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METHODS OF ANALYSIS OF FRAME STRUCTURES ACCORDING TO THE EUROCODE EN 1993-1-1

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Abstract. In accordance with the guidelines contained in the European standard prEN 1993-1-1 (draft September 2020), the stability of multi-storey frames should be checked taking into account the influence of geometric imperfections and deformation of the structure under the applied load. The article presents the calculation methods recommended by the European standard, which allow for the verification of frame bar stability. The calculation method was made dependent on taking into account the influence of global sway imperfection and equivalent local bow imperfections, as well as on the type of static analysis used to determine the internal forces and moments.

Keywords: metal structures, calculation methods, European standard, global imperfections, local imperfections, static analysis.

Introduction. When verifying the stability of multi-storey frames, European code prEN 1993-1-1 recommends:

a) considering the effect of structural imperfections on the behaviour of the frames, and

b) determining the internal forces while taking into account the deformation of the structure caused by the load acting on it.

Therefore, chapters 7.2 and 7.3 of the prEN 1993-1-1 European standard, give the recommendations on methods for checking the stability of the frame members. Depending on the consideration of global sway imperfections, equivalent bow imperfections and the type of design analysis applied (1st or 2nd order), it was recommended to verify the frame members stability according to various calculation methods (M0, M1, M2, M3, M4, M5, and EM) described in the paper.

(All the information in this paper, the text of the recommendations and guidelines, has been strictly and directly taken from the draft European standard prEN 1993-1-1.)

1.1. Considering the effect of structural imperfections. Frame imperfections should be considered as geometric imperfections and modeled as:

a) an imperfect geometry of the frame structure in the following forms: sway imperfections for global analysis of frames and equivalent bow imperfections for global and member analysis – which includes both flexural buckling and lateral torsional buckling;

b) systems of forces: equivalent horizontal forces, introduced for each column for sway imperfections and system of equivalent horizontal forces, introduced for each member, for bow imperfection;

c) imperfection based on elastic critical buckling modes – where the shape of the elastic critical buckling mode of the frame's structure may be used as an unique global and local initial imperfection.

According to the recommendations of the European standard prEN 1993-1-1, frame imperfections may be neglected in the static calculations if the listed conditions are met:

a) considering sway imperfections for global analysis of frames, when

$$H_{Ed} \geq 0{,}15F_{Ed} \tag{1}$$

where: H_{Ed} is the total horizontal load designed, F_{Ed} is the total vertical load designed.

b) considering equivalent bow imperfection for global and member analysis, when at least one moment resistant joint at one member and

$$N_{Ed} \geq 0{,}25N_{cr} \tag{2}$$

where: N_{Ed} is the design value of the compression force and N_{cr} is the critical axial force determined for in-plane flexural buckling of the member considered as hinged at it's ends.

If the above conditions are not met, the values of global sway imperfections and equivalent bow imperfections should be determined according to the following formulas:

a) the initial sway imperfection ϕ:

$$\phi = \phi_0 \alpha_H \alpha_m \tag{3}$$

where ϕ_0 – is the basic value,

ϕ_0 =1/400 – for verification of elastic resistance of cross-sections and members,

ϕ_0 =1/200 – for verification of plastic resistance of cross-sections and members,

α_H – is the reduction factor for height H applicable to columns,

$\alpha_H = \frac{2}{\sqrt{H}} \leq 1{,}0$, H – is the height of the structure in meters,

α_m – is the reduction factor for the number of columns in a row,

$\alpha_m = \sqrt{0{,}5\left(1 + \frac{1}{m}\right)}$, m – is the number of columns in a row including only those columns which carry a vertical load N_{Ed} not less than 50 % of the average value of all the columns in the vertical plane considered,

b) equivalent bow imperfection – flexural buckling

$$e_0 = \frac{\alpha}{\varepsilon}\beta L \tag{4}$$

where α – is the imperfection factor, depending on the relevant buckling curve according to Table 1,

ε – is the material parameter,

$\varepsilon = \sqrt{\frac{235}{f_y}}$, f_y - is the yield strength in N/mm2,

β – is the reference relative bow imperfection according to Table 2,

L – is the member length.

