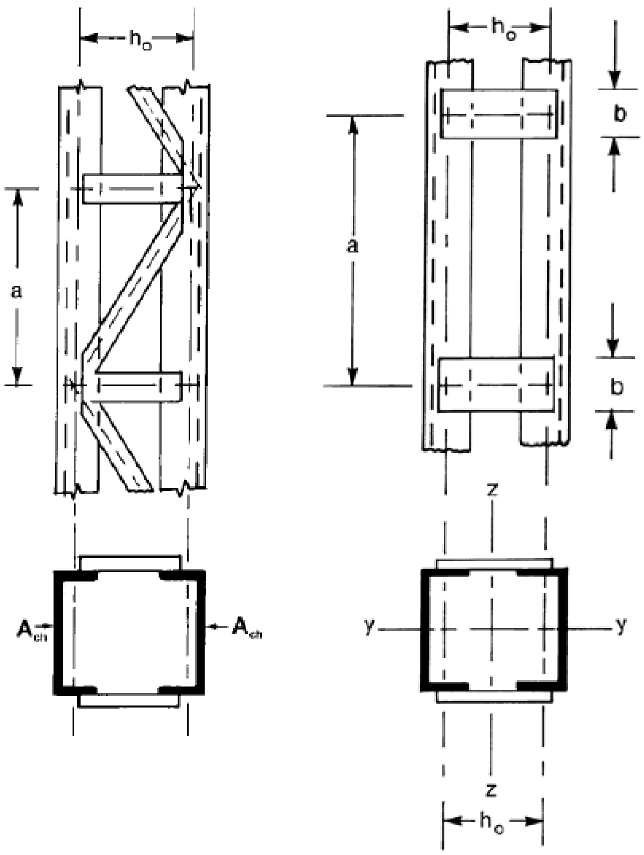
3. Stability of built-up members in compression

3.1 Definitions

Build-up members, made out by coupling two or more simple profiles for obtaining stronger and stiffer section are very common in steel structures, usually for realizing members which are usually under compression. Two of the most common arrangements for built-up members are represented in Figure 3.1. Although the discrete nature of the connections between the two members connected by lacings and/or battenings, the models that will e described in the following for analysing and checking built-up members are based on the assumption that the member is regular and smeared mechanical properties (such as, flexural stiffness) can be assumed throughout the member axis and utilized in calculations. Consequently, some regularity requirements are usually imposed in designing these members and can be listed below as a matter of principles:

- the lacings or battenings consist of equal modules with parallel chords;
- the minimum numbers of modules in a member is three.



a) laced member *b) battened member*

Figure 3.1: Uniform built-up columns with lacings and battenings.

The key models which can be utilized for the stability check of this kind of members will be discussed in the present chapter. Application of both the European and Italian Code of Standards will be also proposed in worked and unworked examples.

3.2 Shear Flexibility of members and critical load

While shear flexibility can usually be neglected in members with solid sections, built-up members are hugely affected by these parameters as a result of the axial deformation of lacings and out-of-plane flexural flexibility of the chord members.

Consequently, the critical load of built-up members have to be evaluated taking into account the role of shear stiffness S_v whose influence has be already discussed in section 2.7 with reference to transverse sections of general shapes. In particular, the key achievement of that discussion is represented by equation (2.58) which can e rewritten even assuming the symbols utilized within the previous chapter:

$$N_{cr,V} = \frac{1}{\frac{1}{N_{cr}} + \frac{1}{S_v}} \quad . \tag{3.1}$$

Based on the above equation, an equivalent value of the flexural slenderness can be easily introduced as often considered in various codes of standards:

$$N_{cr,V} = \frac{\pi^2 EA}{\lambda_{eq}^{\ 2}} \quad , \tag{3.2}$$

that can be defined as follows:

$$\lambda_{eq} = \lambda \sqrt{1 + \frac{\pi^2 EA}{S_v}} \quad . \tag{3.3}$$

Since imperfections play an even important role in both strength and stability checks of built-up members, a conventional eccentricity e_0 is usually introduced for simulating their effect in amplifying the axial action N_{Sd}. For instance, EC3 provides the following value of eccentricity as a function of the member span length L:

$$e_0 = \frac{L}{500} \quad . \tag{3.4}$$

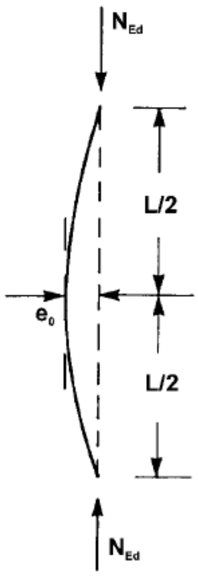


Figure 3.2: Conventional eccentricity e_0 accounting for member imperfections.

Further detail above the EC3 procedure will be discussed in depth in one of the closing paragraph of the present chapter, purposely devoted to code provisions for built-up members. Nevertheless, it is worth emphasizing the role of shear flexibility on the value of eccentricity to be adopted in verifications; indeed, since second order effects are usually of concern, the following magnified value of eccentricity has to be considered to take into account its total value according to equation (2.20):

$$e_{0,tot} = \frac{e_0}{1 - \frac{N}{N_{cr,V}}} \quad . \tag{3.5}$$

The expression of the magnification factor considered in the above equation is based on the definition given in (3.1) of critical load considering the role of shear flexibility $1/S_v$. As a matter of principle, the above eccentricity of the axial force results in an external moment M which can be defined as follows:

$$M = \frac{Ne_0}{1 - \frac{N}{N_{cr,V}}} \quad , \tag{3.6}$$

introducing a further compression in one of the two connected members (is the case of plane built-up members is of interest) which can be estimated as follows:

$$N_f = \frac{N}{2} + \frac{M}{h_0} = \frac{N}{2} \cdot \left[1 + \frac{\frac{2e_0}{h_0}}{1 - \frac{N}{N_{cr,V}}} \right] , \tag{3.7}$$

where h_0 is the distance between the centroids of the two chord members as already represented in Figure 3.1.

