EXPERIMENTAL INVESTIGATIONS ON THE BEHAVIOUR OF STRIP SHEAR CONNECTORS WITH POWDER ACTUATED FASTENERS

Mario Fontana*, Hermann Beck**, Roland Bärtschi***
*Institute of Structural Engineering, ETH Zurich, CH-8093 Zurich, Switzerland
**Hilti Corp., Direct Fastening Development, Principality of Liechtenstein
***Institute of Structural Engineering, ETH Zurich, CH-8093 Zurich, Switzerland

Abstract
Nailed strip shear connectors are presented as an alternative to welded headed stud connectors for composite beams. The strip shear connector has a trapezoidal shape to fit the geometry of metal decks. The strips are fixed by means of powder-actuated fasteners. The legs and the crests of the strip connector are equipped with openings to improve anchorage of the strip in the concrete plate by activating concrete dowels. By means of these openings the overall ductility of the system is improved. The connectors are designed to be used with automatic installation systems to improve installation efficiency.

The objectives of the push-out tests were to derive design parameters and to optimise the geometry of the strip shear connector. The test results indicate that optimised strip shear connectors will achieve high ultimate resistance in the range of 20 kN per fastener and sufficient ductility to allow plastic beam design. Further series of push-out tests are necessary to verify this behaviour statistically and to derive the characteristic resistance.

1. Introduction
Nailed shear connectors in composite beams have been an alternative to welded headed stud shear connectors for over 15 years. An example of a cold formed angle shear connector – whereby one leg of the angle is fixed by two powder-actuated fasteners driven with a powder-actuated tool – is shown in Fig. 1 (Hilti X-HVB shear connector). Compared to welded studs, nailed shear connector systems exhibit the following advantages:

• They require minimum installation equipment and set-up time, therefore allowing flexible scheduling of work on site.

Fig. 1: Hilti X-HVB
• They are efficient for small projects and for projects in remote locations.

• The installation quality is not affected by moisture on site or by zinc coatings of the base material resulting in less work interruptions due to bad weather or less preparation efforts like scraping of paint at the headed stud location.

However, the installation costs of nailed systems based on a “per kN basis” were up to now generally greater in comparison to welded studs. This is due to the fact that the design resistance of, for example, a Hilti X-HVB amounts to just approximately 40 percent of the design shear resistance of a 19 mm welded headed stud shear connector. To improve this situation, two different alternatives were investigated. Experimental research on the first option – the nailed shear rib connector – was begun in [1]. This paper now describes the strip shear connector as the second investigated solution. Both designs allow the use of automatic installation systems. Consequently, the installation speed increases reducing the overall costs of a nailed shear connector system.

2. Description of the nailed strip shear connector

The nailed strip shear connector system consists of two components, the strip shear connector itself and the powder-actuated fasteners fixing the strip connector to the beam’s flange. First investigations on such a type of shear connecting system were reported in [2]. The strip is folded from a flat zinc-coated steel sheet with a thickness in the range of 1.0 to 2.0 mm. The use of the connector on secondary beams with a composite deck spanning perpendicular to the beam is of most practical relevance. Therefore, the distance of the two troughs of the trapezoidal strip connector must be chosen to fit to the geometry of the metal deck (see Fig. 2).

![Fig. 2: Typical nailed strip shear connector system](image-url)

The strip connector is fixed to the beam flange by Hilti powder-actuated fasteners ENPH2-21L15 providing shear transfer between the concrete plate and the steel section. The leg of the steel strip acts as a diagonal reinforcement of the concrete rib. To improve the anchorage of the tension legs the connector strip must be higher than the metal deck. In all Stripcon push-out tests performed at the Swiss Federal Institute of Technology...
(ETH), Zurich, a trapezoidal deck (Vikam TR60/235) with a height of 60 mm was used combined with a strip connector of height 110 mm. The anchorage is provided by the folded shape itself and additionally improved by openings in the crests and the legs of the connector to develop a dowel mechanism within the concrete. Furthermore these openings allow reliable concrete compaction between metal deck and strip connector.

The high strength nails Hilti ENPH2-21L15 allow penetration of the strip connector and the beam flange without any predrilling. The ultimate strength of these fasteners is in the range of 2,200 N/mm² resulting in a shear resistance of approximately 20 kN per fastener. Though the nails show very high strength they remain ductile due to their bainite metallurgical structure as a result of specific heat treatment during manufacturing. The ability to bend without a brittle failure is very important with regard to meeting the ductility requirements of shear connectors in composite beam construction.

