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# MOŽDANICI SA GLAVOM U PROFILISANOM LIMU: PREGLED I KOMENTARI

***Rezime:***

Moždanici sa glavom su najčešće primenjivana mehanička spojna sredstava u spregnutim gredama od čelika i betona. Ponašanje moždanika razlikuje se u zavisnosti od toga da li se primenjuju u punim betonskim pločama ili u spregnutim pločama na profilisanom limu. Iako su proračunski modeli za nosivost moždanika u profilisanom limu dati u standardima za projektovanje, važećim proračunskim procedurama datim u EN 1994-1-1 pripisuju se izvesni nedostaci. Iz tog razloga nekoliko istraživača je predložilo alternativne proračunske modele. U radu su prikazani predloženi modeli proračuna i data je uporedna analiza nosivosti moždanika sa glavom u različitim tipovima profilisanog lima.

*Ključne reči: spregnuta greda od čelika i betona, elastični moždanik, profilisani lim, nosivost na smicanje*

# HEADED STUDS IN PROFILED STEEL SHEETING: OVERVIEW AND COMMENTS

***Summary:***

Headed studs are the most commonly used mechanical shear connectors in composite steel-concrete beams. The behaviour of headed studs differs whether they are applied in solid concrete slabs or composite steel-concrete slabs with profiled steel sheeting. Although design codes provide calculation models for shear resistance of headed studs in profiled steel sheeting, certain weaknesses are attributed to design procedures given in EN 1994-1-1. Alternative design models have been proposed by several researchers. In this paper, novel models are presented and compared through the example of headed studs in different types of profiled steel sheeting.

*Key words: steel-concrete composite beam, headed stud, profiled steel sheeting, shear resistance*

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## 1. INTRODUCTION

For developing shear action between the concrete slab and steel profile in steel-concrete composite beams, headed studs are commonly used as shear connectors. They feature good mechanical performance, sufficient slip capacity and adequate shear resistance.

The behaviour of headed studs differs whether they are applied in solid concrete slabs or composite steel-concrete slabs with profiled steel sheeting. When applied in solid concrete slabs, the resistance of headed studs is mainly dependent on their geometry, material properties of the stud material and the concrete. However, in the case of the application in profiled steel sheeting, several additional factors may affect the shear resistance of headed studs, such as profiled sheeting geometry, the number of connectors and their position within the concrete rib, installation technique – whether studs are installed in pre-punched holes or they are welded through profiled sheeting. For this reason, analytical interpretation of the shear resistance of headed studs in profiled sheeting is more complex than in solid concrete slabs.

Design codes such as EN 1994-1-1 [1] and ANSI/AISC 360-16 [2] provide calculation models for shear resistance of headed studs both in solid slabs and composite slabs on profiled steel sheeting. The design procedure for studs in solid slabs given in EN 1994-1-1 is based on two possible failure modes: stud shear failure and concrete failure, which are analytically interpreted. However, the expressions for shear resistance of headed studs in profiled sheeting are not based on the possible failure modes – instead, they are statistically developed according to the experimental results, and defined through reduction factors that establish the relation between the shear resistance of studs in solid slabs and composite steel-concrete slabs. This statistically-based approach and the application of reduction factors have been criticised by some researchers [3], which pointed out the fact that failure modes significantly differ in the case of solid and composite slabs, and therefore making the correlation between resistances in those two cases is found inadequate. However, the main shortcoming of the current design rules given in EN 1994-1-1 is attributed to the overestimation of the stud shear resistance for some types of profiled steel sheeting which are present in the European construction market, in the case when ribs are transverse to the supporting beam. This is not surprising knowing that the geometry of profiled sheeting used a few decades ago in the time when the expressions for resistance of headed studs were developed, differs from the profiled sheeting used nowadays. A significant overestimation of the resistance has been observed for profiled sheeting with narrow ribs, such as Cofraplus 60 (ArcelorMittal). In addition, the fact that EN 1994-1-1 does not cover cases for alternative positions of headed studs within the rib, except the central position, is found another weakness of the current codified rules.

