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General method according to EN 1993-1-1, §6.3.4

Formulation. Methodology and applications in the context of CAE

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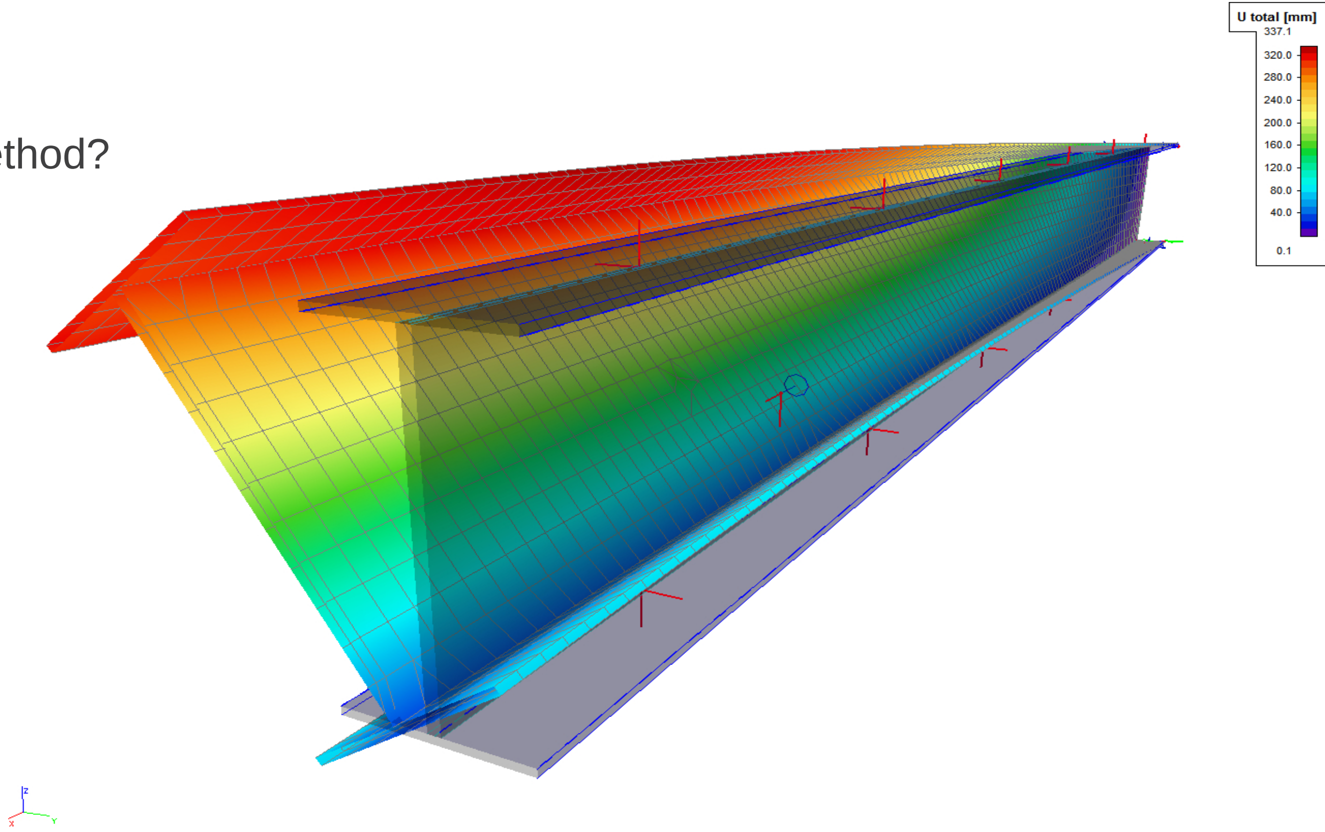
Content of presentation

- What is the General Method?
- When is it used?
- Formulation
- Some examples
- Limitations
- Conclusion



What is the General Method?

- Evaluation of member/2D frame **stability**: **in-plane** & **out-of-plane**
- **Simple formulation**
- **Difficulty**: in deriving the **2 essential parameters** ($\alpha_{ult,k}$ & $\alpha_{cr,op}$)
- Requires the **use of FE software**
- May apply to:
  - **complex** structural **components**
  - structural **components** with **complex restraint conditions & load**

6.3.4 General method for lateral and lateral torsional buckling of structural components

(1) The following method may be used where the methods given in 6.3.1, 6.3.2 and 6.3.3 do not apply. It allows the verification of the resistance to lateral and lateral torsional buckling for structural components such as

- single members, built-up or not, uniform or not, with complex support conditions or not, or
- plane frames or subframes composed of such members,

EN 1993-1-1: 2005 (E) 65

EN 1993-1-1: 2005 (E)

which are subject to compression and/or mono-axial bending in the plane, but which do not contain rotative plastic hinges.

NOTE The National Annex may specify the field and limits of application of this method.

(2) Overall resistance to out-of-plane buckling for any structural component conforming to the scope in (1) can be verified by ensuring that:

$$\frac{\chi_{op}\alpha_{ult,k}}{\gamma_{M1}} \geq 1{,}0 \qquad (6.63)$$

where $\alpha_{ult,k}$ is the minimum load amplifier of the design loads to reach the characteristic resistance of the most critical cross section of the structural component considering its in plane behaviour without taking lateral or lateral torsional buckling into account however accounting for all effects due to in plane geometrical deformation and imperfections, global and local, where relevant;

χ_{op} is the reduction factor for the non-dimensional slenderness $\overline{\lambda}_{op}$, see (3), to take account of lateral and lateral torsional buckling.

(3) The global non dimensional slenderness $\overline{\lambda}_{op}$ for the structural component should be determined from

$$\overline{\lambda}_{op} = \sqrt{\frac{\alpha_{ult,k}}{\alpha_{cr,op}}} \qquad (6.64)$$

where $\alpha_{ult,k}$ is defined in (2)

$\alpha_{cr,op}$ is the minimum amplifier for the in plane design loads to reach the elastic critical resistance of the structural component with regards to lateral or lateral torsional buckling without accounting for in plane flexural buckling

NOTE In determining $\alpha_{cr,op}$ and $\alpha_{ult,k}$ Finite Element analysis may be used.

(4) The reduction factor χ_{op} may be determined from either of the following methods:

a) the minimum value of

χ for lateral buckling according to 6.3.1

χ_{LT} for lateral torsional buckling according to 6.3.2

each calculated for the global non dimensional slenderness $\overline{\lambda}_{op}$.

NOTE For example where $\alpha_{ult,k}$ is determined by the cross section check $\frac{1}{\alpha_{ult,k}} = \frac{N_{Ed}}{N_{Rk}} + \frac{M_{y,Ed}}{M_{y,Rk}}$ this method leads to:

$$\frac{N_{Ed}}{N_{Rk}/\gamma_{M1}} + \frac{M_{y,Ed}}{M_{y,Rk}/\gamma_{M1}} \leq \chi_{op} \qquad (6.65)$$

b) a value interpolated between the values χ and χ_{LT} as determined in a) by using the formula for $\alpha_{ult,k}$ corresponding to the critical cross section

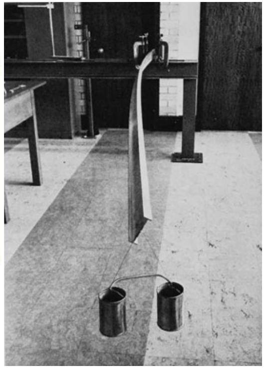
NOTE For example where $\alpha_{ult,k}$ is determined by the cross section check $\frac{1}{\alpha_{ult,k}} = \frac{N_{Ed}}{N_{Rk}} + \frac{M_{y,Ed}}{M_{y,Rk}}$ this method leads to:

66

EN 1993-1-1: 2005 (E)

$$\frac{N_{Ed}}{\chi N_{Rk}/\gamma_{M1}} + \frac{M_{y,Ed}}{\chi_{LT} M_{y,Rk}/\gamma_{M1}} \leq 1 \qquad (6.66)$$

Applications of the General Method



- **Why:** resistance for lateral (**FB**) and lateral-torsional buckling (**LTB**)
- **When:** where §6.3.1 -- §6.3.3 do not apply
- **For:**
  - single members (**built-up** or not, **uniform** or not, with **irregular support** conditions or not)
  - plane **frames** or **sub-frames** composed of such members
- **Load:** compression and/or (mono-axial) **in-plane** bending and shear
- **To watch out:** no plastic hinge rotates!
- The **National Annex may specify** the **field** and **limits of application** of this method

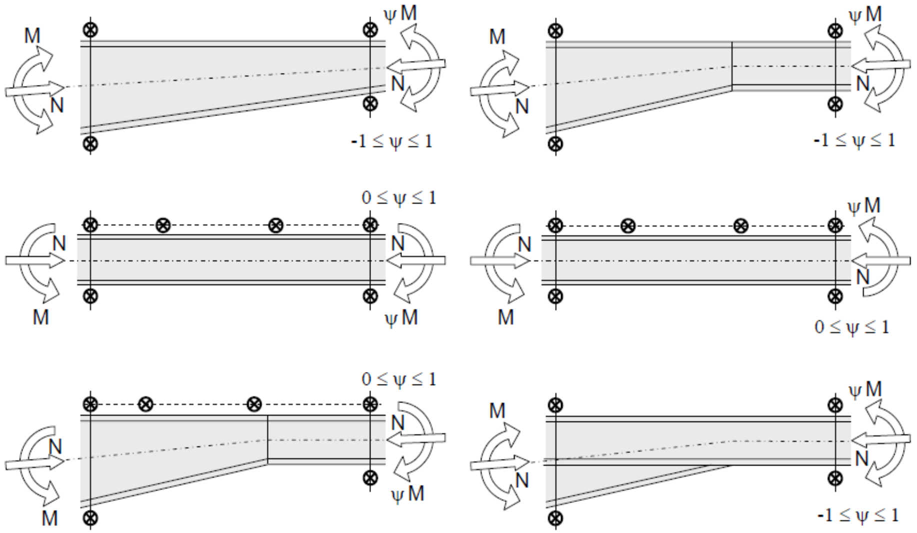
Applications of the General Method

- NBN EN 1993-1-1 ANB:
  - Accepted as a general procedure
  - Only when EC3-1-1, §6.3.1 -- §6.3.3 CANNOT be applied
- NF EN 1993-1-1 NA:
  - Requires that in-plane stability be determined from elastic analysis of the whole structure
- DIN EN 1993-1-1 NA:
  - Limits to I-sections only
  - In-plane stability is limited by formation of first plastic hinge
- BS EN 1993-1-1 NA:
  - Nominally straight components

Applications of the General Method

- SN032a (Access steel, 2010): “*NCCI: General method for out-of-plane buckling in portal frames:*”
  - variable sections, haunches
  - “odd” lateral restraints, different from “simple fork”
  - complex moment distribution

