Industry CPD

Design of solar panel mounting structures made of cold-formed steel

This CPD module, sponsored by GRAITEC UK, explores the structural analysis and design of solar panel mounting structures made of cold-formed steel.

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1 hour of verifiable CPD

Solar energy is quickly emerging as a preferred source of clean and sustainable power. To effectively capture this energy, solar panels – either ground-mounted or roof-mounted – require a robust and dependable support system. To ensure those characteristics for the support system while using cost-effective and reliable materials in assembly, panel manufacturers and installers have adopted a structural system made of durable, long-lasting framing materials, which can be configured, cut, and assembled on or off site to suit very complex geometrical shapes and a wide range of installation needs.

Cold-formed steel (CFS), also known as light-gauge steel (LGS), meets that standard. Its high strength-to-weight ratio ensures robust support for solar panels while minimising structural weight, facilitating easier handling and installation. CFS's precision in manufacturing ensures consistent, accurate dimensions, crucial for the alignment and optimal performance of solar panels. Additionally, its versatility allows it to be formed into various shapes and sizes, accommodating different panel configurations and mounting systems **(Figure 1)**. These attributes, combined with its ductility and non-combustibility, contribute to the safety, efficiency, and durability of solar panel frames, supporting sustainable energy solutions effectively.

Design of CFS members for solar panel framing

A wide range of CFS profiles are used for the framing structure of the solar panels, such as C, Z, Sigma, U, etc. **(Figure 2)**. Members with CFS cross-sections should be designed according to the approach and assumptions presented in EN 1993-1-3.

Geometrical requirements

To qualify as a CFS cross-section that can be designed according to the methodology illustrated in EN 1993-1-3, the geometrical criteria presented in **Figure 3** should be met.

To provide sufficient stiffness and to avoid primary buckling of the stiffener itself, the sizes of stiffeners should be within the following ranges:

$$0.2 \le \frac{c}{b} \le 0.6 \quad (1)$$

$$0.1 \le \frac{d}{b} \le 0.3 \quad (2)$$

in which the dimensions b, c and d are as indicated in **(Fig. 3)**. If $c / b < 0.2$ or $d / b < 0.1$, the lip should be ignored ($c = 0$ or $d = 0$).

Local, distortional and global buckling

One of the biggest challenges in CFS design is the prevention of member buckling. Due to the low thickness-to-width ratio, these members are prone to buckling at stresses below the yield stress when subjected to compressive and/or shear bending forces. Consequently, buckling emerges as a primary design consideration

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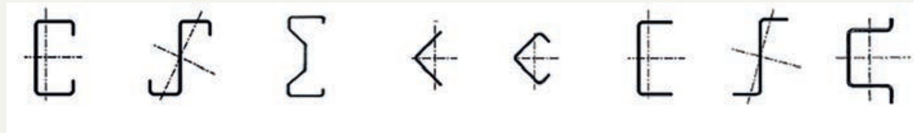
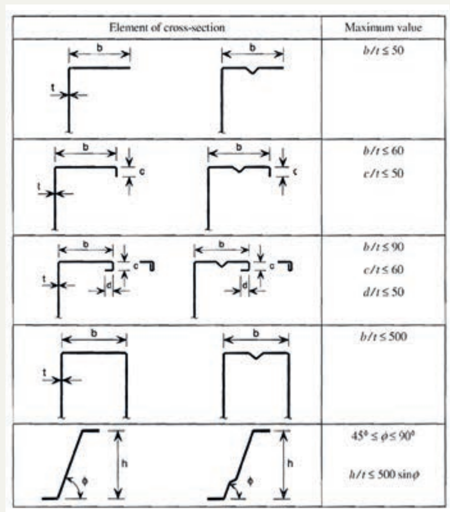
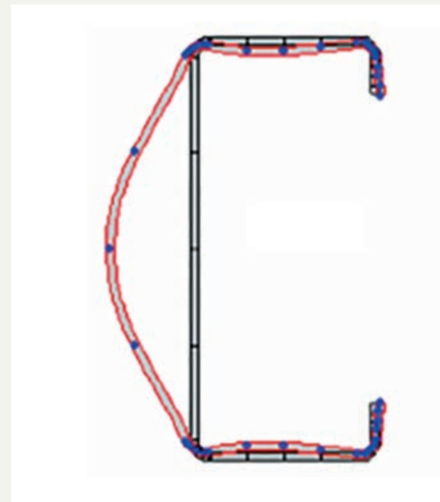
↗FIGURE 1: Custom-made CFS profiles for solar solutions



