Experimental Study on Welded Headed Studs Used In Steel Plate-Concrete Composite Structures Compared with Contactless Method of Measuring Displacement

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Abstract. Steel plate-concrete composite structures are a new innovative design concept in which a thin steel plate is attached to the reinforced concrete beam by means of welded headed studs. The comparison between experimental studies and theoretical analysis of this type of structures shows that their behaviour is dependent on the load-slip relationship of the shear connectors used to ensure sufficient bond between the concrete and steel parts of the structure. The aim of this paper is to describe an experimental study on headed studs used in steel plate-concrete composite structures. Push-out tests were carried out to investigate the behaviour of shear connectors. The test specimens were prepared according to standard push-out tests, however, instead of I-beam, a steel plate 16 mm thick was used to better reflect the conditions in the real structure. The test specimens were produced in two batches using concrete with significantly different compressive strength. The experimental study was carried out on twelve specimens. Besides the traditional measurements based on LVDT sensors, optical measurements based on the digital image correlation method (DIC) and pattern tracking methods were used. DIC is a full-field contactless optical method for measuring displacements in experimental testing, based on the correlation of the digital images taken during test execution. With respect to conventional methods, optical measurements offer a wider scope of results and can give more information about the material or construction behaviour during the test. The ultimate load capacity and load-slip curves obtained from the experiments were compared with the values calculated based on Eurocodes, American and Chinese design specifications. It was observed that the use of the relationships developed for the traditional steel-concrete composite structures is justified in the case of ultimate load capacity of shear connectors in steel plate-concrete composite structures.

1. Introduction

Steel-concrete composite structures have been used in buildings and bridges for over fifty years. This kind of structural system provides the most efficient design by the use of an effective connection between steel and concrete. Many different types of shear connectors have been used, but headed studs are the most common type. The rapid development of composite structures has stimulated many researchers to study different types of assemblies.
In 2009 Nie and Zhao described an experimental study on steel plate-concrete composite (SPCC) beams [1] in which the traditional steel beam is replaced by a steel plate. Five different beams were tested and it was found that the assumption of plane sections remaining plane is justified, the headed studs can ensure full composite action and the stiffness of the shear connectors has significant influence on the stiffness of the beam. Recent studies [2, 3] give more insight into theoretical analysis of SPCC beams and show that the interface slip should be taken into account in the calculation of deflection.

To investigate the behaviour of the shear connectors, push-out tests are commonly used. So far, push-out tests were conducted according to [4] which specify testing arrangements when the shear connectors are used in T or I-beams with a concrete slab of uniform thickness. In the SPCC beam there is no concrete slab and the steel beam is substituted by a steel plate. Therefore push-out tests with a steel section as the steel plate were performed and analysed. Additionally, an innovative method of optical measurement has been tested on selected test specimens.

2. Principles of optical methods of measurement

The contactless optical measurements are used mostly in order to expand the scope of information provided by the standard measuring systems based on traditional sensors such as strain gauges or accelerometers. With optical measurement, it is possible to determine the displacement field on the specimen surface using tracking points called markers, placed on the specimen. For the optical measurement to get the same stability and resolution as using traditional measurement system, it is required to prepare the specimen surface accordingly, and to ensure appropriate lighting conditions. Basing on the full displacement field or in the specific case displacements of two selected points it is possible to generate the strain field on the specimen surface or calculate the strain value on the selected base.

2.1. Digital image correlation method

Digital image correlation method (DIC) is an optical method that is widely used in many areas of research and in civil engineering in particular to measure deformation on an object surface [5]. Moreover, it is relatively easy to use in micro scale for mechanical testing of materials such as steel [6], concrete [7], biomaterials [8] or composite structures [9]. This method is mainly used for pattern tracking. The pattern for DIC method can be defined as a marker placed on the structure or a small part of the specimen surface. In both cases DIC is used for the determination of the horizontal and vertical displacement of selected points using a sequence of images collected during the test by the vision system equipped with a camera or camcorder. These calculations can be done in real time or at the post-processing stage. The idea of the method of tracking the pattern, which is a fragment of the sample surface is presented in figure 1.