In order to improve the existing expressions for stud shear resistance and solve the weaknesses of the current design procedures for headed studs in profiled steel sheeting with ribs transverse to the beam, several design models have been proposed recently. Suggested models with their scope of application are listed in Table 1, together with EN 1994-1-1 model and its limits. Models with the widest range of applications are those proposed by Konrad [4] and Nellinger [3], covering both re-entrant and open trough profiled sheeting, and considering different stud positions inside the rib. The model suggested by Nellinger was later on simplified by Odenbreit and Nellinger [5] into a model more convenient for engineering practice. This model was the base for the design procedure suggested by the working group CEN/

TC250/SC4.PT3 [6], made in particular for open through profiled sheeting with small anchorage depths ($h_{sc} - h_p \leq 2.7d$) or a short distance between the headed stud and the rib wall ($e \leq 60$ mm).

*Table 1 – Design models for the resistance of headed studs in profiled sheeting with ribs transverse to the beam*

| Model | Applicable for open trough profiled sheeting | Applicable for re-entrant trough profiled sheeting | Max. number of studs per rib | Considers stud position inside the rib | Max. profiled sheeting depth [mm] | Other limits |
|---|---|---|---|---|---|---|
| EN 1994-1-1 [1] | yes | yes | 2 | no | 85 | $d \leq 22$ mm<br>$b_0 \geq \max\{h_p, 50 \text{ mm}\}$<br>$h_{sc} - h_p \geq 2d$<br>$h - h_p \geq 50$ mm<br>$h \geq 90$ mm |
| Lungershausen [7] | yes | yes | 3 | no | 140 | $h_{sc}/d \geq 4$<br>$h_{sc} - h_p \geq 2d$ |
| Johnson and Yuan [8] | yes | no | 2 | yes | not specified | 16 mm $\leq d \leq$ 20 mm<br>$0.8 \leq b_0/h_p \leq 3.2$<br>$h_{sc} - h_p \geq 35$ mm |
| Rambo-Roddenberry [9] | yes | no | 2 | yes | 76 | $h_p = \{25; 38; 51; 76\}$ mm |
| Ernst [10] | yes | no | 2 | no | not specified | not specified |
| Konrad [4] | yes | yes | 2 | yes | not specified | 16 mm $\leq d \leq$ 22 mm<br>$h_{sc}/d \geq 4$<br>$h_{sc}/h_p \geq 1.56$ |
| Nellinger [3] | yes | yes | 3 | yes | 155 | 16 mm $\leq d \leq$ 22 mm<br>$h_{sc} - h_p \geq d$ |
| Vigneri [11] | yes | yes | 2 | no | 136 | 19 mm $\leq d \leq$ 22 mm<br>$h_{sc} - h_p \geq 2d$ |

*Notation*: $d$ – diameter of the headed stud; $b_0$ – mean width of the profiled steel sheeting rib; $h_p$ - overall depth of the profiled steel sheeting; $h_{sc}$ – overall height of the headed stud; $h$ – overall depth of a concrete slab.

In this paper, two models proposed by Konrad [4] and Odenbreit and Nellinger [5] are presented. Design predictions given by EN 1994-1-1 and two newly proposed models are compared through the example of headed studs in different types of profiled steel sheeting. Differences in the obtained resistances of headed studs are analysed and discussed, giving a useful overview of the applicability of the codified and proposed design procedures to the engineering audience.

## 2. DESIGN PROCEDURES FOR HEADED STUD SHEAR RESISTANCE

### 2.1. MODEL PROPOSED BY KONRAD

The model proposed by Konrad [4] for ribs transverse to the supporting beam, suggests the calculation of headed stud resistance through a similar algorithm as prescribed in EN 1994-1-1, i.e. the headed stud resistance in solid slabs should be multiplied by a specific reduction factor, $k_{\perp}$. Konrad also defined new expressions for the headed stud resistance inside a solid slab, intending to improve the current EN 1994-1-1 predictions. New expressions include parameters of headed stud diameter and material properties of concrete slab and headed stud, which are also included by EN 1994-1-1. However, unlike the current design procedures, Konrad incorporated the effective area of the weld collar, $A_{\mathrm{Wulst,eff}}$, into the proposed expressions for design resistance.

