the thicknesses of the flange and web, respectively, L_c is the beam length, and E_c and f'_c are the modulus of elasticity and compressive strength of concrete (MPa), respectively. The National Building Code (NBC) [26] of Canada suggests the following equation for the same purpose:

$$Q_n = 36.5(t_f + 0.5t_w)L_c\sqrt{f'_c} \quad (2)$$

To date, there exists a number of studies exploring the behavior of angle shear connectors. Shariati et al. [27–29] determined different design characteristics of angle connectors surrounded with normal and high-strength reinforced concrete under different load conditions. Kiyomiya et al. [30] calculated the strength and deformation in different shear connector types through push-out tests. These researchers declared that the failure of a connector significantly depends on the geometry and location of the connectors and concrete strength. The fatigue strength of the weld between the bottom plate in the composite slab and angle shear connectors was examined by Choi [31] through experimental and numerical investigations. Fukazawa et al. [32] further investigated the possibility of using angle shear connectors under moving loads. The specimens exhibited satisfactory stiffness and durability.

Saidi et al. [33] explored the use of T- and C-shaped angle connectors in a sandwich beam in terms of the relationship between the transmitted shear force and consequent deformation by means of experiment and numerical approaches. They provided a formula to predict the transferred shear force at a sudden decrease of the equivalent stiffness of the shear connector. Ros and Shima [34] observed that the capacity of the shear connector can be largely affected by the line of action of the shear force applied to the connector.

Kiyomiya and Yokota [35] and Yamada and Kiyomiya [36] established the following formula to identify the strength of C-shaped connectors:

$$P = 65L_c\sqrt{(f'_c t_w)} \quad (3)$$

where P is the load carrying capacity (kgf). A relationship was produced by Ros [37] to quantify the ultimate shear capacity of angle shear connectors that depends on the failure type:

(a) (b)

Fig. 1. Typical (a) angle and (b) channel shear connectors.