THE FUTURE OF
STEEL
CONSTRUCTION

Design assisted by finite element analysis – EN 1993-1-14

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Content

- Introduction to new Eurocode for design by FEA – EN 1993-1-14
- Traditional design versus design by FE analysis
- Key components of design by FEA
- Why would we want to do design by FE?
- Conclusions

Horror and excitement

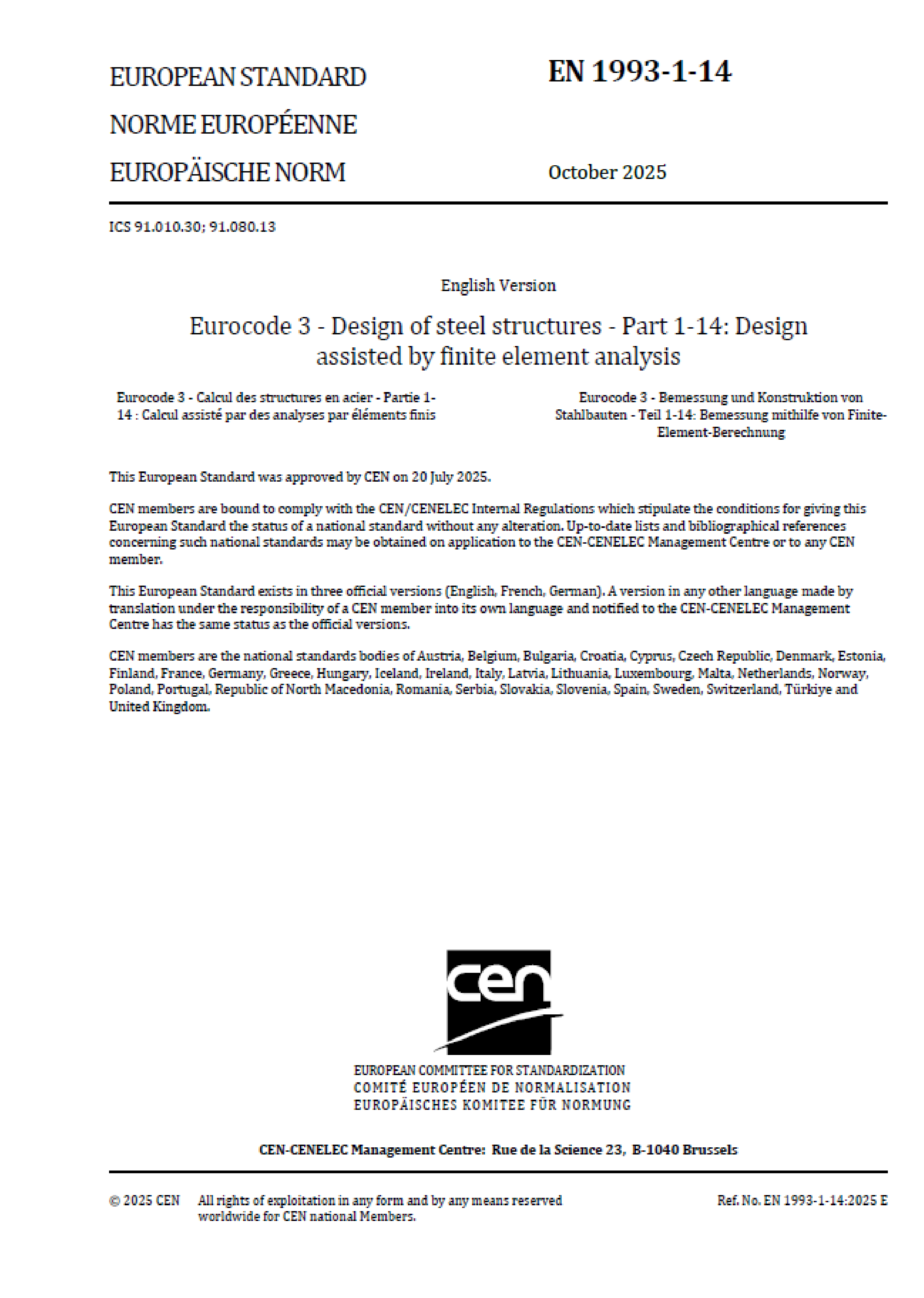
- We have a new Eurocode for design by finite element (FE) analysis
- Expected to generate some excitement but quite of lot of horror

Horror - concerns	Excitement - potential
Existing Eurocodes are bad enough	FE is an immensely powerful tool
Unsafe use	More accurate
Black box	Good to standardise what we're already doing
How do you check designs	Visualise deformed shape and failure mode
Just lots of colourful plots	Visualise highly stressed regions
Whatever happened to $wL^2/8$	Ideas to improve design

Presentation plan: introduce new code, touching on above points

Development of EN 1993-1-14

- Developed by WG22 of CEN TC250/SC3
- Work started in 2016
- Code was published in October 2025
- Applicable to broad range of structures and phenomena – frames, plates, connections, fatigue
- Choice of element and analysis types to match structural phenomena being modelled



EUROPEAN STANDARD
NORME EUROPÉENNE
EUROPÄISCHE NORM

EN 1993-1-14

October 2025

ICS 91.010.30; 91.080.13

English Version

Eurocode 3 - Design of steel structures - Part 1-14: Design assisted by finite element analysis

Eurocode 3 - Calcul des structures en acier - Partie 1-14 : Calcul assisté par des analyses par éléments finis

Eurocode 3 - Bemessung und Konstruktion von Stahlbauten - Teil 1-14: Bemessung mithilfe von Finite-Element-Berechnung

This European Standard was approved by CEN on 20 July 2025.

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CEN-CENELEC Management Centre: Rue de la Science 23, B-1040 Brussels

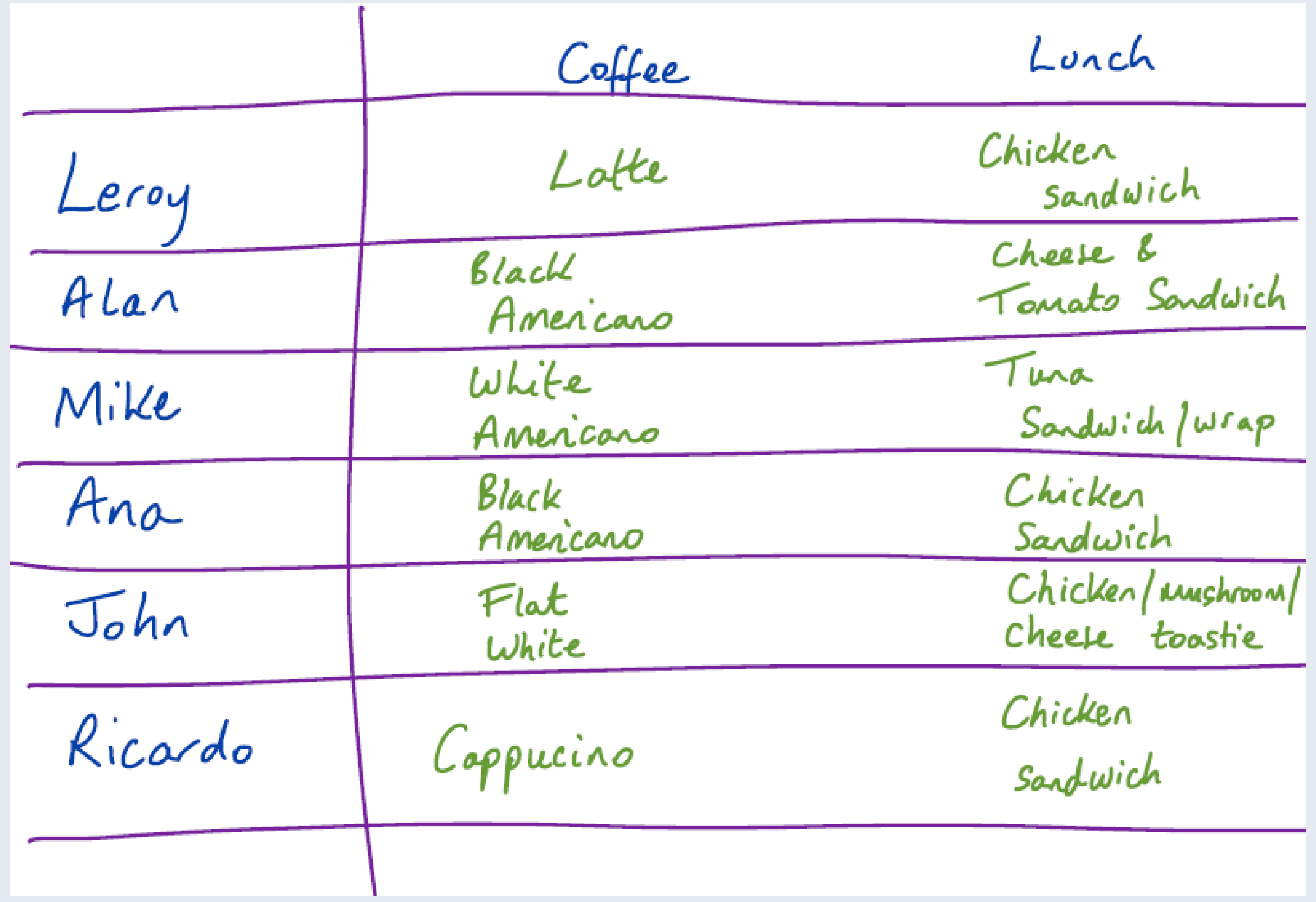
Ref. No. EN 1993-1-14:2025 E

UK input to CEN Enquiry

- The UK mirror group comprised:

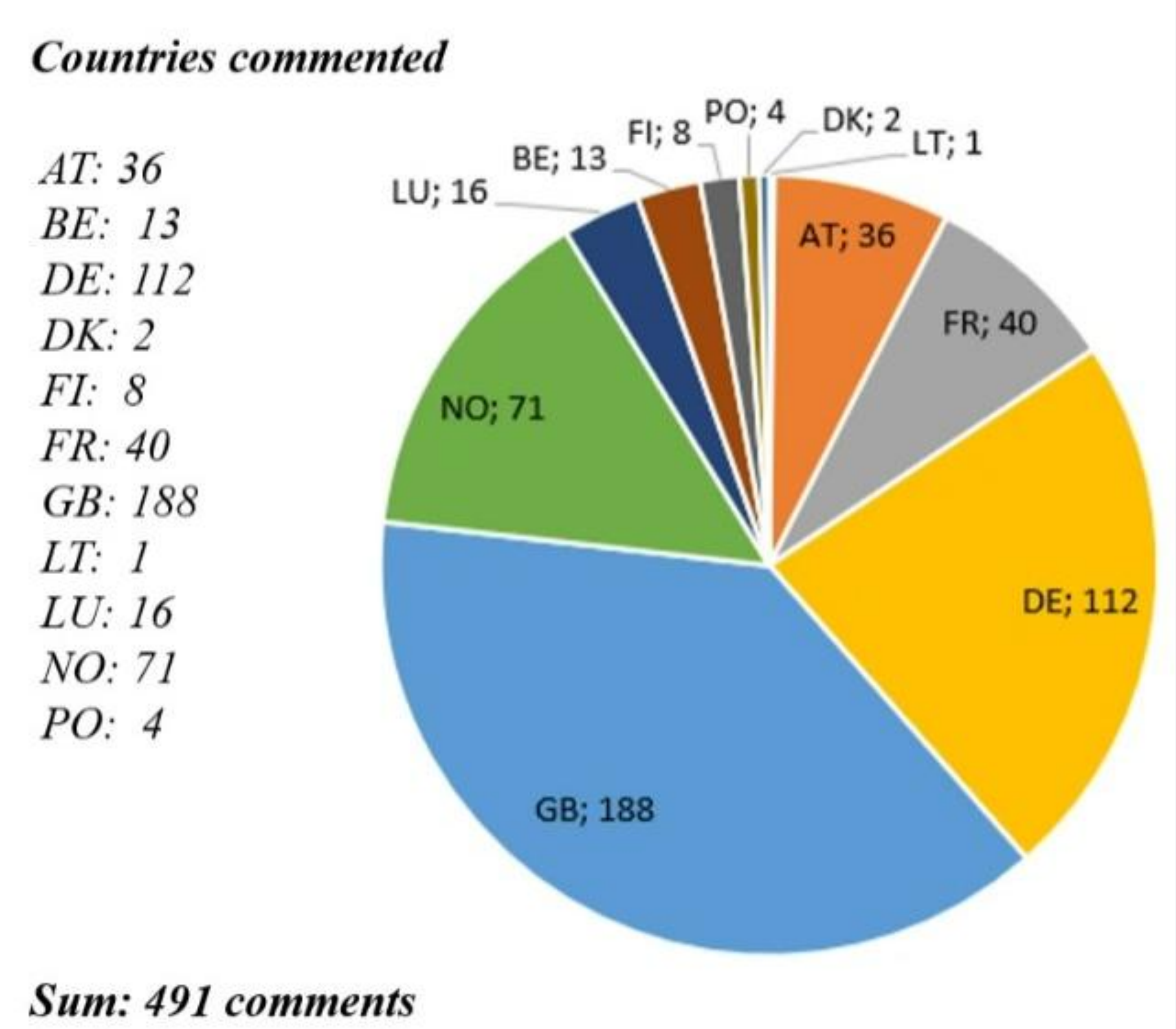
- Leroy Gardner
- Fiona Walport
- Alan Rathbone
- Mike Banfi
- Ana Girao
- John Ward
- Ricardo Pimental