The design resistance of a headed stud in a solid concrete slab is obtained as the minimum between Eqs. (1) and (2), where Eq. (1) refers to the stud shear failure and Eq. (2) refers to the failure of concrete:

$$P_{\mathrm{Rd,s}} = \left[313\, A_{\mathrm{Wulst,eff}} \left(\frac{f_{\mathrm{ck}}}{30}\right)^{2/3} + 240\, d^2 \left(\frac{f_{\mathrm{u}}}{500}\right)\right] \frac{1}{\gamma_{\mathrm{V}}} \qquad \text{[N]} \tag{1}$$

$$P_{\mathrm{Rd,c}} = \left[326\, A_{\mathrm{Wulst,eff}} \left(\frac{f_{\mathrm{ck}}}{30}\right)^{2/3} + 220\, d^2 \left(\frac{f_{\mathrm{ck}}}{30}\right)^{1/3} \left(\frac{f_{\mathrm{u}}}{500}\right)^{1/2}\right] \frac{1}{\gamma_{\mathrm{V}}} \qquad \text{[N]} \tag{2}$$

where:

$A_{\mathrm{Wulst,eff}}$ is the effective area of the weld collar of a headed stud, $A_{\mathrm{Wulst,eff}} = 0.5\, h_{\mathrm{Wulst}}\, d_{\mathrm{Wulst}}$ [mm$^2$];

$d$ is the headed stud shank diameter in mm;

$h_{\mathrm{Wulst}}$ is the height of the weld collar in mm;

$d_{\mathrm{Wulst}}$ is the diameter of the weld collar in mm;

$f_{\mathrm{u}}$ is the characteristic stud tensile strength in MPa, $f_{\mathrm{u}} \leq 740$ MPa;

$f_{\mathrm{ck}}$ is the characteristic cylinder compressive strength of the concrete in MPa, 20 MPa $\leq f_{\mathrm{ck}} \leq$ 100 MPa;

$\gamma_{\mathrm{v}}$ is the partial safety factor, 1.25.

The scope of application of Eqs. (1) and (2) is limited to headed studs of diameter 16 mm $\leq d \leq$ 25 mm. Unlike EN 1994-1-1 which prescribes the reduction factor $\alpha$ when the ratio between headed stud height and diameter is in the range $3 \geq h_{\mathrm{sc}}/d \geq 4$, the model proposed by Konrad explicitly requires that $h_{\mathrm{sc}}/d \geq 4$.

Although expressions for resistance of headed studs in solid slabs might seem as statistically obtained, they were developed assuming certain failure mechanisms. Three load components are considered: pressure on the weld collar, bending of the stud shank and the horizontal component of the tensile force in the stud.

According to Konrad, the design resistance of a headed stud in profiled steel sheeting with ribs transverse to the beam should be obtained as:

$$P_{\mathrm{Rd}} = k_{\perp}\, P_{\mathrm{Rd,c}} \leq P_{\mathrm{Rd,s}} \tag{3}$$

The reduction factor $k_\perp$ is defined as:
- for pre-holed steel sheeting:

$$k_\perp = k_\mathrm{n} \left[ k_\mathrm{e}\, 0.038\, \frac{b_\mathrm{m}}{h_\mathrm{p}} + 0.597 \right] \leq 1 \tag{4}$$

- for welded-through headed studs, with sheeting thickness $t \geq 0.75$ mm:

$$k_\perp = k_\mathrm{n}\, k_\mathrm{Tr} \left[ k_\mathrm{e}\, 0.042\, \frac{b_\mathrm{m}}{h_\mathrm{p}} + 0.663 \right] \leq 1 \tag{5}$$

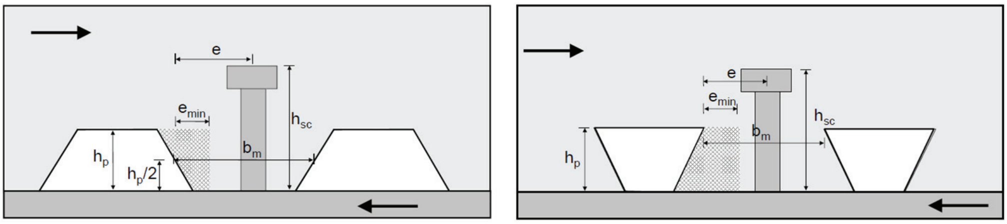
where:

$$k_\mathrm{n} = \begin{cases} 1.0, & n_\mathrm{r} = 1 \\ 0.8, & n_\mathrm{r} = 2 \end{cases}$$

$$k_\mathrm{e} = \begin{cases} 1.0, & 55 \text{ mm} \leq e \leq 100 \text{ mm} \\ 2.0, & e > 100 \text{ mm} \end{cases}$$

$$k_\mathrm{Tr} = \begin{cases} 1.25, & \text{re-entrant trough profile} \\ 1.00, & \text{open trough profile} \end{cases}$$