↗FIGURE 2: Typical CFS profile members used extensively in engineering applications



↗FIGURE 3: Maximum width-to-thickness ratio



↗FIGURE 4: Example of local buckling mode

for all CFS, in contrast to hot-rolled steel, where yielding of the steel predominates as the principal design concern.

Local buckling

Local buckling occurs in one or more cross-sectional elements (web or flanges) but does not involve any displacement or translation of the corner nodes **(Figure 4)**. To account for local buckling of CFS sections, EN 1993-1-3 suggests that the width b of internal plate elements and c of the outstand ones should be reduced to an effective one, b_{eff}, leaving in essence parts of the compressive zone of the section inactive **(Figure 5)**. The effective b_{eff} widths should be determined in accordance with the methods and assumptions illustrated in EN 1993-1-5 for sections without stiffeners. Conversely, an alternative methodology is outlined in EN 1993-1-3 for sections featuring edge or intermediate stiffeners.

To prevent local buckling in CFS sections, stiffeners can be added to control the width-thickness ratio.

Distortional buckling

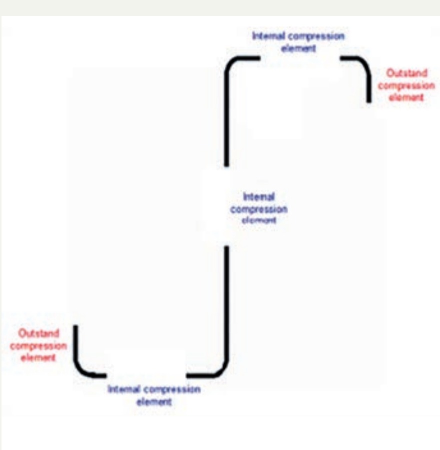
Distortional buckling involves both rotation and translation at the corners of the cross-section. This is observed as a distortion of the cross-section when one portion of the section is 'forced out' by a more rigid response of t he remaining portion **(Figure 6)**. To account for the influence of distortional buckling on CFS sections, EN 1993-1-3 recommends reducing the section's thickness and offers guidance on calculating an effective cross-section with this reduced thickness.

Since both local and distortional buckling can occur in CFS cross-sections, the effective cross-section should have inactive parts due to local buckling and reduced thickness due to distortional buckling **(Figure 7b)**. Such a type of section should be used for the calculation of all the parameters of the effective section such as the effective area A_{eff} or the effective section modulus W_{eff}. These parameters will subsequently be employed to determine the compressive and/or flexural resistance of the section, with local buckling effects duly accounted for.

Global buckling

In contrast to local and distortional buckling, global buckling does not alter the cross-section of the element. The global buckling of CFS members aligns with classical beam theory and includes flexural, torsional, flexural-torsional, and lateral-torsional buckling. This phenomenon should be addressed in the same manner as it is for hot-rolled steel members; however, the cross-sectional characteristics might need to be adjusted.

To prevent global buckling, engineers should implement appropriate structural systems to ensure that susceptible members are adequately restrained. Consequently, single-post solar panel structures should be avoided in favour of frame-like designs, which more easily accommodate the installation of diagonals.



↗FIGURE 5: Example of effective CFS cross-section subjected to uniform axial compression. Parts of the section have been removed to account for local buckling

