Effects of material nonlinearity on the global analysis and stability of stainless steel frames

Stainless steel in structures – Fifth International Experts Seminar

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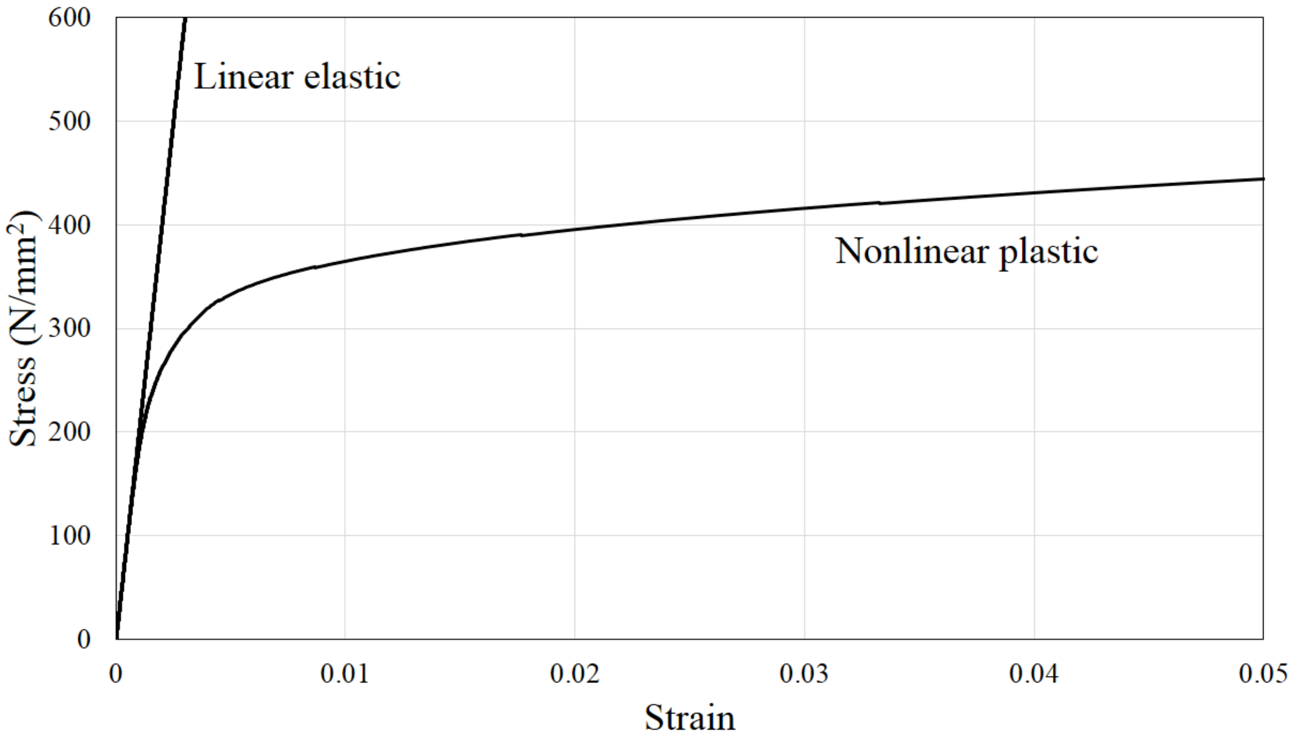
Outline

- Introduction
- Benchmark frame modelling
- Assessment of design approaches
- Conclusions

Introduction

EN 1993-1-1 states that "elastic global analysis may be used in all cases" and that "elastic global analysis should be based on the assumption that the stress-strain behaviour of the material is linear, whatever the stress level is"