$n_\mathrm{r}$ is the number of headed studs in the rib;
$b_\mathrm{m}$, $h_\mathrm{p}$ and $e$ are defined in Figure 1.



open trough profile re-entrant trough profile

*Figure 1 – Geometric parameters according to Konrad* [4]

As well as the current design standard EN 1994-1-1, Konrad's model is limited to the maximum of two headed studs per rib and connectors with a diameter between 16 mm and 20 mm for through deck welding, i.e. from 16 mm to 22 mm in the case of the pre-holed steel sheeting. The minimum anchorage depth of connectors is required to comply with the following condition $h_\mathrm{sc}/h_\mathrm{p} > 1.56$.

However, Eq. (3) is not applicable when the distance $e$ is smaller than 55 mm, which is labelled as the unfavourable position of headed studs. Even though Konrad proposed another equation for connections with $e < 55$ mm, he suggested avoiding such stud placing as the high coefficient of variation had been observed between design predictions and experimental results. However, for some commonly applied profiled steel sheeting, for example, Cofraplus 60 or Cofraplus 77 (Figure 3), the criteria $e > 55$ mm cannot be matched even when a headed stud is placed centrally inside the rib. For that reason, further experimental testing was conducted through the DISCCO project funded by Research Fund for Coal and Steel [12] and analysed by Eggert [13], who tested the following equation given by Konrad:

$$k_\perp = k_\mathrm{n} \left[ 0.317\, \frac{b_\mathrm{m}}{h_\mathrm{p}} + 0.06 \right] \leq 0.8 \tag{6}$$

Eggert reported that Eq. (6) provides mostly safe-sided predictions when compared with experimental push-out test results for two types of profiled steel sheeting: Cofraplus 60 and Cofrastra 56 (ArcelorMittal).

It could be concluded that expressions for the reduction factor $k_{\perp}$ are more complex in comparison to the reduction factor $k_t$, which is defined in EN 1994-1-1, including different parameters such as the number of headed studs, the distance between the stud and the rib wall, profiled sheeting type (re-entrant or open trough), rib width and depth. The reduction factor $k_t$ defined in EN 1994-1-1 is limited to values in the range of 0.60–1.0, which are commonly decisive in the determination of this factor. On the contrary, the reduction factor $k_{\perp}$ does not have limits smaller than 1.0, except in the special case when $e < 55$ mm, when the upper limit is 0.8.

## 2.2. MODEL PROPOSED BY ODENBREIT AND NELLINGER

Unlike the model suggested by Konrad, the model proposed by Odenbreit and Nellinger [5] provides directly two equations for obtaining the shear resistance of headed studs in profiled steel sheeting without the requirement for obtaining the reduction factor and shear resistance of a headed stud in a solid concrete slab previously. Proposed expressions are based on the load-bearing components observed in headed studs in profiled steel sheeting: failure of concrete in tension during concrete cone failure, stud resistance to bending and shear failure of a stud. Load-bearing components are described through simplified static schemes, assuming the possible development of one or two plastic hinges along the headed stud height due to stud bending. Except for the material properties, expressions for headed stud resistance include parameters such as the section modulus of the concrete cone surface, number of studs per rib and profiled sheeting depth, as well as the number of plastic hinges, the position of the upper plastic hinge, headed stud bending resistance and stud diameter. Expressions got their final form by applying adequate calibration factors $C_1$ and $C_2$ in order to match the experimental push-out test results.