- UK 'dominated' the comments at the CEN enquiry stage, indicating strong engagement
- UK NA is under preparation



	Coffee	Lunch
Leroy	Latte	Chicken sandwich
Alan	Black Americano	Cheese & Tomato Sandwich
Mike	White Americano	Tuna Sandwich/wrap
Ana	Black Americano	Chicken Sandwich
John	Flat White	Chicken/mushroom/Cheese toastie
Ricardo	Cappucino	Chicken sandwich

Evidence of physical meeting



Number of code comments

New Eurocode – EN 1993-1-14

While this is a new code, some recommendations existed in the first generation of the Eurocodes, and these were reviewed and utilised to the full.

- EN 1993-1-5 Plated structures
- EN 1993-1-6 Strength and stability of shell structures
- ECCS Design Manual to EN 1993-1-5
- IIW Recommendations (2006-2010) – Fatigue design rules

Use of FEA is becoming increasingly common in structural design. The new code will help to ensure that this is done within a safe and harmonised framework.

A supporting Technical Report - TR 1993-1-141 will sit alongside the new Eurocode and help with practical implementation.

58 pages in total

15 pages - key input parameters

3 pages – types of analysis

2 pages

16 pages – design methodologies for ULS, SLS and fatigue

Annexes: 4 pages

Separation of analysis purpose

Code is primarily for structural designers, following the 'numerical design calculations' track

But can also be used by researchers and product developers through the 'numerical simulations' track

Designers can use either:

- Analysis requiring subsequent design checks
- Direct resistance checks

Implication on model factor γ_{FE}

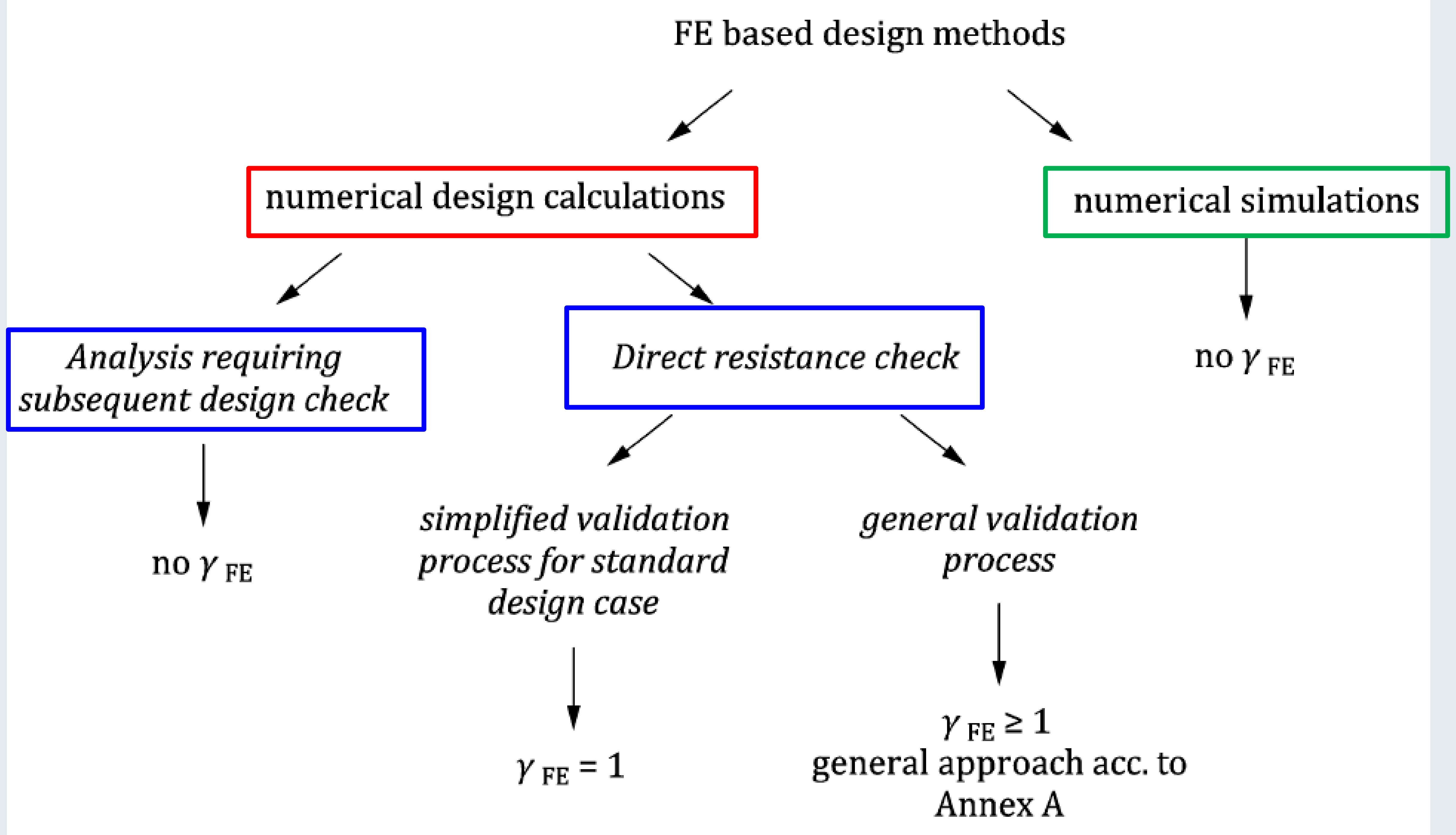


Figure 7.2 — Application of the model factor (γ_{FE})

Analysis types

Simple analysis – lots of member checks needed

The more features that are included in the analysis, the fewer, if any, the required subsequent design checks

Type of analysis	deformations	material law	geometry
Linear elastic analysis (LA)	linear	linear elastic	perfect
Linear elastic bifurcation (eigenvalue) analysis (LBA)	bifurcation	linear elastic	perfect
Materially nonlinear analysis (MNA)	linear	elastic-plastic	perfect
Geometrically nonlinear elastic analysis (GNA)	nonlinear	linear elastic	perfect
Geometrically and materially nonlinear analysis (GMNA)	nonlinear	nonlinear	perfect
Geometrically nonlinear elastic analysis with imperfections (GNIA)	nonlinear	linear elastic	imperfect
Geometrically and materially nonlinear analysis with imperfections (GMNIA)	nonlinear	nonlinear	imperfect

More sophisticated analysis – no member checks needed

Traditional structural design versus direct design by GMNIA

GMNIA is geometrically and materially nonlinear analysis with imperfections

Traditional structural design

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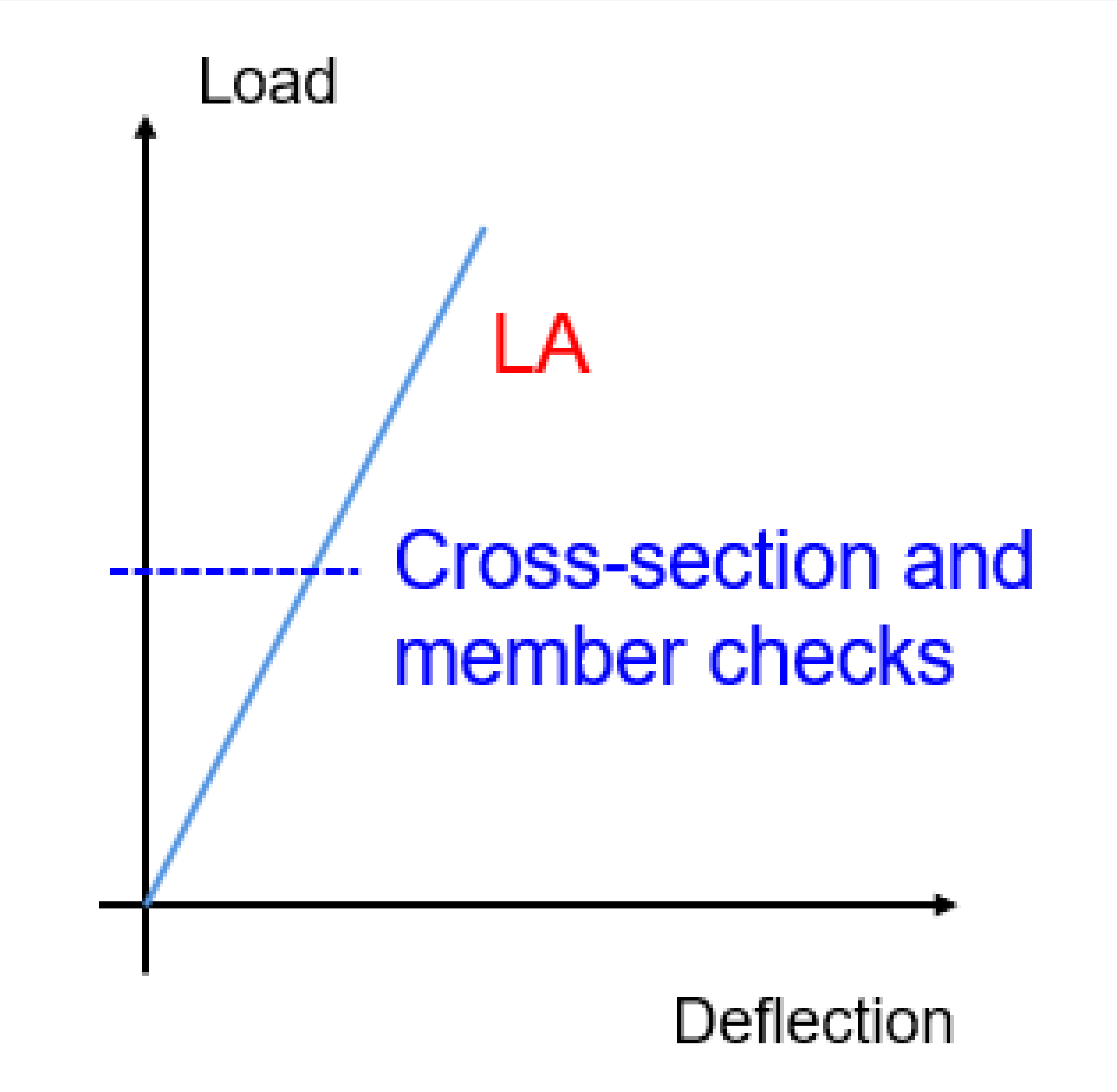
In traditional structural design, we typically use a linear elastic analysis (LA) to obtain internal forces and moments in members.