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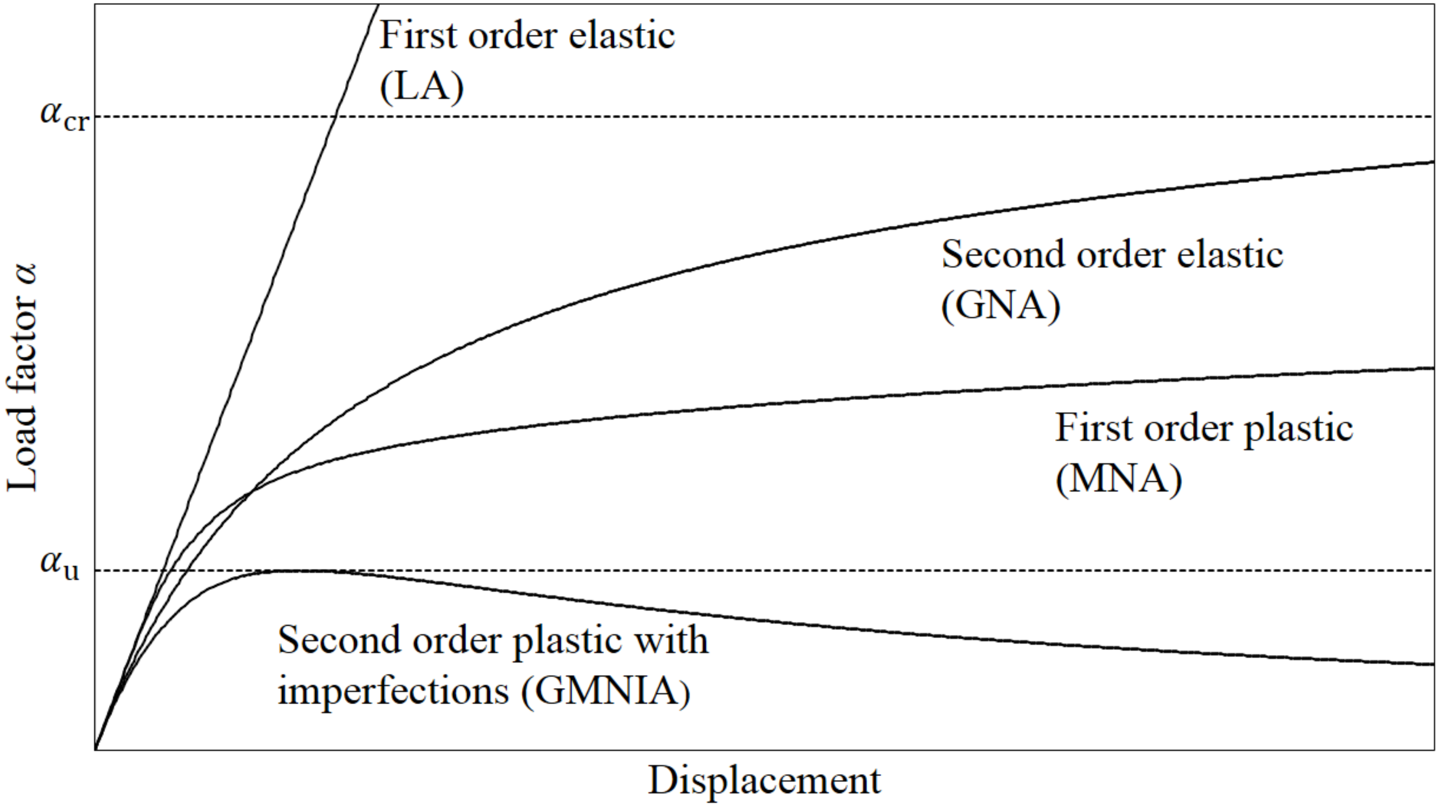
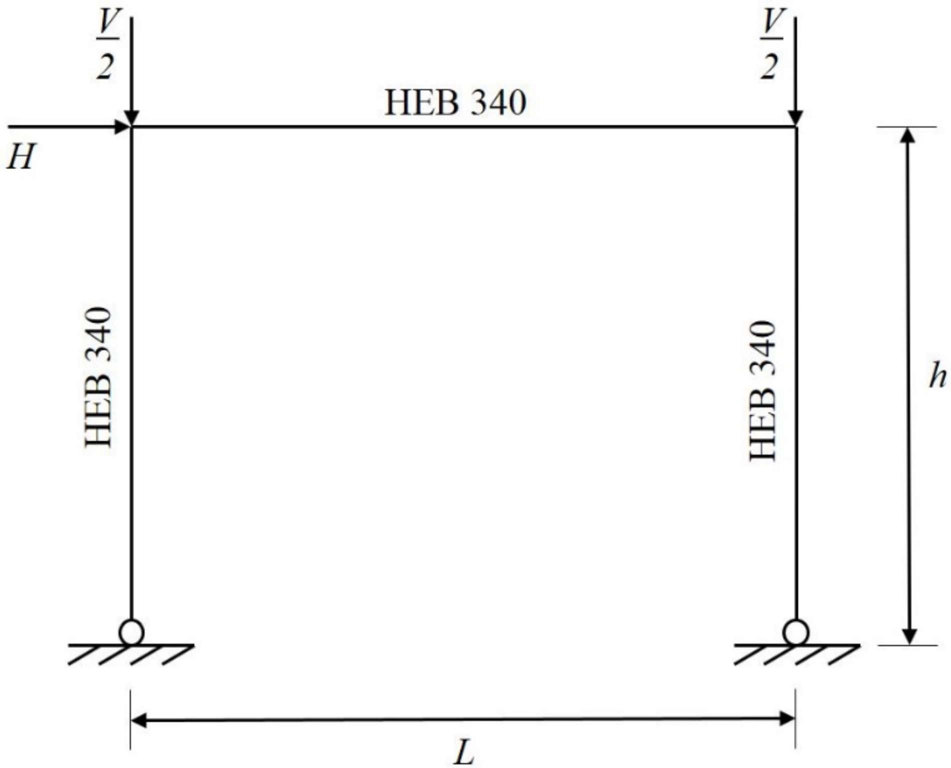