↗FIGURE 6: Examples of distortional buckling modes

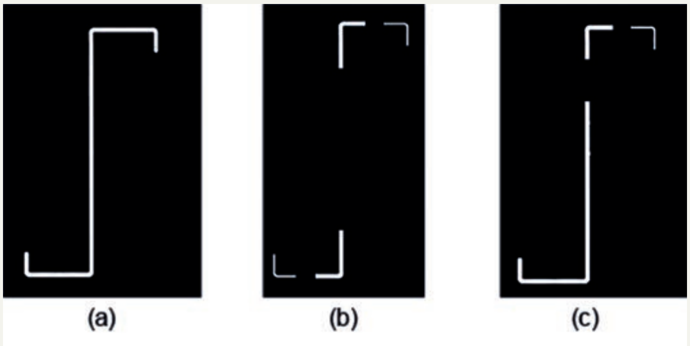


FIGURE 7: Gross cross-section (a), and effective cross-section for pure (b) compression and (c) bending. Both local and distortional buckling have been considered

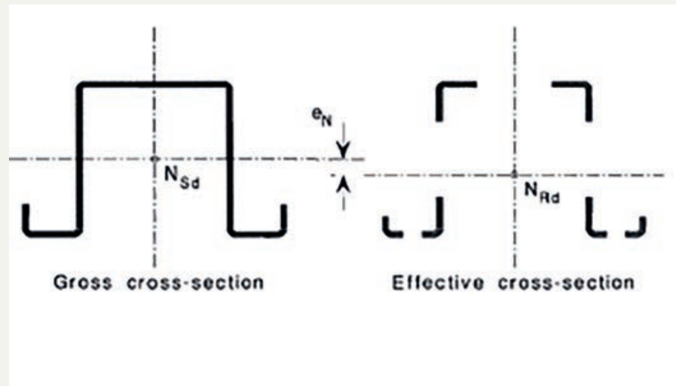


FIGURE 8: Shift e_N of centroidal axes in effective cross-section

Increased yield strength, f_{ya}

During the cold-forming process, steel sheets are shaped into desired profiles at room temperature. This process induces plastic deformation in the steel, leading to an increase in dislocation density within the material's crystal structure. The increased number of dislocations interact and impede further movement of dislocations, making the steel harder and stronger. This phenomenon, known as strain hardening, gives CFS increased yield strength, f_{ya}.

$$f_{ya} = f_{yb} + \left(f_u - f_{yb}\right)\frac{knt^2}{A_g}, \qquad f_{ya} \le \frac{f_u + f_{yb}}{2} \tag{3}$$

where:
f_{yb}: basic yield strength
A_g: gross cross-sectional area
f_u: ultimate yield strength
k: numerical coefficient that depends on the type of forming – $k = 7$ for roll forming or $k = 5$ for any forming
n: the number of 90° bends in the cross-section with an internal radius $r \le 5t$ (fractions of 90° bends should be counted as fractions of n)
t: design core thickness of the steel material before cold-forming.

The increased yield strength due to cold-forming may be considered as follows:
- in axially loaded members in which the effective cross-sectional area A_{eff} equals the gross area A_g
- in determining A_{eff} the yield strength f_y should be taken as f_{ya}.

The increased yield strength f_{ya} may be utilised in determining:
- the cross-section resistance of an axially loaded tension member
- the cross-section resistance and the buckling resistance of an axially loaded compression member with a fully effective cross-section
- the moment resistance of a cross-section with fully effective flanges.

Resistance of cross-sections

Axial tension

The design resistance of a CFS profile subjected to uniform tensile load $N_{t,Rd}$ should be determined from:

$$N_{t,Rd} = \frac{f_{ya} A_g}{\gamma_{M0}} \tag{4}$$

where:
f_{ya}: increased yield strength
A_g : gross area of the cross-section.

Axial compression

The design resistance of a cross-section for compression $N_{c,Rd}$ should be determined from:

$$N_{c,Rd} = \frac{A_{eff} f_{yb}}{\gamma_{M0}} \tag{5}$$

if $A_{eff} < A_g$ (section reduced due to local or/and distortional buckling)

$$M_{c,Rd} = f_{yb}\frac{\left(W_{el} + \left(W_{pl} - W_{el}\right)4\left(1 - \bar{\lambda}_{e,max}/\bar{\lambda}_{e0}\right)\right)}{\gamma_{M0}} \tag{6}$$

where:
for plane elements: $\lambda_{e0} = 0.673$, $\lambda_e = \lambda_p$ (for formulas see EN 1993-1-5, §5.5.2)
for stiffened elements: $\lambda_{e0} = 0.65$, $\lambda_e = \lambda_d$ (for formulas see EN 1993-1-5, §5.5.3)
if $A_{eff} > A_g$ (section with no reduction due to local or/and distortional buckling).

