Behavior investigation of powder actuated shear connectors in composite beams with profiled sheeting

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Abstract. Eurocode 4 and Russian SP266.1325800.2016 composite structure design codes require to use shear connectors for providing a combined action of steel beam and concrete slab. Both codes also allow use steel profiled sheeting as a stay-in-place formwork. In this case, the designer has to use a reduction factor to define the real shear resistance. However, the existing method is mostly based on round-shape welded studs and does not take into account the peculiarity of powder actuated shear connectors.

This paper presents the result of an investigation of the behaviour of powder actuated shear connectors Hilti X-HVB in composite beams. One of the goals was to explore the influence of the steel profiled sheeting’s geometry on shear resistance of the connectors. Fifteen test series were conducted with different numbers of connectors, slab thicknesses, installation parameters of the connectors and types of profiled sheeting. All types of sheeting that were used as the test samples are manufactured according to the Russian national standard and are widely used for composite slab design. Some test cases had smaller edge distances for shear connectors installation in profiled sheeting than allowed by the technical data of the producer, because they took place in real practice in CIS countries.

The test results have been evaluated according to Appendix B of Eurocode 4. The results for samples with solid slabs are in fully agreement with external experience. Most of series with profiled sheeting also match predicted design values; however, there were some series with insufficient results. Therefore, a deeper analysis and additional testing are necessary. The current investigation results could be used to specify the existing reduction factor that is included in the Russian composite structure design code SP266.1325800.2016

Keywords: Shear connection, composite beams, reduction factor, profiled steel sheeting, Hilti X-HVB.

1. Introduction

The composite beams were being investigated in USSR since 1930s. The first range of use for this structures was the bridge building: soviet scientists have been studied the basic principles of qualification and design composite beams with rigid shear connectors [1]. The design approach had been developed and included into the special code SNiP 2.05.03-84 [2]. There were different scientists, who worked on similar approach for civil buildings: B. Markov [3], E. Khautin [4], M. Karpovskiy [5] and other. Due the accumulated experience the first design recommendations have
been developed in 1987 [6]. Then we can an evaluation of design codes [7-8], that leads to national
design code SP 266.1325800.2016 [9] development.
The SP 266 design code allows to design the composite beams at the plastic or elastic stage. In
both cases, the designer has to ensure a full connection between the concrete slab and the
underlying steel beam. A partial connection is not allowed. The distribution of shear force along
the seam joining the reinforced concrete slab to the steel beam has to be determined for each design
region as a difference between the stresses in the concrete and reinforcement cross-sections on the
ends of the design region. The stresses should be determined with geometry properties of the
combined beam cross-section and inelastic deformations from concrete cracking, and shrinkage has
to be taken into account.
The SP code allows to use different types of connectors for shear load accommodation: welded
round, angle, channel-shape, etc. The SP code consists of design formulas of shear resistance for
each type. Powder actuated shear connectors are also allowed: the design of shear resistance has to
be provided by the producer. The Hilti X-HVB has the ETA-15/0876 [10] with all relevant
technical data that could be confirmed by test procedure according to Russian test method standard
GOST R 58336-2018 [11].
If the steel profiled sheeting is used as stay-in-place formwork, it is necessary to estimate the
deck’s influence on bearing capacity of the shear connector by applying the reduction factor. The
formula for ductile connectors depends on the deck’s orientation to steel beam and uses an
approach similar to Eurocode 4. At the same time, the SP 266 allows to use alternative formulas for
defining the reduction factor from shear connectors producers issued in their technical data. The
formulas from the ETA and from the SP 266 are different (Table 1)

| Drawing | ETA-15/0876 | SP 266 |
|---------|-------------|--------|
| ![Diagram](image1) | $S_h \leq P_{rd} \cdot k_{t,l};$  
$k_{t,l} = 0.66 \frac{b_0(h_{an} - h_n)}{h_n^2 \sqrt{n_r}} \leq 1;$  
Note:  
$n_r > 3; -$ not allowed  
It is necessary to match producer’s positioning requirements | $S_h \leq P_{rd} \cdot k_t;$  
$k_t = 0.7 \frac{b_0(h_{an} - h_n)}{h_n^2 \sqrt{n_r}} \leq 1;$  
Note:  
If 1 connector per row - $n_r = 1$  
If $\geq$2 connectors per row - $n_r = 2$  
$b_0 < h_n; -$ not allowed  
$h_{an} \geq h_n + 75$ mm; – not allowed  
If $h_{an} \geq 85$ mm, $b_0 \geq h_n; - k_t = 1$ |
| ![Diagram](image2) | $S_h \leq 0.89 \cdot P_{rd} \cdot k_{t,l};$  
$k_{t,l} = 1.18 \frac{b_0(h_{an} - h_n)}{h_n^2 \sqrt{n_r}} \leq 1;$  
Note:  
$n_r > 3; -$ not allowed  
It is necessary to match producer’s positioning requirements |  
|
As we can see, the SP’s approach is more conservative for the case when the deck is oriented transverse to the underlying steel beam and shear connectors are installed parallel to the deck. These formulas need to be proved by local tests.