In EN 1993-1-1, second order effects are deemed to be sufficiently small when $\alpha_{cr} \geq 10$ for an elastic analysis and $\alpha_{cr} \geq 15$ for a plastic analysis

Introduction



Frame case no.	Boundary conditions	Horizontal loading H
1	Fixed	$0.05V$
2	Fixed	$0.2V$
3	Fixed	$0.5V$
4	Pinned	0

Benchmark frame modelling

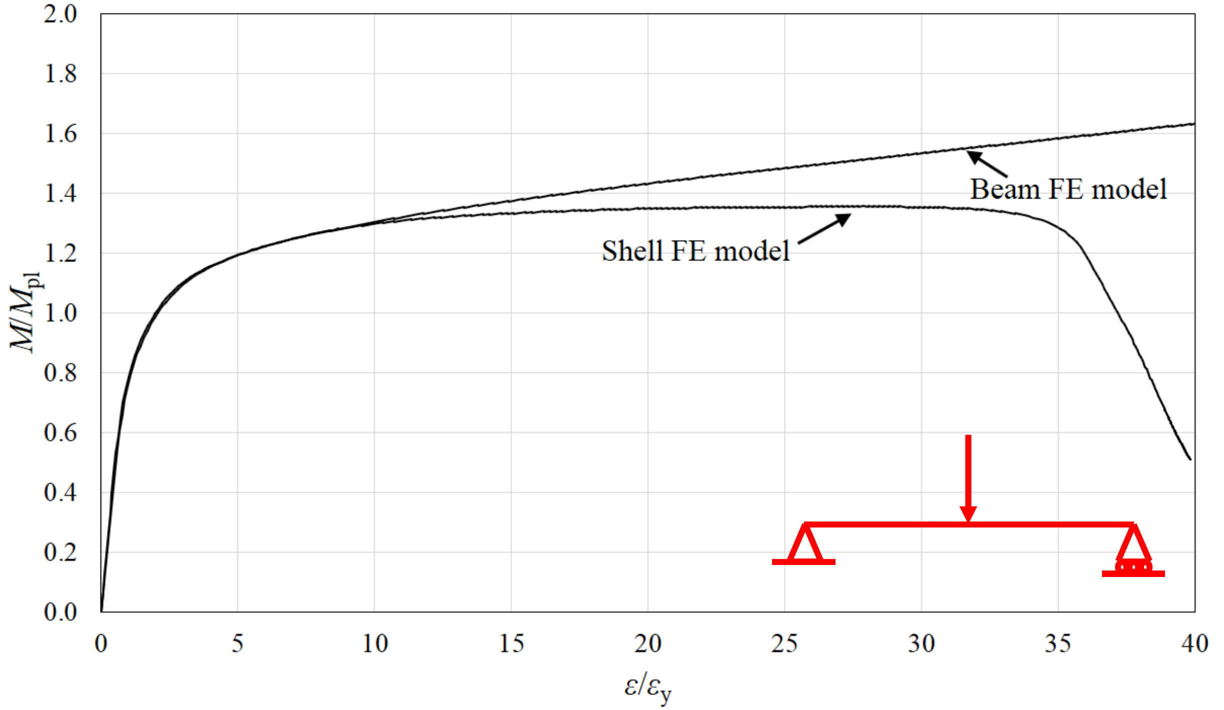
FE modelling

Basic modelling assumptions:

- B31OS
- Two stage Ramberg-Osgood material model
  - $E = 200000\ \mathrm{N/mm^2}$, $f_{\mathrm{y}} = 310\ \mathrm{N/mm^2}$, $f_{\mathrm{u}} = 670\ \mathrm{N/mm^2}$, $n = 6.3$
- Initial member out-of-straightness – $1/1000$
- Initial frame out-of-plumbness – $1/200$
- Modified ECCS residual stress model developed by Yuan et al. (2016) for stainless steel welded I-sections

Ultimate load factor α_u

- Advanced structural analysis commonly carried out using beam elements
  - Beam elements incapable of capturing effects of local buckling