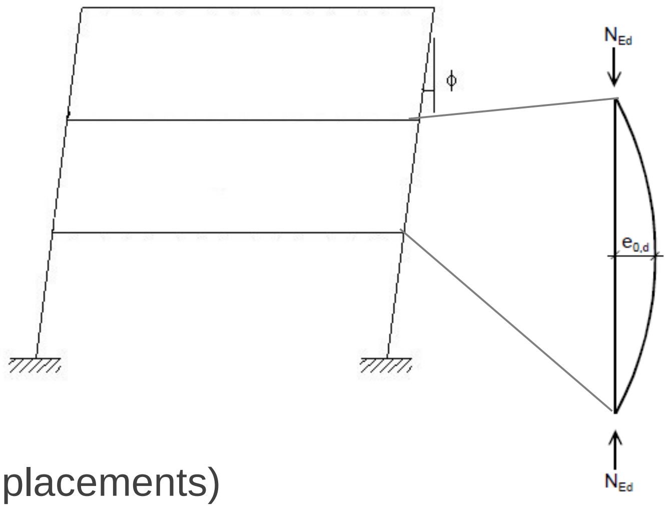
=> Common conditions in portal frames



Examples of structural components in portal frames that can be treated using EN1993-1-1 §6.3.4

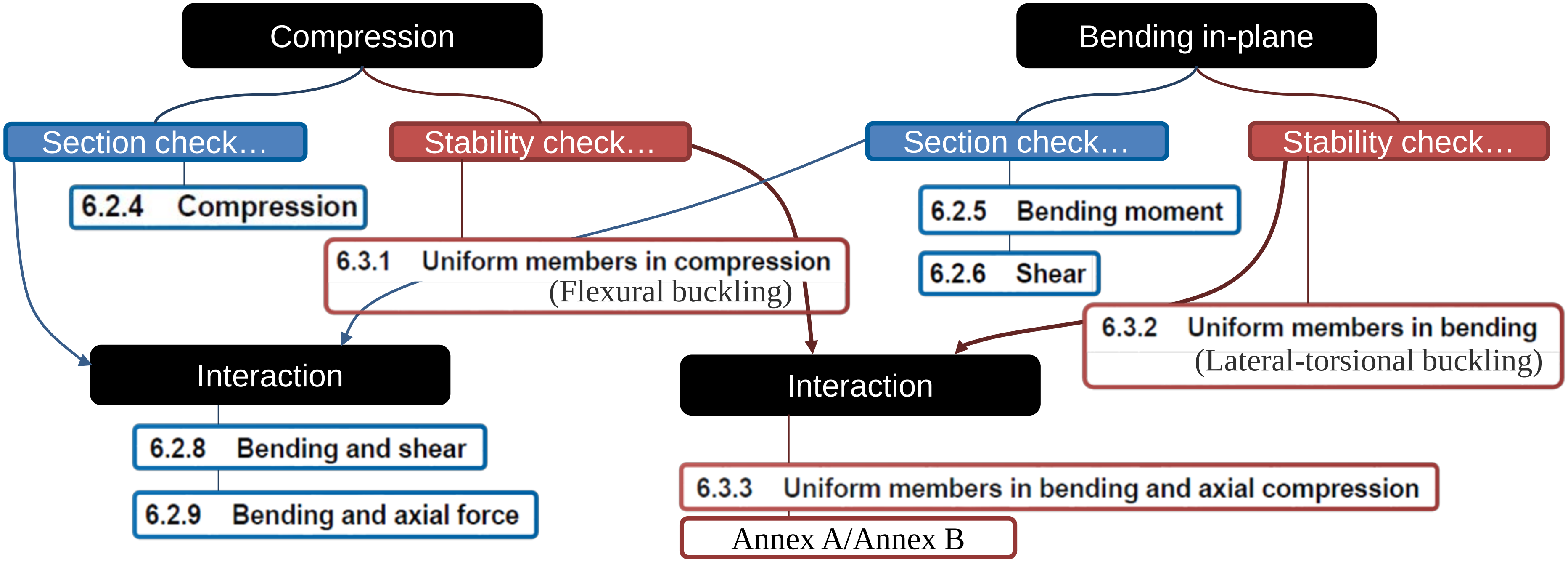
Intermezzo: Stability design of steel frames

- Design against lateral or lateral-torsional buckling:
  - Imperfections:
    - **Global imperfections** of the frame
    - Local (**member**) **imperfections**
  - Deformations:
    - **Second-order** deformation in the **frame** (nodal displacements)
    - Local (**member**) **second-order** deformation
- For uniform members: contained in EN 1993-1-1, Chapters §6.3.1 to §6.3.3



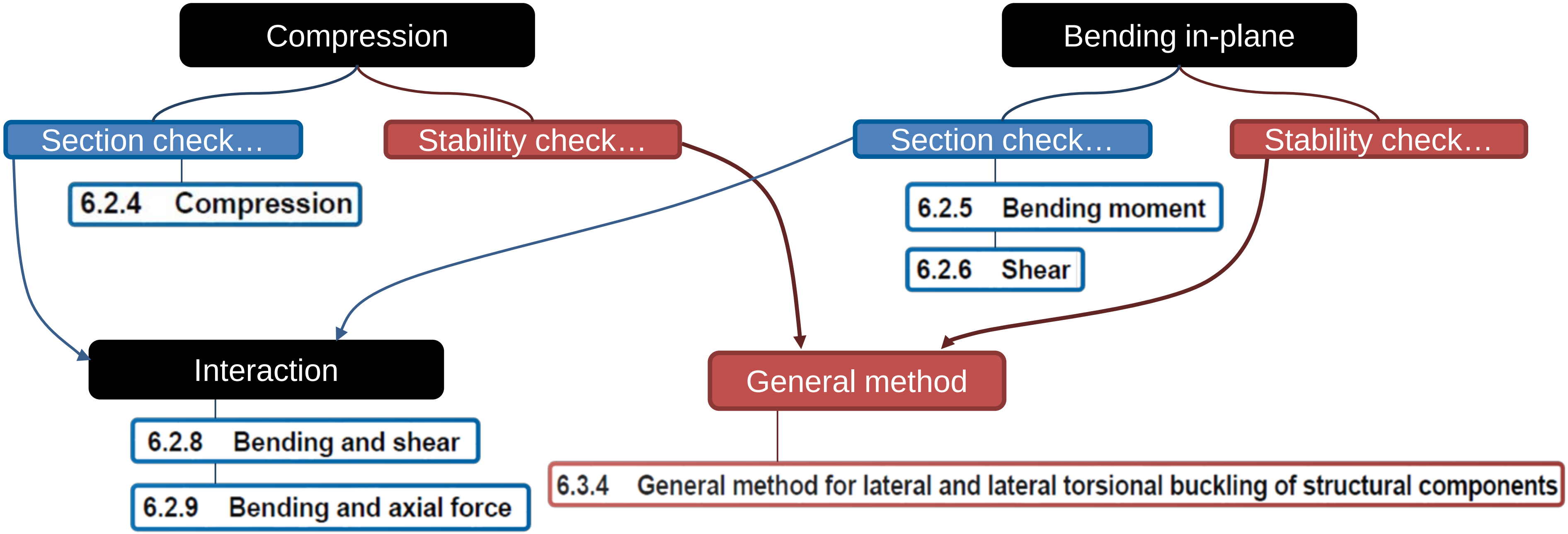
Intermezzo: Stability design of steel frames