Table 1 – Imperfection factors α for buckling curves

Buckling curve	a0	a	b	c	d
Imperfection facto α	0,13	0,21	0,34	0,49	0,76

(The buckling curves shall be determined according to Table 8.3 of prEN 1993-1-1)

Table 2 – Reference relative bow imperfection β

Buckling about axis	Elastic cross-section verification	Plastic cross-section verification
y-y	1/110	1/75
z-z	1/200	1/68

c) equivalent bow imperfection – lateral torsional buckling

$$e_{0,LT} = \beta_{LT}\frac{L}{\varepsilon} \tag{5}$$

β_{LT} – is the reference relative bow imperfection for lateral torsional buckling according to Table 3.

Table 3 – Reference relative bow imperfection βLT for lateral torsional buckling

Cross-section	Condition	Elastic cross-section verification	Plastic cross-section verification
Rolled	h/b ≤ 2,0 h/b > 2,0	1/250 1/200	1/200 1/150
Welded	h/b ≤ 2,0 h/b > 2,0	1/200 1/150	1/150 1/100

In case of modelling the imperfections as equivalent horizontal forces (regarding the sway imperfection) and systems of equivalent horizontal forces (regarding the bow imperfections), this should be done as described in section 7.3.2 (5) and 7.3.3.1(3) prEN 1993-1-1.

As an alternative to the methods briefly described above, the global sway imperfection and the equivalent bow imperfections can be modelled based on elastic critical buckling modes, according to section 7.3.6 prEN 1993-1-1.

1.2. Type of design analysis of the structure. According to prEN 1993-1-1 the internal forces and moments may be determined using either:

a) first-order analysis, using the initial geometry of the structure, or

b) second-order analysis, taking into account the influence of the deformation of the structure.

Second order analysis is not required if the following conditions are satisfied:

$$\alpha_{cr,ns} = \frac{F_{cr,ns}}{F_d} \geq k_0 = 25 \text{ (unless the N.A. gives a different value)} \quad (6)$$

$$\alpha_{cr,sw} = \frac{F_{cr,sw}}{F_d} \geq 10 \quad (7)$$

where:

$F_{cr,ns}$ is the minimum elastic critical flexural buckling load for either the in-plane or out-of-plane member (non-sway) buckling mode,

$F_{cr,sw}$ is the elastic critical in-plane flexural buckling load for a global (sway) buckling mode,

F_d is the designed load value acting on the structure.

$\alpha_{cr,ns}$ is the factor by which the design load would have to be increased to cause elastic instability in the in-plane or out-of-plane member (non-sway) buckling mode,

$\alpha_{cr,sw}$ is the factor by which the designed load would have to be increased to cause an elastic instability in a global, in-plane (sway) mode.

If the condition (6) is satisfied, second order effects due to in-plane or out-of-plane member (non-sway) buckling may be neglected for the global analysis.

When the condition (7) is satisfied, second order effects due to in-plane (sway) buckling may be neglected for the global analysis and first order analysis may be used for the determination of the in-plane (sway) bending moments.

Second order effects due to lateral torsional buckling may be neglected for the global analysis in the following cases (main recommendations):

a) for certain types of sections, e.g. structural hollow sections and welded box sections or in case of sufficient restraints to the compression flange,

b) when the slenderness limit for susceptibility to lateral torsional buckling is not exceeded

$$\bar{\lambda}_{LT} \leq \bar{\lambda}_{LT,0} \quad (8)$$

where: $\bar{\lambda}_{LT}$ – relative slenderness for lateral torsional buckling, $\bar{\lambda}_{LT,0}$ - plateau length of the lateral torsional buckling curves for rolled and welded sections

1.3. Methods of analysis for ultimate limit state design checks. The method of analysis (first or second order analysis combined with the consideration of imperfections) should be compatible with the cross-section and member verification requirements.

According to the type of structure and the extent of the global analysis, imperfections and second order effects should be considered using one of the following approaches:

a) entirely in the global analysis,

b) partially in the global analysis and partially by verification of the buckling resistance of individual members,

c) by verification of the buckling resistance of 'Equivalent Members', using appropriate buckling lengths in accordance with the global buckling modes of the considered structure.