To calculate the correlation coefficient between the reference subset f and the target subset g, whose dimensions are equal to M x N pixels, the zero-mean normalized cross correlation method (ZMNCC) is used, as described by the equation:
\[ CC^{ZMN} = \frac{\sum_{i=1}^{M} \sum_{j=1}^{N} ((f(i,j) - \mu_f) \times (g(i,j) - \mu_g))}{\sqrt{\sum_{i=1}^{M} \sum_{j=1}^{N} (f(i,j) - \mu_f)^2 \times \sum_{i=1}^{M} \sum_{j=1}^{N} (g(i,j) - \mu_g)^2}} \]

where:
\( \mu_f \) - intensity (luminosity) of the reference subset,
\( \mu_g \) - intensity of target subset.

2.2. Sub-pixel resolution of the optical measurements
Measurements based on the standard DIC method without sub-pixel calculations can be applied for laboratory or in-situ tests characterized by large displacements and deformations. In case of very small values of displacements in the tested structure it is necessary to increase the resolution of the optical measurement using sub-pixel calculations. To make it possible, the digital image of the specimen surface needs to be interpolated to obtain intermediate values of the luminosity between discrete pixels. Images collected during the measurements are at the first stage converted to grayscale, so that each pixel discretizing the image is described by an integer value from 0 which indicates the black colour to 255 associated with the white colour. The most frequently used method of interpolation of intermediate values is the bi-cubic spline interpolation [10, 11]. The main idea of the sub-pixel interpolation and measurement is presented in figure 2. By using sub-pixel measurement, it is possible to increase the measurement resolution to the level of 1/10 or even 1/50 of the integer pixel unit.

![Figure 2. General principle of subpixel measurement](Image)

Since the DIC results are computed in pixels or fractional portion of the pixel when sub-pixel measurement is applied it is necessary to convert these results into length units (millimetres or inches). It is done if at least one real dimension visible on the specimen surface is known. The calculations of the conversion factor are based on the simple proportion between the real length of the specific object and its size in the registered image given in pixels. The value of the conversion factor defines the real pixel size in length units and is required for displacement calculations but does not need to be calculated if the strain field or single strain values are the only output values.

3. Experimental program

3.1. Test specimens
Twelve test specimens were prepared and tested according to [4] but differed in their dimensions and the method of concreting. In standard push-out test the steel beam is used due to a specific construction
of a traditional composite structure, but in SPCC beams the steel plate is used instead of T or I-beam, therefore also in push-out tests a steel plate was used. That required a change in the dimensions of the standard test specimens. Moreover, concrete slabs should be cast horizontally to better reflect the conditions in which this type of connection is assembled, but it creates problems during specimen fabrication [12]. The method which is commonly used to solve this issue is cutting the I-beam and welding two parts back together after casting slabs, but that solution is much more difficult in the case of a thin steel plate and was not applied to the described test specimens. Another solution used and described by [13] is casting of the slabs at different times, but this leads to different concrete strength of the slabs.

The push-out test specimens were divided into two types made of the same concrete. Moreover, four specimens were tested in the reverse position due to the observations made with the use of optical measurements based on the digital image correlation method that the upper part of the concrete blocks tend to compress the steel plate. For experimental purposes the test specimens were reversed to counteract this process with the use of a steel plate, which originally served as a bottom plate. Additionally, in those cases test specimens were placed on concrete grout. For each push-out test the dimensions of the test specimen were the same. The concrete blocks were cast on the bottom steel plate and reinforced with steel bars 10 mm in diameter. Additional bars were welded to the bottom steel plate to provide sufficient composite action between the plate and concrete blocks. A simplified 3D model and details of the test specimen is shown in figure 3.