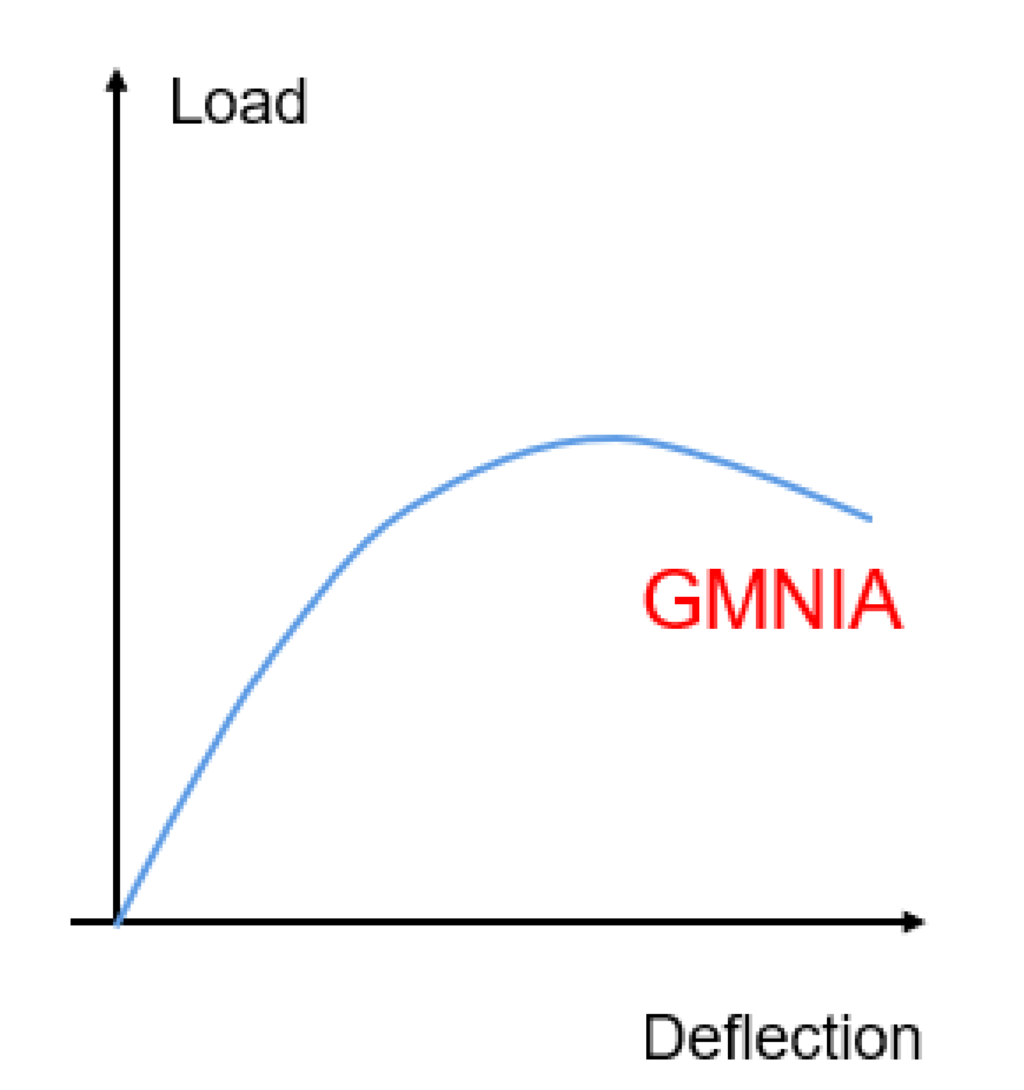
- Analysis is quick and simple, but yielding and buckling are ignored
- Member checks (often lengthy) are required to allow for these effects and verify their capacity
- Distribution of forces and moments in structure can be inaccurate because stiffness changes due to buckling and yielding not captured
- Buckling (effective) lengths can be hard to determine



Structural design by GMNIA

In design by GMNIA, buckling and yielding are directly captured in the analysis.

- Analysis is more complex and member and frame imperfections need to be included
- Interaction between members and distribution of forces more accurately determined
- Design is more direct and member checks are eliminated; cross-section checks still required for beam element models



Nonlinear response as structure deforms, buckles and yields under load

Key ingredients of design by GMNIA

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The key ingredients of design of steel frames by GMNIA using beam elements are presented:

Nominal geometry, nominal material properties, support conditions and loading and load combinations are all defined as usual. The new features are:

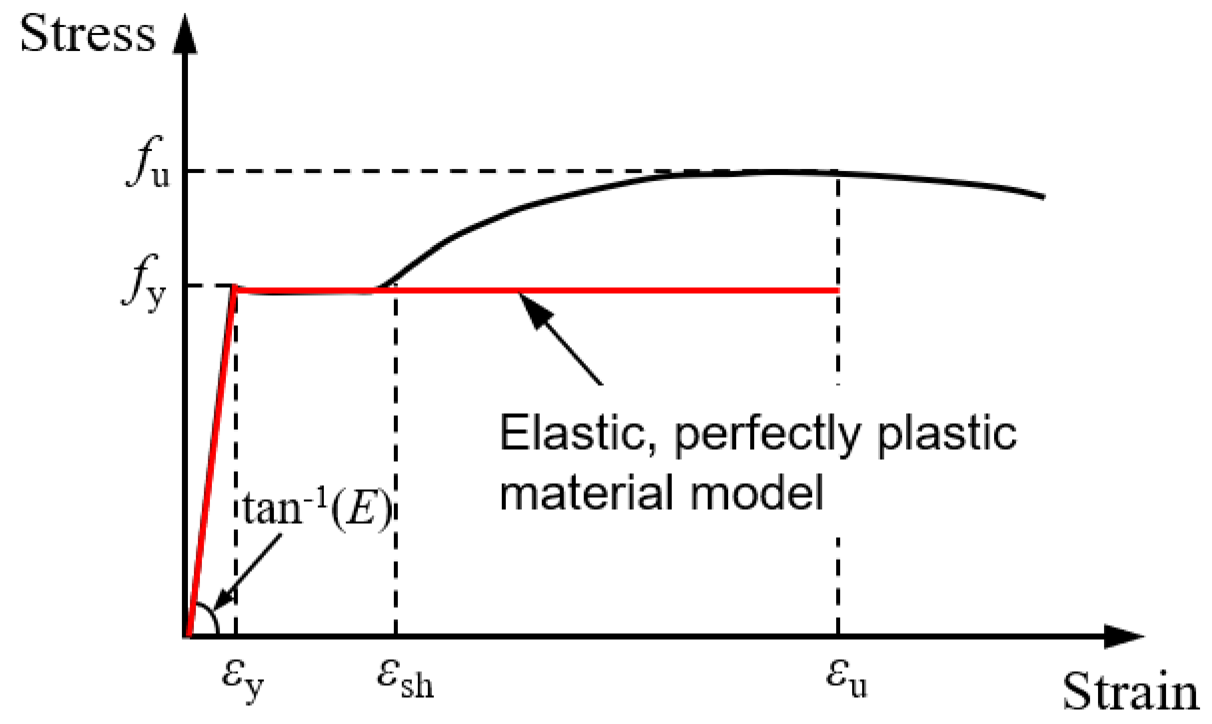
- Material stress-strain curve (Section 5.3)
- Imperfections (Section 5.4)
- Cross-section checks and strain limits (Annex C)
- Model factor γ_{FE} (Annex A)

By performing a GMNIA, yielding and buckling take place in the analysis, so no subsequent design checks are needed for this. Cross-section checks or strain limits are need in beam element FE models.

Material modelling

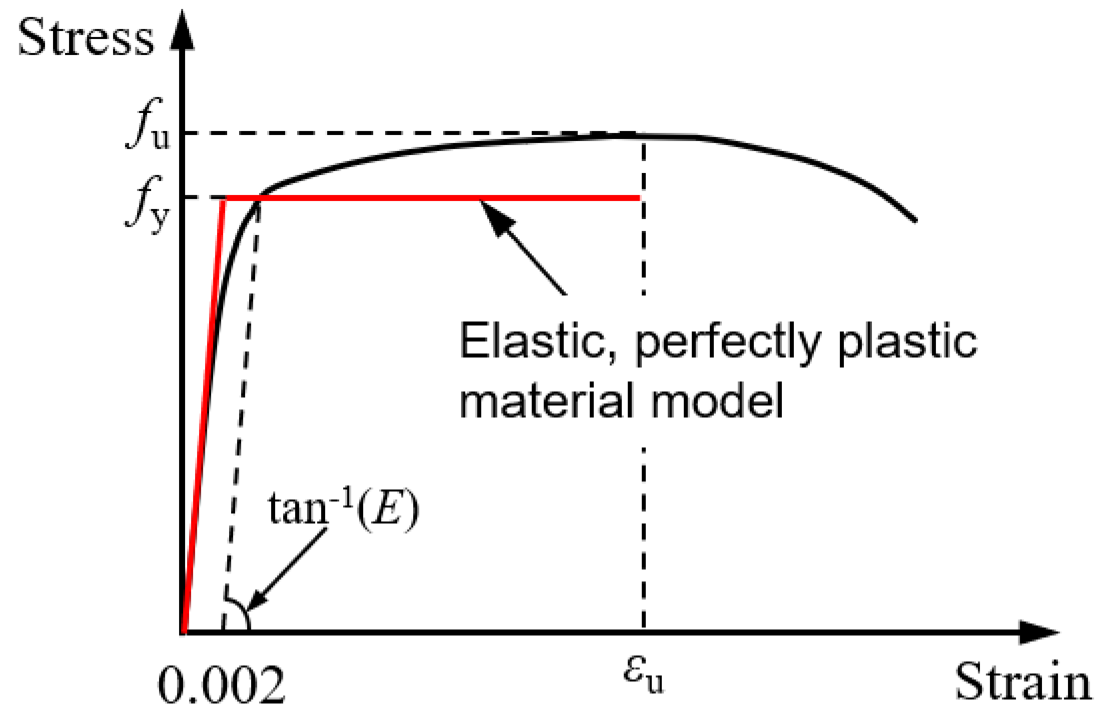
Stress-strain curves

Two main types of σ-ε response – sharply-defined and rounded yielding



Hot-rolled steel (normal and intermediate strength)