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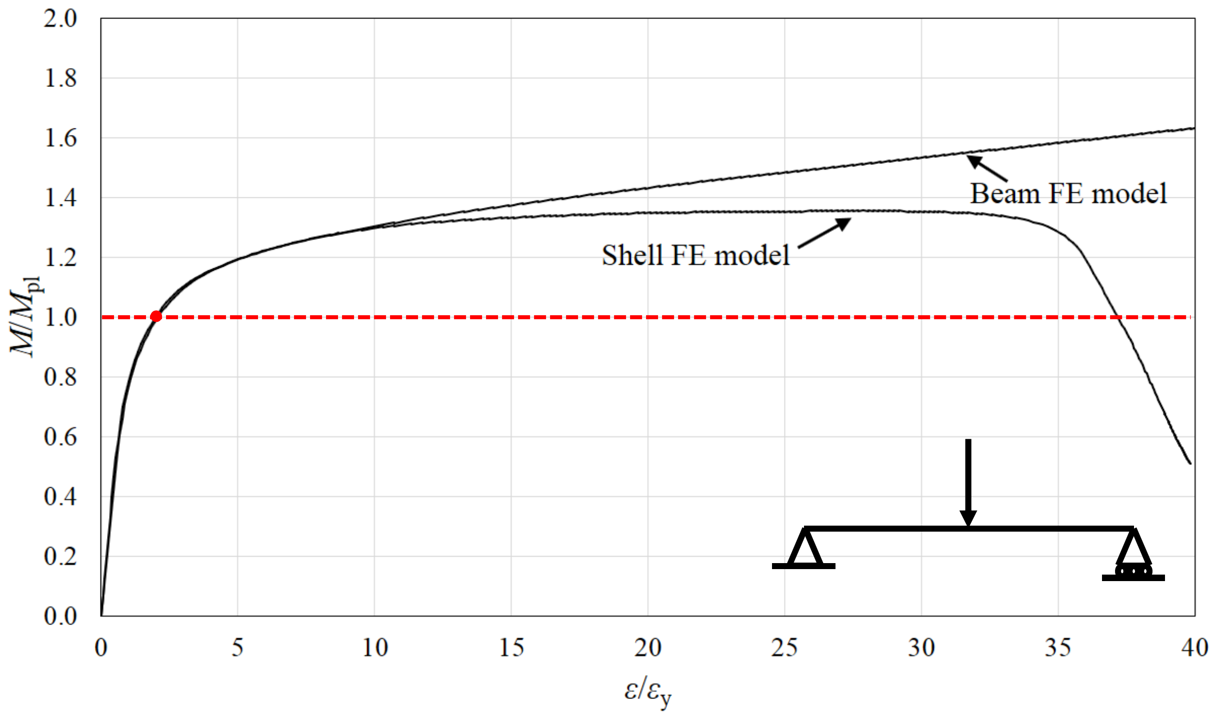

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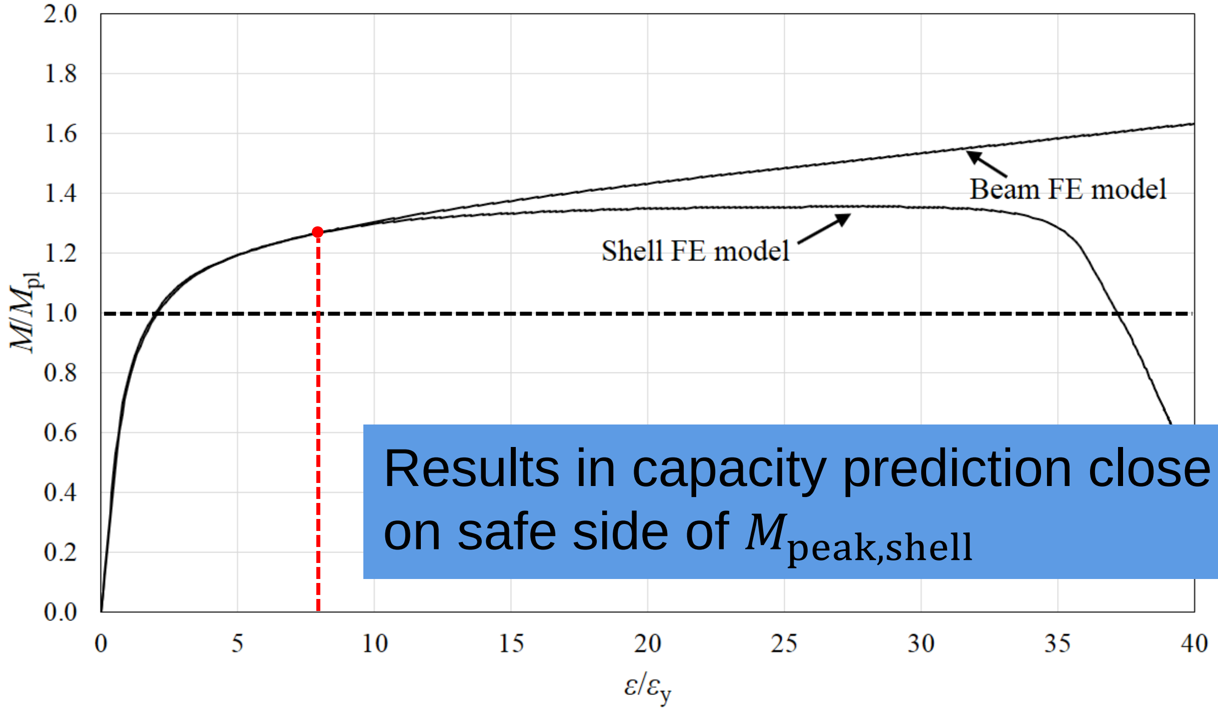
- CSM strain limit used to simulate local buckling