Analytical methods according to EN 1993-1-1, 6.2 & 6.3.1 to 6.3.3

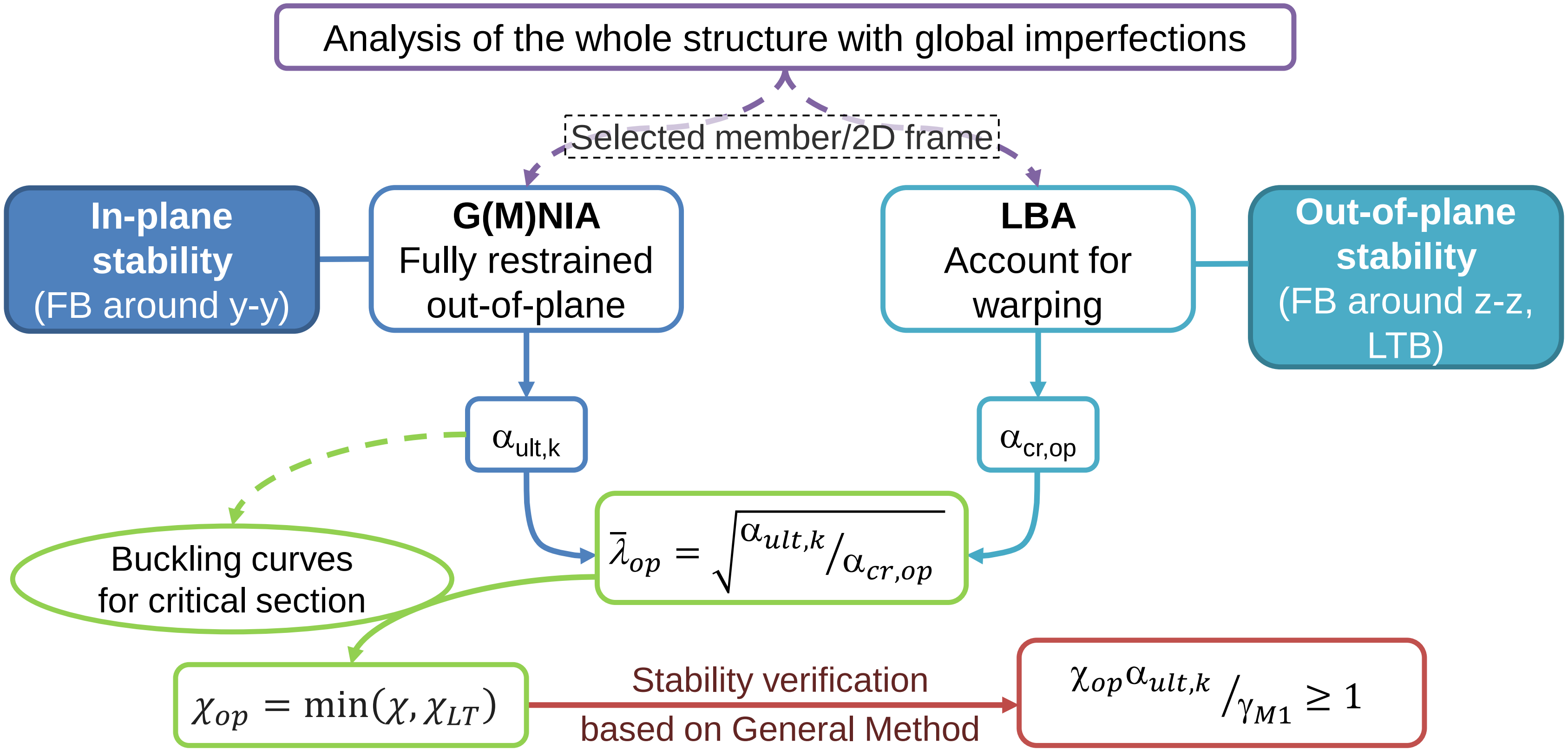


Intermezzo: Stability design of steel frames

Section checks & general method according to EN 1993-1-1, 6.2 & 6.3.4



Formulation of the General Method

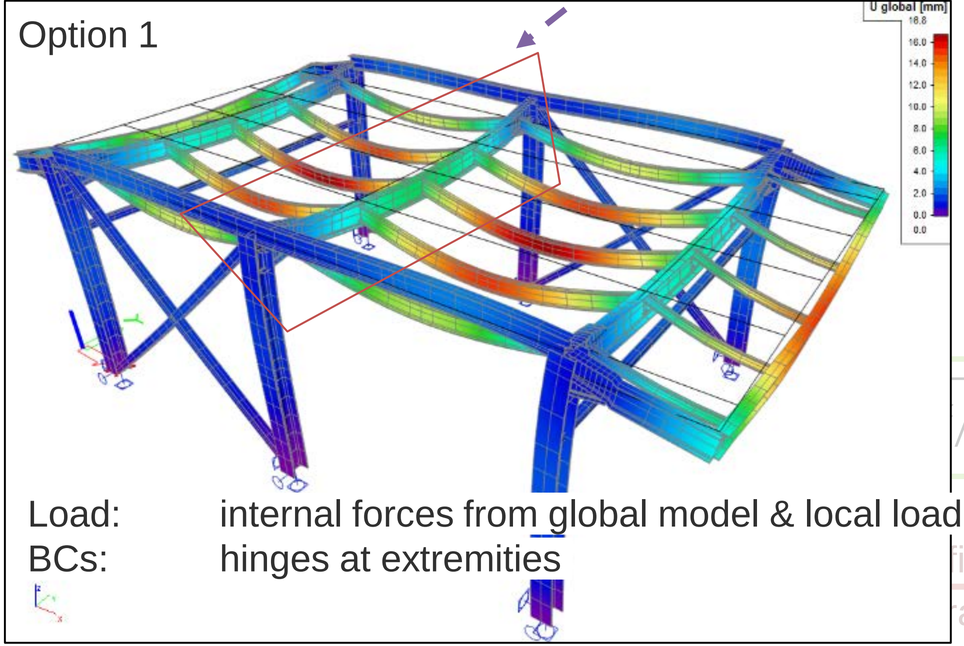


Formulation of the General Method

Analysis of the whole structure with global imperfections

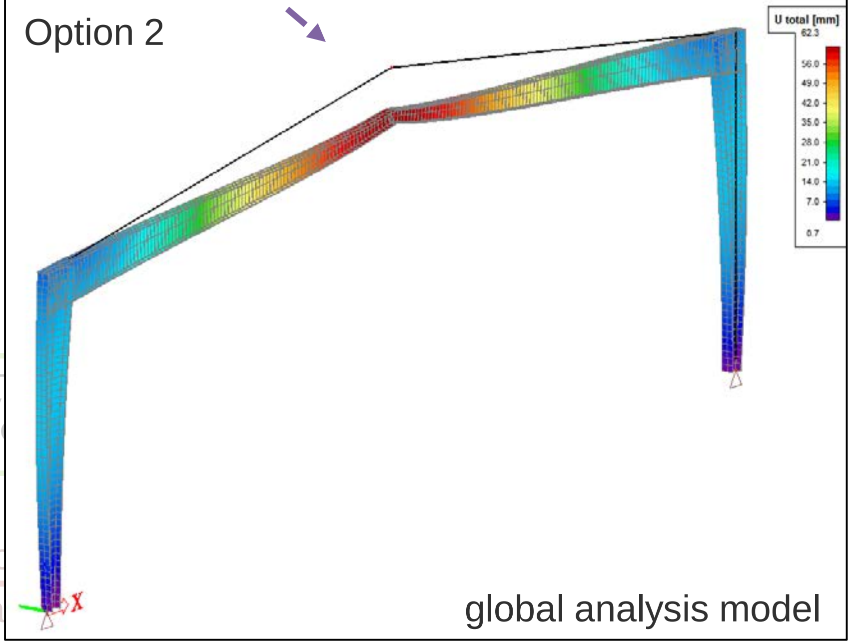
Selected member/2D frame

Option 1



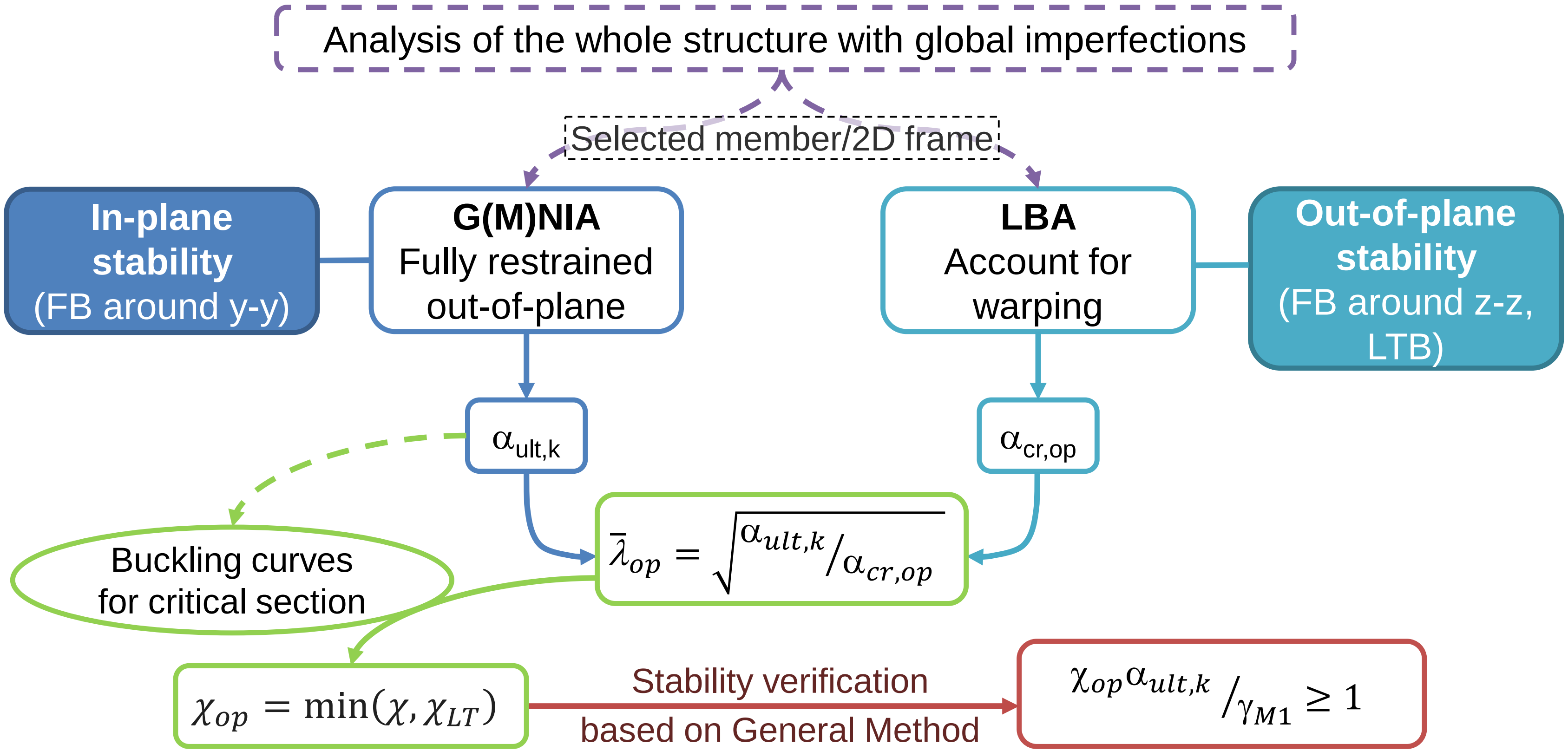
Load: internal forces from global model & local load
BCs: hinges at extremities