3.2. Materials
For each batch twelve standard concrete specimens were prepared for the determination of the compressive strength and modulus of elasticity when the push-out test specimens were cast. Standard tensile tests were conducted on plate and rebar samples. Headed studs yielding strength and ultimate tensile strength were adopted on the basis of data provided by the manufacturer. The characteristic parameters of the concrete and steel components are summarised in table 1.

| Batch | f<sub>c</sub> | E<sub>c</sub> | f<sub>y</sub> | E<sub>y</sub> | f<sub>t</sub> | E<sub>t</sub> |
|-------|--------------|-------------|------------|-------------|------------|-------------|
| 1     | 57.6         | 35.5        | 368.5      | 210.0       | 515.0      | 546.0       |
| 2     | 94.4         | 45.5        | 531.9      | 210.0       | 515.0      | 546.0       |

Figure 3. Simplified model of the test specimen
3.3. Test setup and loading procedure
Test setup was prepared to investigate the behavior of the headed stud welded to the steel plate. To properly assemble the LVDT sensors additional bar was welded to the bottom surface of the steel plate. Bottom steel plate was fixed to the supporting structure. Additional sensors measured the movement of the specimen in horizontal directions and it was confirmed that the sample was firmly fixed.

Optical measurements were carried out using CivEng Vision system developed by one of the authors at Cracow University of Technology [14,15]. The measurements were made from two sides of the specimen using two identical sets of cameras and lenses (A, B). Two digital single-lens reflex cameras (DSLR) Nikon D5300 with matrix resolution 24 Mpx were used. Each camera was equipped with Nikkor zoom lenses with 18-55 mm focal length and extra-low dispersion glasses. The third camera (C) was used to register displacement values from the static materials testing machine. The cameras were connected with synchronizing wires. The photos of both sides of the specimen were taken simultaneously by the cameras with a fixed time interval using a digital intervalometer and saved as RAW files without image compression. The test stand is presented in figure 4.

![Figure 4. Test stand for optical measurement](image)

Due to the uniform texture of the specimen surface, special markers were added to make the optical measurement possible. The markers were placed in the specific points of the specimen – especially on the steel plate to measure the slip value during the test. The specimen surface prepared for optical measurement is shown in figure 5.

4. Test results
Eurocode-4 gives the formula for calculating the design shear resistance of headed stud automatically welded as:

$$P_{ld} = \frac{0.29\alpha d^2 \sqrt{f_{ck} E_{cm}}}{\gamma_V} \leq \frac{0.8 f_u \pi d^2}{4 \gamma_V}$$

(2)

where:

- $f_u$ - specified ultimate tensile strength of stud material but not greater than 500 MPa,
- $f_{ck}$ - characteristic cylinder compressive strength of concrete,
$E_{em}$ - modulus of elasticity of concrete,
$d$ - diameter of stud shank,
$h_{sc}$ - overall nominal height of stud,
$\alpha = 1$ for $\frac{h_{sc}}{d} > 4$.

Figure 5. Specimen surface for optical measurement and marker design and distribution

According to AASHTO LRFD [16] the nominal shear resistance of one stud shear connector embedded in concrete deck can be estimated as:

$$Q_n = 0.5A_{sc}\sqrt{f_c' E_c} \leq A_{sc} F_u$$

(3)

where:
$A_{sc}$ - cross-sectional area of a stud shear connector,
$f_c'$ - compressive strength of concrete for use in design,
$E_c$ - modulus of elasticity of deck concrete,
$F_u$ - minimum tensile strength of a stud shear connector.

According to the Chinese code [9] an analogous value can be calculated as:

$$N_V^C = 0.43A_{s}\sqrt{f_c E_c} \leq 0.7A_s \gamma_f$$

(4)

where:
$A_s$ - cross-sectional area of a stud shear connector,
$f_c$ - compressive strength of concrete,
$\gamma$ - ultimate tensile strength of stud,
$\gamma_f$ - minimum tensile strength to yield strength ratio of stud.
Design shear resistance of the welded headed studs calculated according to Eurocode-4, AASHTO LRFD and Chinese code are shown in table 2.

**Table 2.** Design shear resistance of the welded headed studs calculated according to Eurocode-4, AASHTO LRFD and Chinese code (kN)

|                | Eurocode-4 | AASHTO LRFD | Chinese Code |
|----------------|------------|-------------|--------------|
|                | $P_{rd,1}$ | $P_{rd,2}$  | $Q_{w,1}$    | $Q_{w,2}$   | $N_{v,1}^c$ | $N_{v,2}^c$ |
| Batch 1        | 65.0       | 53.1        | 88.0         | 54.9        | 75.7        | 45.1        |
| Batch 2        | 101.5      | 53.1        | 131.5        | 54.9        | 113.1       | 45.1        |

4.1. Failure mode

In all test specimens after the headed stud reached the yield strength, a shank failure was observed. No other failure modes associated with the concrete part were noticed mainly because concrete strength was not reached. The headed studs and the surfaces of steel and concrete after failure are shown in figure 6.