3. Experimental investigation

3.1 Push-out test set-up and test procedure

![Fig. 3: Push-out test specimen adapted to Eurocode 4](image)

The geometry of the push-out test specimen and the test procedure correspond to the specifications provided in Eurocode 4 [3] except for the fact that strip connectors were used instead of headed studs. Fig. 3 shows the geometry of the standard European push-out test specimen. The vertical slip was measured by 2 gauges on each side, and additionally horizontal gauges were applied to measure the uplift movement of the concrete plates. The load protocol followed the procedure given in Eurocode 4. Before
the actual push-out test was performed a static load of 40% of the expected ultimate capacity $V_u$ was gradually applied followed by 25 load cycles of this load range. The push-out tests were performed deformation controlled with a speed of 0.5 mm/min.

### 3.2 Specimen manufacturing

![Nailhead stand-off](image)

The strip shear connectors were fastened by ENPH2-21L15 powder-actuated fasteners using the Hilti DX750 installation tool. The nailhead stand-offs were recorded. The nailhead stand-off (NHS) as defined in Fig. 4 indicates the correct depth of penetration $h_{nom}$ which governs the fastening quality. In the case of the ENPH2-21L15 the optimum value of NHS is 8.5 mm. NHS is controlled by correct choice of cartridge type and tool setting.

According to Eurocode 4 the concrete of each plate has to be placed in a horizontal position. Therefore the two plates of the specimen differ in age (one day for each specimen) and compressive strength. Table 1 indicates the concrete compressive strength $f_c$ of the two plates. The concrete age at the day of testing varied between one and two weeks. The plates were reinforced according to the specifications given in Eurocode 4.

### 3.3 Push-out test program

Table 1 provides an overview of the test programme, the parameters investigated and the properties of the material. All tests were performed at ETH Zurich and are documented in reports [4], [5] and [6].

#### Table 1: Push-out Tests: Test program and test parameters

<table>
<thead>
<tr>
<th>Series</th>
<th>Specimen</th>
<th>Strip shear connector</th>
<th>Concrete strength $f_c [N/mm^2]$</th>
<th>Deck type and properties</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Type</td>
<td>Thickness t [mm]</td>
<td>Ultimate $f_u [N/mm^2]$</td>
<td>Yield $f_y [N/mm^2]$</td>
</tr>
<tr>
<td>S1</td>
<td>1</td>
<td>1.5</td>
<td>409.8</td>
<td>303.0</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>2.0</td>
<td>465.4</td>
<td>394.0</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>1.5</td>
<td>410.4</td>
<td>303.0</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>1.5</td>
<td>410.4</td>
<td>303.0</td>
</tr>
<tr>
<td>S2</td>
<td>3</td>
<td>6</td>
<td>465.4</td>
<td>394.0</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>1.5</td>
<td>410.4</td>
<td>303.0</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>2.0</td>
<td>465.4</td>
<td>394.0</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>2.0</td>
<td>383.1</td>
<td>348.4</td>
</tr>
</tbody>
</table>

- Cylinder strength: diameter = 150, height = 300
- See fig. 5
### 3.4 Geometry and properties of strip shear connectors

All strip connectors used were made of zinc-plated steel sheets. The steel used for the strip connector in test S2.6 was specified as DX51D according to EN 10142 [7]. For all other connectors tested, steel sheets specified as S280GD according to EN 10147 [8] were used. The material properties listed in Table 1 were evaluated by standard tensile tests according to EN 10002. Fig. 5 shows the detailed geometry of the different types of strip shear connectors listed in Table 1.

![Geometry of strip shear connector](image)

**Fig. 5: Geometry of strip shear connector**
The geometry of the strip connector type 1 was theoretically based on the results of 24 push-out tests performed at Hilti Corporation in 1998. The fundamental behaviour of nailed strip shear connectors, using generally Holorib HR51 as metal deck, was investigated in this test programme. From these tests, the beneficial effect of openings in the legs on the ductility of the connection was obtained. Because of the dove-tail shape of the Holorib 51, the contribution of the Holorib 51 to shear transfer was significantly greater than it would be in the case of a trapezoidal deck like the Vikam TR60/235. Provided the same type of shear connector is used, it will therefore be less stressed in combination with dove-tail metal decks.

