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Push-out tests and a new approach for the design of secondary composite beam shear connections

Stefan Ernst [a,*,1], Russell Q. Bridge [b], Andrew Wheeler [b]

[a] Construction Technology and Research Group, University of Western Sydney, Penrith, Australia

[b] Construction Technology and Research Group, University of Western Sydney, Locked Bag 1797, Penrith South DC NSW 1797, Australia

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ABSTRACT

Most of the design approaches currently used around the world take into account the weakening effect of trapezoidal types of steel decking in the vicinity of a shear connection by applying a reduction factor to the nominal strength that the same connection would have in a solid concrete slab. Numerous push-out test results on shear connections incorporating this type of decking are presented. These demonstrate that not every shear connection incorporating profiled steel decking which is within the limits of the associated standards, can be classified as sufficiently ductile. A new and more reliable design approach is proposed which also allows for the inclusion of special reinforcing devices to overcome these brittle behaviours. The key element of this design approach is to classify the anticipated connection behaviour, with respect to its deformation capacity, into either ductile or brittle, hence ensuring satisfactory shear connection behaviour where these types of trapezoidal steel decking are used.

1. Introduction

In recent years, several trapezoidal steel decks with wide, open steel ribs have begun to be manufactured in Australia, and are now in common use (Table 1). These decks are unlike traditional decks used in Australia that are considered to be closed rib decks. However, similar decking geometries are widely used overseas. This geometry significantly interrupts the flow of force in the vicinity of the shear connectors and comprises a relatively narrow concrete rib in which the shear connectors are located. Experimental work has demonstrated that a wide variety of failure mechanisms exist which can significantly weaken the shear connection and reduce its ductility or slip capacity. The approach primarily used around the world to take into account the weakening effect of this type of decking is to apply a reduction factor to the nominal strength that the same connectors would have in a solid slab application. Several research projects have been undertaken recently [1–4], which indicate that the reduction factor formulae given in Eurocode 4 [5] and BS5950 [6] cannot be used safely with modern decks. New design methods have also been developed which require the shear connection strength to be further reduced. In [1] and [2] for example, the reduction factor would amount to 0.5 for 19 mm diameter stud pairs in a secondary beam application incorporating the Australian types of trapezoidal decks given in Table 1. This would result in a significant underutilization of the stud connector shear capacity.

It is important to note that the new design methods do not take into account the inadequate ductility that the shear connection of composite beams incorporating trapezoidal steel decking can experience. The lack of ductility cannot simply be resolved by further downgrading the stud strength, since it can affect the ultimate strength and deformation capacity of the entire composite beam [7]. As a result of this concern, methods to improve the ductility of the shear connection have been developed, and it has been found possible to reinforce the concrete in the vicinity of the shear connectors against premature concrete-related failures. For dovetailed or closed-rib types of steel decking, a waveform type of reinforcement is known to significantly improve the behaviour of the shear connection close to a free longitudinal concrete edge [8]. Similar waveform reinforcement elements have been found to greatly improve ductility and increase shear strength for trapezoidal steel decking geometries, when pairs of headed studs are used in both internal and edge beam applications [9]. The results of push-out tests on specimens with studs incorporating a ring-type performance-enhancing device that confines the concrete around the base of each connector have also led to a significant improvement in shear connection strength and ductility [10]. However, a systematic investigation into understanding the behaviour of the shear connection and the different load-transfer mechanisms with or without these devices has not been previously undertaken.

* Corresponding author. Tel.: +61 299297144.
E-mail address: stefan.ernst@mpn.com.au (S. Ernst).

1 Current address: MPN Group Pty Ltd., PO Box 443, Milsons Point, NSW, Australia.

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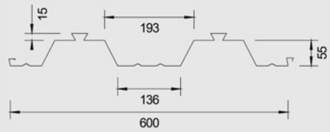
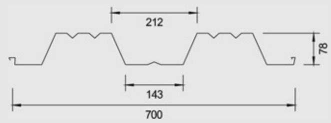
Table 1
Trapezoidal decking currently available in Australia

Manufacturer	Decking	Geometry
Fielders Australia	KF70®	
LYSAGHT	W-DEK®	

It is recognised that the test method used to determine the shear strength can affect the shear connection behaviour. Edge restraints mounted to the test specimens, for example, were found to suppress brittle failures of shear connections [11]. Furthermore, the width of the concrete flange in small-scale push-out tests is considered to have a major effect. Hence, in the tests carried out and reported herein this width was set as a primary variable.