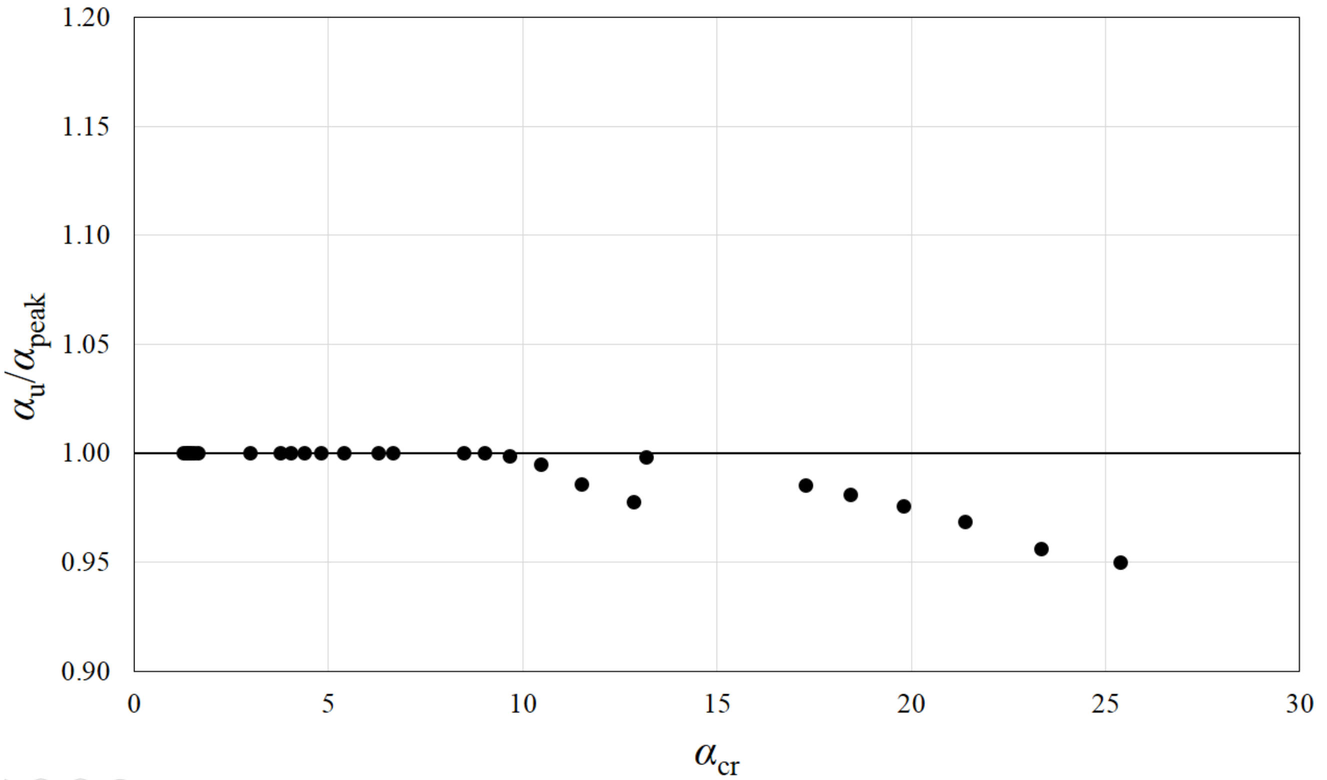


Results in capacity prediction close to but on safe side of $M_{peak,shell}$

Ultimate load factor α_u

Ultimate load factors, as predicted by GMNIA with CSM strain limit, taken to be 'true' benchmark failure values

In cases where peak load occurs first, peak load factor taken as ultimate load factor