2. Test program and push-out specimen

The standard specimen is a piece of I-section 25K2 according to GOST P 57837-2017 [13]. The flanges of the I-section are connected with 600x600 mm normal-weight concrete slabs with different thickness. The slabs’ form (solid, ribbed) depends on test series. Slabs are bonded with the I-section by powder actuated X-HVB shear connectors. The typical appearance of the specimen is shown in Figure 1.

![Typical push-out specimen](image)

**Figure 1.** Typical push-out specimen

The test program consists of 15 series with 3 standard specimens. The program is divided into 3 stages. The first stage consists of the specimens with 95, 125 and 140 mm height connectors that were installed and tested in solid slabs. The goal was to check the reference design resistance from the ETA. There were specimens with the connectors, oriented parallel to the underlying steel beam (P-series) and the connectors oriented transverse (T-series). The ETA contains no data for the T-series. The additional goal was to check the scope of X-HVB shear connectors.
The second stage consists of the specimens with 95 and 125 mm height connectors that were installed fully matching the Hilti’s requirements and tested in slabs with metal decks that are made according to the GOST 24045-2016[14] (Table 2). The goal was to check the applicability of the ETA reduction factor to the local profiled decks.

### Table 2. Geometry of the used metal decks

| Mark  | Drawing | Deck height $h_{nr}$ mm | Sheeting width $b_y$, mm Width / narrow side |
|-------|---------|--------------------------|---------------------------------------------|
| NS44  | ![NS44 Drawing](image) | 44                       | 144/106                                     |
| N60   | ![N60 Drawing](image)  | 60                       | 141/71                                      |
| N75   | ![N75 Drawing](image)  | 75                       | 105/82                                      |

The third stage consists of the specimens that are not compliant with the ETA spacing requirements. Some series had connectors installed in a weak position (X-150P-N60-1, X-150P-N60-2, X-150T-N75 series). The X-150T-N75-1 series had a non-compliance with the requirement to minimum number of connectors in narrow decks (one instead of two). The installation of the connectors in the X-150P-N60-1 formally matched the ETA requirements for weak position. However, the distance between the slab edge and the first bottom connector was only 120 mm, which could be insufficient. The X-150P-N60-2 had 2 connectors per row in weak position with ignorance of the minimum edge distance from the deck gauge to the connector. At the same time, the ETA-15/0876 allows to use similar positioning scheme in cases of narrow decks. The width of such decks should be more than 60 mm – the specimens matched this requirement. The potential problem zone is the distance between the slab edge and the first bottom connector - 120 mm. In the X-150T-N75 series, the minimum edge distance from the deck gauge to the connector had also been ignored. The specimens for X-150T-N75-1 series were made with N75 deck laid by narrow side on the underlying beam. For such decks in this case, the ETA specifies to install not less than 2 connectors per row, but the goal was to check the importance of this requirement by installing 1 connector per row. It is also interesting to compare the results with X-150T-N60 series, because there are 2 connectors per row in a similar deck (Table 3).
Table 3. Specimen spacing in the third test stage

| Series name | Drawing | ETA requirement |
|-------------|---------|-----------------|
| 1           | X-150P-N60-1 | ![Image](image1) |
| 2           | X-150P-N60-2 | ![Image](image2) |
| 3           | X-150T-N75  | ![Image](image3) |
| 4           | X-150T-N75-1 | ![Image](image4) |

3. Testing and result evaluation

The tests were conducted in 2019 in the laboratory of Moscow State University of Civil Engineering. The MTS.MultiAxial.DS1.4811.DS1.50019 was used as a testing machine. The displacements were measured by a transducer on each concrete slab. The force was controlled by the internal transducer in the hydrocylinders. The loading was constant with a fixed speed of 0.83 kN/sec.