Sharply defined yield point and yield plateau

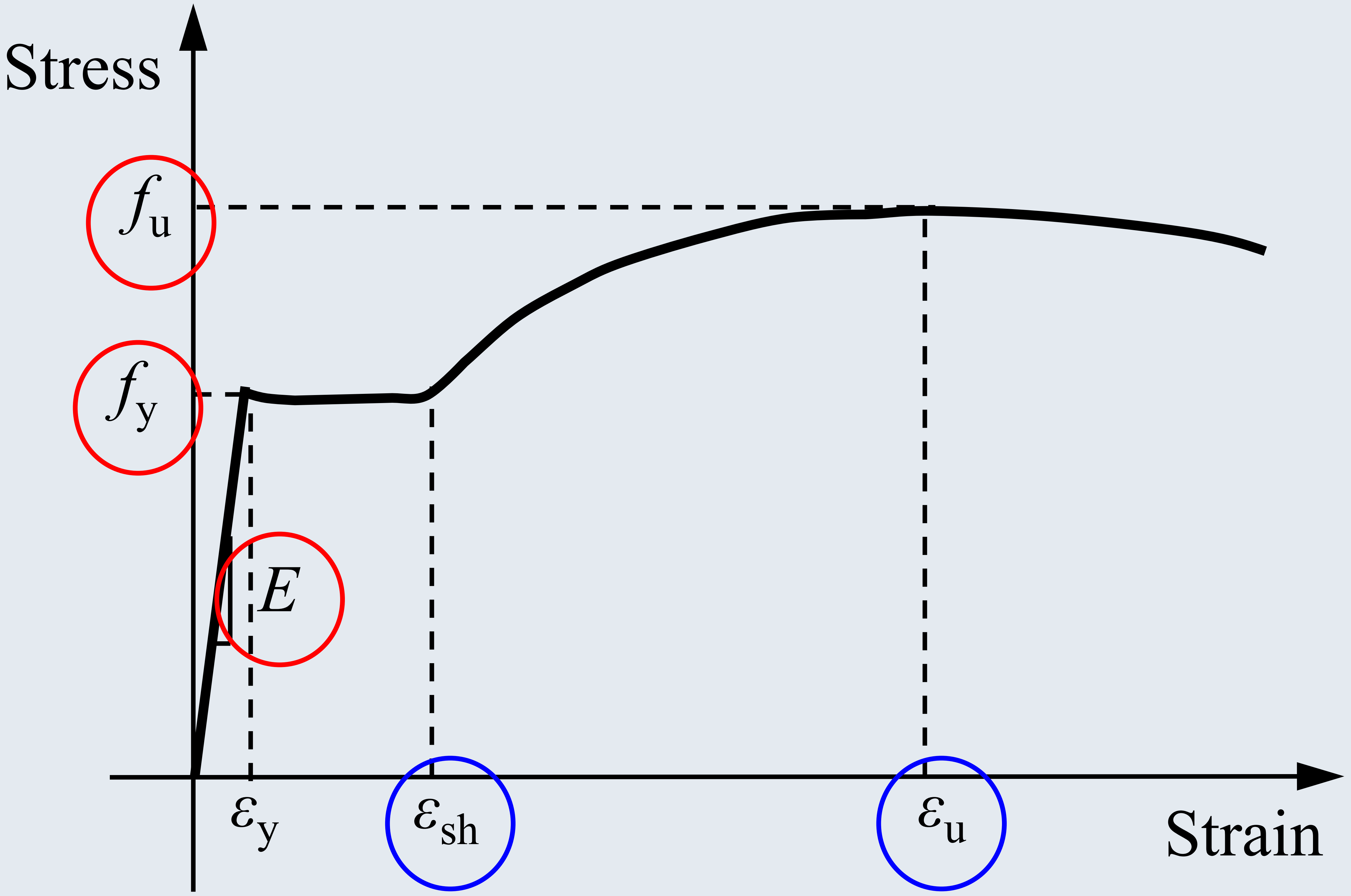


Cold-formed steel, hot-rolled steel (high strength), stainless steel, aluminium

Rounded σ-ε response

- Traditional design is underpinned by elastic, perfectly plastic σ–ε model, but influence of form of σ-ε curve indirectly captured in code design checks (e.g. buckling curves).
- Owing to direct nature of design by GMNIA, an accurate σ-ε description is needed.

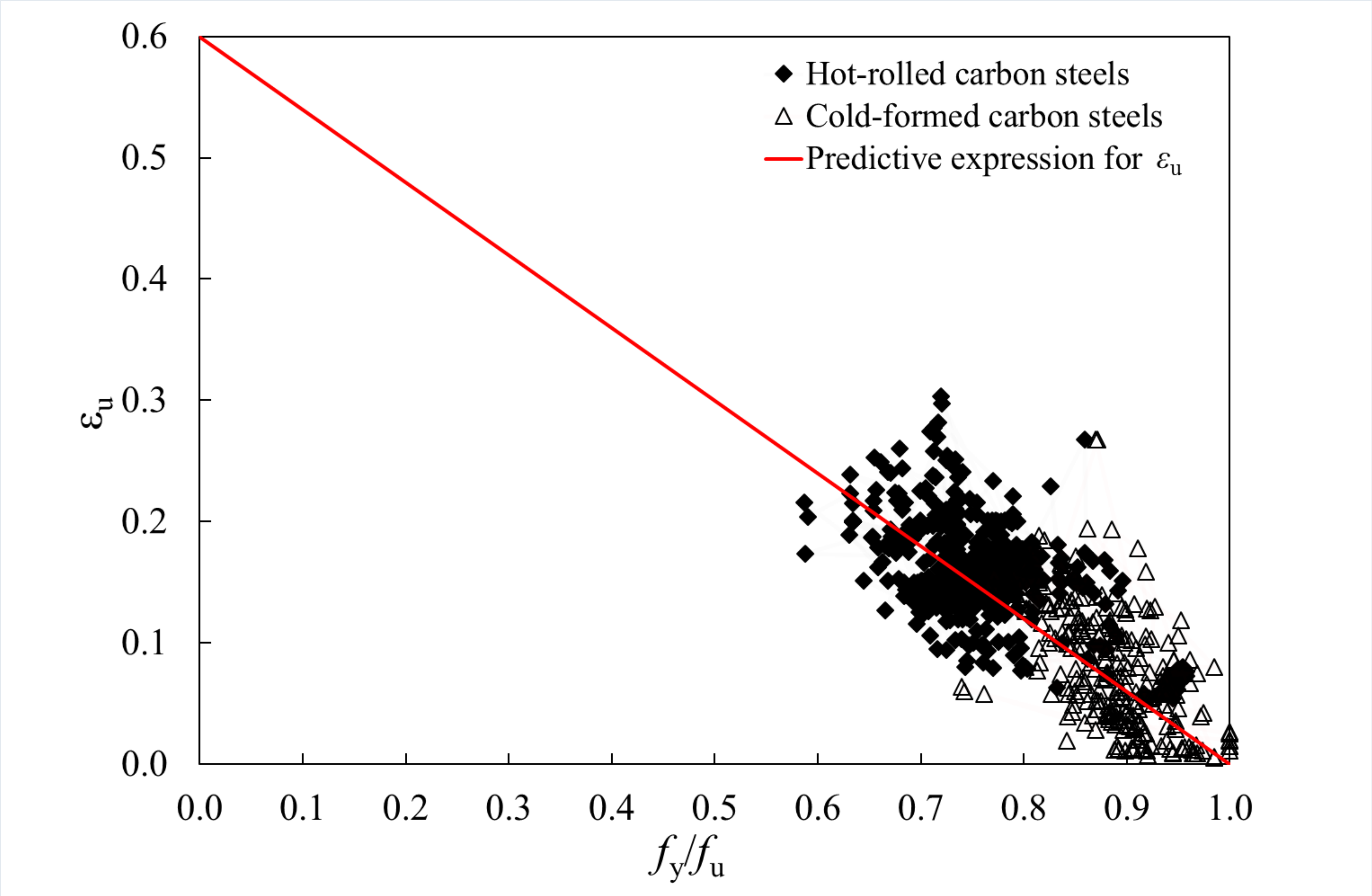
Material model for hot-rolled steel



- *E*, f_y and f_u typically known to structural engineers
- ε_{sh} and ε_u not known – expressions provided in EN 1993-1-14 to determine

Prediction of ε_u and ε_{sh}

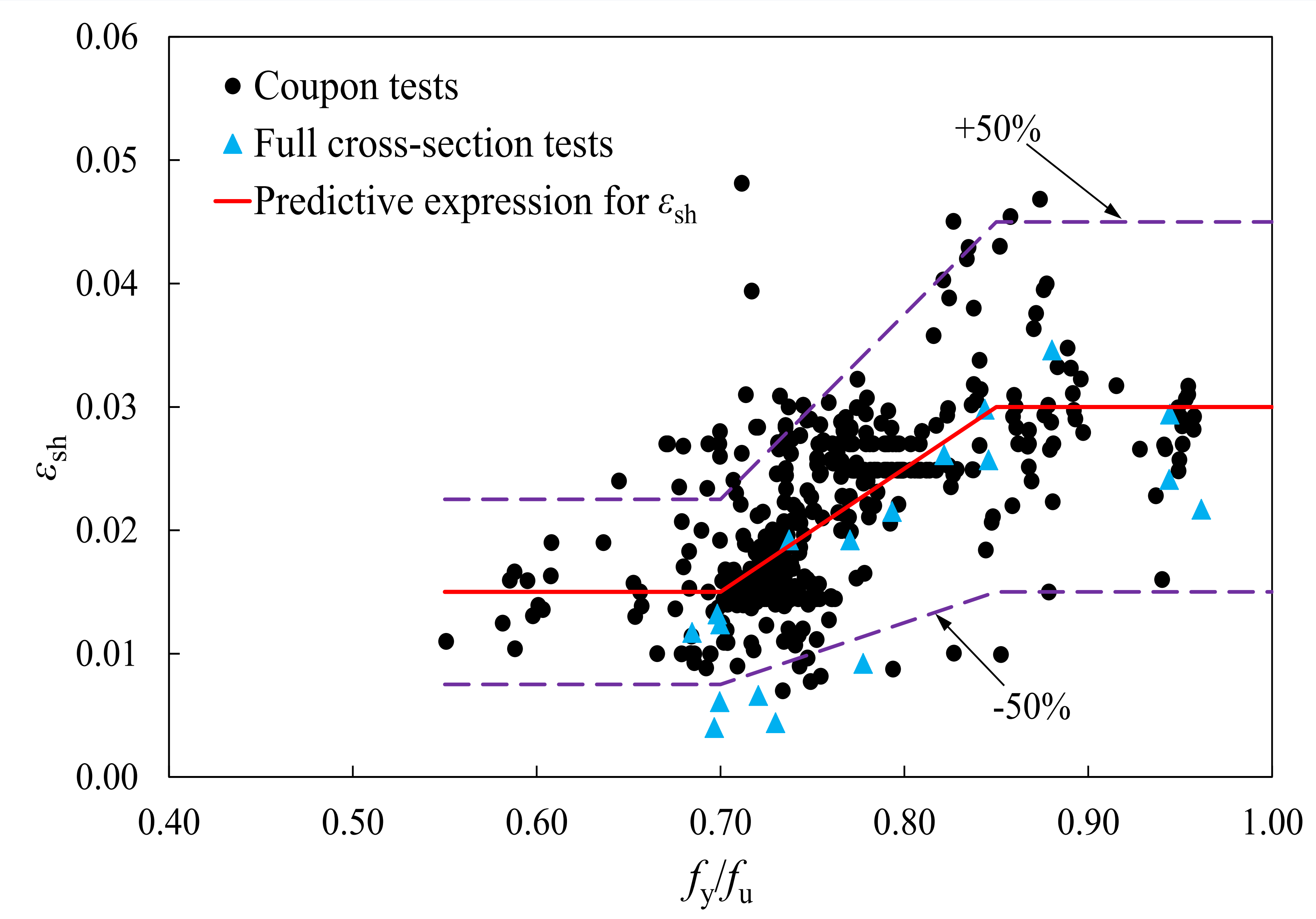
Simple predictive models developed for ε_u and ε_{sh}, calibrated against hundreds of measured σ–ε curves