Ultimate limit state design checks may be carried out using methods of analysis named hereafter M0, M1, M2, M3, M4, M5 or EM. The individual methods are recommended to be used when the following conditions are met:

- Method M0 – if second order effects may be neglected in the global analysis by satisfying the conditions in (6) and (7), and lateral torsional buckling may be neglected in accordance with conditions described above or eq. (8).
- Method M1 – if second order effects may be neglected in the global analysis by satisfying the conditions in (6) and (7), lateral torsional buckling may not be neglected in accordance with conditions described above or eq. (8).
- Method M2 – if second order effects due to member buckling may not be neglected (the condition in (6) is not satisfied) but second order effects due to in-plane. In this method global (sway) buckling may be neglected - the condition in (7) is satisfied).
- Method M3 – if second order effects due to member buckling may not be neglected – the condition in (6) is not satisfied and second order effects due to in plane, global (sway) buckling may not be neglected - the condition in (7) is not satisfied. In this method global (sway) imperfections are included in the global analysis and local bow imperfections may be neglected in the global analysis,
- Method M4 – if second order effects due to member buckling may not be neglected – the condition in (6) is not satisfied and second order effects due to in plane, global (sway) buckling may not be neglected – the condition in (7) is not satisfied. All in-plane second order effects and both global (sway) imperfections and local bow imperfections are included in the global analysis,
- Method M5 – if all in-plane and out-of-plane second order effects, including torsional effects, and global (sway) imperfections and in-plane and out-of-plane local bow imperfections are accounted for in the global analysis,
- Method EM – if second order effects may not be neglected in the global analysis (6) or/and in-plane, global (sway) buckling modes cannot be neglected (7), the "Equivalent Member method" may be used for verification of the buckling resistance of individual members.

Detailed information were presented in Table 4.

Table 4 – Methods of structural analysis in case of values of $\alpha_{cr,ns}$ and $\alpha_{cr,sw}$ factors

Requirements	Method name	Rules of verification of the cross-section resistance and stability of members
$\alpha_{cr,ns} \geq 25$ $\alpha_{cr,sw} \geq 10$ LTB → can be neglected	Method M0 imperfections do not need to be included in the global analysis	The verification of the cross-sectional resistance may be based on the first order's internal forces and moments. Verification of the buckling resistance of individual members may be omitted. Imperfections do not need to be included in the global analysis.
$\alpha_{cr,ns} \geq 25$ $\alpha_{cr,sw} \geq 10$ LTB → can't be neglected	Method M1 imperfections do not need to be included in the global analysis	The verification of the cross-sectional resistance may be based on first order's internal forces and moments. The out-of-plane verification of the buckling resistance of individual members is required and may be based first order's internal forces and moments. Imperfections do not need to be included in the global analysis.
$\alpha_{cr,sw} \geq 10$	Method M2 global (sway) imperfections should be included in the global analysis	The verification of the cross-sectional resistance may be based on first order's internal forces and moments. The in-plane and out-of-plane verification of the buckling resistance of individual members is required and may be based on first order's internal forces and moments considering appropriate buckling lengths for the non-sway mode and corresponding bending moment diagrams. The global analysis may neglect equivalent bow imperfections, but should consider global (sway) imperfections.