The internal axial force in a member should be taken as acting at the centroid of its gross cross-section. This is a conservative assumption but may be used without further analysis. However, the design compression resistance of a cross-section refers to the axial load acting at the centroid of its effective cross-section. If this does not coincide with the centroid of its gross cross-section, the shift e_N of the centroidal axes **(Figure 8)** should be considered. When the shift of the neutral axis gives a favourable result in the stress check, then that shift should be neglected only if the shift has been calculated at yield strength and not with the actual compressive stresses.

Bending moment

The design moment resistance of a cross-section for bending about one principal axis $M_{c,Rd}$ is determined as follows:

$$M_{c,Rd} = \frac{f_{yb} W_{eff}}{\gamma_{M0}} \tag{7}$$

if the effective section modulus W_{eff} is less than the gross elastic section modulus W_{el}

$$M_{c,Rd} = f_{yb}\frac{\left(W_{el} + \left(W_{pl} - W_{el}\right)4\left(1 - \bar{\lambda}_{e,max}/\bar{\lambda}_{e0}\right)\right)}{\gamma_{M0}} \tag{8}$$

where:
$\lambda_{e,max}$: is the slenderness of the element which correspond to the largest value of λ_{e0}, λ_e
for double supported plane elements: $\lambda_{e0} = 0.5 + \sqrt{0.25 - 0.055(3 + \psi)}$, $\lambda_e = \lambda_p$ and ψ is the stress ratio (for formulas see EN 1993-1-5, §5.5.2)
for outstand elements: $\lambda_{e0} = 0.673$, $\lambda_e = \lambda_p$ (for formulas see EN 1993-1-5, §5.5.2)
if the effective section modulus W_{eff} is equal to the gross elastic section modulus W_{el}.

For biaxial bending the following criterion should be used:

$$\frac{M_{y,Ed}}{M_{cy,Rd}} + \frac{M_{z,Ed}}{M_{cz,Rd}} \le 1 \tag{9}$$

where:
$M_{y,Ed}$, $M_{z,Ed}$: bending moment about the major and minor main axis respectively
$M_{cy,Rd}$, $M_{cz,Rd}$: resistance of the cross-section if subject only to moment about the main y-y axis and z-z axis respectively.

Shear force

The design shear resistance $V_{b,Rd}$ should be determined from:

$$V_{b,Rd} = \frac{\frac{h_w}{\sin\varphi} t f_{bv}}{\gamma_{M0}} \quad (10)$$

where:
f_{bv}: shear strength considering buckling
h_w: web height between the midlines of the flanges
ϕ: slope of the web relative to the flanges.

Torsion
If loads are applied eccentric to the shear centre of the cross-section, the effects of torsion should be considered. The direct stresses due to the axial force N_{Ed} and the bending moments $M_{y,Ed}$ and $M_{z,Ed}$ should be based on the respective effective cross-section. The shear stresses due to transverse shear forces, the shear stress due to uniform (St. Venant) torsion and the direct stresses and shear stresses due to warping, should all be based on the properties of the gross cross-section.

In cross-sections subject to torsion, the following conditions should be satisfied:

$$\sigma_{tot,\ Ed} \leq \frac{f_{ya}}{\gamma_{M0}} \quad (11)$$

$$\tau_{tot,\ Ed} \leq \frac{f_{ya}/\sqrt{3}}{\gamma_{M0}} \quad (12)$$

$$\sqrt{\sigma_{tot,\ Ed}{}^2 + 3\tau_{tot,\ Ed}{}^2} \leq 1.1\frac{f_{ya}}{\gamma_{M0}} \quad (13)$$

where:
$\sigma_{tot,Ed}$: the design total direct stress due to axial force or/and bending about y or/and z axis and warping calculated on the relevant effective cross-section
$\tau_{tot,Ed}$: the design total shear stress due to warping, uniform (St. Venant) torsion and transverse shear force about y or/and z axis, calculated on the gross cross-section.