Option 2

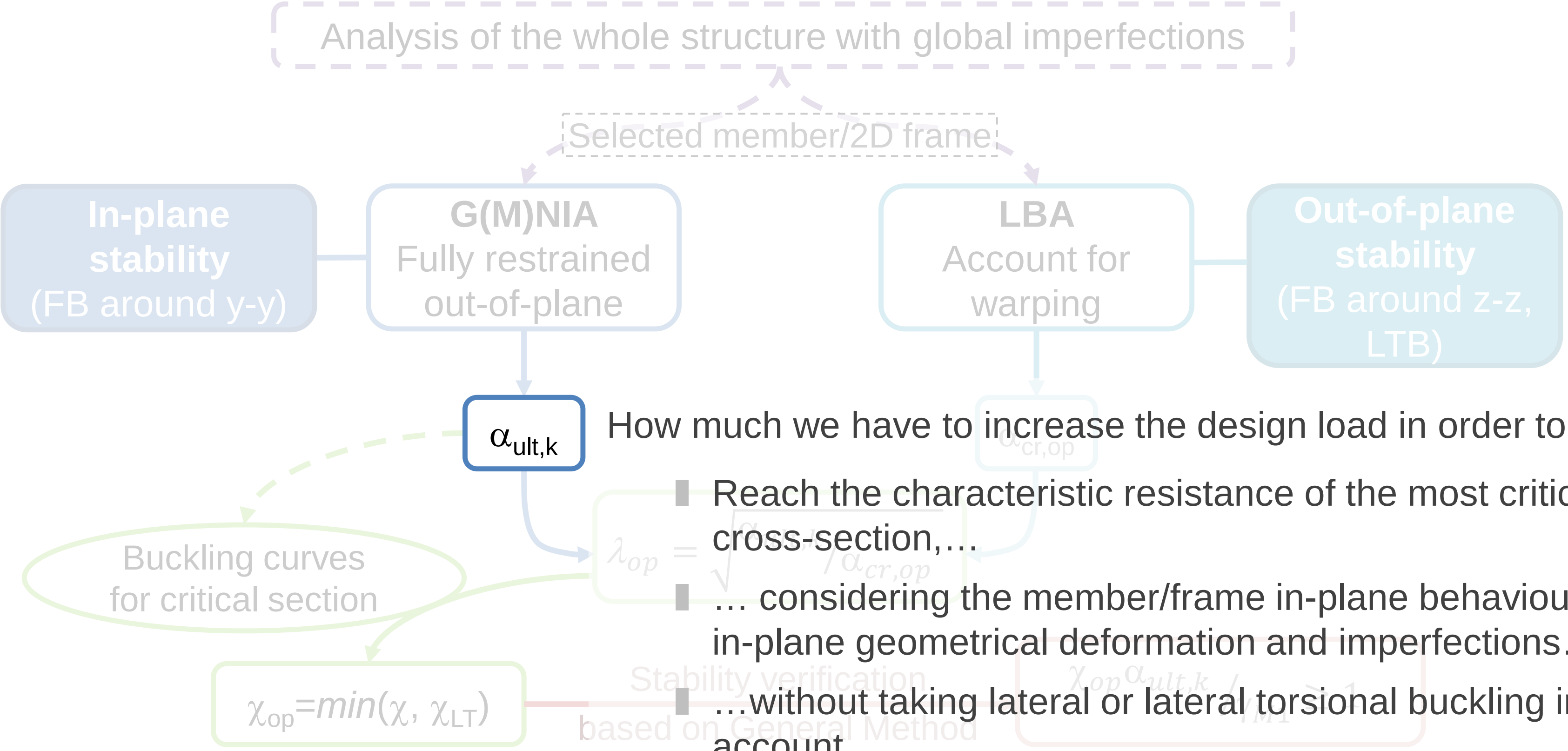


global analysis model

Formulation of the General Method



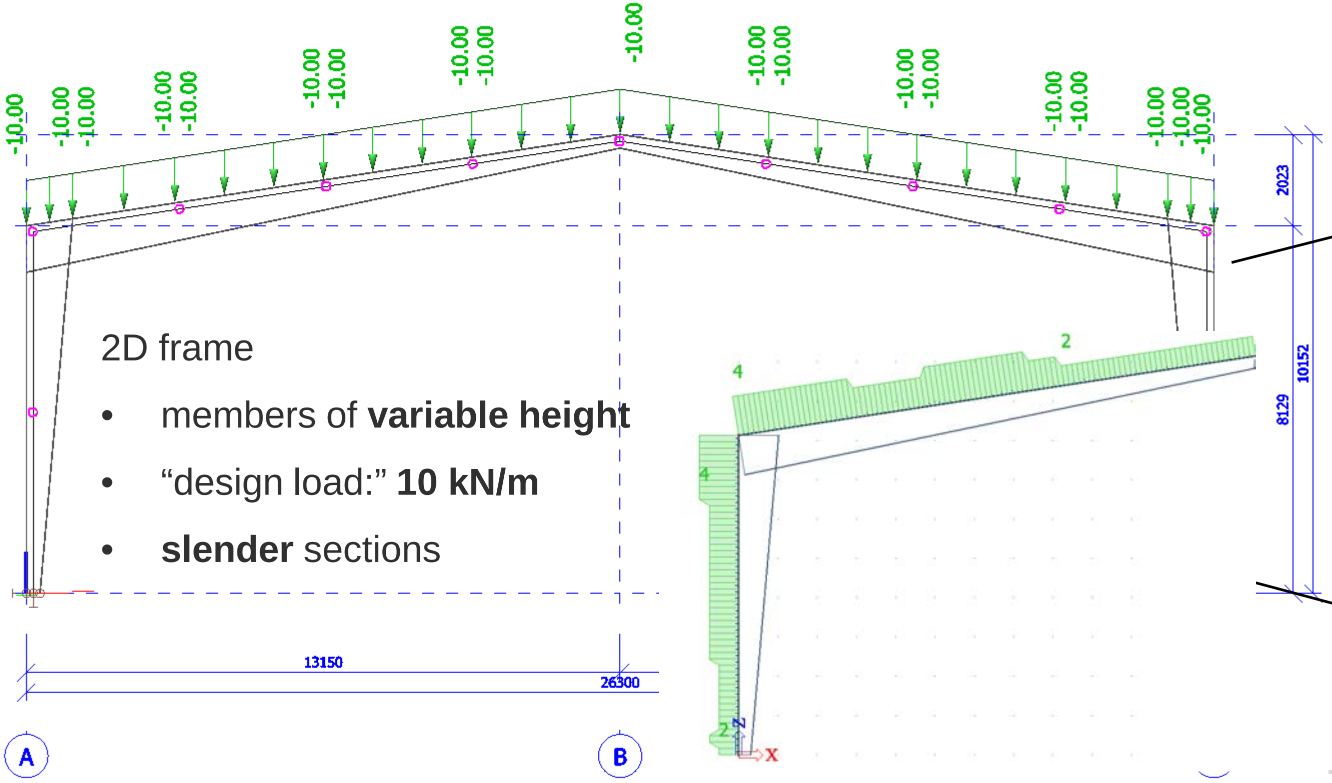
Formulation of the General Method



How much we have to increase the design load in order to:

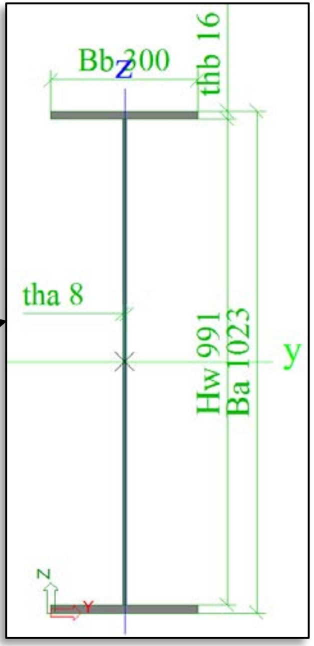
- Reach the characteristic resistance of the most critical cross-section,…
- … considering the member/frame in-plane behaviour: in-plane geometrical deformation and imperfections…
- …without taking lateral or lateral torsional buckling into account

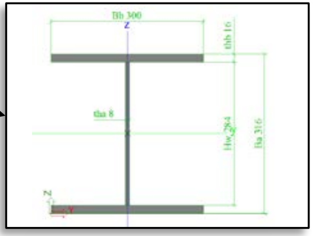
Formulation of the General Method & **Example**



2D frame

- members of **variable height**
- “design load:” **10 kN/m**
- **slender** sections





Formulation of the General Method & **Example**

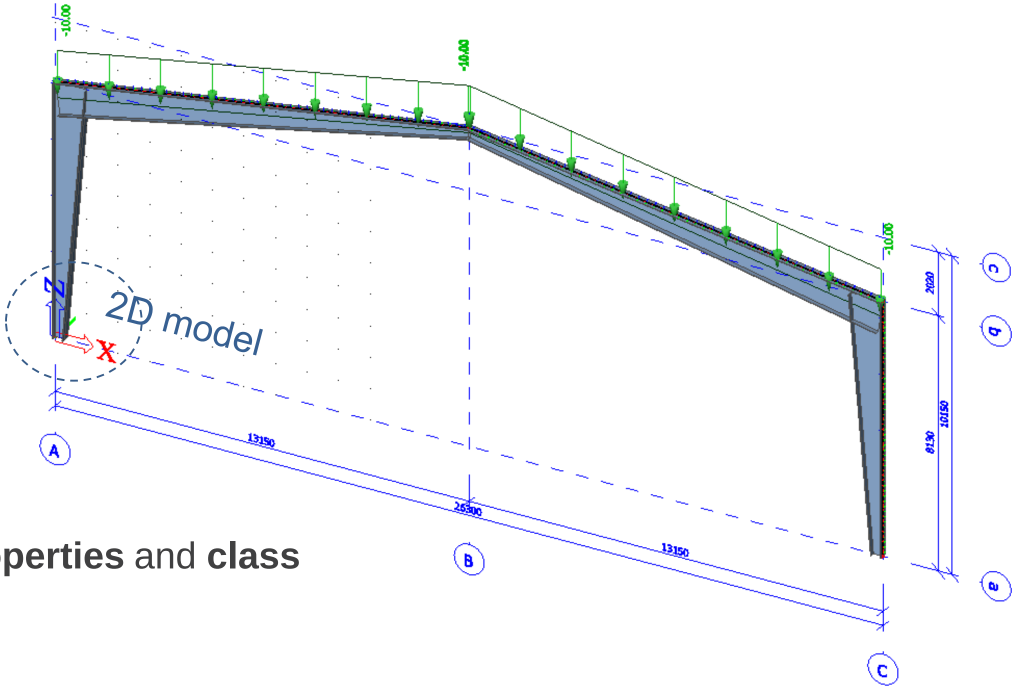
Model: 2nd order analysis of the **frame** taking into account **all in-plane effects**:

In-plane stability
(FB around y-y)

G(M)NIA
Fully restrained out-of-plane

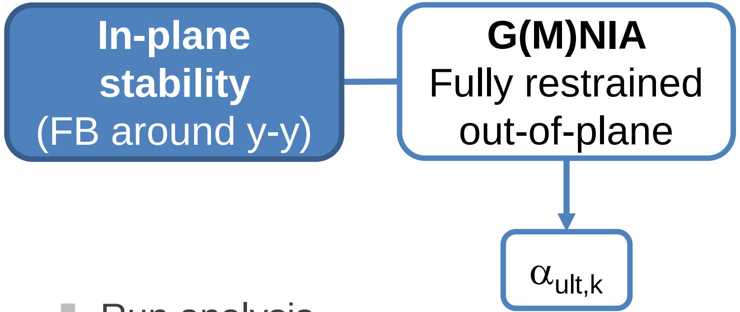
$\alpha_{ult,k}$

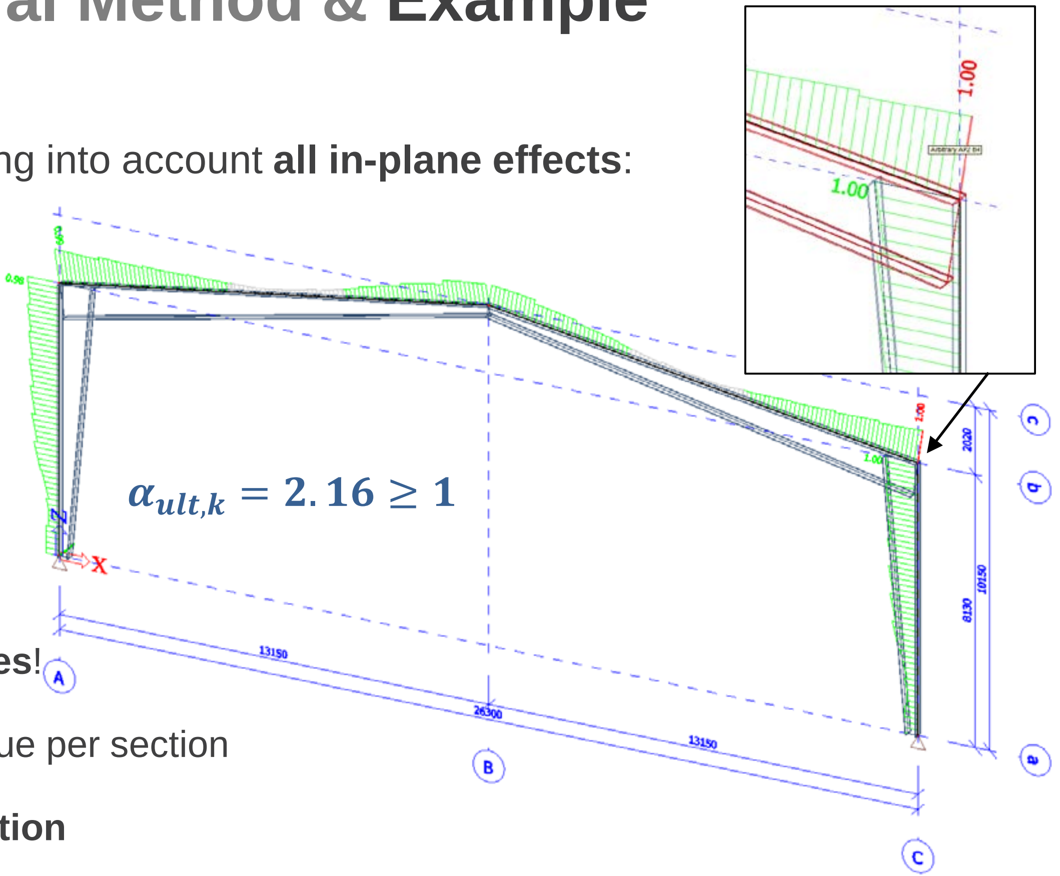
- 3 DoF **beam** elements
- ~**10 sections** per member
- per section: (effective) **cross-section properties** and **class**
- global and member **imperfections**