The following two section point out the theoretical basis and the key code provisions for both braced and battened members.

3.3 Laced members

Laced members are made out of two chord connected by a bracing system with inclined lacings, in which each segment of longitudinal profile between two braced nodes can be regarded as an isolated beam-column, whose lateral slenderness is considerably reduced at least throughout the plane of lacings. An example of bidimensional braced (or laced) members are represented in Figure 3.1, but even 3-D laced solutions can be adopted especially when longitudinal members are realized through L-shaped (or similar) profiles.

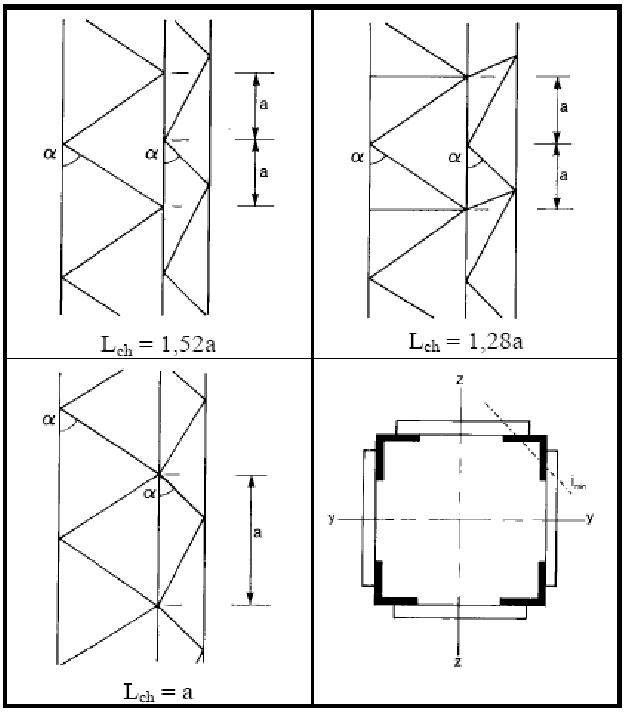


Figure 3.3: General laced members.

3.3.1 Theoretical insights

The theoretical discussion on laced members basically focuses on evaluating shear stiffness S_v for the various possible bracing schemes which are for instance represented in Figure 3.5. Since various possible arrangements can be considered when designing laced members, only one of these solutions will be described in details.

In particular, the one represented in Figure 3.4 will be analysed, considering that its final shear flexibility stems out as a results of the two following strain contributions:

- axial elongation in diagonal lacings;

- axial shortening of the horizontal connection.

The first contribution δ_1 can be easily quantified by considering that the length of the diagonal member is $L_d = a / \sin\phi$ and is stressed by an axial force $N_d = T / \cos\phi$. The

$$\Delta = \varepsilon \cdot L_d = \frac{N_d}{EA_d} \cdot L_d \ , \tag{3.8}$$

which can be easily simplified as follows:

$$\Delta = \frac{T}{\cos\phi} \cdot \frac{1}{EA_d} \cdot \frac{a}{\sin\phi} = \frac{T}{EA_d} \cdot \frac{a}{\sin\phi \cdot \cos\phi} \ . \tag{3.9}$$

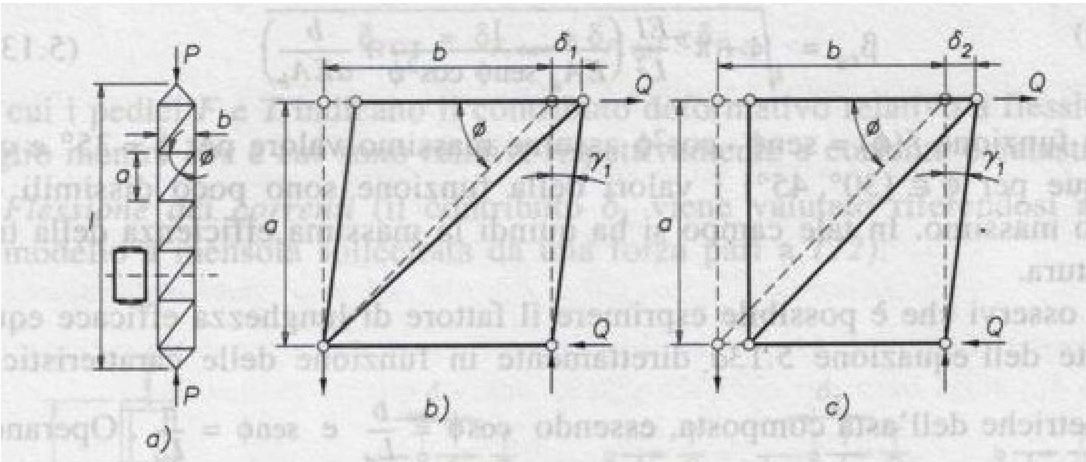


Figure 3.4: Shear stiffness of lacings in built-up members.

Consequently, δ_1 can be expressed as a function of the diagonal elongation Δ as follows:

$$\delta_1 = \frac{\Delta}{\cos\phi} = \frac{T}{EA_d} \cdot \frac{a}{\sin\phi \cdot \cos^2\phi} \ . \tag{3.10}$$

The second contribution δ_2, related to the transverse displacement is related to the axial deformation of the horizontal member under the compressive action T:

$$\delta_2 = \frac{T}{EA_b} \ , \tag{3.11}$$

being EA_b the axial stiffness of the horizontal connection.