**Figure 6.** Mode of failure: steel surface, concrete surface and headed studs

4.2. Load-slip response

The analysis of the load-slip curves for the tested specimens shows characteristic behaviour observed in push-out tests. The test specimens in series C and D (reversed) were made of concrete described as Batch 2 and series E and F (reversed) as Batch 1 as in table 1. At the beginning of the loading procedure the relationship is almost linear until yield strength is reached in the headed studs. In this first elastic part of the load-slip curve the measured slip was very small. After that, the load-slip curve slope changes significantly and a rapid increase in slip is observed until ultimate tensile strength of the stud is reached, which results in a stud shank failure. After exceeding the ultimate value the specimens failed suddenly. The load-slip curves for all test specimens are shown in figure 7. The descending part (after ultimate load capacity was reached) of the curves are not shown on the plot. Experiments conducted on reversed specimens did not affect significantly the results.
Figure 7. Load-slip curves

The comparison of load-slip curves in the traditional measurements based on LVDT sensors and the optical measurements based on the digital image correlation method and pattern tracking methods for selected test specimens are shown in figure 8. Figure 9 shows a sample displacement map for the concrete section. The optical measurement method used in this experiment has confirmed its usefulness and will be used in future studies of steel plate-concrete composite beams.

4.3. Shear connector load capacity

According to Eurocode-4 at least three test specimens should be tested and the deviation of any individual test result from the mean value obtained from all tests should not exceed 10%. If these criteria are met, the design resistance can be calculated based on test results.

\[
P_{kd} = \frac{f_u}{f_{ut}} \frac{P_{Rk}}{\gamma_V} \leq \frac{P_{Rk}}{\gamma_V}
\]

where:
\(f_u\) - minimum specified ultimate strength of connector material,
\(f_{ut}\) - actual ultimate strength of connector material in the test specimen,
\(\gamma_V\) - partial safety factor for shear connection (recommended value is 1.25).
As shown in table 3, the calculated results correspond well with the values obtained in accordance with design specifications.

**Table 3.** Comparison of test results of shear connector load capacity and values calculated according to Eurocode-4, ASSHTO LRFD and Chinese code (kN)

|        | Test / Eq. (2) | Test / Eq. (3) | Test / Eq. (4) |
|--------|----------------|----------------|----------------|
| C1     | 77.5           | 1.07           | 1.03           | 1.26           |
| C2     | 72.3           | 1.00           | 0.96           | 1.17           |
| C3     | 66.5           | 0.92           | 0.89           | 1.08           |
| D4     | 80.5           | 1.11           | 1.07           | 1.31           |
| D5     | 72.0           | 0.99           | 0.96           | 1.17           |
| D6     | 76.6           | 1.06           | 1.02           | 1.24           |
| E1     | 82.1           | 1.13           | 1.10           | 1.33           |
| E2     | 82.8           | 1.14           | 1.11           | 1.35           |
| E3     | 84.9           | 1.17           | 1.13           | 1.38           |
| E4     | 84.7           | 1.17           | 1.13           | 1.38           |
| E5     | 81.2           | 1.12           | 1.08           | 1.32           |
| F6     | 80.2           | 1.11           | 1.07           | 1.30           |

**Figure 8.** Traditional measurements based on LVDT sensors vs. optical measurement

**Figure 9.** Sample displacement map for concrete section of test specimen
5. Conclusions

Push-out tests of welded headed studs used in innovative steel plate-concrete composite beams were carried out to investigate the behaviour of shear connectors welded to a steel plate. The experimental studies showed the characteristic behaviour of the push-out test specimens visualized in terms of the load-slip curves and proved that equations derived for traditional steel-concrete composite structures could be applied also in the described case. The best agreement can be observed when experimental results are compared with the values obtained from Eurocode-4 or ASSHTO formulas. The results can be used in future studies including theoretical and numerical studies on steel plate-concrete composite beams and parametric analysis of push-out tests of shear connectors, which are inexpensive and less time-consuming compared with experimental studies.

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