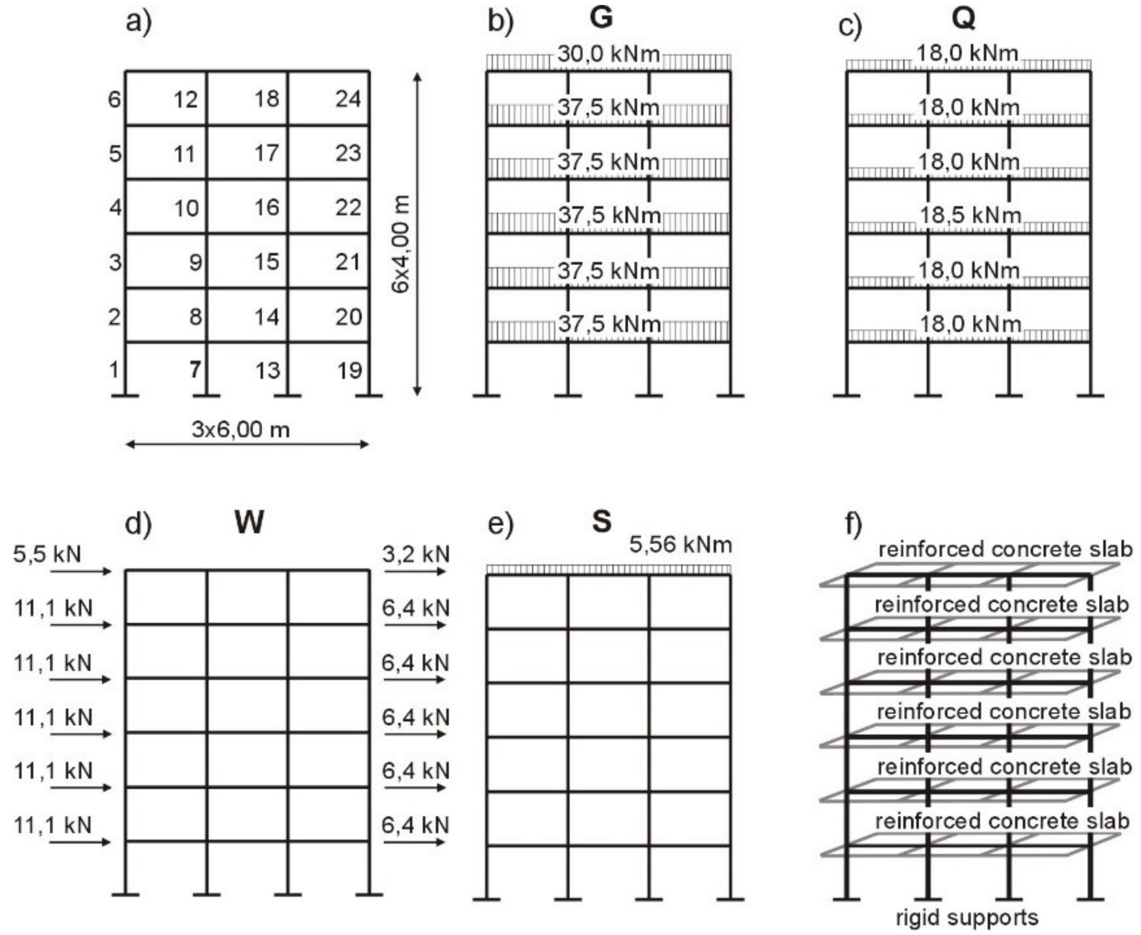
$\alpha_{cr,sw} < 10$ $N_{Ed} \leq N_{cr} / 4$	Method M3 global (sway) imperfections should be included in the global analysis	The verification of the cross-sectional resistance should use the partial factor γM1 and be based on the second order's internal forces and moments. The in-plane and out-of-plane verification of the buckling resistance of individual members is required and should be based on second order internal forces and moments. The in-plane buckling length for the non-sway mode may be used.
$\alpha_{cr,sw} < 10$ $N_{Ed} > N_{cr} / 4$	Method M4 global (sway) imperfections and member bow imperfections(in-plane) should be included in the global analysis	The verification of the cross-sectional resistance should use the partial factor γM1 and be based on second order's internal forces and moments. The in-plane verification of the buckling resistance of individual members in bending and axial compression may be omitted. The out-of-plane verification of the buckling resistance of individual members in bending and axial compression is required and should be based on the second order's internal forces and moments.
$\alpha_{cr,sw} < 10$ $N_{Ed} > N_{cr} / 4$	Method M5 global (sway) imperfections and member bow imperfections considering lateral torsional buckling (in-plane and out-of-plane) should be included	The verification of the cross-sectional resistance should use the partial factor γM1 and be based on the second order's internal forces and moments. The verification of the buckling resistance of individual members may be omitted. The out-of-plane local bow imperfection can either be assumed from Table 1 or Table 2, whichever is larger.
	EM method Equivalent Method (optional)	The verification of the cross-sectional resistance may be based on first order internal forces and moments. Imperfections do not need to be included in the global analysis. The verification of the buckling resistance of individual members may be carried out using the first order's internal forces and moments, considering the system effects(possible sway buckling modes) to determine the appropriate buckling length of each individual member.

LTB – lateral torsional buckling

2. Calculation example. In order to show the practical application of the calculation procedure described in the European standard prEN 1993-1-1, a calculation example was made.

A non-bracing, three-span, six-storey sway frame was taken into account. The geometrical dimensions, the static schema and the way of loading the frame were shown in the Fig. 1. All columns were made from HEB 300 profiles, all beams from IPE 400 (floor beams) and IPE 300 (roof beams) profiles. The structure of the frame was made from steel grade S235.