Finally, the shear deformation of the elementary cell of the considered laced member can be evaluated by considering both contributions:

$$\gamma = \frac{\delta_1 + \delta_2}{a} = T \cdot \left(\frac{1}{EA_d \sin\phi \cdot \cos^2\phi} + \frac{b}{aEA_b} \right) \ . \tag{3.12}$$

Since, by definition, the shear stiffness is the force T resulting in a unit value of the shear deformation γ (namely, $T = S_v \cdot \gamma$) the following definition can be determined for S_v, suitably expressed in terms of shear flexibility $1/S_v$:

$$\frac{1}{S_v} = \frac{1}{EA_d \sin\phi \cdot \cos^2\phi} + \frac{b}{a \cdot EA_b} \ . \tag{3.13}$$

Consequently, the critical load for these laced members can be expressed by introducing equation (3.12) in (3.1):

$$N_{cr,V} = \frac{1}{\dfrac{1}{N_{cr}} + \dfrac{1}{EA_d \sin\phi \cdot \cos^2\phi} + \dfrac{b}{a \cdot EA_b}} \ , \tag{3.14}$$

and an equivalent slenderness value can be defined according to equation (3.3):

$$\lambda_{eq} = \lambda \sqrt{1 + \pi^2 EA \cdot \left[\frac{1}{EA_d \sin\phi \cdot \cos^2\phi} + \frac{b}{a \cdot EA_b} \right]} \ . \tag{3.15}$$

An equivalent value of the β_{eq} coefficient for the laced member (related to the flexural stiffness *EI* along the axis perpendicular to the lacings plane) can be even defined as follows:

$$\beta_{eq} = \sqrt{1+\pi^2 \frac{EI}{L} \cdot \left[\frac{1}{EA_d \sin\phi \cdot \cos^2\phi} + \frac{b}{a \cdot EA_b} \right]} \quad , \tag{3.16}$$

and if one remembers the possible definitions of $\cos\phi = b/L_d$ and $\sin\phi = a/L_d$ the following simplification can be found for the above relationship:

$$\beta_{eq} = \sqrt{1+\pi^2 \frac{I}{L^2 b^2 a} \cdot \left[\frac{L_d^{\,3}}{A_d} + \frac{b^3}{A_b} \right]} \quad . \tag{3.17}$$

3.3.2 Code provisions

The key code provisions for laced members will be examined in the following with reference to both Italian and European Standards.

3.3.2.1 European Code [14] provisions

The stability check, along with all the structural verification dealing with members and connections, have to be carried out by assuming an accidental eccentricity due to imperfections which can be defined according to equation (3.4). Consequently the design action in the single chord of a laced member whose total axial force is N_{Sd} can be derived according to the following equation which summarized the concept formulated in paragraph 3.3.1.

$$N_{f,Sd} = \frac{N_{Sd}}{2} + \frac{M}{h_0} = \frac{N_{Sd}}{2} \cdot \left[1 + \frac{\dfrac{2e_0}{h_0}}{1 - \dfrac{N_{Sd}}{N_{cr}} - \dfrac{N_{Sd}}{S_v}} \right] \quad . \tag{3.18}$$

The value of the critical load N_{cr} has to be determined by neglecting the shear flexibility influence which is present explicitly at the denominator of equation (3.18). Consequently, the usual expression can be considered:

$$N_{cr} = \frac{\pi^2 EIe_{ff}}{L^2} \quad , \tag{3.19}$$

where the effective moment of inertia I_{eff} is defined for one of the two axes which does not cross all the connected chord sections:

$$I_{eff} = 0.5 \cdot A_f \cdot h_0^{\;2} \quad , \tag{3.20}$$

being A_f the area of the single chord section and h_0 the distance between their centroids.

A virtual shear force V_S has to be also considered for the strength check of the connections and can be determined as a function of the above eccentricity e_0:

$$V_S = \frac{\pi M_S}{L} = \frac{\pi}{L} \cdot \frac{e_0}{1 - \dfrac{N_{Sd}}{N_{cr}} - \dfrac{N_{Sd}}{S_v}} \quad . \tag{3.21}$$

Moreover, the diagonal members have to be checked considering the following values of axial force N_d:

$$N_d = \frac{V_S \cdot d}{\pi \cdot h_0} \quad . \tag{3.22}$$

The values of shear stiffness S_v, needed for defining the total eccentricity and its effects in terms of axial force in members $N_{f,Sd}$ and the other above mentioned actions, can be taken according to Figure 3.5.

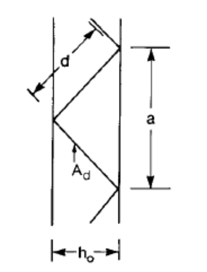
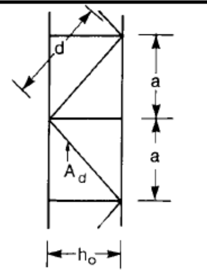
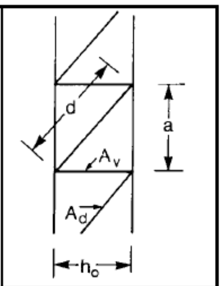
System	 	 	
S_V	$\frac{nEA_d a h_0^2}{2d^3}$	$\frac{nEA_d a h_0^2}{d^3}$	$\frac{nEA_d a h_0^2}{d^3\left[1+\frac{A_d h_0^3}{A_V d^3}\right]}$
n is the number of planes of lacings A_d and A_V refer to the cross sectional area of the bracings			

Figure 3.5: Shear stiffness of lacings in built-up members.

Finally, some basic rules are provided in EC3 for design details of laced members as summarized below:

- when the single lacing systems on opposite faces of a built-up member with two parallel laced planes are mutually opposed in direction as shown in Figure 3.6, the resulting torsional effects in the member should be taken into account;
- Tie panels should be provided at the ends of lacing systems, at points where the lacing is interrupted and at joints with other members.