Although design against torsion in provided in EN 1993-1-3, avoiding torsion in CFS sections is crucial for maintaining structural integrity and stability. Several key strategies can be employed to achieve this. First, designers should prioritise using bracing systems such as diagonal bracing or cross-bracing to resist torsional forces effectively. Additionally, optimising the section design to ensure that loads are applied through the centroid of the section helps minimise eccentricity and reduces torsional effects. Properly designed connections that can transfer loads without permitting torsional rotation are equally important. Lastly, avoiding eccentric loads and ensuring a continuous load path throughout the structure helps prevent the development of torsion in CFS sections, promoting overall structural stability and performance.

Corrosion resistance
Unprotected steel and steel structures exposed to the atmosphere inevitably corrode. For structures made of CFS, corrosion is particularly crucial to address, as it can further diminish their already minimal thickness, compromising their stability. Therefore, corrosion protection is a critical concern for CFS members and should be considered accordingly.

The standard form of corrosion protection for CFS sections is the continuous hot-dip zinc coating applied as a pre-coat to the roll of the strip steel from which the section is formed. Galvanised steel strip and its coating is supplied to the specifications of BS EN 10346 and BS EN 10143. Galvanised strip steel is usually produced with a standard Z275 coating, meaning 275 grams of zinc per m^2 summed over the faces of steel strip. This corresponds to approximately 0.02mm overall thickness of zinc per face. Other coating thicknesses are available for special applications. Zinc-aluminium coating is also available. AZ150 is a common alternative to Z275.

Design of joints
There are several joining methods suitable for CFS members. Compared with thicker connections (t > 3mm), connections in thin-walled elements exhibit lower plate stiffness. Consequently, additional effects may arise in both the ultimate limit state and serviceability state, with the safety level more reliant on rigorous quality control. Examples of such effects include fastener tilting in hole-bearing failure and significant sheet distortion when a fastener is subjected to tension, causing the sheet to pull over the fastener head.

Designing joints for CFS members should be performed based on the assumptions and requirements of EN 1993-1-8. However, specific rules must apply for thicknesses t < 4mm, as outlined at EN 1993-1-3, §8. This passage covers the design of splices and end connections for CFS members subjected to compression, connections between CFS members with mechanical fasteners and welds.

Design of joints of CFS members extends beyond the scope of this article; hence, further elaboration on this subject will not be provided within this section.

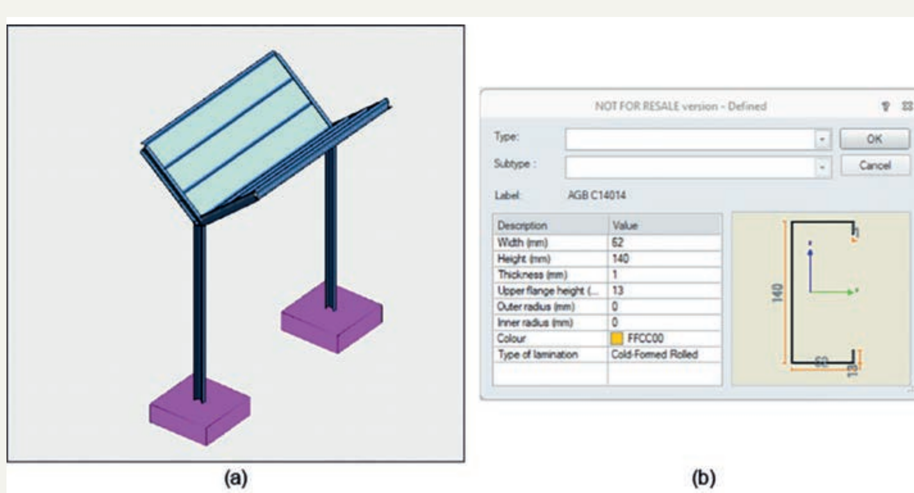
Case study with Advance Design

In this section, a solar panel framing structure will be designed using GRAITEC Advance Design – a finite-element structural analysis software. The solar panel framing structure comprises two columns, four rafters and eight purlins all made of CFS **(Figure 9a)**. A typical C-section is used for all the structural elements of this model **(Figure 9b)**. Both columns have fixed supports, while wind and snow load are applied to the structure.