Formulation of the General Method & Example

Model: 2nd order analysis of the **frame** taking into account **all in-plane effects**:

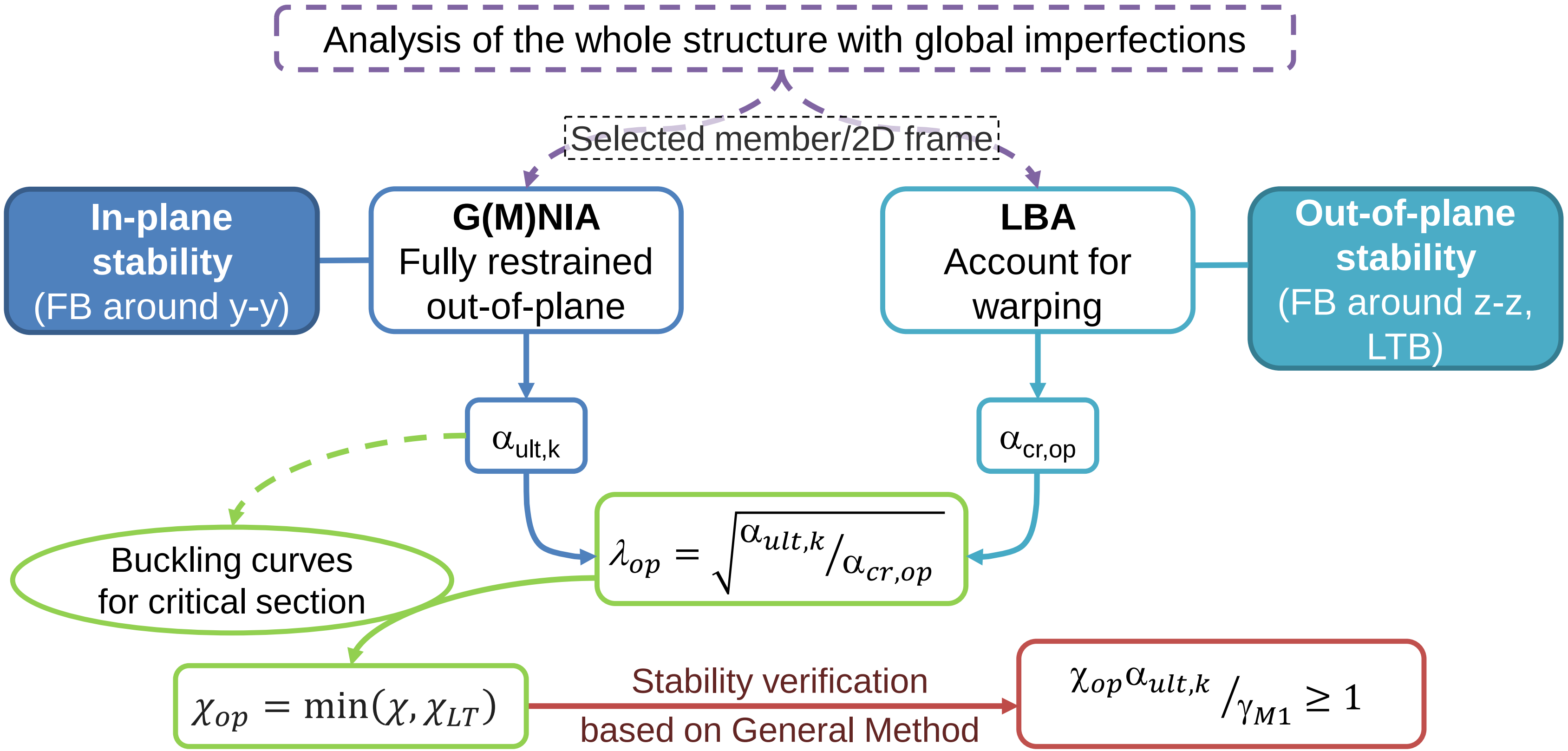




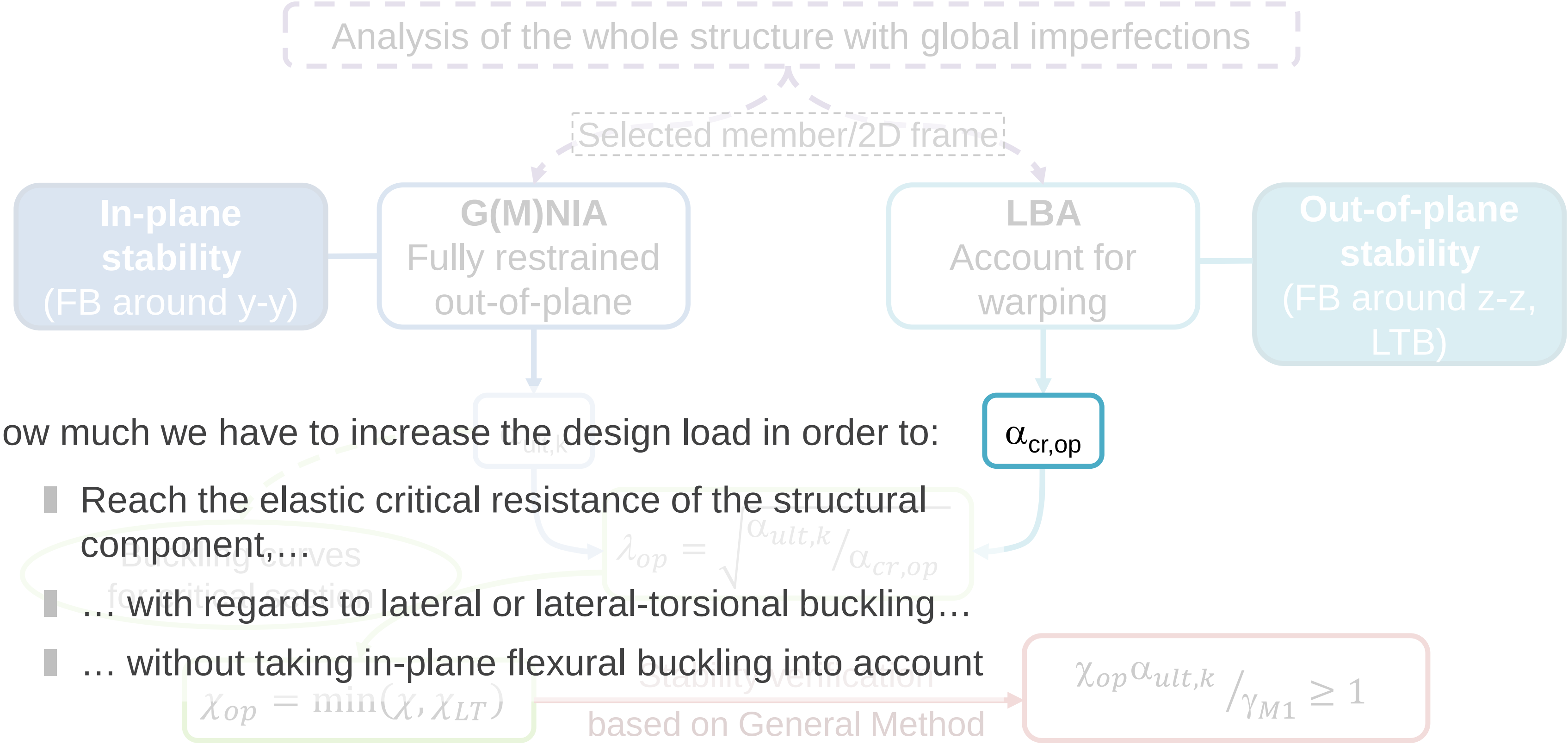
$$\alpha_{ult,k} = 2.16 \geq 1$$

- Run analysis
  - Make sure **no plastic hinge rotates**!
- Derive unity **Cross-Section Check** value per section
- ➔ Maximal unity check == **critical section**

Formulation of the General Method



Formulation of the General Method



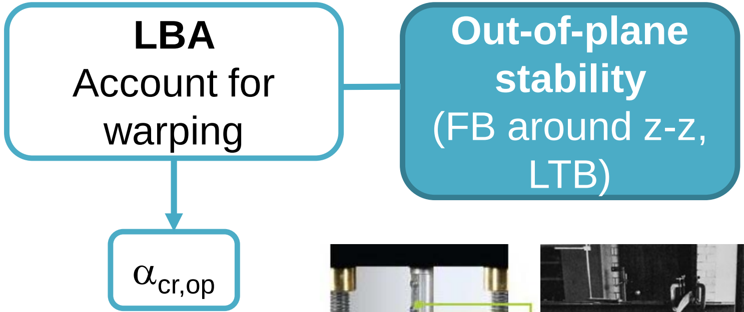
How much we have to increase the design load in order to:

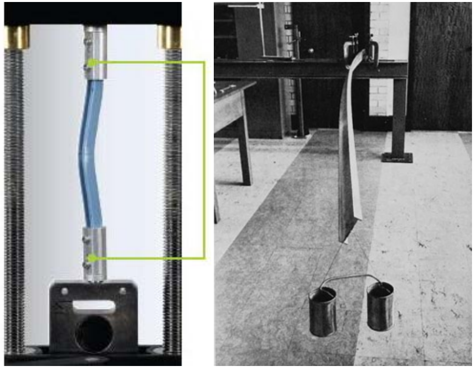
- Reach the elastic critical resistance of the structural component,…
- … with regards to lateral or lateral-torsional buckling…
- … without taking in-plane flexural buckling into account

Formulation of the General Method

Linear stability analysis of the frame **ignoring all in-plane effects**:

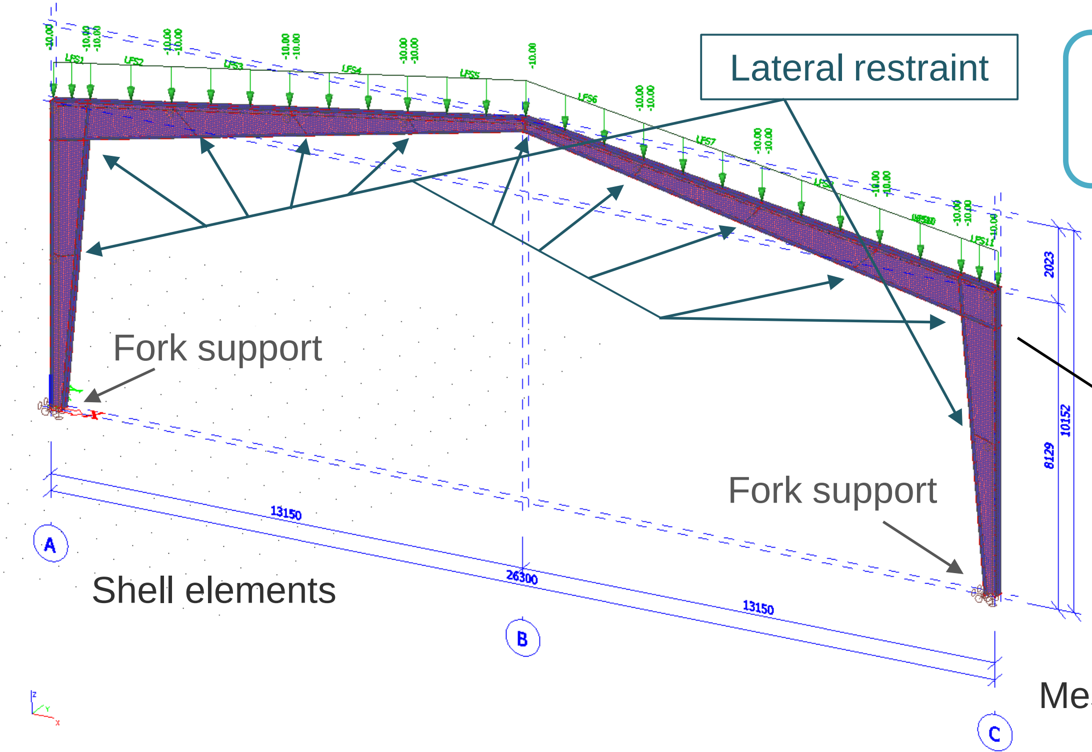
- Elastic analysis
- No imperfections needed
- Warping deformation needed:
  - Shell elements
  - 7DoF beam elements
- The first eigen mode representing LB or LTB is the critical
- $\alpha_{cr,op}$: the load factor for this critical mode
- $\alpha_{cr,op} \geq 1$





Formulation of the General Method & Example

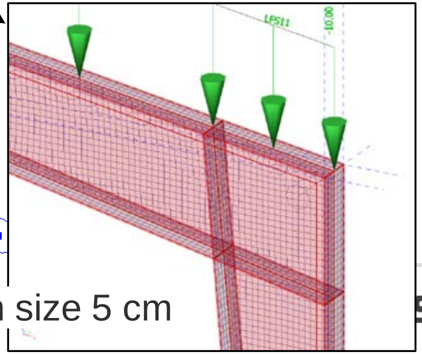
Linear stability analysis of the frame **ignoring all in-plane effects**:



LBA
Account for warping

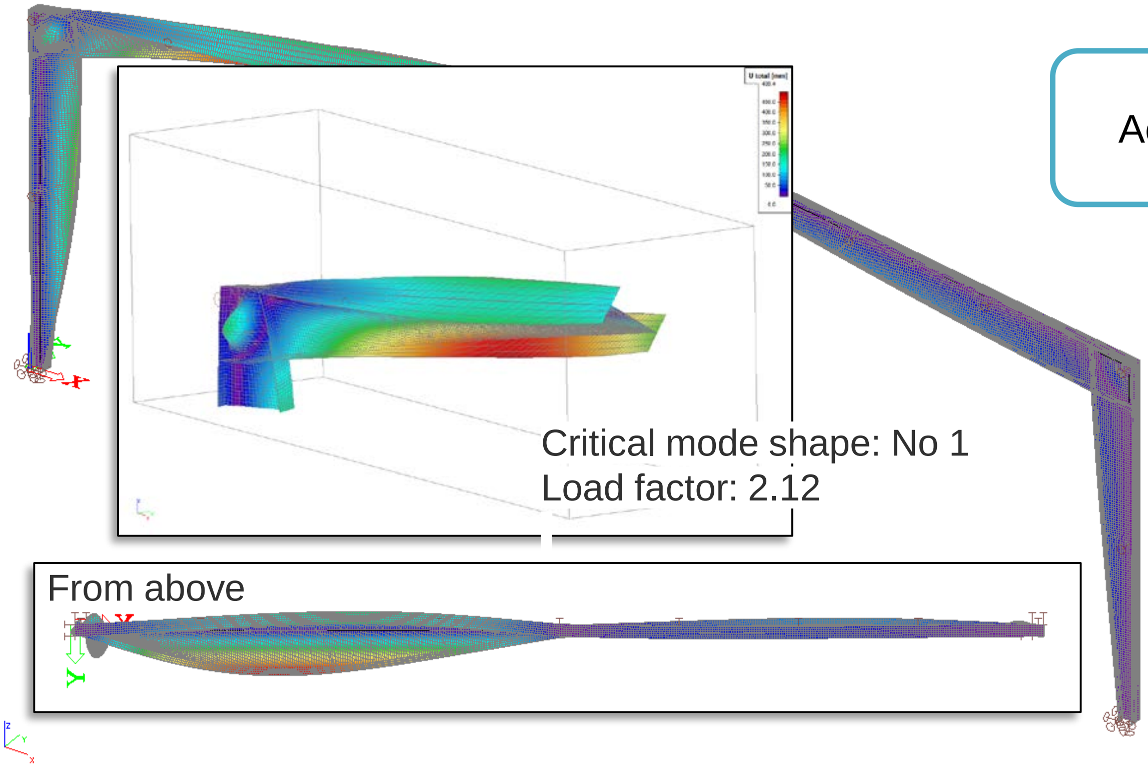
Out-of-plane stability
(FB around z-z, LTB)

$\alpha_{cr,op}$



Formulation of the General Method & **Example**

Linear stability analysis of the frame **ignoring all in-plane effects**:

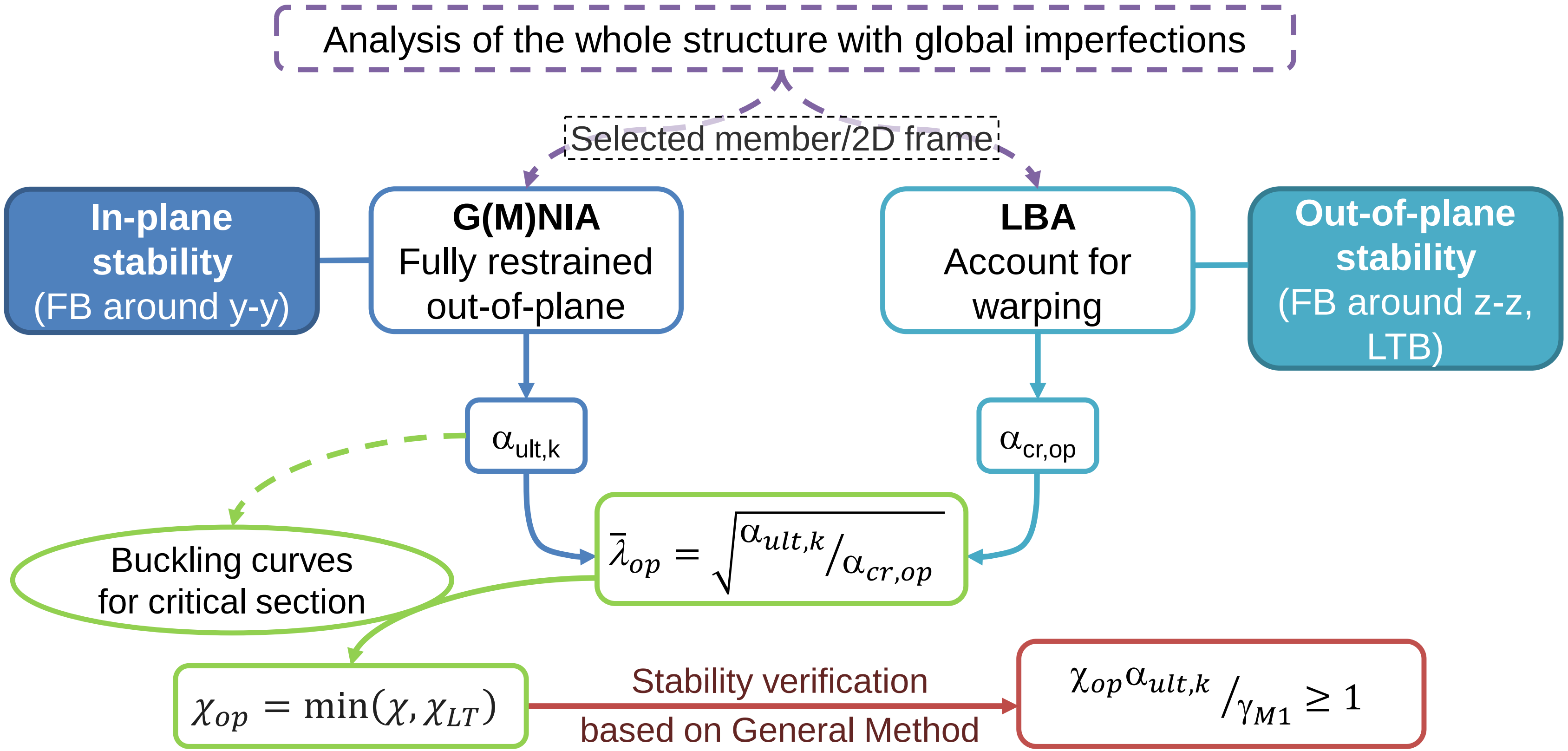


LBA
Account for warping
→ $\alpha_{cr,op}$

Out-of-plane stability
(FB around z-z, LTB)