2. Push-out test specimens

A total of 36 push-out tests in five separate test series were conducted to determine the behaviour of the shear connection in secondary beam applications. In order to reduce the parameters, it was decided to undertake the complete investigation using the Lysaght W-Dek® geometry (see Table 1). Some specimens included plain concrete ribs with the same geometry but with the steel decking omitted. This allowed the influence that the sheeting has on the load transfer mechanism of the connection to be investigated. When used, the decking (made from high-tensile galvanised G550 steel) was anchored into the concrete slab at both of its ends by cutting the decking into small tabs and bending them over about 135°. This was done in order to prevent the decking separating from the concrete ribs and to simulate the anchorage developed by the decking in a wider internal secondary beam where the decking extends over the concrete slab for a much greater width. However, this high level of anchorage may cause a strengthening effect on the decking in the shear connection close to a free edge. The other main factors investigated were the overall width of the slab and the inclusion of stud performance-enhancing devices and waveform reinforcement elements. The main test variables are summarised in Table 2. As a reference, some solid slab specimens with similar stud configurations were also tested, thus providing information about the differences in strength and behaviour induced by the concrete ribs.

All of the test specimens were designed to satisfy the requirements of Eurocode 4 [5]. The concrete slabs had an overall depth of 150 mm, and were 1050 mm long with two concrete ribs containing headed stud shear connectors. All of the studs were 19 mm diameter with a specified overall height of 127 mm after welding. The studs were automatically welded in the centre of each concrete rib in all but four specimens. In these four specimens, the studs were placed in a diagonal position 30 mm on either side of the lap joint or central stiffener. In the specimens where steel decking was used, it needed to be pre-holed in order to place the studs in the central position, due to the fact that this decking geometry includes either a central longitudinal stiffener or a lap joint in this position of the pans. Pre-holing of the steel decking is not common practice in Australia, but it has the major advantage of producing substantially better and far more reliable stud welds with fewer failures. In some of the test specimens, a number of studs had strain gauges fitted internally in their shank to determine the tensile force that developed in the connectors during the tests. The strain gauges were placed in a 2 mm diameter central hole that extended from the top of the stud to 20 mm below the underside of the head. The holes were sealed with a special adhesive to protect the gauges which were calibrated using the results of stud tensile tests.

Fig. 1. Stud performance-enhancing device being fitted around a stud and finally clipped under the stud head.

The stud performance-enhancing device consisted of a 4 mm diameter round steel wire that spiralled around the stud. At the bottom of the spiral was a circular retaining loop with an inner diameter of 35 mm which prevented excessive lateral movement of the device during the concrete pouring operation but still permitted the base of the device to be fitted over the head of a 19 mm diameter stud. The outer diameter of the main spiral was 76 mm diameter and was constant for a height of about 60 mm above the soffit of the decking while the pitch of the spiral was less for the bottom 40 mm. The spiral diameter then reduced at a constant rate over the remaining height, reaching a minimum diameter of 33 mm where it is a tight fit over the top of the head of the stud (Fig. 1). The waveform reinforcement element was designed to provide 20 mm concrete cover at the underside surfaces of the concrete ribs. It was placed directly on top of the lap joints and tied to the top reinforcement to hold it in position. The element consisted of four longitudinal 6 mm diameter round bars of the geometry shown in Fig. 2 which were positioned at 150 mm transverse spacings in the wider concrete slab specimens and welded to transverse bars at the positions indicated in Fig. 2. For the specimens that were 400 mm wide the transverse spacing was reduced to 100 mm for the two outside wires. A section through a typical test specimen including the spiral enhancing device and the waveform element is shown in Fig. 3.

The top reinforcement was placed 20 mm below the top surface. Sufficient longitudinal reinforcement was added in order to prevent local bending failures of the concrete slab (see also [12]). Where no waveform reinforcement elements were used, the specimens included a bottom layer of reinforcement placed directly on top of the concrete ribs with 10 mm diameter transverse bars welded to the underside of the longitudinal 6 mm diameter reinforcing bars and extending into the concrete ribs. To determine the effect of this bottom layer of reinforcement on the shear connection behaviour, two additional tests with this reinforcement removed were carried out.

In a number of the specimens, strains in the concrete, at critical locations across the horizontal plane between the concrete ribs and