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Different profiled sheeting configurations in steel-concrete composite beams

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Abstract

For obtaining shear resistance of a welded headed stud in profiled steel sheeting, EN 1994-1-1:2004 defines reduction factors that should be multiplied with the resistance of a headed stud in a solid concrete slab. Two reduction factors are prescribed, for sheeting ribs that are parallel and transverse to the supporting beam. However, the design code does not recognise cases when the angle between ribs and the beam is in the range between 0° and 90°. This research is focused on the specific case in the steel-concrete composite beam design when the angle between profiled sheeting ribs and the beam is 45°. The experimental investigation has been conducted through push-out tests, comparing the response of the connection with a rib-to-beam angle of 45° and the connection with ribs transverse to the supporting beam. In addition, numerical models based on finite element analysis have been made and validated against experimental data. According to the obtained results, similar failure mechanisms manifested through concrete pull-out failure and separation of the concrete cone are observed in shear connections with rib-to-beam angles of 45° and 90°. An increase in the connection resistance is noticed with the decrease of a rib-to-beam angle.

Keywords

headed stud, profiled steel sheeting, steel-concrete composite beam, rib-to-beam angle, push-out test

1 Introduction

Steel-concrete composite floor structures have gained popularity in construction due to the efficient material usage that they provide. Composite steel-concrete beams with welded headed stud shear connectors are commonly applied due to their increased resistance compared with steel beams. Implementation of composite steel-concrete slabs cast in profiled steel sheeting provides a safe working platform during construction, savings in concrete consumption and reduction of the total floor weight.

Design codes prescribe procedures for calculating the shear resistance of headed studs in solid concrete slabs as well as in composite slabs with profiled steel sheeting. According to EN 1994-1-1:2004 [1], the design shear resistance of welded headed studs in profile steel sheeting is obtained by multiplying the shear resistance of welded headed studs in solid concrete slabs with the reduction factor.

The design code recognises two reduction factors: k_t and k_l, when sheeting ribs are transverse and parallel to the supporting beam, respectively. Reduction factors are obtained by relations depending on the depth and width of the profiled sheeting rib, headed stud height and number of headed studs per rib. The maximum value of the reduction factor k_t is limited to 0.6–1.0, depending on the number of studs per rib, profiled sheeting thickness and installation technique (0.7–1.0 for through deck welding, 0.6–0.75 for profiled sheeting with holes). It is not uncommon that these upper limits of the reduction factor are decisive in the determination of headed stud shear resistance.

Besides current design standards, several different models for obtaining shear resistance of welded headed studs in profiled steel sheeting were proposed in the past decades, mostly focusing on the case when profiled sheeting ribs are transverse to the supporting beam [2–6]. While design procedures on the calculation of headed stud resistance in profiled sheeting prescribed in EN 1994-1-1:2004 are based on statistical evaluation of experimental results and their correlation to the resistance of studs in solid slabs, alternative design models are mostly based on the exact failure mechanisms present for studs cast in composite steel-concrete slabs. Some of the novel design procedures were developed with the intention to provide more precise predictions and safe-sided results, as experimental studies had proved that EN 1994-1-1:2004 overestimates headed stud shear resistance in the case of narrow sheeting ribs [6–8].

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However, the design code and the proposed models do not consider cases when the angle between profiled sheeting ribs and the beam is in the range between 0° and 90°. By searching the relevant literature in this field, the authors noticed the lack of available experimental results that cover the behaviour of welded headed studs in profiled sheeting ribs with the angle between ribs and the beam other than 0° (ribs are parallel to the beam) or 90° (ribs are transverse to the beam). On the other side, such configurations are not uncommon in building design and construction, especially when a floor layout is of an irregular shape.

In this paper, experimental and numerical investigations of the shear behaviour of headed studs in profiled steel sheeting with the angle between ribs and the beam of 45° are presented. The research was conducted through standardised push-out tests according to EN 1994-1-1:2004, Annex B [1]. The response of the specimen with the angle between ribs and the beam of 45° was compared with the response of the control specimen with ribs transverse to the beam. According to the results of experimental research, finite element numerical models were developed and used for further investigations of the shear connection behaviour.