The stability of the most stressed frame column was checked. The selection of the column for the stability verification was made on the basis of the buckling analysis (LBA), as shown in Fig. 2. The method of verification of the member stability was adopted in accordance with the diagram – Fig. 3. The view of modelled imperfection was shown on Fig. 5.



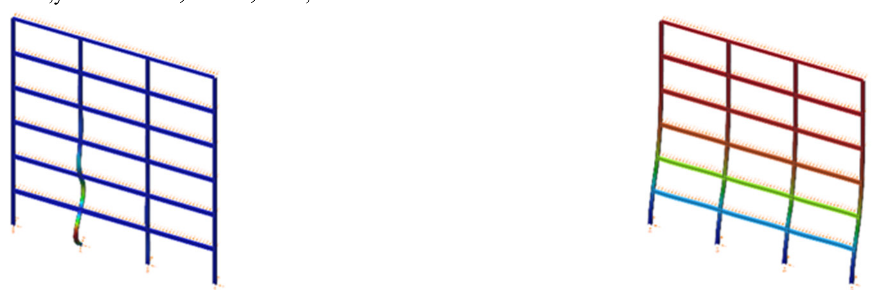
Combination of load of action taking into account: 1,35G + 1,05Q + 0,9W + 0,75S

Figure 1. View of analysed frame, frame dimensions, frame elements numbers and load of the frame

The procedure (when checking the stability of the frame column) is presented in 2.1.

2.1. The calculation procedure:

a) performance of buckling analysis (Linear Buckling Analysis) and determination of critical load factors $\alpha_{cr,ns}$ and $\alpha_{cr,ns}$. Based on results of this analysis, for future calculation the column number 7 was taken into account. The value of elastic critical axial force for flexural buckling about y-y axis and z-z axis, are $N_{cr,y}$ = 23009,9 kN, $N_{cr,z}$ = 16078 kN.

