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# NUMERICAL MODELLING OF WEB CRIPPLING UNDER REALISTIC END SUPPORT CONDITIONS

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**Abstract**

Determination of web crippling resistance of thin-walled steel sections can be achieved by two different methods: by laboratory experiments or with numerical models, dividing the geometry into finite elements. Trapezoidal sheeting is particularly sensitive to concentrated loading. The support conformation has a significant influence on the resistance of the profile. Understanding the influential support parameters and taking into account in calculations is essential, since it can have a major influence on the bearing resistance and failure mode. The American and the European standards differ in their approach regarding the boundary conditions. The Eurocode does not consider the fixing of the sheets to the roof purlins or beams, which is generally applied in the construction industry. The present study investigates the web crippling resistance of trapezoidal cross-sections with numerical finite element models for several support configurations, considering also the influence of bottom flange fixing.

**Keywords**: *cold-formed steel, trapezoidal sheeting, web crippling resistance, Eurocode, finite element model.*

## 1. Introduction

### 1.1. Web crippling of cross-sections with multiple webs

The failure modes of thin-walled sections include the local buckling of the web under concentrated shear forces, namely the web crippling. Deep trapezoidal profiles are especially sensitive to the studied failure type, because of the thin (0.3–1 mm), but high (up to 150 mm) web plate subjected to shear. The transversal force resistance of web can be less than the bending resistance of the whole profile.

In case of roof sheeting or decking of composite slabs, the main applications of trapezoidal sheets, usually the highest shears are concentrated at the supports. In design practice is extremely important to use the real parameters of the bearings. The length of the sheet-to-support contact surface and the length of the free end in console has a significant influence on the web crippling resistance. With adequate support conformation a design capacity can be achieved that is not determined by the web crippling failure.

### 1.2. End support conformations

In practice, deep sheets are mostly used as roof decking, for increased distance between the supports. The general characteristics of the bearing supports differ based on the materials used for the primary structure and the design details. The upper plane of the concrete purlins generally does not follow the roof angle. As a consequence, the sheet-to-purlin contact is a theoretical line. At the ridge support, the trapezoidal profile has a cantilever free end (**Fig. 1**).

The orientation of steel purlins can follow the roof angle, but there are cases when their upper plane remains horizontal.

The cantilever length of trapezoidal profiles at eave support can be variable (**Fig. 2**). In many cases the designer does not give any specification concerning the end length.

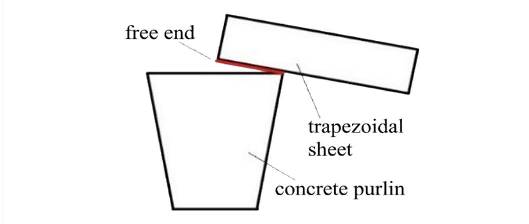


**Fig. 1.** *Typical ridge support for concrete purlins.*

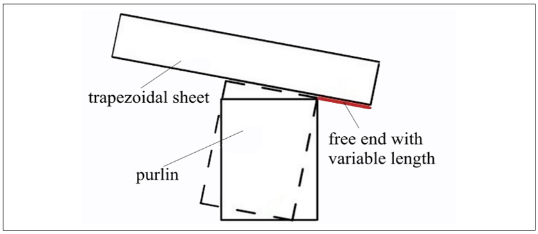


**Fig. 2.** *Eave supports for concrete and for steel roof purlins.*

End supports differ in two main parameters. One is the bearing surface's length that can be the width of the bearing element's upper flange or a narrow edge for inclined supports. The second parameter is the length of the sheet portion being in console. The present study does not inspect the web crippling resistance at intermediate supports.

## 2. Particularities of analytical calculations

### 2.1. AISI Standard

The investigation of web crippling resistance of steel sections began in the 1940's at Cornell University, with the set of experiments conducted by Winter and Pian [1], in which they studied back-to-back lipped channels, under 4 different loading types: IOF – interior one-flange loading, EOF – end one-flange loading, ITF – interior two-flange loading and ETF – end two-flange loading (Fig. 3).

The standardization of the laboratory experiments was carried out by LaBoube and Schuster [2], which has been included in the AISI S909-17 [3].