The results were estimated by the Eurocode 4 methodology. Test results for X-150P-N44 series were excluded due to technical reasons. The reduction factors and design shear resistances were defined according to the ETA-15/0876 and SP266 approach. The results are presented in Table 4.
Table 4. Testing and evaluation results

| Series name | Connector height, mm | Profiled sheathing mark | \(b_0\), mm | \(n_t\) | ETA-15/0876 | SP 266 | Design resistance per connector from the testing, kN |
|-------------|----------------------|--------------------------|-------------|--------|-------------|--------|--------------------------------------------------|
| X-120P      | 95                   | -                        | -           | -      | 26.0        | -      | 30.7                                             |
| X-150P      | 125                  | -                        | -           | -      | 30.0        | -      | 32.9                                             |
| X-160P      | 140                  | -                        | -           | -      | 30.0        | -      | 31.0                                             |
| X-120T      | 95                   | -                        | -           | -      | -           | -      | 26.0                                             |
| X-150T      | 125                  | -                        | -           | -      | -           | -      | 34.3                                             |
| X-120T-N44  | 95 NS44 118 2        | 0.89                     | 24.9        | 1.0    | 28.0        | 27.8                                           |
| X-150T-N44  | 125 NS44 118 2       | 0.89                     | 26.7        | 1.0    | 30.0        | 30.8                                           |
| X-120P-N44  | 95 NS44 118 2        | 1.0                      | 28.0        | 1.0    | 28.0        | 28.9                                           |
| X-150P-N44  | 125 NS44 118 2       | 1.0                      | 30.0        | 1.0    | 30.0        | -                                              |
| X-150T-N60  | 125 N60 71 2         | 0.89                     | 26.7        | 0.63   | 18.9        | 18.0                                           |
| X-150T-N75-2| 125 N75 105 1        | 0.69                     | 20.7        | 0.46   | 13.8        | 20.9                                           |
| X-150P-N60-1| 125 N60 141 1        | 1.00                     | 30.0        | 1.0    | 30.0        | 26.5                                           |
| X-150P-N60-2| 125 N60 141 2        | 1.00                     | 30.0        | 1.0    | 30.0        | 18.5                                           |
| X-150T-N75  | 125 N75 82 2         | 0.89                     | 26.7        | 0.51   | 15.3        | 22.4                                           |
| X-150T-N75-1| 125 N75 105 1        | 0.77                     | 23.1        | 0.65   | 19.5        | 18.4                                           |

The specimens at the first stage showed excellent results in all cases. All failures were linked with dowel shearing. The results for the T-series testified that the connectors could be installed in this way and the technical data, which has been obtained for parallel-to-steel-beam-oriented connectors, could be used for calculating shear resistance of transverse oriented connectors.

The second stage results are contradictory: for connectors with transverse orientation to the underlying beam, the ETA approach predicts the shear resistance more precisely than SP 266 in all cases, except the X-150T-N60. In this series, the narrow side of the deck was used. There were 2 connectors per row installed with 100 mm between the connectors. This case is covered by ETA: the predicted shear resistance for X-HVB 125 needs to be more than 26.7 kN per connector. In all three cases, we observed the rib shearing as a failure mode with much less ultimate resistance per connector(Figure2). One of the possible reasons is an unfavorable specimen geometry that provides non-uniform stress distribution between 3 pairs of connectors (Figure 3). Additional tests or numerical simulations are required to reliably determine the reasons for this behavior of the connectors in such situation.
Figure 2. Concrete rib shearing from the X-150T-N60 series

Figure 3. The X-150T-N60 specimen.

The third stage results fully confirm the ETA requirements. However, a deeper analysis could provide useful data about ductile shear connectors in a weak position: in most series, the distance between the slab edge and the first bottom connectors was insufficient. It causes premature concrete failure near the bottom connectors. Checking the moment when the bottom rib cracks could help to investigate the stress redistribution between remaining shear connectors. For example, in the X-150P-N60-1, X-150P-N60-2, X-150T-N75 series, more precise data could be obtained by considering the shear force redistribution. The X-150T-N75 with narrow ribs and connector per row provided a result similar to X-150T-N60 series with concrete rib shearing. The behavior of shear connectors in narrow ribs with $b_0/h_p < 1.8$ requires an additional investigation.
4. Conclusions

Results of the tests confirm the application limits of the Hilti X-HVB and provide a basis for further investigation of shear connectors’ behavior in composite beams made with Russian profiled sheeting. The tests confirmed the applicability of shear connectors with traverse orientation to underlying steel beam in solid slab without additional testing.

The SP 266 approach for defining the reduction factor is too conservative in comparison with ETA formulas. The ETA approach could be used for local decks with wide rows (with \(b_0/h_p \geq 1.8\)) when manufacture’s application limits are observed. The scope of the shear connectors in narrow ribs requires an additional investigation.

The SP 266 needs to be updated with additional requirements for shear connectors spacing. The GOST R 58336-2018 for shear connectors test method needs to be updated with restriction of minimal distance between the slab edge and the first bottom concrete rib with the connectors.

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