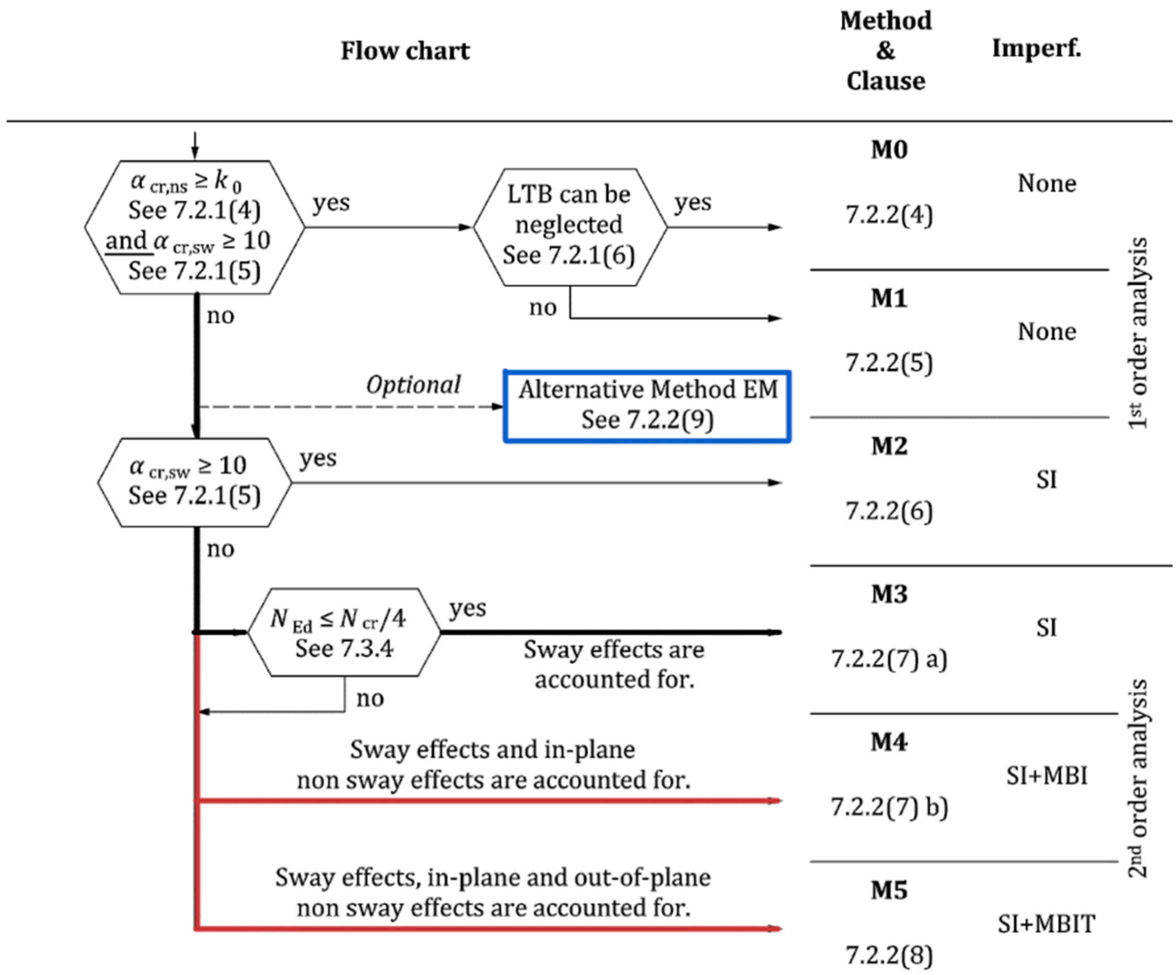


factor αcr,ns = 5,45 out-of-plane member (non-sway) buckling mode

factor αcr,ns = 9,46 in-plane (sway) buckling mode

Figure 2. Out-of-plane and on-plane frame buckling mode

b) Based on above information, calculation method number 3 (Method M3, Figure 1) was taken into consideration. Taking account the fact that more complex methods may be used in place of less complex methods, for comparison purposes, the column stability was also checked according to the M4, M5 and EM methods.



LTB – Lateral torsional buckling, EM – Equivalent member method, SI – Sway imperfection, MBI – Member bow imperfection (in-plane), MBIT – Member bow imperfection considering lateral torsional (in-plane and out-of-plane) buckling. All section numbers are given in accordance with the European standard prEN 1993-1-1

Figure 3. Methods of structural analysis applicable to ultimate limit state design checks

c) Verification of stability of column according to:

Alternative Method EM

type of analysis:	1st order analysis
global sway imperfection:	neglected
local bow imperfection in-plane (buckling):	neglected
local bow imperfection out-of-plane (lateral torsional buckling):	neglected

The verification of the buckling resistance of column no. 7 was made according to section 8.3 prEN 1993-1-1, considering the system effects to determine the appropriate buckling length of the column. Results were shown in Table 5.

Method M3

type of analysis:	2nd order analysis
global sway imperfection:	included
local bow imperfection in plane (buckling):	neglected
local bow imperfection out-of-plane (lateral torsional buckling):	neglected

The in-plane and out-of-plane verification of the buckling resistance of column no. 7 were made according to prEN 1993-1-1. The in-plane buckling length for the non-sway mode was used. The critical length of the Lcr column was assumed to be equal to its height L0 measured in the axes of the frame structure. Results were shown in Table 5.

The global sway imperfection calculations:

$\phi = \phi_0 \alpha_H \alpha_m$

$\phi_0 = \frac{1}{200}$ – for imperfection of plastic resistance of cross-sections and members,

$\alpha_H = \frac{2}{\sqrt{H}} = \frac{2}{\sqrt{24}} = 0{,}408$ – is the reduction factor for height H applicable to columns,

$\alpha_m = \sqrt{0{,}5\left(1 + \frac{1}{m}\right)} = \sqrt{0{,}5\left(1 + \frac{1}{4}\right)} = 0{,}790$ – is the reduction factor for the number of columns in a row, m – number of columns in a row

$\phi = \phi_0 \alpha_H \alpha_m = \frac{1}{200} \cdot 0{,}408 \cdot 0{,}790 = 1{,}61 \cdot 10^{-3}$

Method M4

type of analysis:	2nd order analysis
global sway imperfection:	included
local bow imperfection in-plane (buckling):	included
local bow imperfection out-of-plane (lateral torsional buckling):	neglected

The in-plane verification of the buckling resistance of column no. 7 was omitted. The resistance of cross-sections were made. The out-of-plane verification of the buckling resistance of column no. 7 was made using buckling length as a the non-sway frames. The critical length of the Lcr column was assumed to be equal to its height L0 measured in the axes of the frame structure. Results were shown in Table 5.