It is still common to determine the concentrated shear resistance of the web by testing, since the failure of thin-walled sections is caused by several factors acting simultaneously [4]. Several test sets were done with various cross-sections. The analytic relation (1) of the AISI S100-16 [5] was developed based on the empirical results [6]. The code defines the web crippling resistance in function of the following parameters: sheet thickness ($t$), yielding strength ($F_y$), slope of the web ($\theta$), inner bending radius ($R$), bearing length – length of contact surface between the profile and the support ($N$), web height ($h$).

$$P_n = Ct^2F_y sin\theta\left(1 - C_R\sqrt{\frac{R}{t}}\right)\left(1 + C_N\sqrt{\frac{N}{t}}\right)\left(1 - C_h\sqrt{\frac{h}{t}}\right) \quad (1)$$

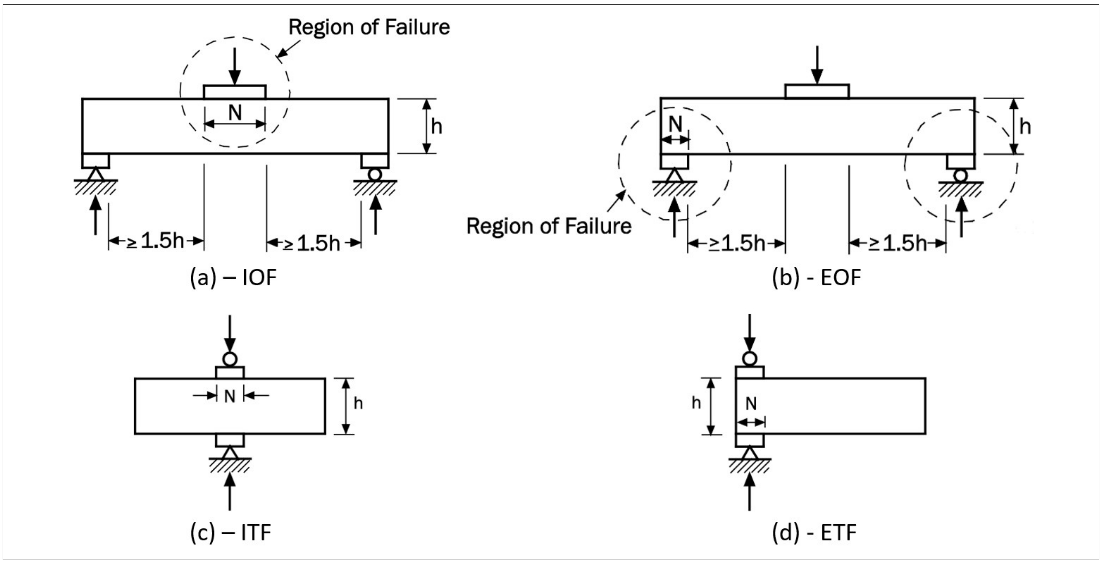


**Fig. 3.** *Distinguished loading types (source – AISI S909-17 [3])*

## 2.2. Eurocode

The analytic relation of the Eurocode 3-1-3 [7] is based on the AISI standard [8], but addresses separately the cross sections having one, two, or multiple webs. The web crippling resistance of profiles with multiple webs is defined by relation (2), where the variables are similar to that of the American code: sheet thickness ($t$), yielding strength of the base material ($f_{yb}$), elastic modulus ($E$), inside bend radius ($r$), effective bearing length ($l_a$), slope of the web ($\phi$).

$$R_w = \frac{\alpha \cdot t^2 \sqrt{f_{yb} \cdot E}}{\gamma_{M1}} \cdot \left(1 - 0.1 \cdot \sqrt{\frac{r}{t}}\right) \left(0.5 + \sqrt{0.02 \cdot \frac{l_a}{t}}\right)\left(2.4 + \left(\frac{\Phi}{90}\right)^2\right) \tag{2}$$

## 2.3. Comparison of standards

Both of the standards take into account the support characteristics. The AISI code provides constants (C, $C_R$, $C_N$, $C_h$), that depend on the cross-section shape (C, Z, Omega, trapezoidal sheet), the presence or lack of fixings and the loading condition (IOF, EOF, ITF, ETF).

The relation in Eurocode for the thin-walled profiles with multiple webs separates the support conformations with the help of variables ($\alpha$) and ($l_a$). Parameter ($\alpha$) takes values based on the loading category/ loading condition. The effective bearing length ($l_a$) depends on the loading category and the width of the support.