$$\alpha_{cr,op} = 2.12 \geq 1$$

Formulation of the General Method



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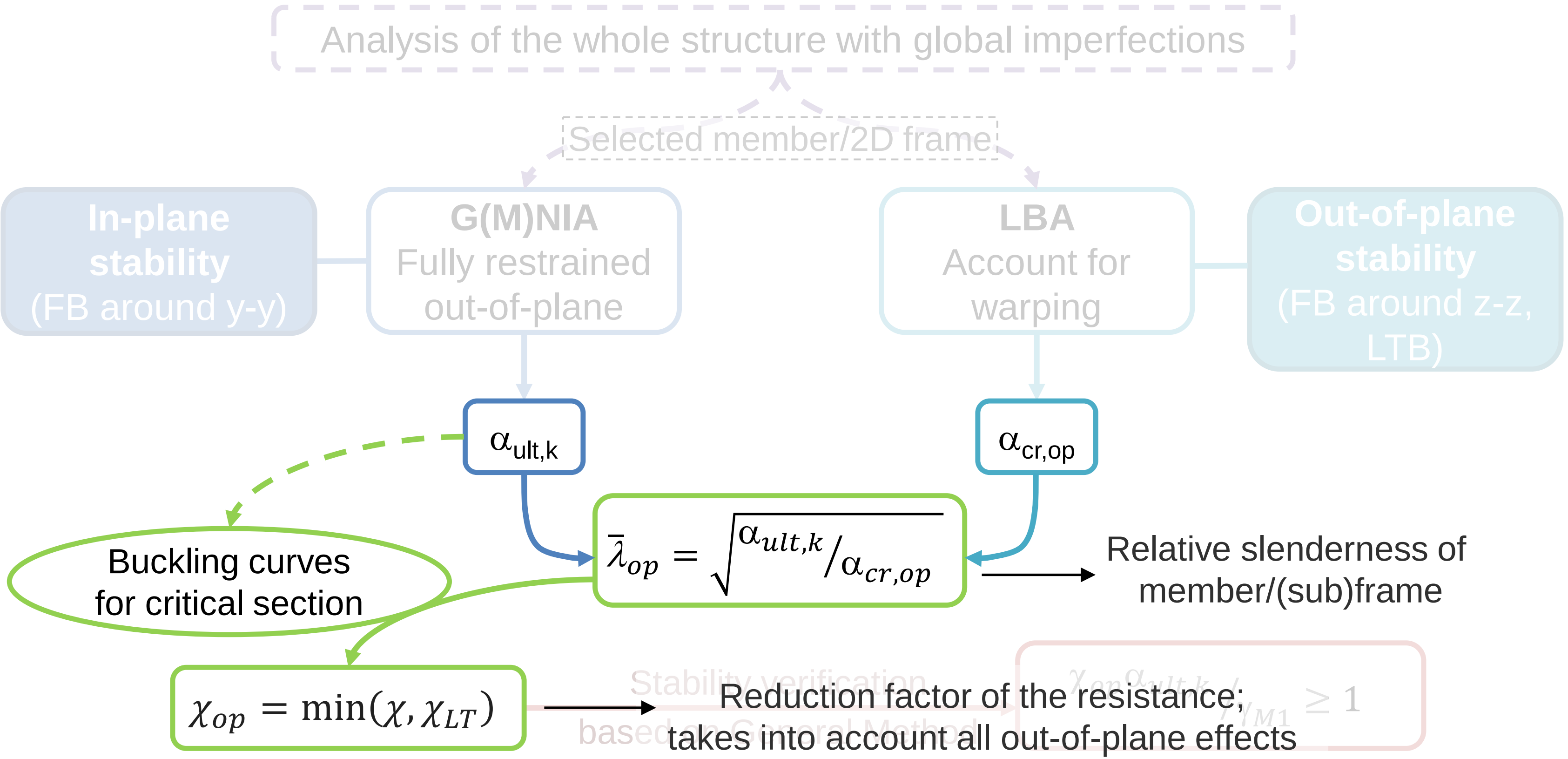
Formulation of the General Method



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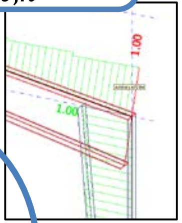
Formulation of the General Method

$$\bar{\lambda}_{op} = \sqrt{\alpha_{ult,k} / \alpha_{cr,op}}$$

Critical section from calculation of $\alpha_{ult,k}$



FB z-z: $\bar{\lambda}_{op} > 0.2$

- YES → EN 1993-1-1, §6.3.1
- NO → $\chi = 1$

LTB: $\bar{\lambda}_{op} > \bar{\lambda}_{LT,0}$

- YES → EN 1993-1-1, §6.3.2
- NO → $\chi_{LT} = 1$

EN 1993-1-1, §6.3.1

$$\chi = \frac{1}{\Phi + \sqrt{\Phi^2 - \bar{\lambda}^2}}$$

$$\Phi = 0.5\left[1 + \alpha(\bar{\lambda} - 0.2) + \bar{\lambda}^2\right]$$

Table 6.1: Imperfection factors for buckling curves

Buckling curve	a_0	a	b	c	d
Imperfection factor α	0,13	0,21	0,34	0,49	0,76

EN 1993-1-1, §6.3.2

$$\chi_{LT} = \frac{1}{\Phi_{LT} + \sqrt{\Phi_{LT}^2 - \bar{\lambda}_{LT}^2}}$$

$$\Phi_{LT} = 0.5\left[1 + \alpha_{LT}(\bar{\lambda}_{LT} - 0.2) + \bar{\lambda}_{LT}^2\right]$$

Table 6.3: Recommended values for imperfection factors for lateral torsional buckling curves

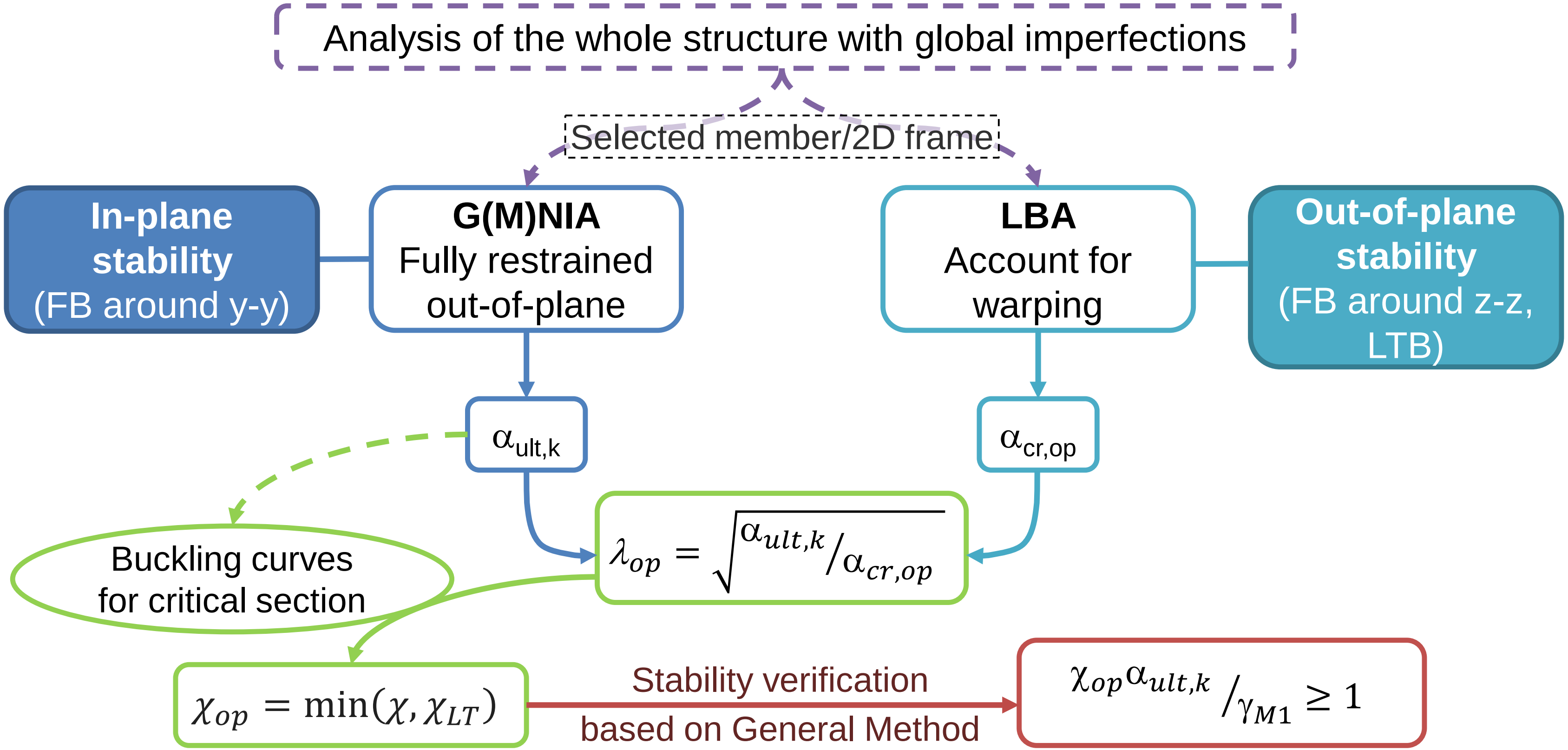
Buckling curve	a	b	c	d
Imperfection factor α_{LT}	0,21	0,34	0,49	0,76

$$\chi_{op} = min(\chi, \chi_{LT})$$

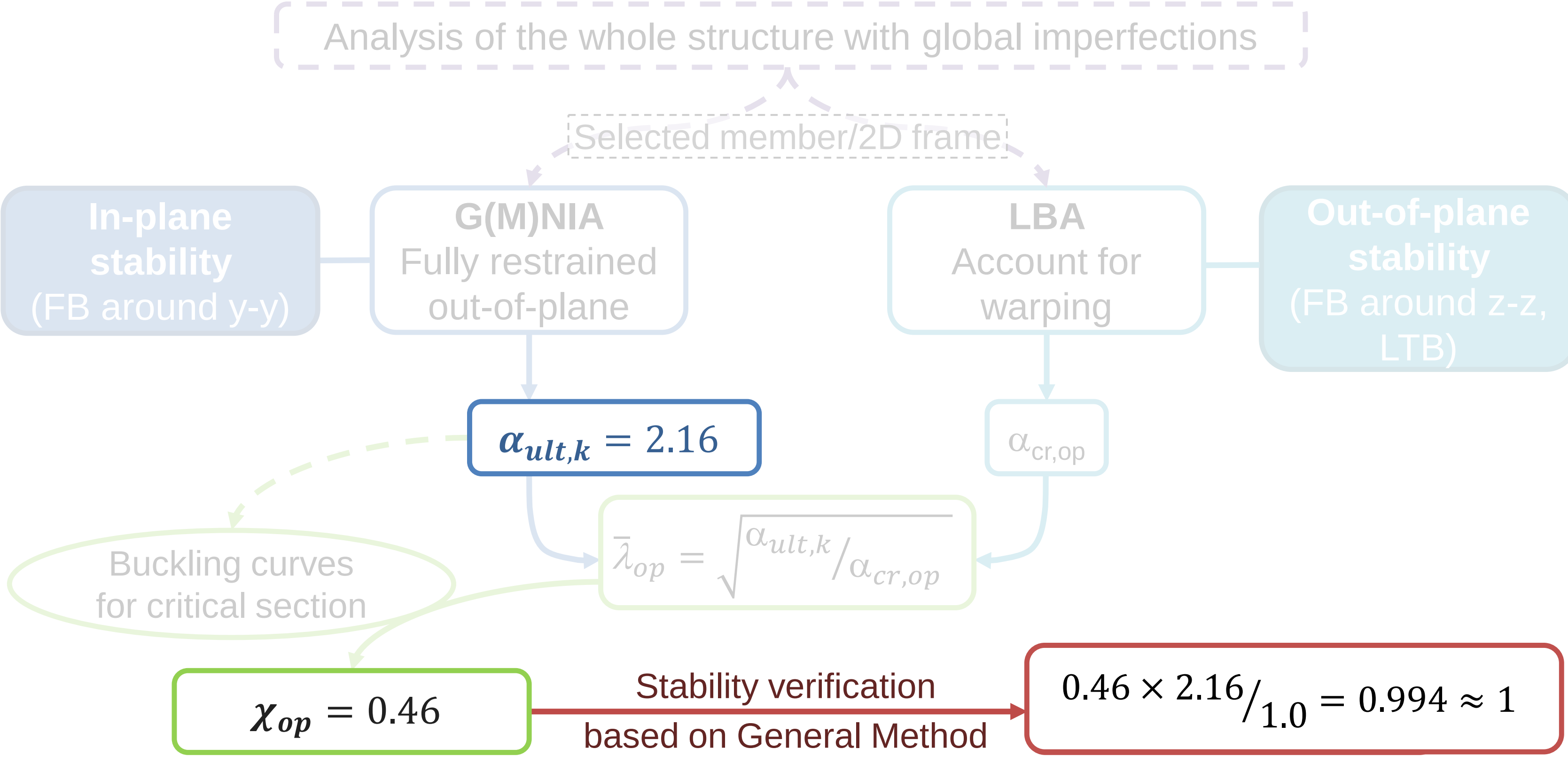
Formulation of the General Method & Example