2 Experimental investigations

2.1 Materials and Methods

In order to assess the shear performance of headed studs in profiled steel sheeting, experimental investigations were conducted through push-out tests according to EN 1994-1-1:2004, Annex B [1]. The layout of developed specimens marked with S45 and S, with rib-to-beam angles of 45° and 90°, respectively, are presented in Figure 1. Both types of specimens are made of two steel-concrete composite slabs and steel profile HEB 260. An open trough profiled steel sheeting Cofraplus 60 (ArcelorMittal, Luxembourg) is implemented, with pre-punched holes for headed studs. Mesh reinforcement Ø8 mm is placed in the upper zone of the slab. Each specimen contains two headed studs per sheeting rib, i.e. eight headed studs in total. The diameter of a headed stud is 16 mm, while the height is 100 mm. The transverse distance between headed studs is 100 mm.

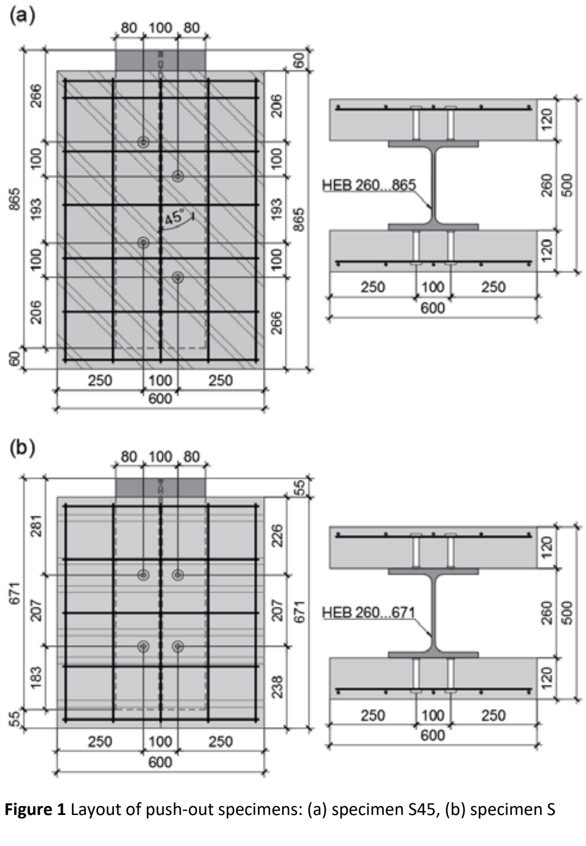

Figure 1 Layout of push-out specimens: (a) specimen S45, (b) specimen S

According to investigations [6,8], the recess in the concrete slab base which is marked as optional according to EN 1994-1-1:2004 [1] does not affect experimental results. Therefore, it is not provided in specimens. The width of a concrete slab of 600 mm includes the potential development of the concrete cone according to recommendations proposed for slabs with profiled steel sheeting transverse to the supporting beam [7], considering the selected headed stud height and transverse distance between connectors. Slab depth is set to 120 mm, and detailing requests regarding the minimum slab depth and minimum connector height above the headed stud are satisfied [1]. Slab lengths for specimens S and S45 are 671 mm and 865 mm, respectively. A longer length of the slab S45 is selected with the intention to include sufficient parts of concrete ribs and involve possible failure zones throughout the concrete slab.

The test set-up is shown in Figure 2. Vertical load is applied on the top of the steel profile. Application of transverse loading in push-out tests with concrete slabs with profiled steel sheeting was performed by several researchers [9], whereas recommendations proposed in [7] advise the application of transverse load only when the ratio between the stud height and rib height is smaller than 1.56. As this study covers cases when the ratio between the stud height and rib height is greater than 1.56, transverse loading is not applied. A layer of fresh gypsum is put on beneath concrete slabs to enable good contact with the supporting plate.