The global sway imperfection – as above

The local bow imperfections (buckling):

$e_0 = \frac{\alpha}{\varepsilon} \cdot \beta \cdot L$

$\alpha = 0{,}34$ – is the imperfection factor, depending on the relevant buckling curve

$\varepsilon = 1{,}00$ – is the material parameter defined in 5.2.5(2)

$\beta = \frac{1}{75}$ – is the reference relative bow imperfection, see Table 2

$L = 4{,}00\ m$ – is the member length

$e_0 = \frac{\alpha}{\varepsilon} \cdot \beta \cdot L = \frac{0{,}34}{1{,}00} \cdot \frac{1}{75} \cdot 4000$=18 mm

Method M5

type of analysis:	2nd order analysis
global sway imperfection:	included
local bow imperfection in-plane (buckling):	included
local bow imperfection out-of-plane (lateral torsional buckling):	included

In this case the verification of the buckling resistance of individual members according to 8.3 may be omitted. The verification of the cross-sectional resistance according to section 8.2 prEN 1993-1-1was made using the partial factor γM1.

The global sway imperfection – as aboveю

The local bow imperfections (buckling) – as aboveю

The local bow imperfections (lateral torsional buckling). The out-of-plane local bow imperfection can either be from Table 2 and Table 3, whichever is larger.

$e_{0,LT} = \beta_{LT} \cdot \frac{L}{\varepsilon}$

$\beta_{LT} = max\left(\frac{1}{250}, \frac{1}{200}\right) = \frac{1}{200}$ – is the reference relative bow imperfection for lateral torsional buckling

$L = 4{,}00\ m$ – is the member length

$\varepsilon = 1{,}00$ – is the material parameter defined in section 5.2.5(2) prEN 1993-1-1

$e_{0,LT} = \beta_{LT} \cdot \frac{L}{\varepsilon} = \frac{1}{200} \cdot \frac{4000}{1{,}00} = 20\ mm$