The major difference between the codes is that Eurocode does not deal with the influence of sheet-to-support fixing, meanwhile, AISI specifies different constants if the sheeting is fixed to the bearing. In the following chapters, the web crippling resistance is investigated for end supports with fixed or free-hanging ends.

# 3. Finite element modelling

## 3.1. The studied geometry

The PCB80 trapezoidal profile without web stiffeners, tested in the GRISPE project [9, 10] has been selected as the reference geometry. In addition, other geometries were analyzed, but the parametric study was carried on the 0.75 mm thick PCB80 section by BACACIER. In FE models, the width of the support was 40 mm, such as in the laboratory tests (Fig. 4 and Fig. 5).

The numerically studied end configurations had variable console lengths ($l_{end}$) (Fig. 6). Five cases were modelled with and without fastening, where $l_{end}$ = 0/20/40/80/160 mm and $l_{sb}$ = 40 mm.

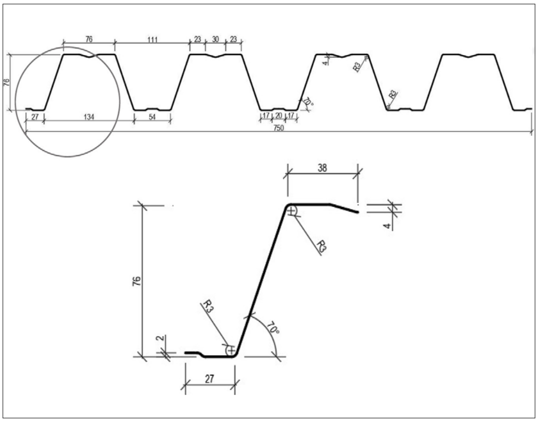


**Fig. 4.** *Dimensions of the reference profile.*

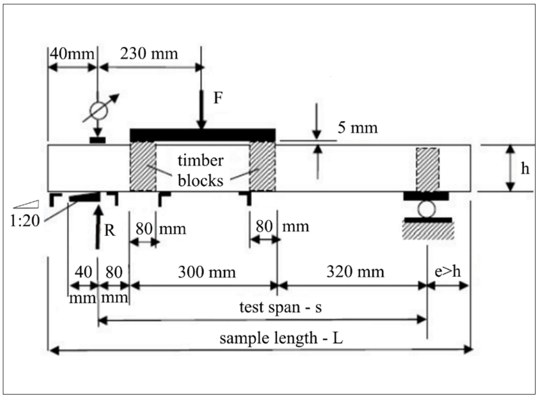


**Fig. 5.** *Experimental setup (source – GRISPE test report. [10])*

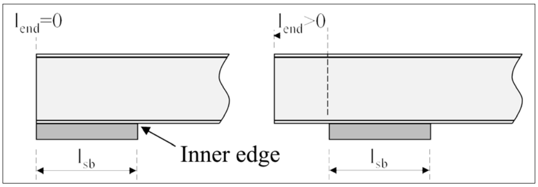


**Fig. 6.** *Representation of console lengths*

## 3.2. The numerical model

The authors developed several numerical models [11, 12] with Ansys Workbench 2020 R2 and Ansys Mechanical 2019 finite element analysis softwares. The calculations were performed considering the geometrical and the material nonlinearities.

In practice, trapezoidal profiles are connected with seam fasteners at longitudinal overlaps, which constrains the spreading of the sheet. As a consequence, the failure of each web can be considered identical. To reduce the computational time, only half of a rib was introduced in the FE model, while on the longitudinal sides symmetry boundary conditions were applied. Close to the imposed load, the profile lies on an inclined steel plate and on the opposite side a hinge is provided. Loading is introduced as a vertical displacement transmitted to the bottom flange, that is increased with each time increment (**Fig. 7**).

The mesh formulation follows the expected distribution of the deformations. The mesh is refined where larger displacements can take place. In the end zone, the indicated size of the finite elements is 3 mm, on the load-transfer portion is 6 mm and on the remaining segment is 10 mm. The meshing is quadrilateral dominant and second order SHELL281 finite elements were used. The contour of the rounded corners was divided into 4 segments.