$$\varepsilon_u = 0.6(1 - \frac{f_y}{f_u})$$

but ≥ 0.06 for hot-rolled steels

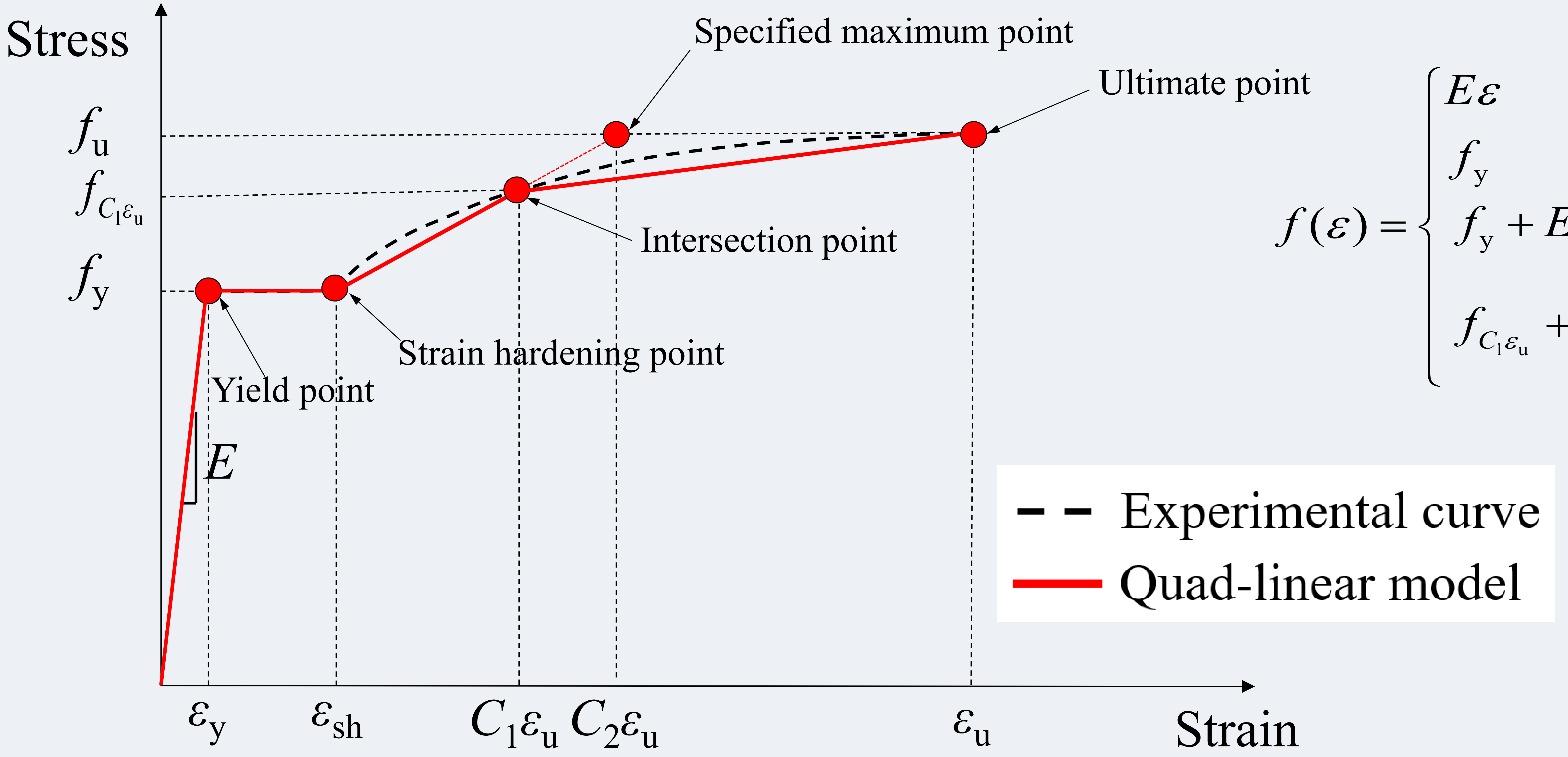
Prediction of ultimate strain ε_u



$$\varepsilon_{sh} = 0.1\frac{f_y}{f_u} - 0.055 \quad \text{but } 0.015 \le \varepsilon_{sh} \le 0.03$$

Prediction of strain hardening strain ε_{sh}

Quad-linear stress-strain model for hot-rolled steel



$$f(\varepsilon) = \begin{cases} E\varepsilon & \text{for } \varepsilon \le \varepsilon_y \\ f_y & \text{for } \varepsilon_y \le \varepsilon \le \varepsilon_{sh} \\ f_y + E_{sh}(\varepsilon - \varepsilon_{sh}) & \text{for } \varepsilon_{sh} \le \varepsilon \le C_1\varepsilon_u \\ f_{C_1\varepsilon_u} + \dfrac{f_u - f_{C_1\varepsilon_u}}{\varepsilon_u - C_1\varepsilon_u}(\varepsilon - C_1\varepsilon_u) & \text{for } \varepsilon_{sh} \le \varepsilon \le C_1\varepsilon_u \end{cases}$$

$$E_{sh} = \frac{f_u - f_y}{C_2\varepsilon_u - \varepsilon_{sh}}$$

- Only requires E, f_y and f_u to define full σ-ε curve
- Ideal for design by GMNIA and included in Section 5 of EN 1993-1-14

Yun, X. and Gardner, L. (2017) Stress-strain curves for hot-rolled steels. Journal of Constructional Steel Research;133:36-46.

Imperfections for design by GMNIA

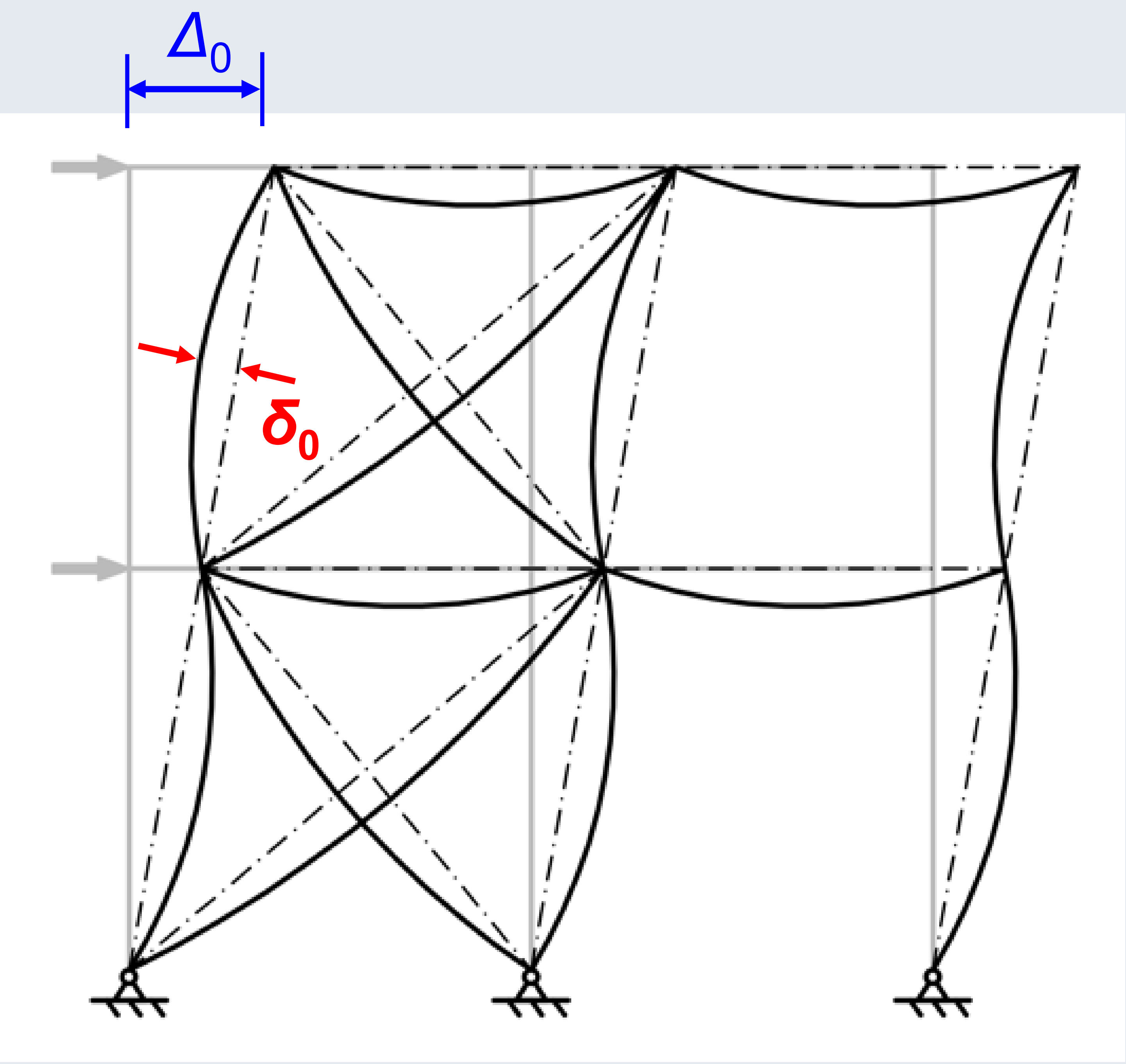
Imperfections for GMNIA

In design by GMNIA, buckling is captured directly in analysis. Representative geometric imperfections and residual stresses should therefore be assigned, as set out in Section 5 of EN 1993-1-14.

- Imperfections needed at frame (Δ_0) and member level (δ_0). Two options:

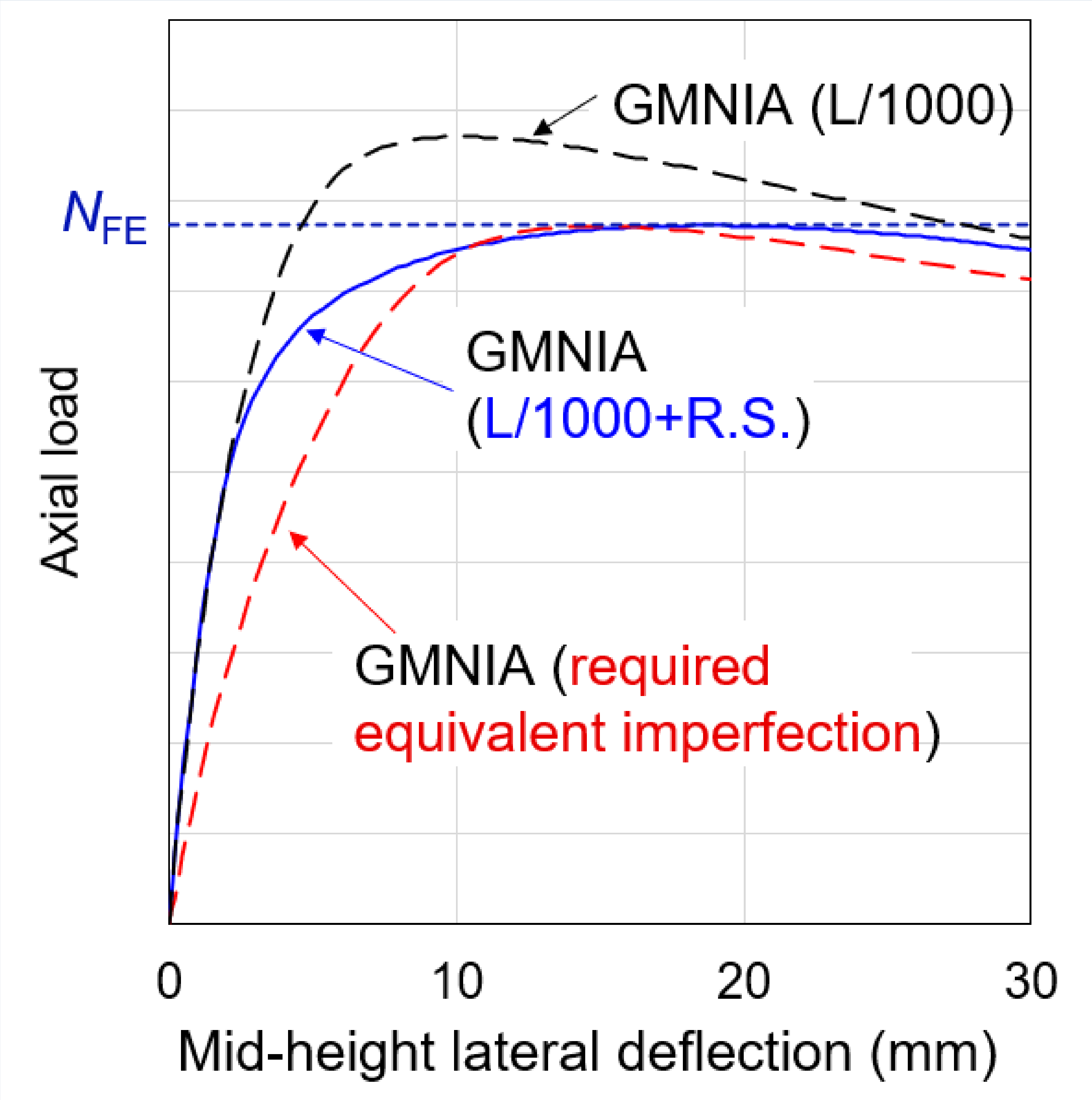
(1) Geometric imperfections + Residual stresses

(2) Equivalent imperfections
- larger imperfections to account for the combined influence of geometric imperfections and residual stresses



Walport, F., Gardner, L. and Nethercot, D. A. (2020). Equivalent bow imperfections for use in design by second order inelastic analysis. Structures. 26, 670-685.