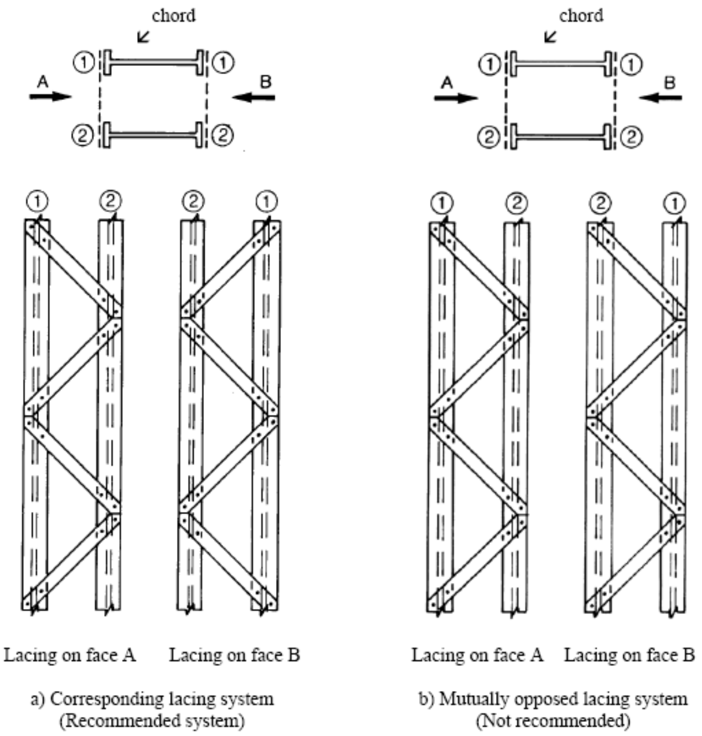


Figure 3.6: Practical design rule for built-up member with two parallel laced planes.

3.3.2.2 Italian Code [15] provisions

The current Italian code on steel structures is widely inspired to EN 1993-1-1 – Eurocode 3 provisions. In particular, for laced the two codes basically provide the same design rules for carrying out stability checks.

3.3.2.3 Former Italian Code [12] provision

An extended version of the Omega Method, already introduced in section 2.8.2 for solid sections is provided by the Italian Code for addressing the issue of stability check in laced members. Curves *c* or *d* can be assumed in the cases of section flanges and webs thinner or thicker than 40 mm, respectively.

Figure 3.7 shows the possible arrangement addressed by the code, which introduces for their equivalent stiffness λ_{eq} the following equation, substantially equivalent to the one derived within the previous section:

$$\lambda_{eq} = \sqrt{\lambda_y^2 + \frac{10 \cdot A}{L_0 \cdot L_t^2} \cdot \left[\frac{L_d^3}{A_d} + \frac{L_t^3}{A_t} \right]} \ . \tag{3.23}$$

being A the area of the transverse section of the chord members, A_t the area of the horizontal members, and the other distances reported in the mentioned Figure 3.7.

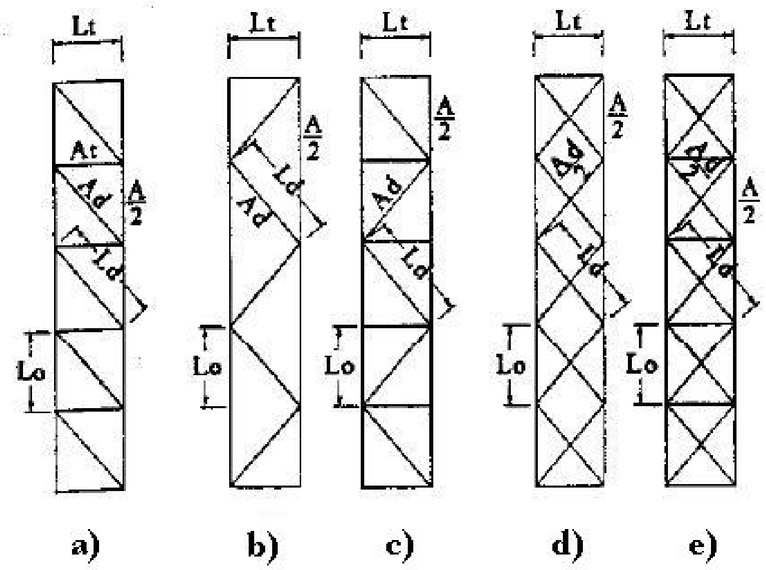


Figure 3.7: Laced members as considered in the Italian Code.

The slenderness λ_y is referred to the built-up transverse section as a whole, around on of the two principal axes which does not cross all the single chord members.

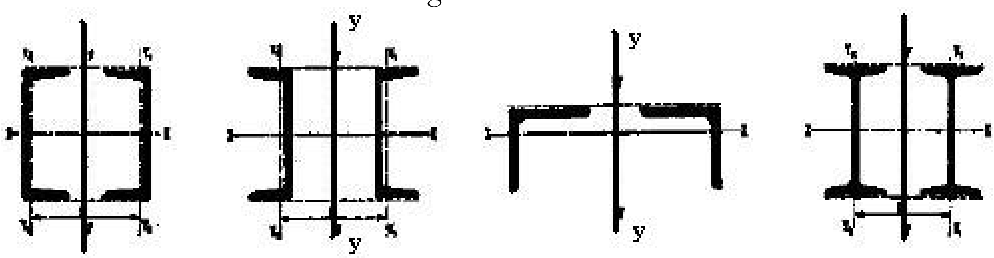


Figure 3.8: General built-up section and main axes as considered in the Italian Code.

For the schema b), c), d) and e) in Figure 3.8 the following simplified relationship can be assumed for the equivalent slenderness:

$$\lambda_{eq} = \sqrt{\lambda_y^2 + \frac{10 \cdot A \cdot L_d^3}{L_0 \cdot L_t^2 \cdot A_d}} \ . \tag{3.24}$$

The stability check of these members is performed by considering a virtual shear force V defined as follows:

$$V = \frac{\omega N}{100} \ . \tag{3.25}$$

where N is the axial force. The value of the coefficient ω can be derived as a function of λ_{eq} according to curve *c* or *d* as specified above.

Finally, it is worth noting that, as a matter of principle, the coefficient ω has the same mechanical meaning of the inverse of the χ factor reported in 2.8.1.

3.3.3 Worked example

Let us consider the laced member in Figure 3.9 stressed in compression under an axial force whose design value is N_{Sd}=3500 kN. The member is 10 m high and simply hinge at its ends. Chord members are realized through IPE 450 profiles while diagonals consists in steel plates with 60x12 mm^2 rectangular section both made out of grade S235 steel.