Additionally, the existence of a stiffener in the troughs of the Vikam TR60/235 influences the geometry of the strip shear connector. Therefore, the troughs of the strip connector are also made with a centre ridge to fit the shape of the metal deck. This geometrical condition is advantageous with regard to an easy positioning of the strip connector on site. However, the ridge element in the plane of the nails affects the uniform load distribution to all nails.

4. Possible failure mechanism of nailed strip shear connectors

The following failure modes may potentially occur:

<table>
<thead>
<tr>
<th>Failure in the nailed interface:</th>
<th>Concrete failure:</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Shear failure of the nail shank</td>
<td>• Bearing failure of the concrete dowels</td>
</tr>
<tr>
<td>• Pullout of nails combined with local bearing deformations in the flange</td>
<td>• Shear failure of the concrete dowels</td>
</tr>
<tr>
<td>Steel failure of the strip connector:</td>
<td>• Shear failure of the concrete rib</td>
</tr>
<tr>
<td>• Local bearing failure in the nail interface</td>
<td>• Splitting of the concrete plate</td>
</tr>
<tr>
<td>• Net section fracture in the tension leg</td>
<td></td>
</tr>
<tr>
<td>• Net section fracture in the nailed troughs</td>
<td></td>
</tr>
</tbody>
</table>

For greatest efficiency of a nailed shear connector system, it is important to develop an ultimate capacity close to the total nail shear capacity of all fasteners installed. However, to allow plastic design of the composite beam the strip shear connector must develop sufficient plastic deformations at a high load level. Therefore, the thickness of the sheet must not be too thick to avoid brittle nail shank fracture without local bearing deformations. On the other hand, the following conditions require a stiff strip connector sheet:

• Smaller shear connecting contribution of the open trapezoidal metal deck.
• Greater stress in the tension legs as four nails are fixed per trough.
• Existence of the ridge in the trough, with two nails on both sides of the ridge.
In previous tests with the dove-tail-shaped Holorib metal deck no ridge was necessary and only two fasteners were installed per trough. Strip connectors of thickness 1.0 and 1.5 mm were used. For both thicknesses ultimate loads above 20 kN per fastener with excellent ductile behaviour especially due to local bearing deformations in the interface were developed. Consequently, finding the optimum design of the strip connector for use with the open trapezoidal Vikam TR60/235 required an iterative process to finally achieve satisfying results.

5. Description of load-deformation behaviour – test results

The changes in geometry from strip connector type 1 to type 8 reflect the continuous improvements based on the experience made during the test programme. For a better understanding of that process, the tests are described in their chronological sequence. The list of the push-out tests in Table 1 follows that sequence.

The result of test S1.1 reflects excellent ductile behaviour, developed from plastic steel deformations in the tension leg. Failure was governed by net section fracture in the tension legs. However, the ultimate load with 14.08 kN per fastener was significantly smaller than expected from the tests with the Holorib HR51, where resistances slightly above 20 kN per fastener were observed. Therefore, changes to type 1 were made to increase the strength of the tensile legs of the strip connector. Test S1.4 used a type 1 connector shape with greater thickness (2 mm instead of 1.5 mm) and with increased steel strength. Types 2 and 3 were made of the same material in the same steel thickness as used in test S1.1, but the slot width in the tension leg was reduced to 15 mm (test S1.5) or no slot was made (test S1.6).

Fig. 6: Load-deformation behaviour of series S1
However, these measures were only partially successful due to non-uniform load distribution between top and bottom rib observed in all three tests S1.4, S1.5 and S1.6. From examinations of cut specimens it was clearly seen, that the connector troughs located in the bottom rib of the plate were subjected to higher forces than those in the top rib. Furthermore, it could be seen that the nails located next to the tension leg were more stressed than those separated by the ridge in the trough. Net section fracture of the tension legs located in the bottom rib governed failure in test S1.4, whereas net section fracture of the nailed trough determined the ultimate capacity in tests S1.5 and S1.6. All three tests principally showed ductile behaviour, but again the loads achieved did not fulfil the targets (see Table 2).