Equivalent geometric bow imperfections



Required equivalent imperfections e_0 back-calculated for 100s of column buckling results N_{FE} (minor and major axis) modelled with L/1000 + RS, resulting in:

$$\frac{e_0}{L} = \alpha\beta = \frac{\alpha}{150}$$

Captures influence of different residual stress patterns

α is the familiar imperfection factor taken from EN 1993-1-1 or EN 1993-1-4

Walport, F., Gardner, L. and Nethercot, D. A. (2020). Equivalent bow imperfections for use in design by second order inelastic analysis. Structures. 26, 670-685.

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Imperfection combinations

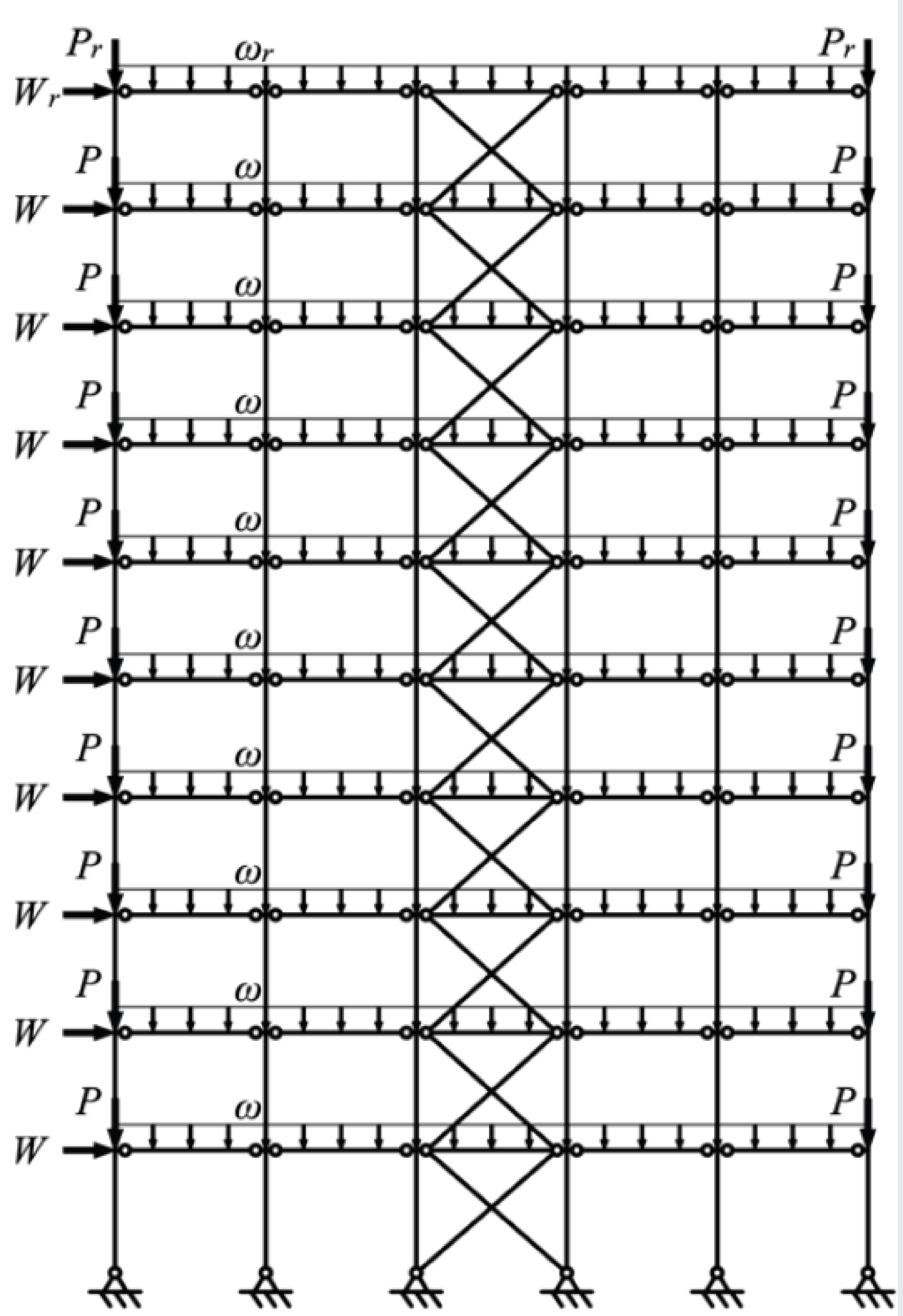
- Codes (including EN 1993-1-14) generally say ‘use the imperfection shape that leads to the lowest resistance’.

- Easier said than done! And not practical to exhaustively check all combinations in typical structures.

- We have sought to determine imperfection definition methods that give most severe, or close to most severe results, considering two methods:

(1) Directly defined imperfections
(2) Eigenmode-affine imperfections

Planned for inclusion in UK NA

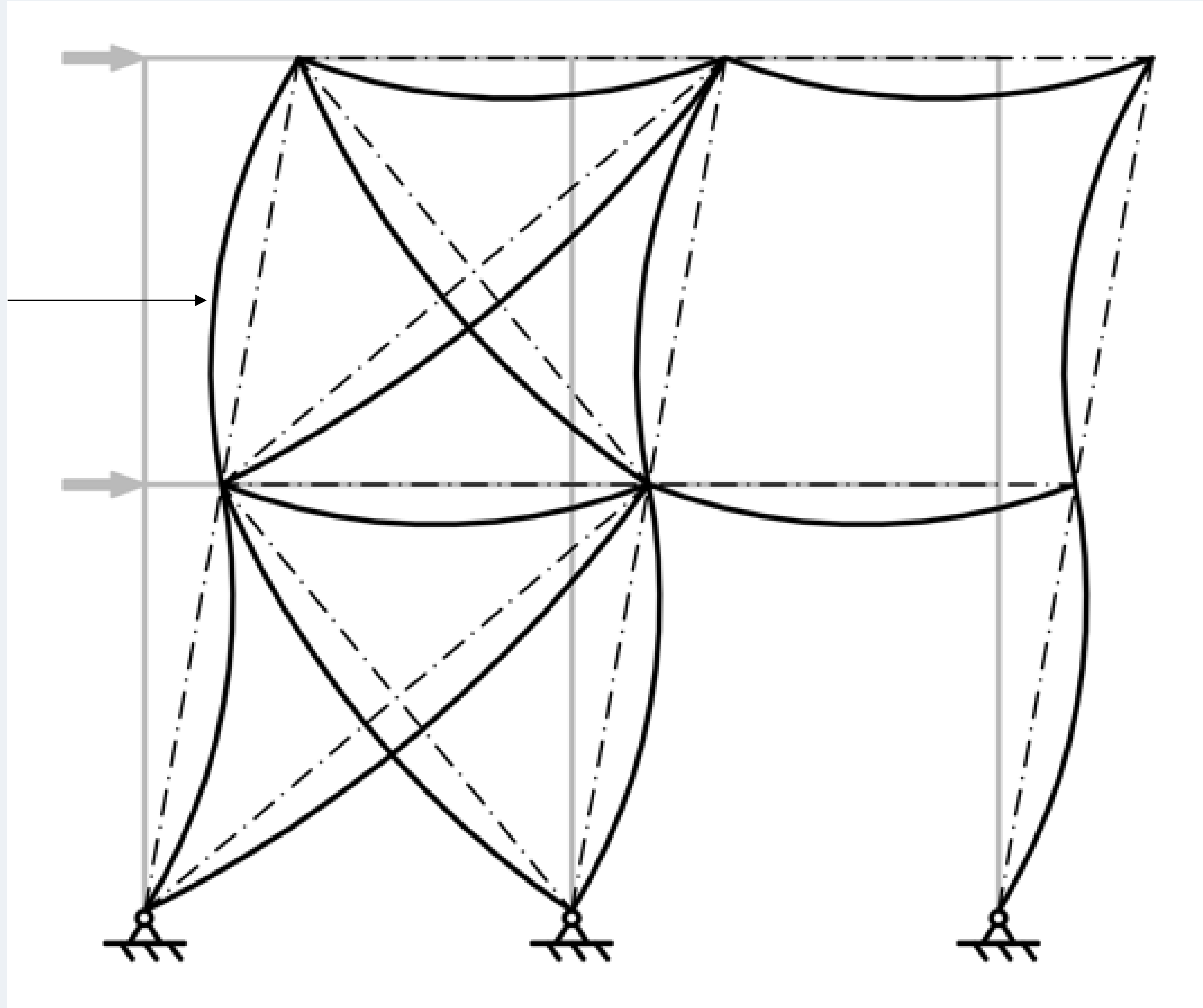


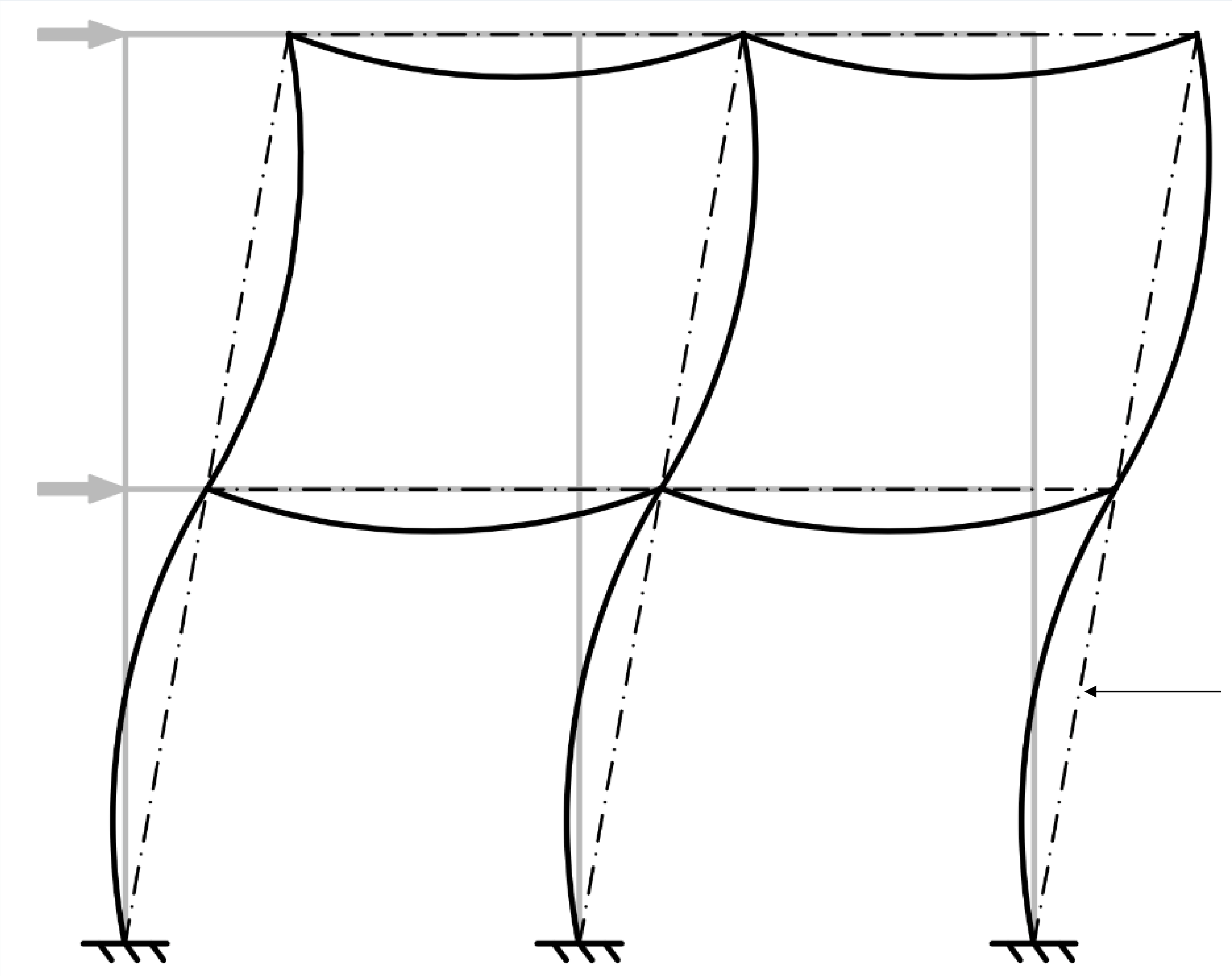
Definition of initial geometric imperfections