IPE 450 data:

- depth	h	450 mm;
- width	b	190 mm;
- flange thickness	t_f	14.6 mm;
- web thickness	t_w	9.4 mm;
- radius	r	21 mm;
- area	A_f	9880 mm^2;
- Moment of inertia with respect to the strong axis	I_y	33740 10^4 mm^4;
- Moment of inertia with respect to the weak axis	I_z	1676 10^4 mm^4.

Other geometrical properties are reported in Figure 3.9.

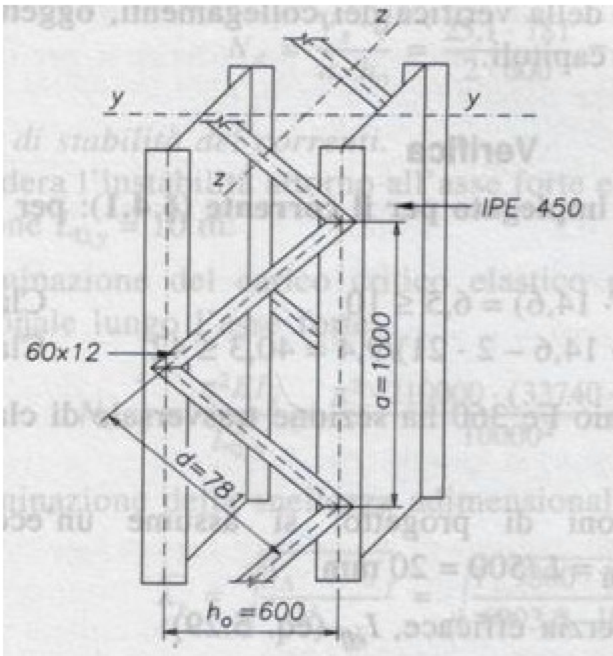


Figure 3.9: Laced member.

3.3.3.1.1 Stability check according to EC3 provisions.

The same exercise can be also faced within the framework of the EC3 provisions which can be applied following the procedures described within the previous paragraphs.

<u>Step #1: classifying the transverse section:</u>

Since the adopted steel grade is f_y=235 MPa, the value ε=1 can be assumed for the parameter mentioned in Table 2.2 and Table 2.3. The following values of the length-to-thickness ratios can be evaluated for flange and web:

- flange $c/t_f=(190/2)/14.6=6.5\leq10$ Class 1;
- web $d/t_w=(450-2\cdot14.6-2\cdot21)/0.4=40.3\leq42$ Class 3

Finally, the profile IPE 450 made out of steel S235 is in <u>class 3</u> if loaded in compression.

<u>Step #2: evaluating the design actions:</u>

The eccentricity e_0 which has to be considered for taking into account the possible imperfection effects is defined as follows according to equation (3.2):

$$e_0 = \frac{L}{500} = 20\ mm\ .$$

The effective value of the moment of inertia of the built-up section I_{eff} can be also calculated according to equation (3.20):

$$I_{eff} = 0.5 \cdot h_0^{\ 2} \cdot A_f = 0.5 \cdot 600^2 \cdot 9880 = 1778.4 \cdot 10^6\ mm^4\ .$$

and the shear stiffness can be assumed on the basis of the formula reported in Figure 3.5 with reference to the scheme under consideration:

$$S_v = \frac{n \cdot E \cdot A_d \cdot a \cdot h_0^{\ 2}}{2 \cdot d^3} = \frac{2 \cdot 210000 \cdot 720 \cdot 1000 \cdot 600^2}{2 \cdot 781^3} = 114261.8 \cdot 10^3\ N = 114261.8\ kN\ .$$

The elastic critical load N_{cr} can be then easily evaluated:

$$N_{cr} = \frac{\pi^2 \cdot E \cdot I_{eff}}{L^2} = \frac{\pi^2 \cdot 210000 \cdot 1778.64 \cdot 10^4}{10000^2} = 36859.4 \cdot 10^3\ N = 36859.4\ kN\ ,$$

in which the overall effective length L=10000 mm has been considered since the calculation is aimed at deriving the total effect of the eccentricity e_0 on the beam-column as a whole. Indeed, the moment M_S induced by the eccentricity e0 can be evaluated as follows:

$$M_S = \frac{N_{Sd} \cdot e_0}{1 - \frac{N_{Sd}}{N_{cr}} - \frac{N_{Sd}}{S_v}} = \frac{3500 \cdot 20}{1 - \frac{3500}{36859.4} - \frac{3500}{114261.8}} = 80053.4\ kNmm\ .$$

Taking into account the magnification effect due to second order displacements.

Finally, the actions on the various members can be easily derived by means of the relationships reported at the end of the previous paragraph:

- the axial force on the longitudinal chord member:

$$N_{f,Sd} = \frac{N}{2} + \frac{M_S}{h_0} = \frac{3500}{2} + \frac{80053.4}{600} = 1883.4\ kN\ ,$$

- the shear force V_S:

$$V_S = \frac{\pi M_S}{L} = \frac{3.14 \cdot 80053.4}{10000} = 25.1\ kN\ ,$$

- the axial force N_d in the diagonal members:

$$N_d = \frac{V_S \cdot d}{n \cdot h_0} = \frac{25.1 \cdot 781}{2 \cdot 600} = 16.4\ kN\ .$$

<u>Step #3: performing the stability check of the chord members:</u>

The reduction factor χ due to the slenderness of the member has to be calculated by looking after the possible instability in both the principal direction *y* and *z*, as represented in Figure 3.10.