Therefore, the type 6 strip connector used in test S2.3 incorporated further circular openings in the crests and an additional anchor tab at its ends (cf. Fig. 5). Both measures were intended to improve the anchorage of the strip connector in the concrete, especially of the upper “free” tension leg of the strip connector. The improved anchorage finally led to a more uniform load distribution between the top and the bottom ribs resulting in a high resistance of 21.03 kN per fastener. A further adaptation in the geometry was to change the parallel slot geometry into a conical one to prevent net section fracture at the bottom of the slot. The goal was to achieve the fracture in the middle of the tension leg and improve overall ductility by utilising a greater strain length.

In the last 2 tests S2.5 and S2.6 the geometry of type 6 was further modified resulting in the geometry of type 8, with slight adaptations in geometry and location of the openings in the crest and the leg. To further investigate the effect of the steel sheet strength, type 8 used in test S2.5 was manufactured of higher strength steel than for type 8 used in S2.6.

Fig. 7: Load-deformation behaviour of series S2
Table 2: Push-out tests: Summary of test results

<table>
<thead>
<tr>
<th>Series</th>
<th>Specimen</th>
<th>Ultimate Load $V_u$ [kN]</th>
<th>Deformations $\delta$ [mm]</th>
<th>Dominating Failure Mechanism</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>total per nail a</td>
<td>$\delta_u$ at $V_u$</td>
<td>$0.9 \delta_u$</td>
</tr>
<tr>
<td>S1</td>
<td>1</td>
<td>450.4</td>
<td>14.08</td>
<td>4.1</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>584.5</td>
<td>18.27</td>
<td>6.1</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>511.5</td>
<td>15.98</td>
<td>5.5</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>532.2</td>
<td>16.63</td>
<td>6.4</td>
</tr>
<tr>
<td>S2</td>
<td>3</td>
<td>672.8</td>
<td>21.03</td>
<td>7.2</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>539.0</td>
<td>16.84</td>
<td>6.8</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>663.8</td>
<td>20.74</td>
<td>7.5</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>707.2</td>
<td>22.10</td>
<td>7.4</td>
</tr>
</tbody>
</table>

In test S2.5, the upper tension legs failed in the middle of the net sectional area. This indicates the effectiveness of the improved anchorage measures at the ends of the strip connector and in the top concrete rib and also proves the effectiveness of the slot adaptations. The achieved ultimate load per nail was 20.7 kN. Though this value is sufficiently high for an economic use of the nailed system, it does not reach the ultimate loads of up to 25.7 kN developed for the rib shear connectors reported in [1]. This difference can be explained by the existence of the ridge in the strip connector trough, which is detrimental to a uniform load distribution to all fasteners installed for the entire deformation range.

Ductility and interestingly also the ultimate load were greater for test S2.6 in which the strip connector with the smaller strength was used. This behaviour indicates an improved load distribution to all fasteners installed due to earlier plastic bearing deformations in the strip in the vicinity of the fasteners. The intention of test S2.4 followed the same assumption that local bearing deformations of the thinner 1.5 mm strip type 7 might activate all nails more uniformly. In comparison with types 2 and 3 the width of type 7 was increased from 80 to 100 mm to prevent premature failure owing to net section fracture of the nailed trough. However, as indicated by Table 2 and Fig. 7, the assumed behaviour did not occur due to the reduction in connector thickness which also reduced the bending stiffness of the ridge affecting again the equal activation of all four fasteners installed on both sides of the ridge.

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a Total number of nails: 32 for each test.

b Note: According to Eurocode 4 the calculation of $\delta_{uk}$ requires 3 equal push-out tests performed and certain limits of the scatter of the 3 tests within a series. Nevertheless, as the ductility is an essential criterion, $\delta_{uk}$ is calculated here just based on the result of a single test to allow a first ductility assessment.

C Only occurred in the bottom rib of the concrete plate
6. Conclusions and outlook

Based on the results of this test programme on nailed strip shear connectors the following conclusions are summarised:

- Optimised design of the strip shear connector results in a high resistance of the nailed connections above 20 kN per fastener. With nail shank fracture, connector bearing deformations and partially net section fracture in the tension legs, a combined failure behaviour was observed. Therefore, the resistance of the fasteners was not as high as in the case of the nailed rib shear connectors [1].
- The characteristic deformations $\delta_{uk}$ were greater than the required limit of 6 mm indicating that the connector performance allows for plastic beam design.
- For the definition of design resistances further series of push-out tests must be performed.

Recently, beam tests were performed by the authors to verify the behaviour observed in the push-out tests in a full scale beam situation. The results will be reported later in a future publication.

7. References