- $\boldsymbol{\alpha_{ult,k} = 2.16 \geq 1}$
- $\boldsymbol{\alpha_{cr,op} = 2.12 \geq 1}$
- $\bar{\lambda}_{op} = \sqrt{\alpha_{ult,k} / \alpha_{cr,op}} = \sqrt{2.16/2.12} = 1.01$
- At critical section: FB curve **b**, $\alpha = 0.34$
- $\Phi = 0.5\left[1 + \alpha(\bar{\lambda} - 0.2) + \bar{\lambda}^2\right] = 1.15$
- $\chi = \dfrac{1}{\Phi + \sqrt{\Phi^2 - \bar{\lambda}^2}} = \mathbf{0.59}$
- At critical section: LTB curve **d**, $\alpha_{LT} = 0.76$
- $\Phi_{LT} = 0.5\left[1 + \alpha_{LT}(\bar{\lambda}_{LT} - 0.2) + \bar{\lambda}_{LT}^2\right] = 1.32$
- $\chi_{LT} = \dfrac{1}{\Phi_{LT} + \sqrt{\Phi_{LT}^2 - \bar{\lambda}_{LT}^2}} = \mathbf{0.46}$
- $\chi_{op} = \min(\chi, \chi_{LT}) = \mathbf{0.46}$

Formulation of the General Method



Formulation of the General Method



Example 2

From: “*Background document to EN 1993-1-1,*”

G. Sedlacek, J. Naumes, 2009

- A support frame from the Schwebebahn in Wuppertal
- Variable cross-section
- Fork supports modelled at column feet
- Beam laterally supported eccentrically in 2 points
- Asymmetric loading
- Non-uniform distribution of N and M_y

Example 2

From: "*Background document to EN 1993-1-1,*"

G. Sedlacek, J. Naumes, 2009

With FEM, see Figure 4.7 the numerical values are

$$\alpha_{ult,k,min} = 1,69$$

$$\alpha_{crit} = 3,41$$

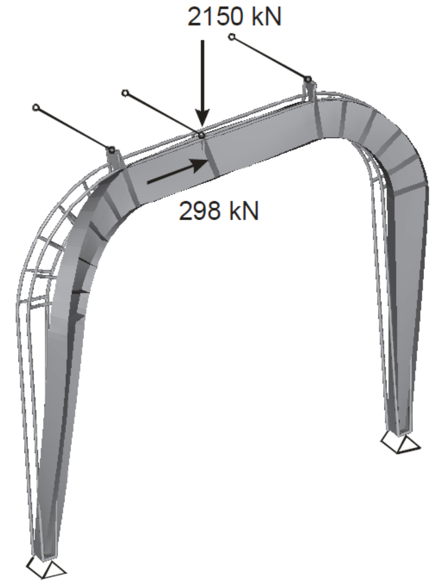
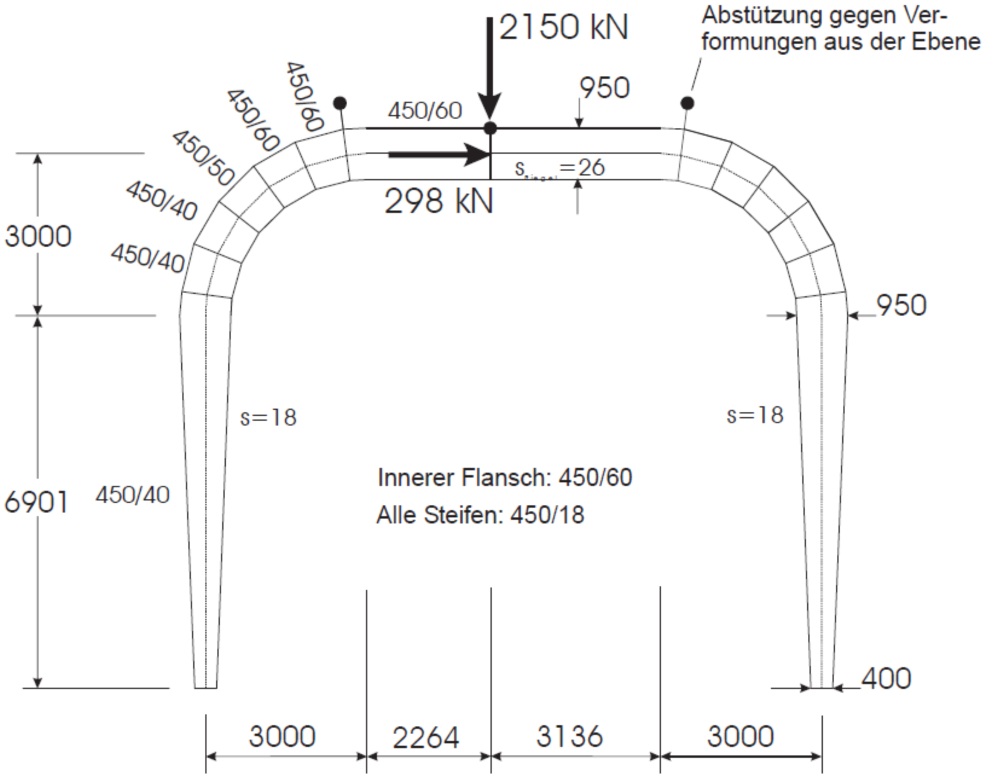


Figure 4.7: First eigenmode of the support frame from FEM-analysis *(→ α_{crit} = 3,41)*

For the verification flexural buckling curve *c* has been used as safe-sided approach. All relevant calculation steps are given in Figure 4.6.



Ergebnisse der FEM-Berechnung:

$$\alpha_{crit} = 3{,}41$$
$$\alpha_{ult,k,\min} = 1{,}69$$

Ermittlung des Abminderungsbeiwertes:

$$\bar{\lambda}_{\text{mod}} = \sqrt{\frac{\alpha_{ult,k,\min}}{\alpha_{crit}}} = \sqrt{\frac{1{,}69}{3{,}41}} = 0{,}704$$
$$\beta = 1$$
$$\alpha_{LT} = 0{,}49$$
$$\chi_{LT} = 0{,}722$$

Nachweis:

$$\chi_{LT} \cdot \alpha_{ult,k,\min} \geq \gamma_{M1}$$
$$0{,}722 \cdot 1{,}69 = 1{,}22 > 1{,}10$$

Figure 4.6: Example for the lateral torsional buckling verification acc. to the general method

Limitations of the General Method

- ECCS TC8 Stability (2006): *"Field and limits of application of the General Method:"*
  - Linear members and truss and frame structures built-up out of linear members,
  - where the lateral (torsional) buckling is related to a straight member behaviour. Sufficient lateral supports should be present such that the behaviour with respect to overall buckling between these lateral supports can be regarded as a straight member behaviour.

  - For structures/components out of the scope of the general method, a rigorous method like 3D GMNIA should be applied
  - The General Method is always on the safe side when compared to a full 3D GMNIA

Conclusion

- The general method is **used for stability** verifications for:
  - standard or **complex structural components**
  - with **complex loading** or **boundary conditions** (or not)
  - loaded in **compression** and/or **in-plane bending**
- The method takes into account:
  - **in-plane** imperfections & loss of **in-plane** stability by **GMNIA** of the structural component
  - **out-of-plane** loss of stability by **LBA** of the component (eventually, by the reduction factor χ_{op})
  - **out-of-plane** imperfections by adopting the appropriate **buckling curve** in the derivation of χ_{op}

References

[1] G. Sedlacek, J. Naumes, *CEN / TC250 / SC3 / N1639E - rev2, Background Document to EN 1993-1-1*, Aachen, 2009.

[2] A. Bureau*, Résistance au flambement et au déversement d'un Poteau a inertie variable selon l'EN 1993-1-1*, Revue Construction Métallique, issue 3, 2007

[3] L. Zdravkov, *Using of general method of standard EN 1993-1-1 to design of self-supporting cone roofs*, 4th International Conference of Advanced Construction, Kaunas, Lithuania, 2014.

[4] SN032a-EN-EU, *NCCI: General method for out-of-plane buckling in portal frames,* Access Steel, 2010.

[5] B. Snijder, R. Greiner, J.-P. Jaspart, TC8-2006-015, *Field and limits of application of the General Method*, ECCS TC8 Stability, 2006.

[6] R. Greiner, *Stabilitätsnachweis von Stabwerken nach dem Eurocode – neue Möglichkeiten,* Institut für Stahlbau und Flächentragwerke, Technische Universität Graz, 2005

[7] T. Van Leemput, M. Van Mieghem, *Algemene methode voor knikken en kippen van constructieve onderdelen*, Master Thesis, Lessius Mechelen, 2012

General method in context

Internal forces from…	Modelled imperfections	EN 1993-based checks required
1^{st} order analysis	none	§6.2 & in-plane FB $L_b \neq L$ out-of-plane FB /LTB (§6.3)
2D (in-plane) 2^{nd} order analysis	In-plane global inclination	§6.2 & in-plane FB $L_b = L$ out-of-plane FB /LTB (§6.3)
2D (in-plane) 2^{nd} order analysis	In-plane (1) global inclination & (2) member imperfections	§6.2 & out-of-plane FB /LTB (§6.3)
3D 2^{nd} order analysis, warping included	Global inclination Member imperfections	Section checks only (§6.2)
(General method) 1^{st} order for whole structure 2^{nd} order for component/frame	In-plane (1) global inclination & (2) member imperfections	§6.2 & $\chi_{op}\alpha_{ult,k}/\gamma_{M1} \geq 1$

Thank you for your attention

More information on www.scia.net