<u>Step #3.1: calculation of χ_y for instability in the z direction:</u>

As far as the possible instability in the plane orthogonal to the y-axis (namely, buckling in z direction) is considered, the vale of the effective length coincides with the overall span length of the member, since no lacings restraints buckling in the considered direction, lying the diagonal members in a plane parallel to the y-axis. Consequently $L_{0,y}$*=10000 mm* and the moment of inertia of the single longitudinal chord member is I_y:

$$N_{cr,y} = \frac{\pi^2 \cdot EI_y}{L_{0,y}^{\ 2}} = \frac{\pi^2 \cdot 210000 \cdot 33740 \cdot 10^4}{10000^2} = 6993.0 \cdot 10^3\ N = 6993.0\ kN\ .$$

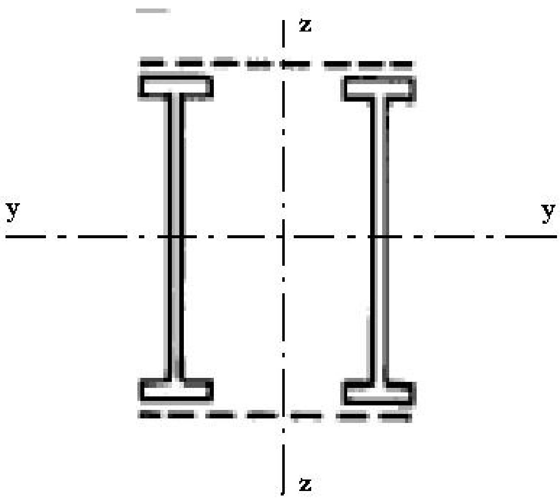


Figure 3.10: Transverse section of the built-up member.

The non-dimensional slenderness can be derived as a function of the elastic critical load $N_{cr,y}$ as follows:

$$\bar{\lambda}_y = \sqrt{\frac{\beta_A \cdot A \cdot f_y}{N_{cr,y}}} = \sqrt{\frac{1 \cdot 9880 \cdot 235}{6993000}} = 0.5762 \ .$$

According to Figure 2.15 the profile follows the *curve a* and, consequently, the following value of the reduction factor χ_y can be evaluated:

$$\Phi_y = 0.5 \cdot \left[1 + \alpha \cdot \left(\bar{\lambda}_y - 0.2\right) + \bar{\lambda}_y^{\,2}\right] = 0.5 \cdot \left[1 + 0.21 \cdot \left(0.576 - 0.2\right) + 0.576^2\right] = 0.705 \ ,$$

and

$$\chi_y = \frac{1}{\Phi_y + \sqrt{\Phi_y^{\,2} - \bar{\lambda}_y^{\,2}}} = \frac{1}{0.705 + \sqrt{0.705^2 - 0.576^2}} = 0.8997 \ .$$

Step #3.2: calculation of χ_z for instability in the y direction:

On the contrary, as far as the possible instability in the plane orthogonal to the z-axis (namely, buckling in y direction) is considered, the value of the effective length coincides with the diagonal spacing, since buckling in y direction is forced by lacings to develop only between two adjacent nodes. Consequently $L_{0,z}$=*1000 mm* and the moment of inertia of the single longitudinal chord member is I_z, have to be determined according to

$$N_{cr,z} = \frac{\pi^2 \cdot EI_z}{L_{0,z}^{\,2}} = \frac{\pi^2 \cdot 210000 \cdot 1676 \cdot 10^4}{1000^2} = 34737.1 \cdot 10^3 \ N = 34737.1 \ kN \ .$$

The non-dimensional slenderness can be derived as a function of the elastic critical load $N_{cr,z}$ as follows:

$$\bar{\lambda}_z = \sqrt{\frac{\beta_A \cdot A \cdot f_y}{N_{cr,z}}} = \sqrt{\frac{1 \cdot 9880 \cdot 235}{34737100}} = 0.2585 \ .$$

According to Figure 2.15 the profile follows the *curve b* and, consequently, the following value of the reduction factor χ_y can be evaluated:

$$\Phi_z = 0.5 \cdot \left[1 + \alpha \cdot \left(\bar{\lambda}_z - 0.2\right) + \bar{\lambda}_z^{\,2}\right] = 0.5 \cdot \left[1 + 0.34 \cdot \left(0.259 - 0.2\right) + 0.259^2\right] = 0.544 \ ,$$

and

$$\chi_z = \frac{1}{\Phi_z + \sqrt{\Phi_z^{\,2} - \bar{\lambda}_z^{\,2}}} = \frac{1}{0.544 + \sqrt{0.544^2 - 0.259^2}} = 0.979 \ .$$

Step #3.3: calculating the axial bearing capacity :

Since $\chi_y<\chi_z$, the strong axis of the built-up section is the z-axis, which is the weak one for the single member. This observation points out the huge effect of lacings in changing the behaviour of the single member to obtain a built-up one. Finally, the axial load bearing capacity can e evaluated as follows:

$$N_{f,y,Rd} = \chi_{\min} \cdot \beta_A \cdot A \cdot \frac{f_{ay}}{\gamma_{M1}} = 0.899 \cdot 1 \cdot 9880 \cdot \frac{235}{1.05} = 1986.1 \cdot 10^3 \ N = 1986.1 \ kN \ .$$

and the built-up member complies with the stability check according to Ec3 provisions:

$$N_{f,y,Sd} = 1883.4 \ kN < N_{f,y,Rd} = 1986.1 \ kN \ .$$

3.4 Battened members

Battened members are widely utilized as a technological solution for realizing beam-columns in industrial buildings. Some theoretical insights are given in the following about the mechanical behaviour of this kind of members, the procedure for stability check and the related code provisions.

3.4.1 Theoretical insights

Due to the significant flexural stiffness of battenings and the related connections with the chord members, the nodes between the longitudinal profiles and the horizontal battenings is usually assumed as completely fixed, rather than hinges as usually considered for laced members.

Consequently, the lateral shear flexibility of this kind of members can be determined considering the following three contributions:

- bending in longitudinal members;
- bending in battening;
- shear strains in battenings.