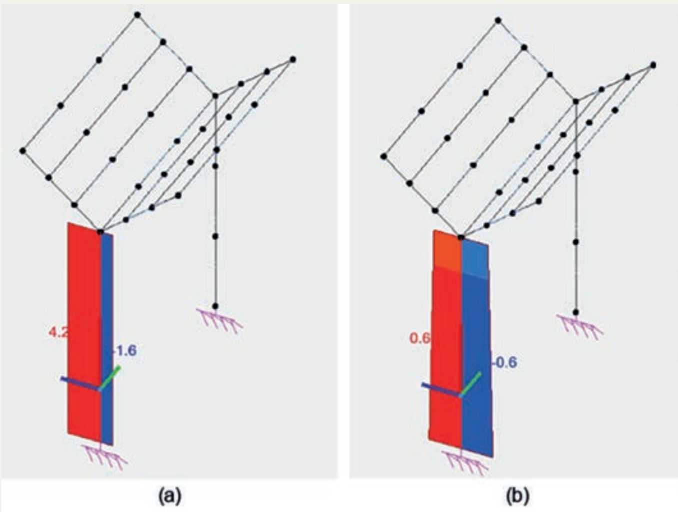
Advance Design is equipped with an extensive suite of tools adept at analysing and designing members with CFS profiles. In addition to the extensive library of CFS profiles available within the software, its solver can accurately consider phenomena such as local and distortional buckling, the effects of torsion and warping, as well as the effects of the deformed geometry (second-order effects); by activating the Advanced Stability feature, found the in the Properties window of the steel element, under Steelwork Design / Advanced Stability **(Figure 11)**.

By accessing the Advanced Stability dialog, extensive possibilities unfold. The nodal springs tab allows the users to add local restraints such as anti-sag bars or torsional restraints **(Figure 12)**.

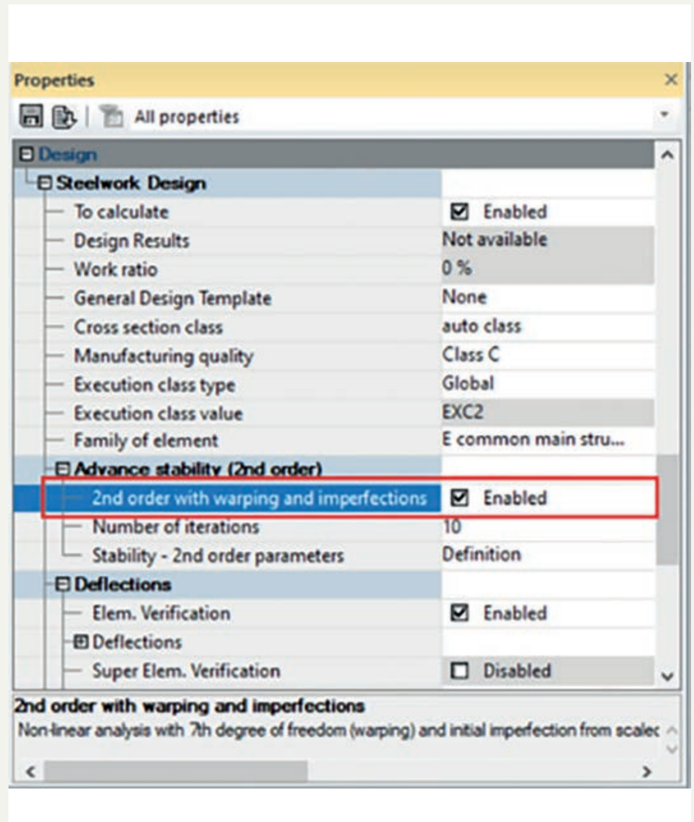
The Bedding tab allows for the introduction of