Direct definition method

Imperfect geometry directly defined by offsetting nodal coordinates of FE mesh
Directions of global sway and member bow imperfections to follow a set of prescribed rules (e.g. beam bow downwards, columns alternate sign)

Sinusoidal bow imperfections in members



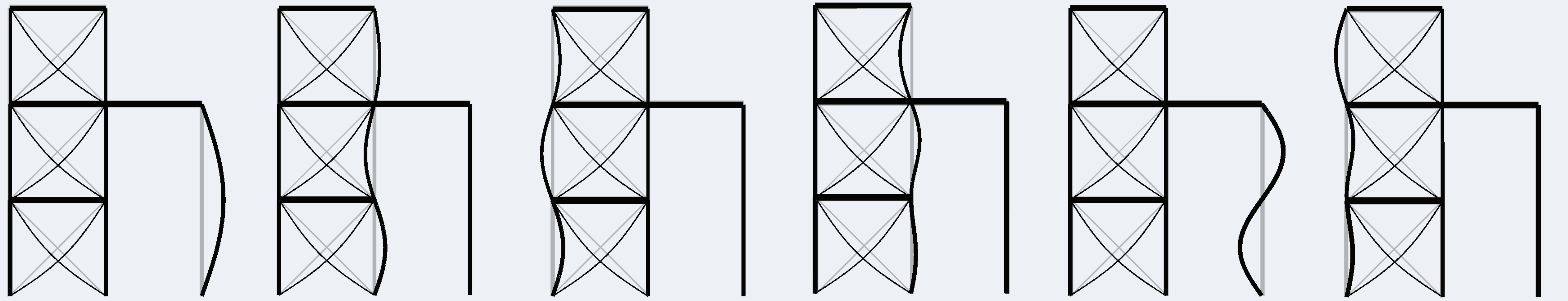


Overall out-of-plumbness for frame imperfections

Definition of initial geometric imperfections

Eigenmode method

Ultimate load capacity α_{GMNIA} taken as the lowest among n results obtained by considering the first n buckling modes individually. A value of n = 6 is recommended

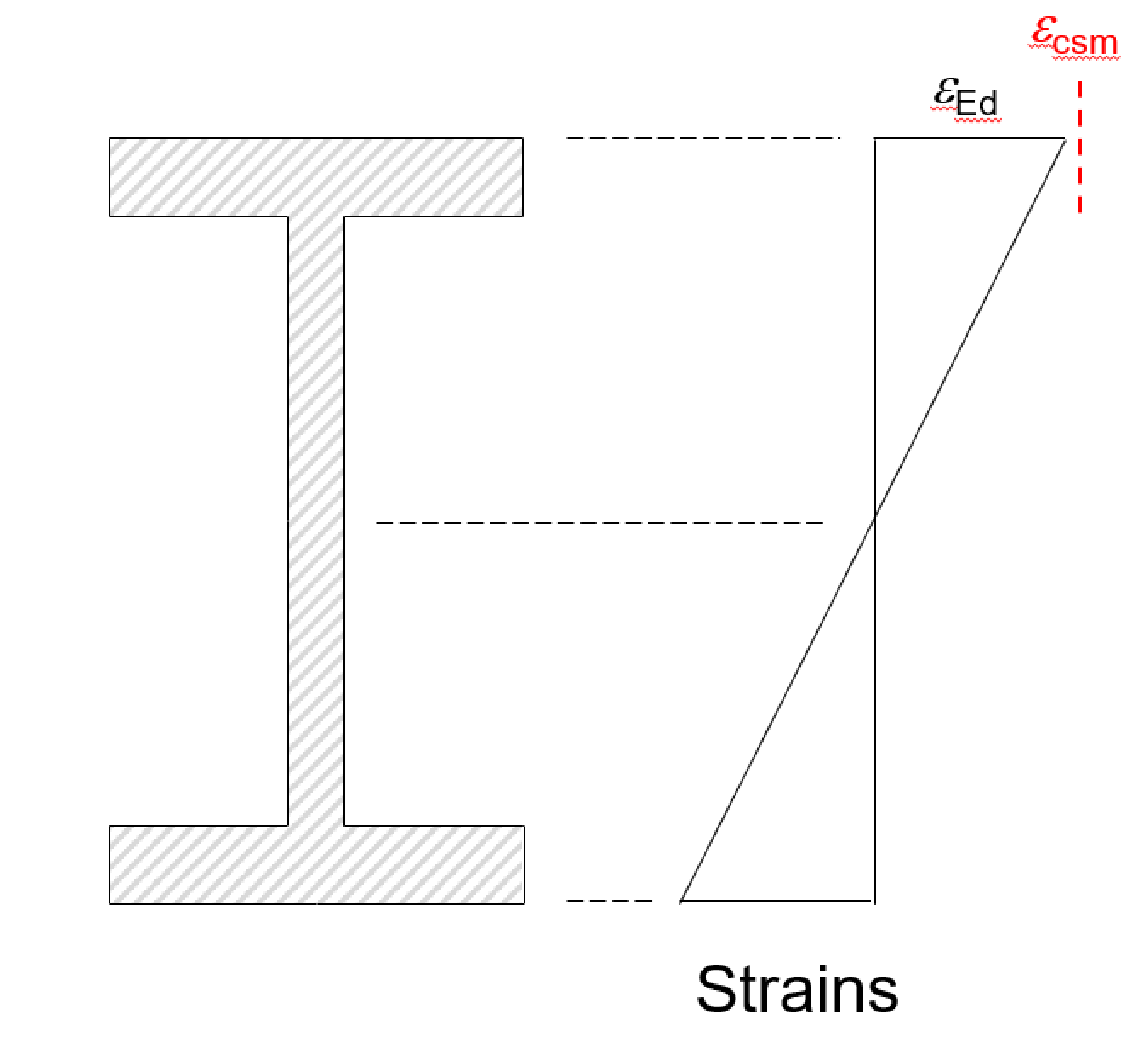


Imperfection 1	Imperfection 2	Imperfection 3	Imperfection 4	Imperfection 5	Imperfection 6
↓	↓	↓	↓	↓	↓
α_1	α_2	α_3	α_4	α_5	α_6

α_{GMNIA} = minimum of α_1, α_2, α_3, α_4, α_5, α_6

Strain limits and model factor γ_{FE}

Strain limits in place of cross-section checks – Annex C



Stain limits, developed in the continuous strength method (CSM), can be used in place of cross-section checks

Strain limits are given as a simple function of the cross-section slenderness and replace the need for cross-section classification

Strain limit ε_{csm} is applied to outer compressive fibre strains ε_{Ed} of all cross-sections in structure

Application of strain limits

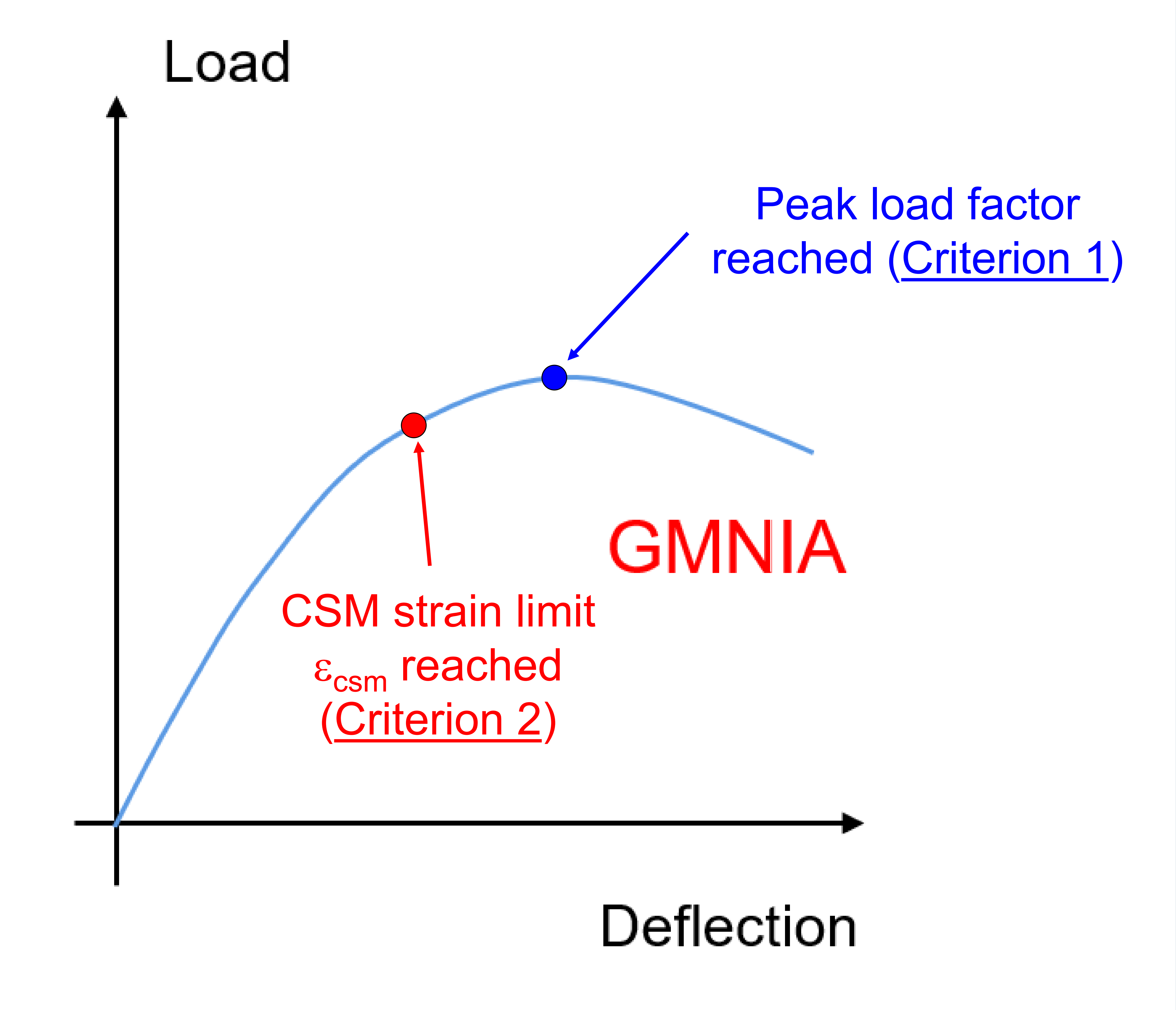
Failure of structure is defined as the first to occur of either:

(1) Peak load factor is reached (in member or frame stability governed cases), or

(2) CSM strain limit ε_{csm} is reached (in cross-section strength governed cases)

Design resistance determined by applying γ_{FE} and γ_{M1}

Strain limits provide more realistic representation of cross-section failure and bring corresponding resistance benefits



Model factor γ_{FE}

- Model factor γ_{FE} accounts for the model accuracy and variability

- For standard cases, $\gamma_{FE} = 1.0$

'Standard design case: numerical model based design check of failure modes for which Eurocode based design resistance model also exists'

- Otherwise, γ_{FE} is calculated based on comparisons of FE model results with experimental data, and application of rules given in Annex A of EN 1993-1-14

GMNIA structural resistance – R_{GMNIA}

Characteristic resistance – $R_{b,k} = R_{GMNIA}/\gamma_{FE}$

Design resistance – $R_{b,d} = R_{b,k}/\gamma_{M1}$

Procedure to determine γ_{FE}

1. Determine $m_x = R_{test,known}/R_{check}$ for each sample
2. Calculate mean m_x and coefficient of variation V_x of n samples
3. Determine model factor

$$\gamma_{FE} = \frac{1}{m_x(1-k_n V_x)} \geq 1.0$$

where k_n is the characteristic fractile factor

Why would we want to do design by FE?