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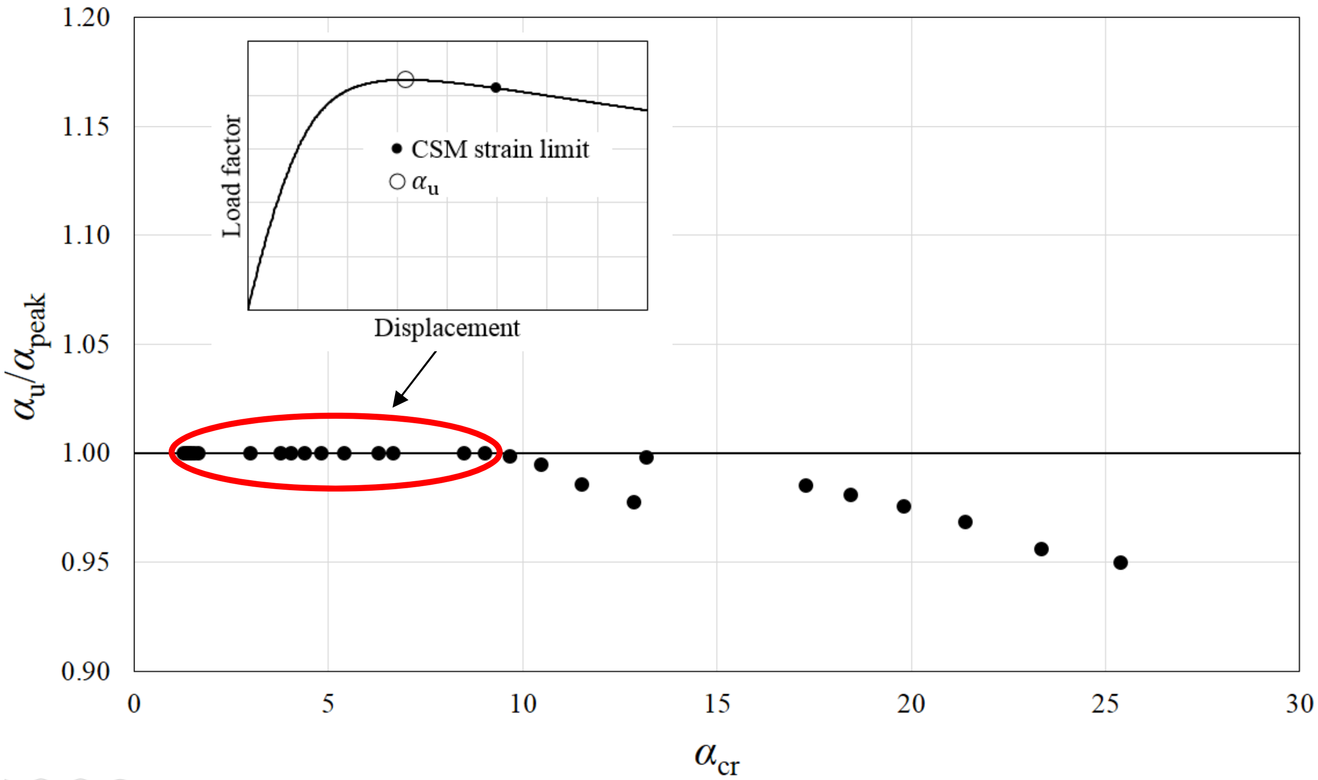