The resistance of a headed stud applied in a steel-concrete slab with profiled sheeting ribs transverse to the beam is defined as the minimum between Eqs. (7) and (8), where Eq. (7) incorporates possible failure of concrete, and Eq. (8) considers the failure of a headed stud:

$$P_{\mathrm{Rd},1} = C_2 \left[ \frac{\alpha_{\mathrm{ct}} f_{\mathrm{ctm}} W}{h_{\mathrm{p}}\, n_{\mathrm{r}}} + \frac{n_{\mathrm{y}}\, M_{\mathrm{pl}}}{h_{\mathrm{s}} - d/2} \right] \frac{1}{\gamma_{\mathrm{V}}} \tag{7}$$

$$P_{\mathrm{Rd},2} = C_1 f_{\mathrm{u}} \pi \frac{d^2}{4} \frac{1}{\gamma_{\mathrm{V}}} \tag{8}$$

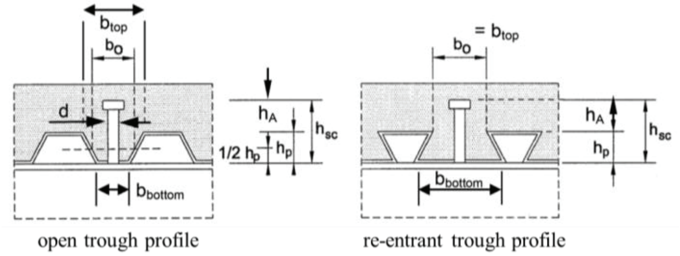
where:
$C_1$ is the calibration factor, suggested value is 0.6;
$C_2$ is the calibration factor, suggested value is 0.9;
$\alpha_{\mathrm{ct}}$ is the factor that accounts for the relaxation of concrete strength, proposed as $\alpha_{\mathrm{ct}} = 0.85$;
$f_{\mathrm{ctm}}$ is the concrete tensile strength, $f_{\mathrm{ctm}} \geq 20$ MPa;
$W$ is the section modulus of the concrete cone surface, $W = 0.4\, h_{\mathrm{sc}}\, b_{\mathrm{max}}^{\;3} / b_{\mathrm{top}}$;
$h_{\mathrm{sc}}$ is the overall shear connector height;
$b_{\mathrm{max}}$ is the maximum width of the rib;
$b_{\mathrm{top}}$, $h_{\mathrm{p}}$ and $h_{\mathrm{A}}$ are defined in Figure 2;
$n_{\mathrm{r}}$ is the number of headed studs in the rib;
$n_{\mathrm{y}}$ is the number of plastic hinges,

$$n_y = \begin{cases} 1, & h_A \leq 2d\sqrt{n_r} \\ 2, & h_A > 2d\sqrt{n_r} \end{cases}$$

$M_{pl}$ is the bending resistance of a stud, $M_{pl} = f_u d^3 / 6$;
$f_u$ is the characteristic stud tensile strength, $f_u \geq 400$ MPa;
$d$ is the stud shank diameter;
$h_s$ is the position of the upper plastic hinge, $h_s = \beta\, h_{sc} \leq h_p$;

$$\beta = \begin{cases} 0.41, & \text{re-entrant trough profile} \\ 0.45, & \text{open trough profile} \end{cases}$$

$\gamma_v$ is the partial safety factor, 1.25.



open trough profile re-entrant trough profile

*Figure 2 – Geometric parameters according to Nellinger* [3]

It is noted that unlike the original model suggested by Nellinger [3], the simplified model proposed by Odenbreit and Nellinger [5] does not incorporate the influence of different stud positions inside the rib.

## 3. COMPARATIVE ANALYSIS

A comparison between design rules given in EN 1994-1-1 [1] and presented models proposed by Konrad [4] and Odenbreit and Nellinger [5] is shown in the example of several different types of commercially available profiled steel sheeting. Six different open trough profiled steel sheeting and three re-entrant profiled steel sheeting are analysed, all presented in Figure 3. In each case, one headed stud of a diameter of 19 mm is assumed to be centrally placed inside the rib, which is the common solution applied in steel-concrete composite building design. Headed stud height is varied in the range from 100 mm to 150 mm depending on the profiled sheeting depth (Table 2), making the detailing requirements given in EN 1994-1-1 satisfied. Characteristic stud tensile strength is adopted as 500 MPa, while the concrete class is C30/37. Profiled steel sheeting has pre-punched holes.

Shear resistance calculated according to EN 1994-1-1 [1], Konrad [4] and Odenbreit and Nellinger [5] is presented and compared in Table 2. The graphical presentation of the results is shown in Figure 4.