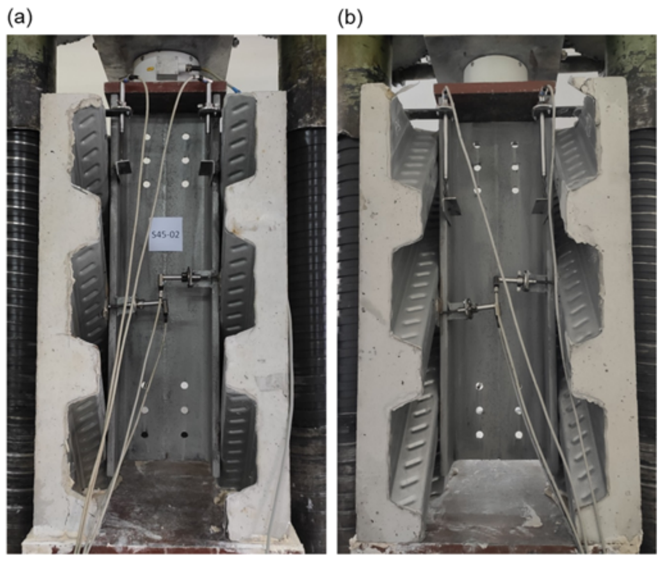

Figure 2 Push-out test set-up: (a) front side, (b) back side

Four displacement transducers on the top of the specimen were used for measuring vertical slip between the concrete slab and steel profile. Additional four displacement transducers were installed close to headed studs for measuring the horizontal separation between the concrete slab and steel profile. A load cell installed on the top of the specimen was used for measuring the applied load.

Loading was applied according to EN 1994-1-1:2004, Annex B [1], including 25 loading cycles in the range from 5% to 40% of the expected failure load, and final loading involving the specimen failure. Load and displacements were measured until the load dropped to 80% of the maximum measured load.

In addition to conducted push-out tests, steel and concrete components of push-out specimens were tested through standardised procedures [10,11] to obtain their material properties, valuable for interpretation of results and further numerical analysis. Material properties of steel parts and concrete are summarised in Table 1.

Table 1 Material properties

Part	Mechanical properties (mean values)
concrete (specimen S)	$f_{c,cube}$ = 43.7 MPa
concrete (specimen S45)	$f_{c,cube}$ = 45.3 MPa
headed stud	f_y = 421.0 MPa, f_u = 509.0 MPa
steel profile	f_y = 297.3 MPa, f_u = 418.6 MPa
profiled steel sheeting	f_y = 347.7 MPa, f_u = 408.2 MPa

2.2 Results and Discussion

According to the measured data, load-slip curves for specimens S and S45 are obtained and plotted in Figure 3. Two curves match in the initial part, up to the load of approximately 170 kN. Afterwards, a drop of stiffness is present for specimen S with the angle between sheeting ribs and the beam of 90°. Specimen S45 reaches the maximum load of 331.6 kN, while specimen S has the ultimate load of 274.0 kN. It is observed that the connection with the angle between profiled sheeting ribs and the beam of 45° has approximately 20% higher ultimate load than the connection with ribs transverse to the beam. Moreover, a certain difference between the two analysed connections is present in the terms of slip capacity. A slip at 0.9 of the ultimate load at the descending branch of the load-slip curve is 4.82 mm for specimen S45, and 4.09 mm for specimen S.

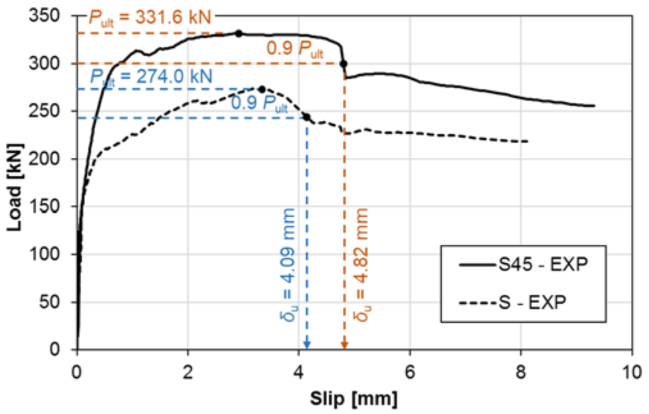

Figure 3 Experimental load-slip curves

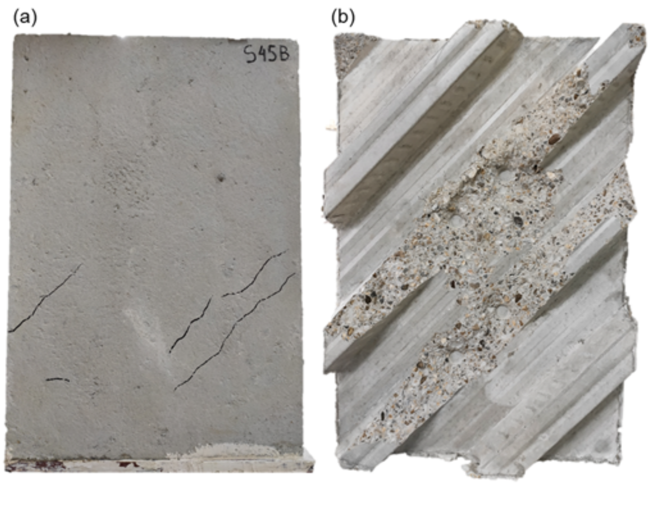

Figure 4 Specimen S45: (a) cracks on the concrete slab surface, (b) concrete cone failure