Why would we want to design using FE?

- GMNIA gives incredible insight into the behaviour of the frame, the level of redistribution, the critical failure mechanism and ideas for improving performance.
- More accurate and more uniform level of reliability of structures
- Some kind of elements – unusual shaped cross-sections, curved members etc are outside the scope of the main codes
- Material/weight/carbon emission savings can be around 5-10% typically, and potentially up to 15-20%, with no compromise on safety

More resistance and safer

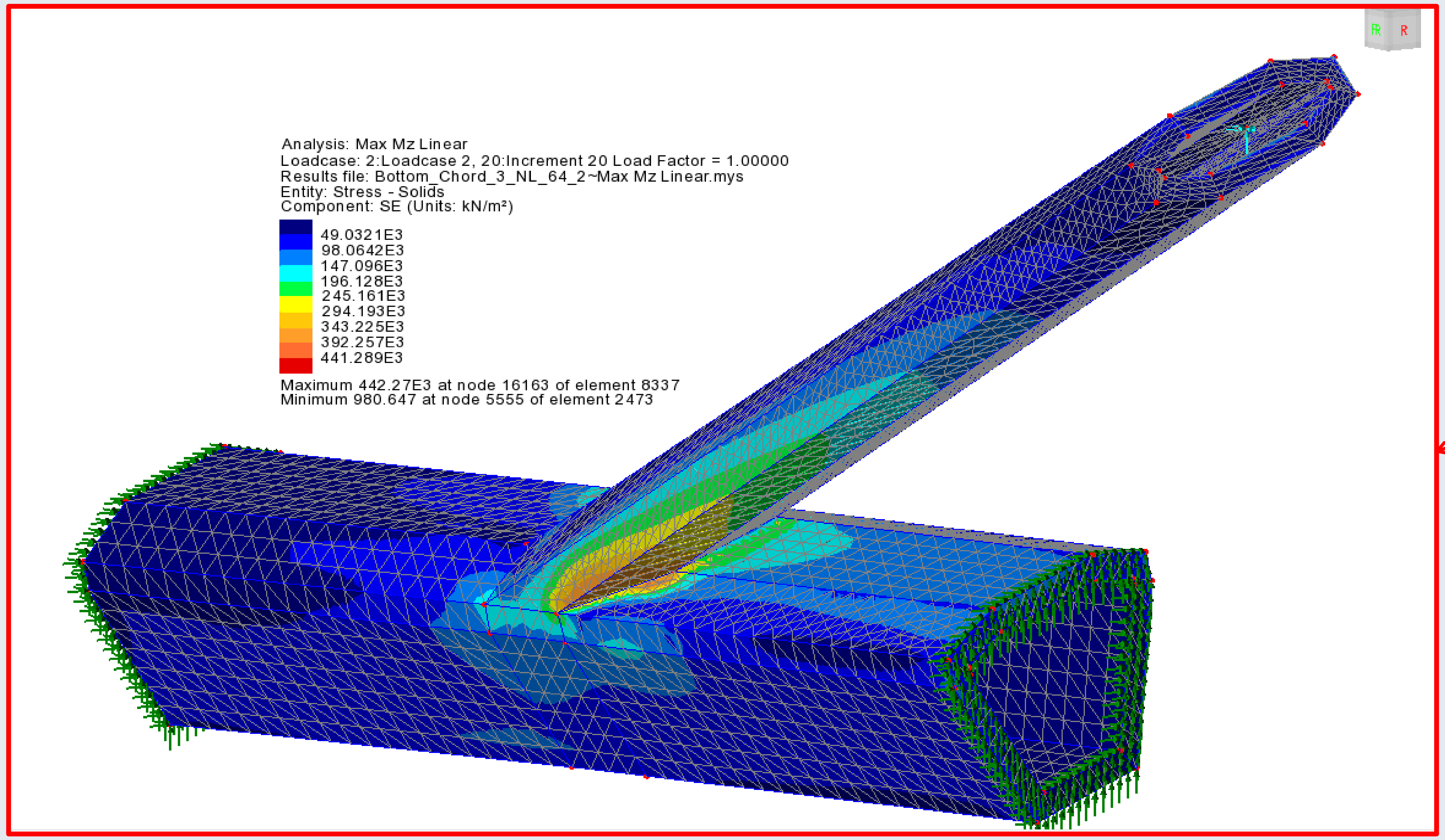
Structure type	$\alpha_{design}/\alpha_{benchmark}$							
	Design by FE (GMNIA + strain limits)				Traditional EC3 design			
	Mean	CoV	Min.	Max.	Mean	CoV	Min.	Max.
Beams (3PB & UDL)	0.96	0.05	0.73	1.02	0.91	0.08	0.68	1.06
Beam-columns	0.97	0.06	0.71	1.02	0.87	0.12	0.52	1.03
Beams (LTB)	0.98	0.03	0.88	1.01	0.91	0.08	0.52	1.07
Moment frames	0.97	0.05	0.73	1.06	0.84	0.11	0.56	1.02
Pitched portal frames	0.97	0.06	0.84	1.06	0.95	0.07	0.81	1.06

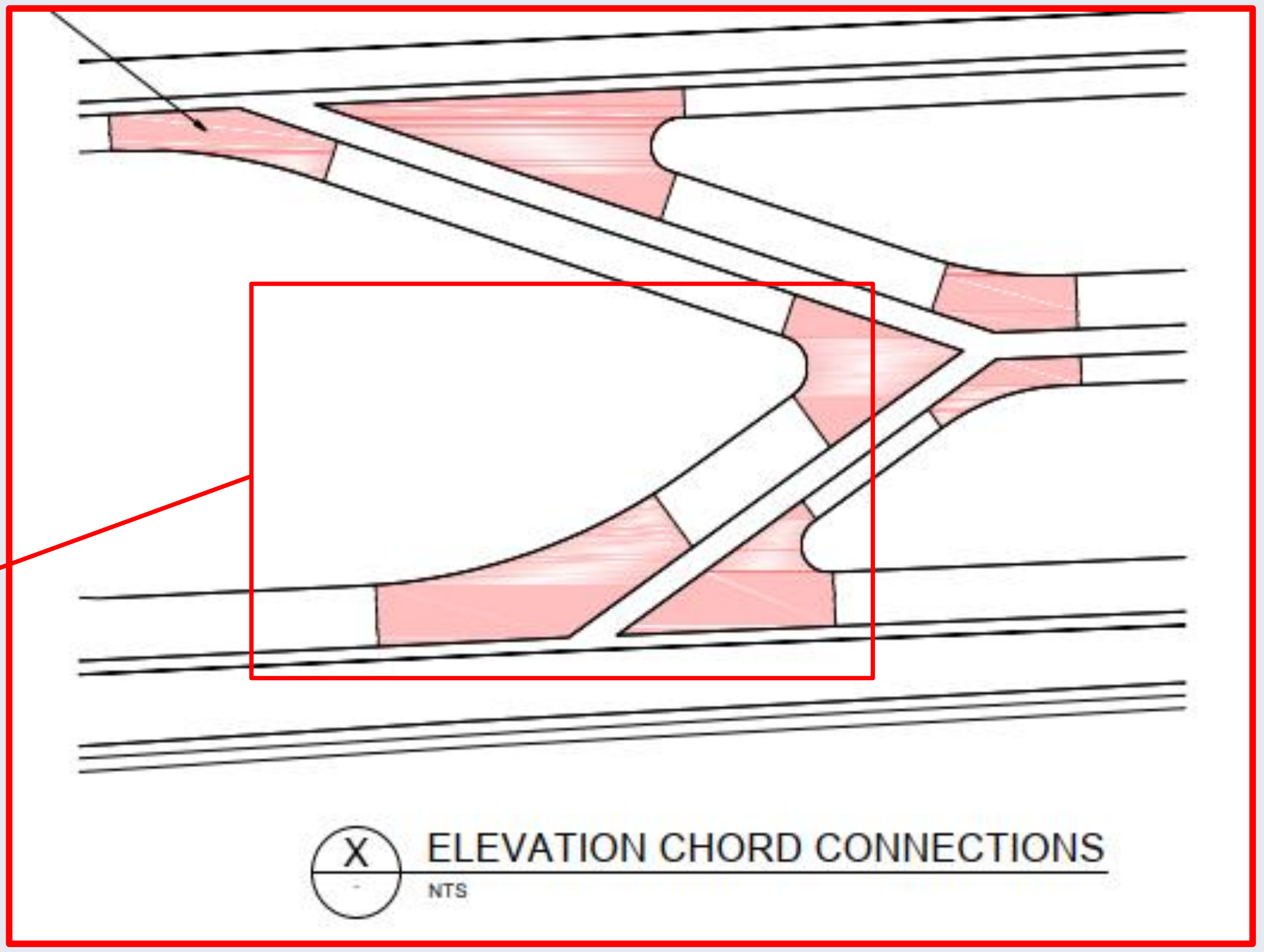
- Design methods benchmarked against hundreds of experiments and shell FE model results
- Nominal material properties, no partial factors etc to allow direct comparisons
- For beams, GMNIA + strain limits gives 5% more resistance on average – 0.96 vs 0.91
- EC3 gives results up to 6% on the unsafe side, while GMNIA + strain limits is only 2% on the unsafe side
- So, design by FE gives more resistance (on average) but fewer results on the unsafe extremes

Why would we want to design using FE?

Practical example:

- Truss design involved section type not covered by EN 1993-1-1 or EN 1993-1-8
- FE analysis required to check the design
- FE analysis allowed novel design to be realised safely without the need for physical experiments





Ensuring safety and checking FE designs

- Concerns (rightly so) about user competence, black box, how to check designs etc
- Section 1 of EN 1993-1-14 says '(1) This document gives rules intended for engineers who are experienced in the use of FE.'
- Training, benchmarking, model validation, internal QA procedures
- Fundamentals – equilibrium, load paths
- Deflections, deformed shapes and failure modes
- Spot checks – $wL^2/8$!
- Check all input
- Check key output
- Provide careful documentation (as detailed in Section 9 of new Standard) of all model input (geometry, material, boundary conditions etc), so that results can be replicated, and key output
- Feel, intuition, experience

Conclusions

Conclusions

- A new Eurocode (EN 1993-1-14) has been published for design by FEA
- Traditional design approaches of course remain valid
- Design by FEA should be more accurate, brings new insights and can bring opportunities for greater design efficiency, reductions in embodied carbon
- Recommendations to ensure safe adoption presented
- An important part of the future of structural design

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