According to EN 1994-1-1, the design resistance of a headed stud with 19 mm in diameter is the same for almost all of the considered profiled steel sheeting types. In each case, the reduction factor $k_t$ is 0.75, which is the upper limit value. Therefore, it may be concluded that EN 1994-1-1 is not sensitive to the variations in profiled steel sheeting geometry. On the contrary, the other two models predict values in the wide range from 31.79 kN to 68.05 kN.

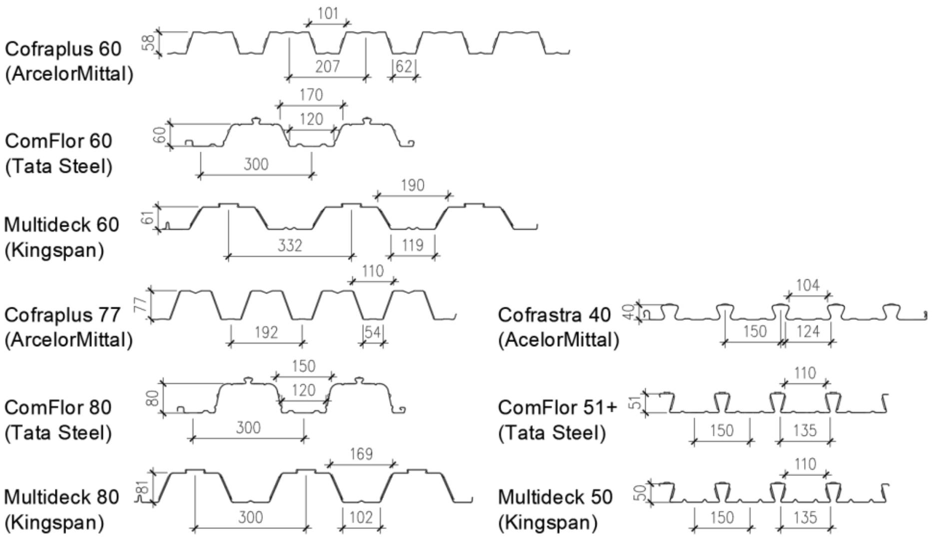


*Figure 3 – Geometry of considered profiled steel sheeting*

*Table 2 – Comparison between design resistance for headed studs in ribs transverse to the beam*

| Profiled steel sheeting | | Headed stud height | Design resistance | | | Ratio | | |
|---|---|---|---|---|---|---|---|---|
| | | | EN1994-1-1 | Konrad | Odenbreit, Nellinger | $P_{Rd,K}$ $/P_{Rd,EN}$ | $P_{Rd,O}$ $/P_{Rd,EN}$ | $P_{Rd,O}$ $/P_{Rd,K}$ |
| | | $h_{sc}$ [mm] | $P_{Rd,EN}$ [kN] | $P_{Rd,K}$ [kN] | $P_{Rd,O}$ [kN] | | | |
| Open trough | Cofraplus 60 | 125 | 62.34 | 40.42 | 33.19 | 0.65 | 0.53 | 0.82 |
| | ComFlor 60 | 125 | 62.34 | 55.08 | 60.30 | 0.88 | 0.97 | 1.09 |
| | Multideck 60 | 125 | 62.34 | 55.44 | 68.05 | 0.89 | 1.09 | 1.23 |
| | Cofraplus 77 | 150 | 58.75 | 31.79 | 30.90 | 0.54 | 0.53 | 0.97 |
| | ComFlor 80 | 150 | 62.34 | 52.87 | 44.10 | 0.85 | 0.71 | 0.83 |
| | Multideck 80 | 150 | 62.34 | 52.87 | 51.93 | 0.85 | 0.83 | 0.98 |
| Re-entrant | Cofrastra 40 | 100 | 62.34 | 63.97 | 59.64 | 1.03 | 0.96 | 0.93 |
| | ComFlor 51+ | 100 | 62.34 | 59.47 | 57.23 | 0.95 | 0.92 | 0.96 |
| | Multideck 50 | 100 | 62.34 | 60.57 | 57.85 | 0.97 | 0.93 | 0.96 |