During the testing, crack patterns were noticed on the surface of concrete slabs of both specimens. Those cracks followed the direction of concrete ribs, as shown in Figure 4a in the example of specimen S45, but did not affect specimen failure. Failure forms of specimens were observed after the testing when specimens were demounted. Both connections featured concrete pull-out failure, present through the separation of the concrete cone with headed studs from the rest of the concrete slab. The concrete cone followed the direction of concrete ribs, as illustrated in Figure 4b for the specimen with the angle between sheeting ribs and the beam of 45°. After concrete surrounding headed studs was removed, the condition of headed studs was observed. Stud connectors deformed in the direction of the applied shear force but did not rupture.

Experimentally obtained shear resistances of headed studs in profiled steel sheeting are compared with corresponding design predictions according to EN 1994-1-1:2004 [1] for ribs that are transverse and parallel to the supporting beam. Design predicted values calculated without partial safety factors, with mean and characteristic values of material properties are presented in Figure 5. The experimentally obtained resistance of headed studs in specimen S is below the design prediction for headed studs in ribs transverse to the beam calculated with mean values of material properties. This result agrees with findings that EN 1994-1-1:2004 overestimates the resistance of headed studs in narrow sheeting ribs as Cofraplus 60 [6–8]. Nevertheless, shear resistance obtained with characteristic values of material properties is close to the experimental push-out test results. The experimental resistance of headed studs in specimen S45 is between characteristic predictions for ribs transverse and parallel to the beam, but closer to the second one. According to the presented results, the increase of the resistance of headed studs in profiled sheeting with a rib-to-beam angle of 45° compared with headed studs in ribs transverse to the beam is not negligible.

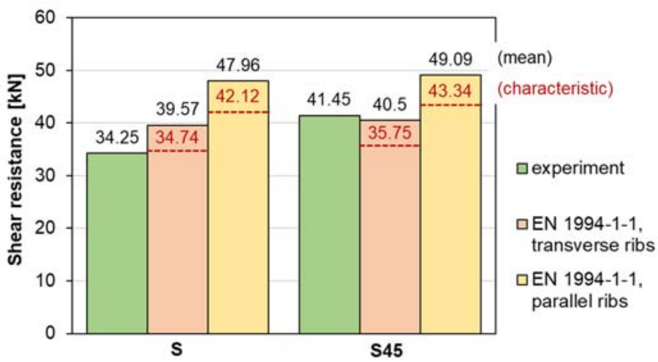

Figure 5 Comparison between experimental shear resistance and shear resistance of a headed stud according to EN 1994-1-1:2004

3 Numerical analysis

3.1 Finite element models

In order to investigate in detail the load-slip performance of connections with different profiled sheeting configurations, finite element models were developed in the software package Abaqus, using Dynamic Explicit solver.

Models of push-out tests presented in Figure 6 follow the geometry of experimentally tested specimens. Model S45 is made setting the single symmetry condition, while the double symmetry condition is applied to model S, all with the intention to minimise computation time. All other parameters listed in the following are adopted as the same for both connections, S45 and S. Concrete slab, headed studs and steel profile are modelled as solid parts, profiled sheeting is modelled as shell part, whereas reinforcement bars are modelled as trusses. The displacement is applied at the top surface of the steel profile through the smooth step amplitude function. The base surface of the stiff supporting plate to which concrete slabs are laid is fixed. The time increment for the mass scaling method is set to 0.003 s. Contacts between different parts of the model are assigned through the general contact: "hard" contact in the normal direction and penalty contact in the tangential direction, applying the appropriate friction coefficients. For modelling the contact between reinforcement bars and concrete, embedded constrain is applied. Finite elements C3D8R are used for meshing solid parts, elements S4R are used for shells, and elements T3D2 are applied to trusses. Mesh size is varied throughout the model, with the smallest finite elements of 2 mm at the region of expected failure zones around headed studs and surrounding concrete, and the largest elements of 10 mm at the periphery regions of the model.