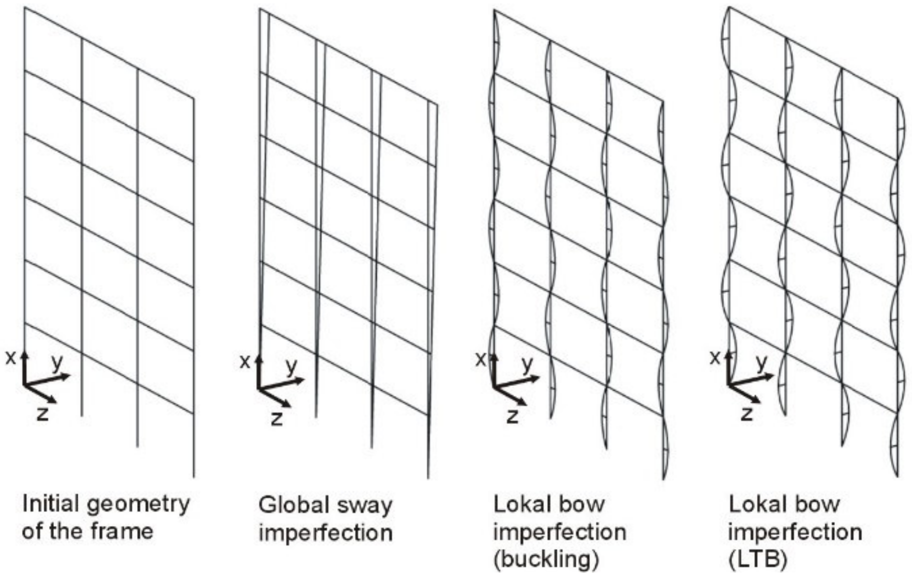


Figure 4. View of global sway imperfection and equivalent local bow imperfection

Table 5 – Results of analysis

		Calculation method			
		EM	M3	M4	M5
Internal forces and moments	N_{Ed} N_{Rd} M_{yEd} M_{yRd} M_{zEd} M_{zRd}	2432,3 kN 3503,3 kN 60,7 kNm 439,1 kNm - 203,7 kNm	2432,3 kN 3503,3 kN 72,6 kNm 439,1 kNm - 203,7 kNm	2432,3 kN 3503,3 kN 118,8 kNm 439,1 kNm - 203,7 kNm	2432,3 kN 3503,3 kN 46,8 kNm 439,1 kNm 41,0 kNm 203,7 kNm
buckling about y-y axis	μ_y χ_y	1,189 0,930	1,000 0,954	- -	- -
buckling about z-z axis	μ_z χ_z	1,00 0,807	0,829 0,807	0,830 0,807	- -
bending about y-y axis	χ_{LT}	1,000	1,000	-	-
interaction factors	k_{yy} k_{yz} k_{zy} k_{zz}	1,028 - 0,677 -	0,984 - 0,677 -	- - 0,465 -	- - - -
resistance of cross-sections		-	-	0,965	1,006
$\frac{N_{Ed}}{\frac{\chi_y N_{Rk}}{\gamma_{M1}}}+k_{yy}\frac{M_{y,Ed}+\Delta M_{y,Ed}}{\chi_{LT}\frac{M_{y,Rk}}{\gamma_{M1}}}+k_{yz}\frac{M_{z,Ed}+\Delta M_{z,Ed}}{\frac{M_{z,Rk}}{\gamma_{M1}}}$		0,889	0,891	-	-
$\frac{N_{Ed}}{\frac{\chi_z N_{Rk}}{\gamma_{M1}}}+k_{zy}\frac{M_{y,Ed}+\Delta M_{y,Ed}}{\chi_{LT}\frac{M_{y,Rk}}{\gamma_{M1}}}+k_{zz}\frac{M_{z,Ed}+\Delta M_{z,Ed}}{\frac{M_{z,Rk}}{\gamma_{M1}}}$		0,954	0,972	0,978	-

3. Conclusions. Based on the analysis of the content of the European standard prEN 1993-1-1, and on the basis of the sample calculations carried out, the following conclusions can be drawn:

- the European standard prEN 1993-1-1 presents 7 design procedures allowing to check the stability of bars in multi-storey frames;
- the choice of the calculation method depends on the sensitivity of the frame structure to buckling both in the frame plane and in the plane perpendicular to the frame plane;
- depending on the consideration in the static calculations of global sway imperfections, equivalent local arc imperfections, as well as the 1st or 2nd order analysis, the stability of the members

in the center-centered compression of multi-storey frames is checked by assuming their critical length appropriate for the given buckling mode (Lcr), equal to the length measured in the axes of the supports (L0), or by checking only the resistance of their cross-section.

Overall conclusion: The more complicated and advanced is the static analysis used to determine the internal forces and moments in the bars of the frame structure, the simpler the method of verifying their load capacity.

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МЕТОДИ АНАЛІЗУ КАРКАСНИХ КОНСТРУКЦІЙ ВІДПОВІДНО ЄВРОКОДУ EN 1993-1-1

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Анотація. Відповідно до вказівок, що містяться в європейському стандарті prEN 1993-1-1 (проект вересня 2020 року), стійкість багатоповерхових рам має перевірятися з урахуванням впливу геометричних відхилень та деформацій конструкції під дією прикладеного навантаження. У статті наведено методи розрахунку, рекомендовані європейським стандартом, які дозволяють перевірити стійкість балок каркасу. Вибір методу розрахунку залежав від урахування впливу глобального відхилення у вигляді розгойдування та еквівалентних відхилень у прогину, а також від типу статичного аналізу, що використовується для визначення внутрішніх сил та моментів.

Ключові слова: металоконструкції, методи розрахунку, європейський стандарт, глобальні відхилення, локальні відхилення, статичний аналіз.

МЕТОДЫ АНАЛИЗА КАРКАСНЫХ КОНСТРУКЦИЙ В СООТВЕТСТВИИ С ЕВРОКОДОМ EN 1993-1-1

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Аннотация: В соответствии с указаниями, содержащимися в европейском стандарте prEN 1993-1-1 (проект сентября 2020 года), устойчивость многоэтажных рам должна проверяться с учетом влияния геометрических отклонений и деформаций конструкции под действием приложенной нагрузки. В статье представлены методы расчета, рекомендованные европейским стандартом, которые позволяют проверить устойчивость балок каркаса. Выбор метода расчета зависел от учета влияния глобального отклонения в виде раскачивания и эквивалентных локальных отклонений в виде прогиба, а также от типа статического анализа, используемого для определения внутренних сил и моментов.

Ключевые слова: металлоконструкции, методы расчета, европейский стандарт, глобальные отклонения, локальные отклонения, статический анализ.