The measured yield strength of 362.8 MPa was considered. For the numerical analysis a bi-linear material model was used for the steel elements. The elastic zone had a Young's modulus of $E = 210$ GPa, while the plastic zone of $E = 2.1$ GPa. Instead of the $t = 0.75$ mm design thickness, the measured mean thickness of the base material of $t_{real} = 0.684$ mm was introduced in the calculation. (**Fig. 8**)

The finite element model was validated on the GRISPE project's **[9, 10]** experiments. The web crippling resistance obtained with the model differs by 0.23% from the experimental value, while the second load maximum in the post-elastic domain is less by 13.34% than the measured one **[11]**. The deformed shape and the failure mode identified with the FE model correspond to those observed in the laboratory.

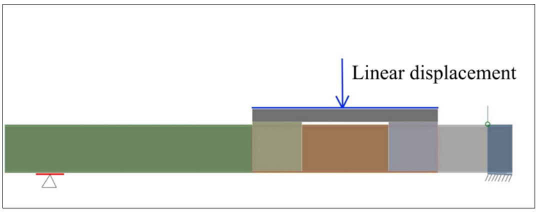


**Fig. 7.** *Boundary conditions*

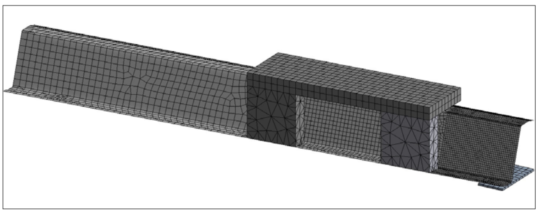

**Fig. 8.** *Meshing*

## 4. Results

In the recent European experiments **[10, 13]** trapezoidal profiles were not connected to the support, while in the construction practice a sheet-to-purlin or sheet-to-beam fixing is always present. This chapter compares the web crippling resistance of fastened and unfastened ends for variable end lengths in console. The investigation of the fixing's influence at intermediate supports is less relevant. In general there is no loading condition that tends to separate the bottom flange of the trapezoidal profile from the bearing.

The rigidity of the screw and the washer is increased compared to the sheet. Tension forces lead to significant deformations only on the bottom flange of the thin-walled profile. To reduce computational time only, the effect of the fastener was introduced in the Ansys model. The bottom flange was bonded to the support at a circular perimeter, equal to the dimension of the washer.

### 4.1. Short consoles

Unfastened short ends tend to rotate around the inner edge of the support, causing an upward movement of the bottom flange. The phenomenon was observed both in the experiments and in the numerical simulations. Stress concentrations appear at the contact point between the sheet's web and the support's edge.

Fastening of the end constrains the rotation of the end section and changes the stress distribution. The stresses are concentrated along the whole contact edge between the rounded bottom corner and the support. **Fig. 9** presents the deformed shape and **Fig. 10** the stress distribution of the following conformation: support width ($l_{sb}$) 40 mm, free end length ($l_{end}$) 0 mm.

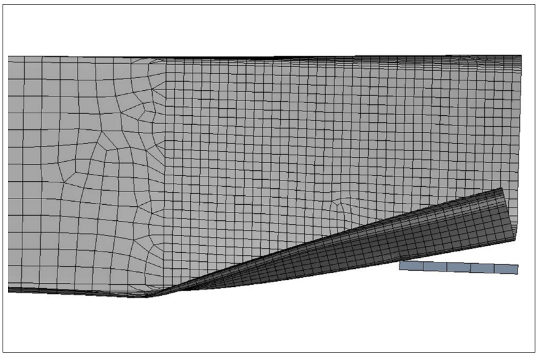

**Fig. 9.** *Typical deformation of short consoles, without fastening.*

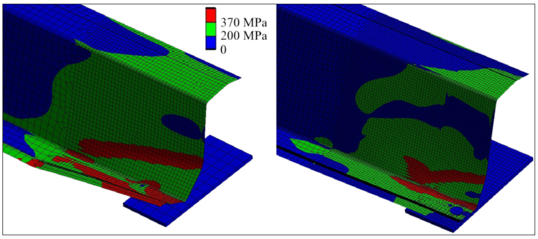


**Fig. 10.** *Stress distribution at short ends, without fastening (left) and with fastening (right).*

### 4.2. Long consoles

In the case of long free ends, the concentrated support reaction tends to have a more local-like effect. The end section of the profile does not deform, the behavior of the cross-section becomes similar to that in the case of loads applied in the field.