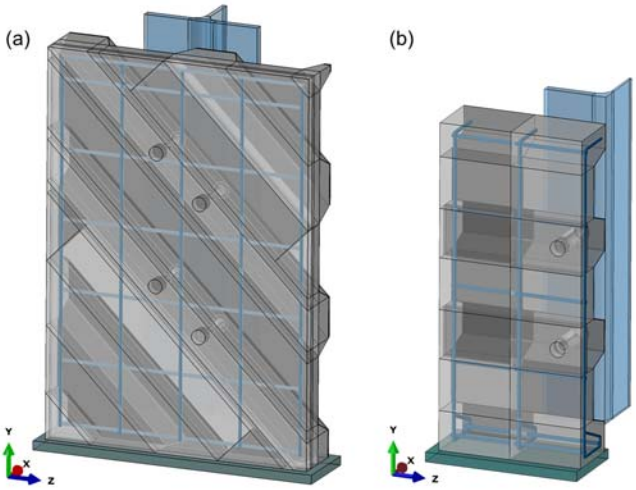

Figure 6 Finite element models: (a) model S45, (b) model S

Material behaviour is modelled according to measured material properties listed in Table 1. To describe the behaviour of steel parts, such as headed studs, steel profile, profiled steel sheeting, and reinforcement, simplified linear models including elastic and plastic material responses are used. As the failure of the connection is related to the failure of concrete, special attention is put on choosing the adequate model to describe concrete behaviour. Best results are obtained using the concrete damage plasticity model, following the stress-strain relations and definition of damage variables according to Pavlović [12]. The concrete compressive stress-strain curve for strains ε_{cu1} < 3.5‰ is defined according to EN 1992-1-1 [10], whereas for strains ε_{cu1} > 3.5‰, a stress-strain curve proposed by Pavlović [12] is applied with the input parameters: $\alpha = 8$, $\alpha_{tD} = 0.5$, $\alpha_{tE} = 0.6$, $\varepsilon_{cuE} = 0.05$, $\varepsilon_{cuF} = 0.20$. The tensile stress-strain curve is applied as linear before reaching the tensile strength f_{ctm}, and sinusoidal after f_{ctm} is reached [12]. The dilation angle is set to 38°, whereas other concrete damage plasticity parameters are applied as recommended in the software user manual [13].

3.2 Results and Discussion

Load-slip curves obtained by experimental testing and numerical simulations are compared in Figure 7. A satisfying match between experimental and numerical curves is accomplished for both models, S45 and S. Comparison between ultimate loads obtained through experimental and numerical analyses are compared in Table 2. Differences between maximum loads are 4% for both specimens, S45 and S. According to presented results, it may be concluded that developed finite element models provide accurate predictions of the connection behaviour.

Table 2 Comparison of experimental and numerical ultimate loads

Model	Ultimate load, EXP $P_{ult,exp}$ [kN]	Ultimate load, FEA $P_{ult,fea}$ [kN]	Ratio $P_{ult,fea}$ / $P_{ult,exp}$
S45	331.6	319.8	0.96
S	274.0	262.5	0.96

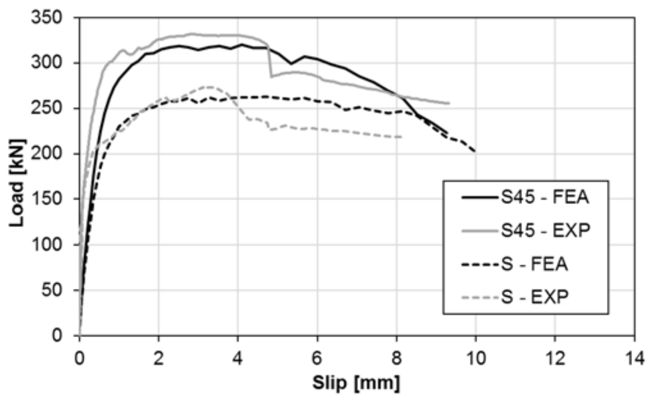

Figure 7 Comparison of experimental and numerical load-slip curves

Numerical models provide further information on the behaviour of shear connections that could not have been assessed during the experimental testing. Stress distribution in headed studs at the connection slip of 6 mm is presented in Figure 8. For both connections with angles between sheeting ribs of 45° and 90°, a concentration of stresses is noticed at the bottom of the stud shank near the weld collar. However, stresses are lower in model S45 than in model S. Values of stresses corresponding to the material yield strength indicate the development of a plastic hinge. Another concentration of stresses is observed in the upper part of the headed stud shank, although a hinge is not completely formed. The deformed shape of headed studs is characterised by single curvature.