Without going in depth about the mathematical demonstration, the following formula can be obtained for the shear flexibility $1/S_v$:

$$\frac{1}{S_v} = \frac{a^2}{24 \cdot E \cdot I_{ch}} + \frac{ab}{12 \cdot E \cdot I_b} + \frac{\chi_V \cdot a}{b \cdot A_b \cdot G} \ .$$

and the following value of the elastic critical load $N_{cr,V}$ can be defined according to equation (3.1):

$$N_{cr,V} = \frac{\pi^2 EI}{L^2} \cdot \left[\frac{1}{1 + \frac{\pi^2 EI}{L^2} \cdot \left(\frac{a^2}{24 \cdot E \cdot I_{ch}} + \frac{ab}{12 \cdot E \cdot I_b} + \frac{\chi_V \cdot a}{b \cdot A_b \cdot G} \right)} \right] ,$$

or, equivalently, the following equivalent expression of the β coefficient for the battened member can e introduced:

$$\beta_{eq} = \sqrt{1 + \frac{\pi^2 EI}{L^2} \cdot \left(\frac{a^2}{24 \cdot E \cdot I_{ch}} + \frac{ab}{12 \cdot E \cdot I_b} + \frac{\chi_V \cdot a}{b \cdot A_b \cdot G} \right)} \ ,$$

Although, the overall shear flexibility of the member can be determined by summing the three above contributions, the values of both flexural and shear stiffness of the battenings are usually significantly greater than out-of-plane flexural stiffness of the chord member. Consequently a simpler expression can be assumed for the equivalent coefficient β_{eq}:

$$\beta_{eq} = \sqrt{1 + \frac{\pi^2 EI}{L^2} \cdot \frac{a^2}{24 \cdot E \cdot I_{ch}}} \ ,$$

Specific code provisions about the battened members will be reported and commented in the following paragraph.

3.4.2 Code provisions

The key code provisions for battened members will be examined in the following with reference to both Italian and European Standards.

3.4.2.1 European Code [14] provisions

Since battenings are usually assumed infinitely stiff with respect to the chord sections, EC3 provided a lower bound for their moment of inertia I_b with respect to the one of the chord member and other geometrical parameters:

$$\frac{n \cdot I_b}{h_0} \geq 10 \cdot \frac{I_f}{a} \quad . \tag{3.26}$$

a being the battening spacing.

The compressive force $N_{f,Sd}$ acting on the single chord member can be determined as follows for taking into account the effect of eccentricity e_0 due to imperfections:

$$N_{f,Sd} = \frac{N_{Sd}}{2} + 0.5 \cdot \frac{M_S \cdot h_0 \cdot A_f}{I_{eff}} \quad . \tag{3.27}$$

where the moment M_s is defined as follows:

$$M_S = \frac{N_{Sd} e_0}{1 - \frac{N_{Sd}}{N_{cr}} - \frac{N_{Sd}}{S_v}} \quad . \tag{3.28}$$

and the effective moment of inertia can be estimated as follows:

$$I_{eff} = 0.5 \cdot h_0^{\,2} \cdot A_f + 2 \cdot \mu \cdot I_f \quad . \tag{3.29}$$

The parameter μ is basically defined as a function of slenderness λ:

$$\mu = \begin{cases} 1 & if \ \lambda \leq 75 \\ 2 - \lambda/75 & if \ 75 \leq \lambda \leq 150 \\ 0 & f \ \lambda > 150 \end{cases} \quad , \tag{3.30}$$

where the mentioned slenderness is defined as follows

$$\lambda = \frac{L}{i_0} \quad , \tag{3.31}$$

and $i_0 = \sqrt{0.5 \cdot I_1 / A_f}$ with I_1 equal to I_{eff} in equation (3.29) assuming μ=1.

The elastic critical load N_{cr} in equation (3.28) can be evaluated according to the following expression:

$$N_{cr} = \frac{\pi^2 E I_{eff}}{L^2} \quad , \tag{3.32}$$

and the shear stiffness S_v can be evaluated as follows if the limitation (3.26) is respected:

$$S_v = \frac{2\pi^2 E I_f}{a^2} \quad . \tag{3.33}$$

On the contrary, in the general case, the shear stiffness S_v has to be evaluated as follows:

$$S_v = \frac{24 E I_f}{a^2 \cdot \left(1 + \frac{2 \cdot I_f}{n \cdot I_b} \cdot \frac{h_0}{a}\right)} \leq \frac{2 \cdot \pi \cdot E \cdot I_f}{a^2} \quad . \tag{3.34}$$

The shear force to e considered in local verifications according to the equilibrium conditions represented in Figure 3.13 can be evaluated as already described for laced members according to equation (3.20).

Finally, EC3 as already mentioned for the Italian code, classifies the battened members on the basis of the distance between the longitudinal chord members. In particular, for closely spaced members, the above provision does not apply and the general procedure given for the usual members described in section 2 can be applied.

Examples of closely spaced battened members are represented in Figure 3.11 and considering different types of longitudinal profiles.

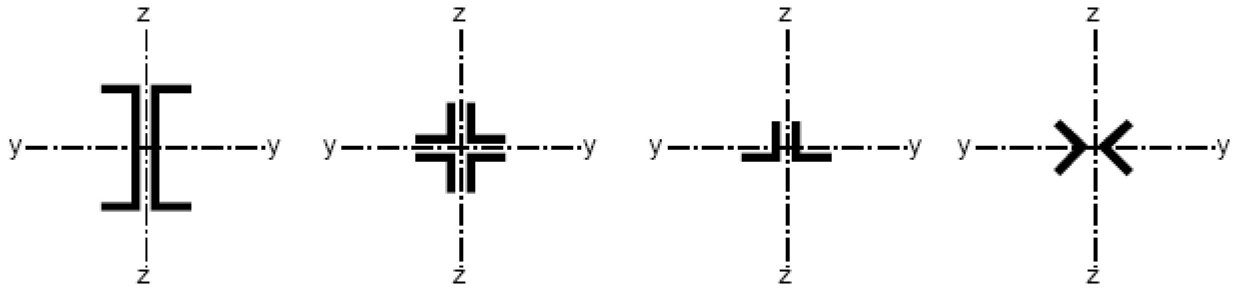


Figure 3.11: Closely spaced built-up members.