**Fig. 11.** shows the deformed shape and stress distribution of the PCB 80 cross-section having 80 mm end length, with and without fastener. The behavior of the profile is similar in both cases. It can be noticed that for the fastened configuration the stresses are more symmetric to the support.

### 4.3. Effect of fasteners on the web crippling resistance

The force-displacement curves for the fastened and unfastened ends were compared for variable end lengths. For short ends, the fixing significantly influences the bearing resistance. The effect of the fasteners for long consoles is neglectable.

In terms of numbers (**Fig. 12**), for short consoles (AISI – EOF, EN – category 1), the presence of fastener led to a 20-23% increase in the section's resistance to web crippling, which corresponds to the difference provided by the AISI S100-16 calculation. For long ends (AISI – IOF, EN – category 2), sheet-to-support fixing is insignificant, which is in accordance with the American standard. (**Table 1.**)

## 5. Conclusions

For the determination of the true web crippling resistance of trapezoidal cross-sections it is essential to know the real support parameters. The validated finite element models show that for end configurations with short consoles, fasteners have a significant influence on the profile capacity, which is considered in the American standard.

The Eurocode does not give guidance regarding the studied parameter, which leads to underestimation of the sheet capacity for concentrated loads. The authors consider it important for struc-

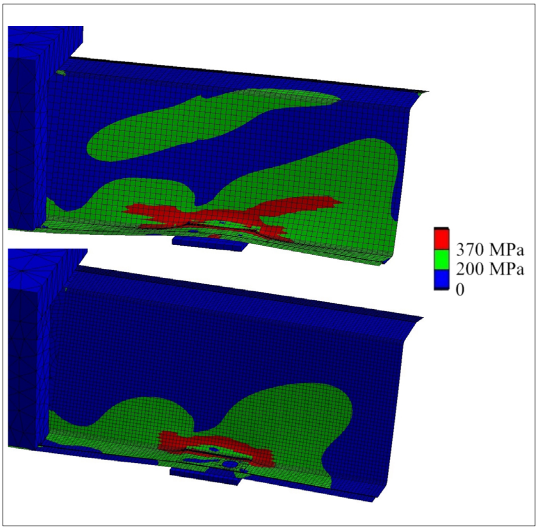


**Fig. 11.** *Stress distribution at long ends, unfastened (above) and fastened (below).*

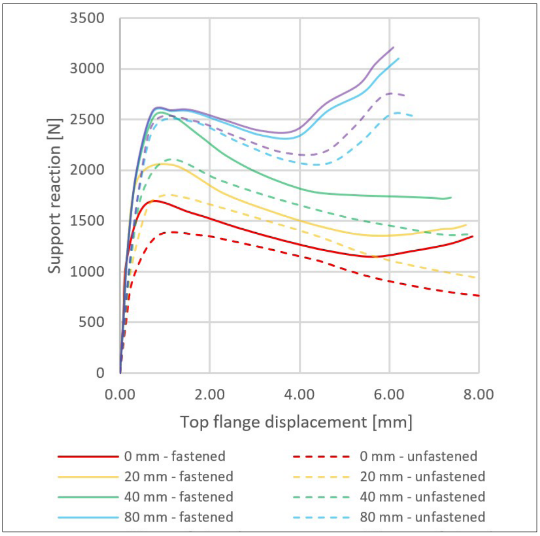


**Fig. 12.** *Force-displacement curves from the numerical simulations for increasing free end lengths with and without fastening.*

**Table 1.** *Changes in web crippling resistance due to fasteners for variable free end lengths*

| $l_{end}$ | $R_{w.Rd}$ without fastener [N] | $R_{w.Rd}$ with fastener [N] | Influence of fixing [%] |
|---|---|---|---|
| 0 | 1360 | 1672.7 | 22.99 |
| 20 | 1747.9 | 2104.7 | 20.41 |
| 40 | 2105.6 | 2528.5 | 20.08 |
| 80 | 2479.3 | 2580.6 | 4.09 |
| 160 | 2489.6 | 2592.5 | 4.13 |

tural engineers to be aware of the significance of providing proper support details.

In the future, we will propose the revision of the relevant chapter of the Eurocode, to take into account the effect of sheet-to-support fasteners on the web crippling resistance of thin-walled steel profiles with multiple webs.

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