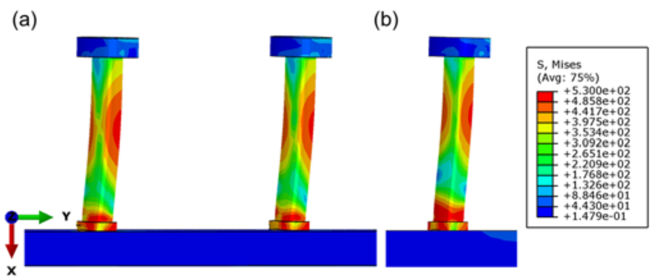

Figure 8 Stresses in headed studs at the slip of 6 mm: (a) model S45, (b) model S

The crack pattern and failure of concrete are presented in Figure 9. Finite elements with a high per cent of concrete compression damage are noticed behind headed studs in both models, S45 and S, according to Figure 9a, referring to the concrete rib punching. However, compression damage is more widespread in model S than in model S45. Cracks caused due to exceeding the concrete tensile strength induce the development of concrete cones, as shown in Figure 9b. The connection failure is followed by the separation of concrete cones from the rest of the concrete slabs. Concrete cones are formed around headed studs and follow the direction of sheeting ribs for both analysed rib-to-beam angles of 45° and 90°, which agrees with the experimental findings.

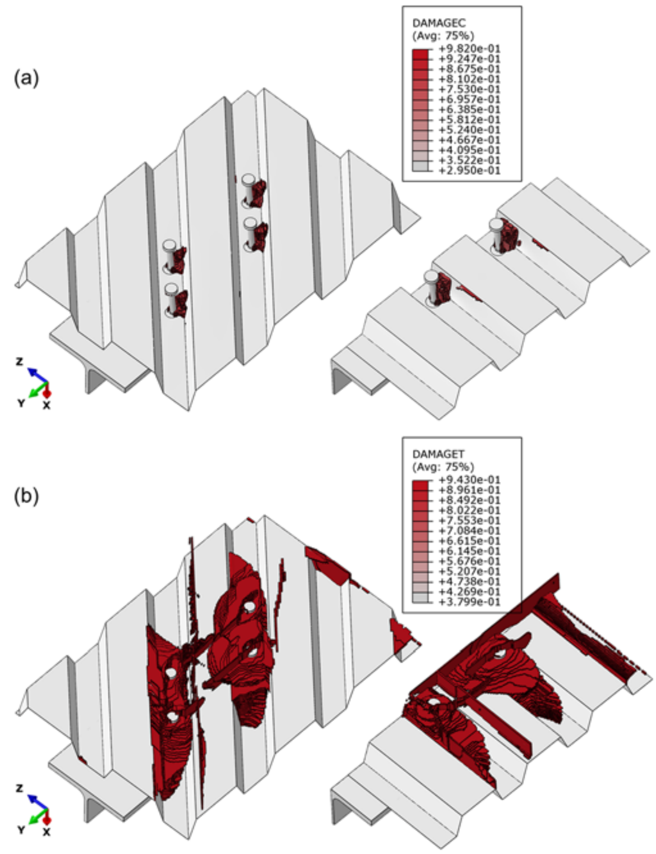

Figure 9 Concrete damage: (a) compression damage, (b) tension damage

4 Conclusions

Experimental and numerical investigations conducted to analyse the headed stud response to shear load for two different profiled sheeting configurations are presented in this paper. The behaviour of the connection with headed studs installed in profiled steel sheeting with a rib-to-beam angle of 45° is compared to the behaviour of stud connectors in profiled sheeting ribs transverse to the beam.

Results indicate that the connection with the angle between profiled sheeting ribs and the beam of 45° has approximately 20% higher ultimate load than the connection with a rib-to-beam angle of 90°. In addition, the connection with the smaller rib-to-beam angle features a slightly larger slip. Both connections failed due to concrete pull-out failure. Concrete cones were developed around headed studs in the direction of sheeting ribs. Deformation of headed studs and distribution of stresses in connectors were similar in both connections.

Presented results are the base for future investigations of the influence of different profiled sheeting configurations on the connection resistance and ductility. Developed numerical models could be used for further parametric studies, varying the rib-to-beam angle and headed stud and profiled sheeting geometry, to establish appropriate relations between the connection resistance and the angle between profiled sheeting ribs and the beam.

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