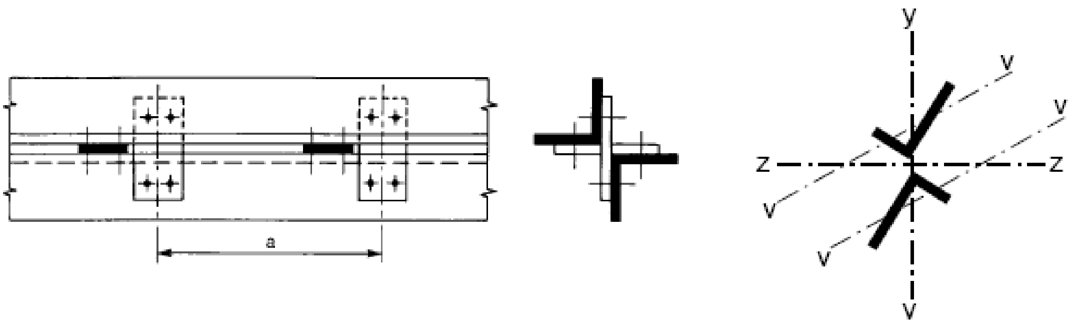


Figure 3.12: So-called star-battened members.

With reference to the various arrangements represented in the two last figures the built-up member can e classified as "closely spaced" if the limitations in Table 3.1 apply.

Table 3.1: Maximum spacings for interconnections in closely spaced built-up or star battened angle members [14].

Type of built-up member	Maximum spacing between interconnections
Members according to Figure 3.11 connected by bolts or welds	15 i_{min}
Members according to Figure 3.12 connected by pair of battens	70 i_{min}

3.4.2.2 Italian Code [15] provisions

Provisions for battened members within the Italian Code are completely equal to the corresponding ones which can be found in EN 1993-1-1 Eurocode 3 as well as already told about laced ones. However, an explicit formula is suggested within the commentary for determining the slenderness λ to be considered in equation (3.31):

$$\lambda = \frac{L}{i_0} = L \cdot \sqrt{\frac{2 \cdot A_C}{0.5 \cdot h_0^2 \cdot A_C + 2 \cdot I_C}} \quad . \tag{3.35}$$

being $A_C = A_f$ the area of the transverse section of the profile connected within the battened member.

Finally, strength verification of connections (either bolted or welded) between battenings and chord members has to be carried out by introducing the shear force V_{Ed} as a function of the eccentricity e_0:

$$V_{Ed} = \pi \cdot \frac{M_{Ed}}{L} \quad . \tag{3.36}$$

taking the design value of the bending moment by equation (3.28).

The effect of shear force V_{Ed} on the various members of the built-up beam-column can be taken into account by considering the free-body diagram and the resulting bending and shear stresses represented in Figure 3.13.

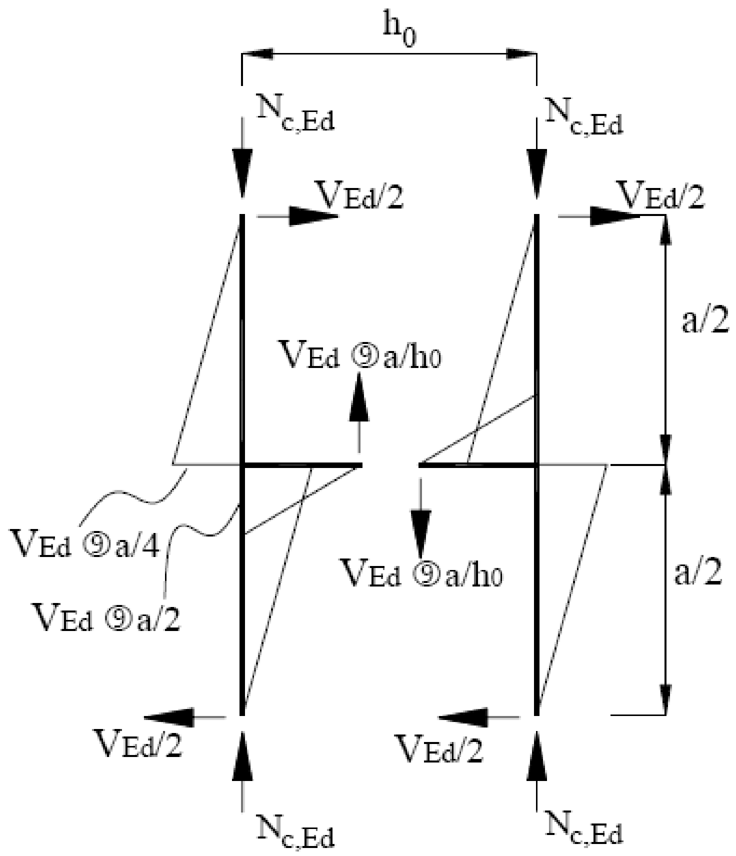


Figure 3.13: Moments and forces in an end panel of a battened built-up member.

3.4.2.3 Former Italian Code [12] provisions

An extended version of the Omega Method, already introduced in section 2.8.2 for solid sections and extended to laced ones in section 3.3.2.2, is provided by the Italian Code for addressing the issue of stability check in battened members. Curves *c* or *d* can be assumed in the cases of section flanges and webs thinner or thicker than 40 mm, respectively.

Provided that spacing between the chord profiles is parameter of concern for the mechanical behaviour of the built-up members, two classes of members can be recognised:

- closely spaced members;
- spaced members.

No specific design requirements are provided for the first ones, which can be checked against strength as well as stability as provided for simple members.

On the contrary, for spaced members the following expression of the equivalent slenderness in the direction(s) of concern for battenings is given:

$$\lambda_{eq} = \sqrt{\lambda_y^2 + \lambda_1^2} \ . \qquad (3.37)$$

where λ_1 is the maximum slenderness of the single chord considering an effective length equal to the battening spacing.

Further design requirements are imposed on battened built-up members:

- battening should be realized by rectangular plates whose aspect ratio is not smaller than 2;
- the maximum spacing of battenings has to be no wider than 50 ρ_{min}, the minimum gyration radius for the single member. This limit is even stricter (40 ρ_{min}) for steel of grade S275 and S355;
- shear force to be considered for local checks has to be evaluated as follows:

$$V_S = \frac{\omega N}{100} \ . \qquad (3.38)$$

3.4.3 Worked examples

3.5 Unworked examples