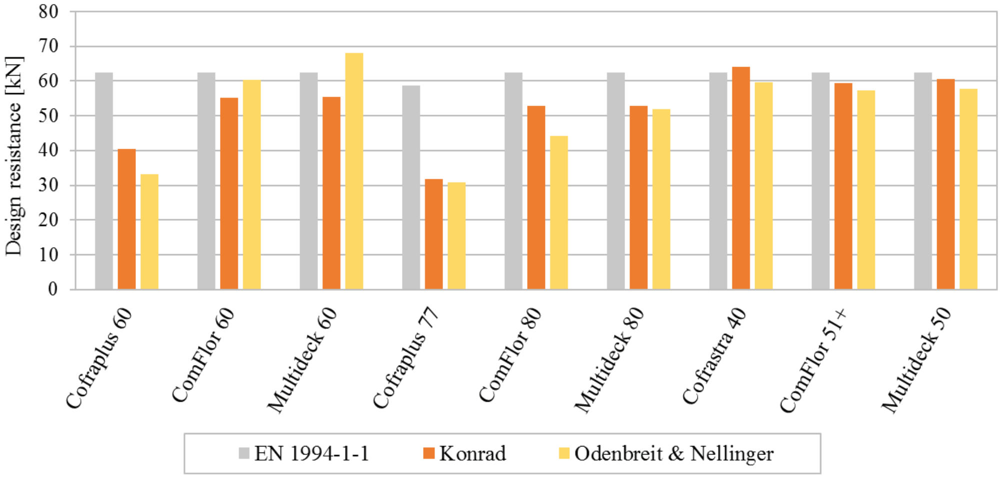


*Figure 4 – Design resistance of a headed stud connector (d = 19 mm)*

For re-entrant profiled sheeting Cofrastra 40, ComFlor 51+ and Multideck 50, design values according to all three analysed models do not considerably vary. However, differences in predictions obtained for open trough profiled steel sheeting are significant. The largest variations of up to 50% of the design resistance according to EN 1994-1-1 are present for profiled steel sheeting Cofraplus 60 and Cofraplus 77, which have narrow ribs of the mean width of 81.5 mm and 82.0 mm, respectively. This is not surprising considering that the experimental results proved overestimation of the shear resistance by EN 1994-1-1 predictions for these types of profiled steel sheeting [12]. Therefore, the design of a composite steel-concrete beam with profiled steel sheeting with narrow ribs should be carefully accessed in practice, considering the possible application of alternative design models.

The trend in design resistance values for models proposed by Konrad and Odenbreit and Nellinger cannot be easily determined, meaning that for some of the considered profiled sheeting types, design resistance according to Konrad is larger than according to Odenbreit et al, whereas in other cases, it is otherwise. The values of the headed stud resistance in open trough profiled sheeting predicted by Konrad are smaller than the ones calculated according to EN 1994-1-1. However, it is not the case for all resistance values according to the model proposed by Odenbreit and Nellinger, which for example assumes somewhat larger resistance than EN 1994-1-1 for profiled sheeting Multideck 60.

## 4. CONCLUSIONS

In this paper, a brief overview of the recently proposed design models for headed studs in profiled steel sheeting with ribs transverse to the beam is given. Although different models have been proposed in the past years, the focus of this paper is put on two models with a relatively wide scope of application proposed by Konrad and by Odenbreit and Nellinger. Both models were developed with the intention to solve some weaknesses observed in the codified design procedures of EN 1994-1-1.

Comparative analysis including various types of re-entrant and open trough profiled steel sheeting showed that novel design models are more sensitive to variations in profiled sheeting geometry than EN 1994-1-1. The most significant dissimilarities between design predictions are present for open trough profiled sheeting with narrow ribs. In this case, the design resistance according to novel models is nearly 50% smaller than according to EN 1994-1-1.

In order to solve Eurocode overestimations in headed stud resistance, the working group CEN/TC250/SC4.PT3 proposed analytical expressions for obtaining resistance of headed studs when placed in narrow ribs or near the rib wall in an unfavourable position, or when insufficient anchorage depth is applied. These expressions are expected to be available in the next generation of Eurocodes. Until then, the calculation of headed stud shear resistance should be carefully approached particularly in these special cases when the application of alternative design procedures is suggested to get safe-sided results.

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