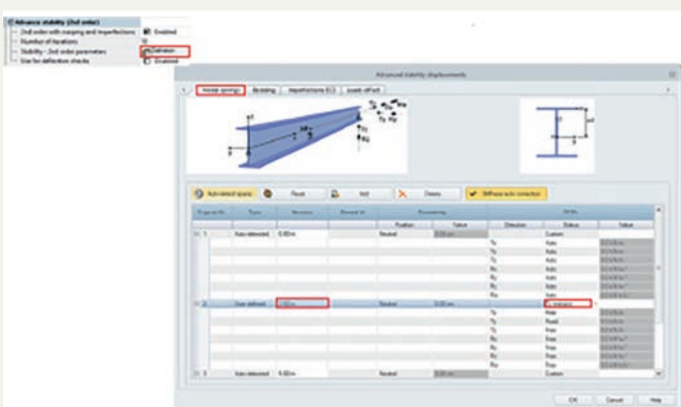
↗FIGURE 9: Solar panel framing structure modelled in Advance Design (a); information of CFS profile used for structural elements (b)



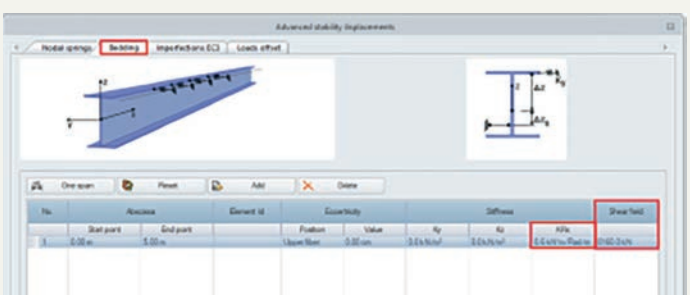
↗**FIGURE 10:** Envelope of design efforts: (a) axial force and (b) bending moment about major axis



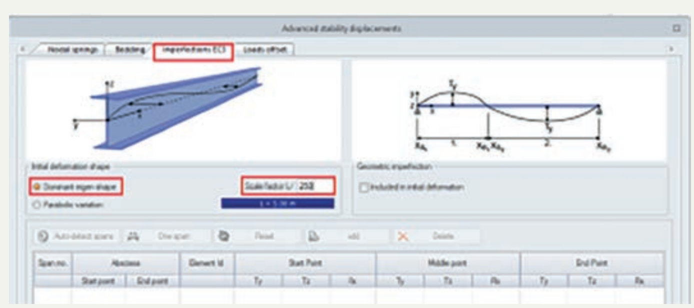
↗**FIGURE 11:** Advanced Stability feature



↗**FIGURE 12:** Anti-sag bar introduced as punctual T_y restraint along cold-formed purlin



↗**FIGURE 13:** Bedding tab of Advanced Stability dialog box



↗**FIGURE 14:** Imperfections tab of Advanced Stability dialog box

linear restraints along the member, to account for the rotational stiffness provided by the trapezoidal sheeting to a cold-formed purlin **(Figure 13)**.

In the Imperfections tab, the user can define deformation to be introduced as a local imperfection along the member. The deformation shape is based on the dominant eigen mode. A scale factor is then applied to the eigen mode to turn it into a deformation **(Figure 14)**.

In the Loads offset tab, the position of the applied forces can be prescribed, so the shift of the centre of gravity of a CFS due to different phenomena can be considered adequately, increasing or decreasing the torsional effects **(Figure 15)**.

Utilising the dedicated Steel Design functionality, users can seamlessly design CFS sections through the interface **(Figure 16)** and generate detailed reports that include all the verification formulas employed.

Conclusion

This article examines the structural analysis and design of solar panel mounting structures composed of CFS. Following an overview of the guidance offered by Eurocode 3 (EN 1993-1-3 and EN 1993-1-5) on this subject, a case study utilising GRAITEC Advance Design was also presented.

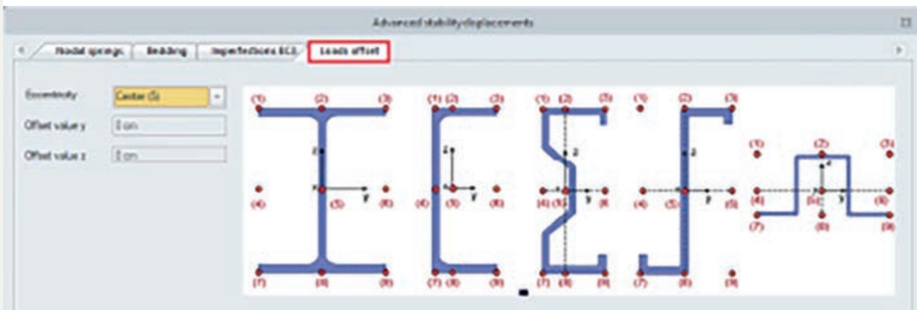


FIGURE 15: Loads offset tab of Advanced Stability dialog box

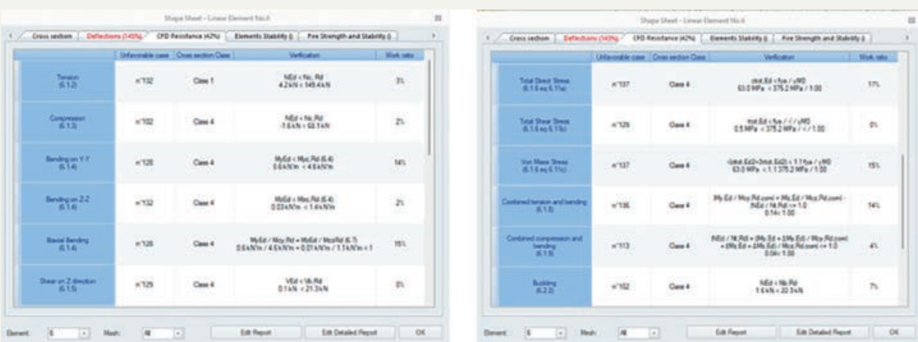


FIGURE 16: Shape sheet – design of CFS profiles in Advance Design

REFERENCES

1) British Standards Institution (2006) *BS EN 1993-1-3:2006 Eurocode 3. Design of steel structures - General rules - Supplementary rules for cold-formed members and sheeting*, London: BSI

2) British Standards Institution (2006) *BS EN 1993-1-5:2006+A2:2019 Eurocode 3. Design of steel structures - Plated structural elements*, London: BSI

3) Whittle J. and Ramseyer C. (2009) 'Buckling capacities of axially loaded, cold-formed, built-up C-channels', *Thin-Walled Struct.*, 47 (2), pp. 190–201; https://doi.org/10.1016/j.tws.2008.05.014

4) Piyawat K., Ramseyer C., and Kang T.H.-K. (2011) 'Nonlinear buckling of built-up cold formed sections', *Int. J. Theor. Appl. Mech.*, 2 (2), pp. 146–164; https://doi.org/10.1504/IJTAMM.2011.043536

5) Stone T.A. and LaBoube R.A. (2005) 'Behavior of cold-formed steel built-up I-sections', *Thin-Walled Struct.*, 43 (12), pp. 1805–1817; https://doi.org/10.1016/j.tws.2005.09.001

6) Ellobody E. and Young B. (2005) 'Behavior of cold-formed steel plain angle columns', *J. Struct. Eng.*, 131 (3), pp. 457–466; https://doi.org/10.1061/(ASCE)0733-9445(2005)131:3(457)

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Questions

To claim your CPD certificate, answer the questions online at **www.istructe.org/industry-cpd**.
The module will close on 1 September 2024.

1) Which of the following geometrical criteria is NOT a criterion for being a CFS cross-section according to EN 1993-1-3?
a) $b / t \leq 50$
b) $b / t \leq 60$
c) $b / t \leq 90$
d) $b / t \leq 20$

2) What type of buckling is depicted in this figure?
a) Local buckling
b) Distortional buckling
c) Global buckling
d) Lateral-torsional buckling

3) What loading conditions is the section in Figure 7c subjected to?
a) Tension
b) Pure compression
c) Pure bending
d) Torsion

4) How is distortional buckling of CFS sections considered in EN 1993-1-3?
a) By reducing the thickness of the section
b) By reducing the weight of the section
c) It is not considered at all
d) With the effective widths b_{eff}

5) How is local buckling of CFS sections considered in EN 1993-1-3?
a) By reducing the thickness of the section
b) By reducing the weight of the section
c) It is not considered at all
d) With the effective widths b_{eff}