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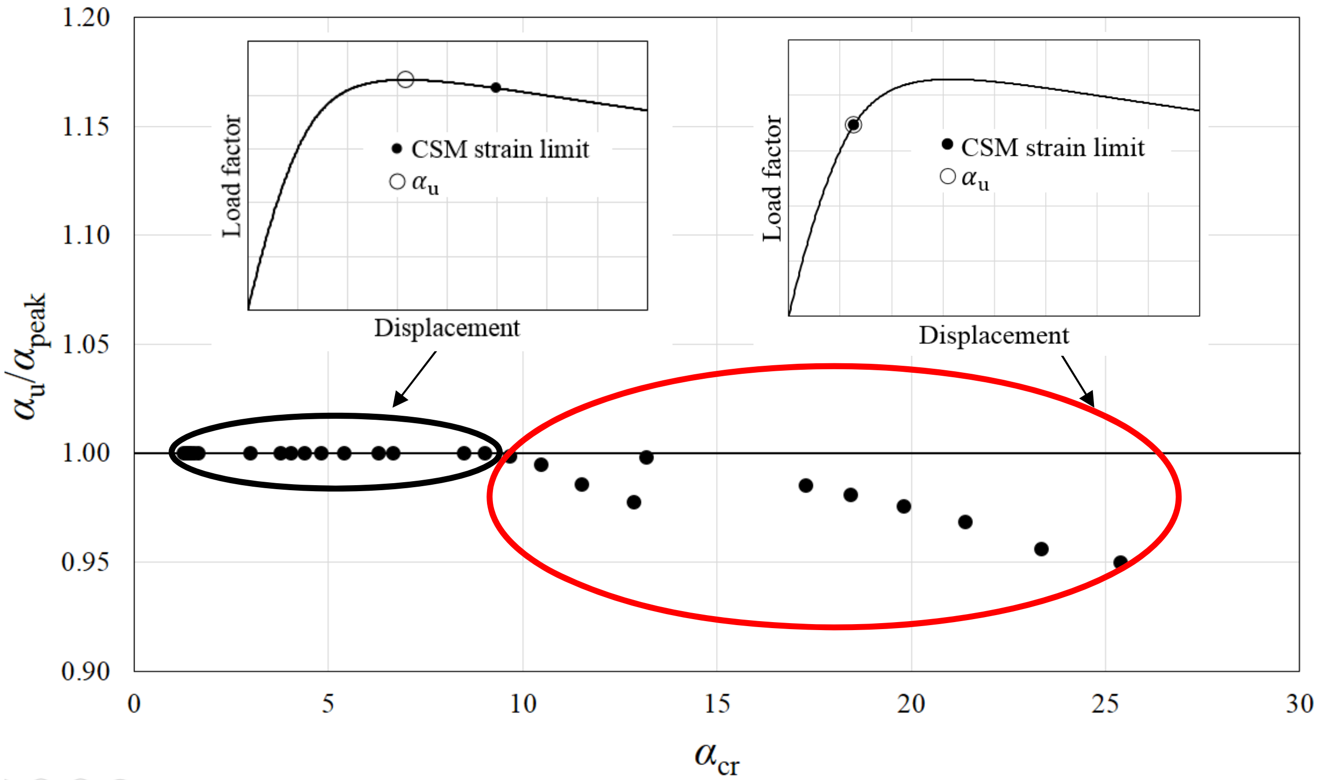
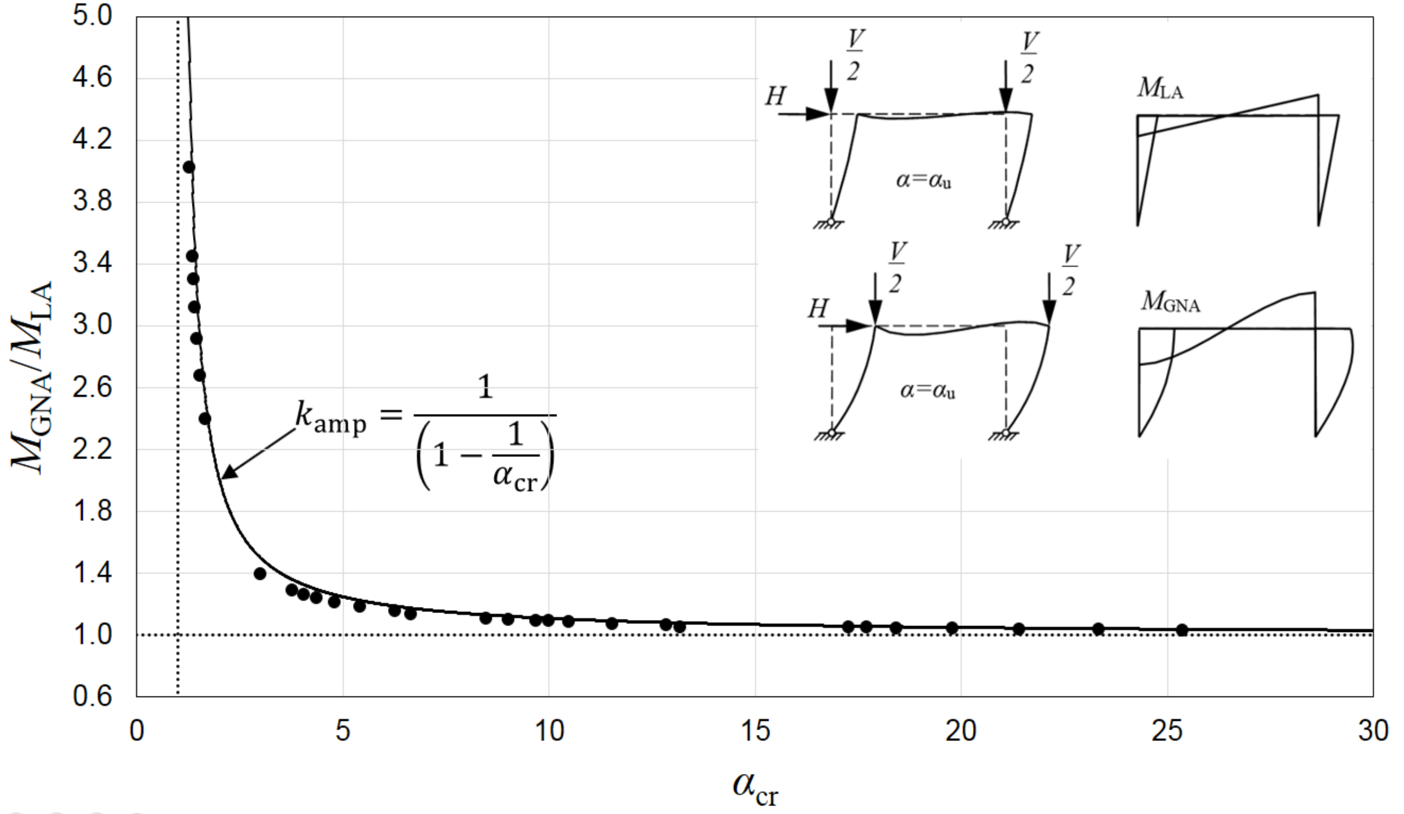
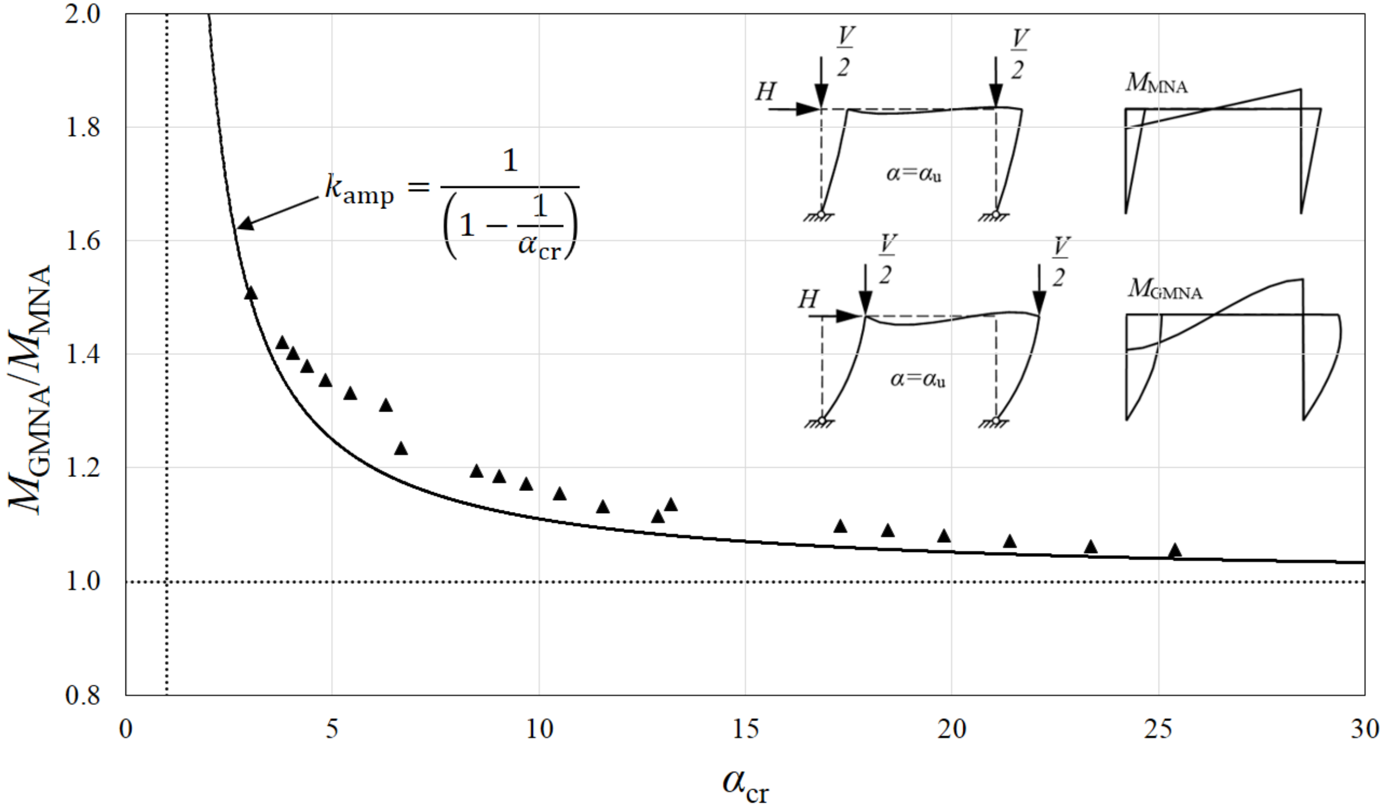


Relationship between bending moments from first and second order elastic analyses



Frames with high values of α_{cr} are not sensitive to second order effects. As α_{cr} reduces, second order effects become increasingly significant.

Relationship between bending moments from first and second order plastic analyses



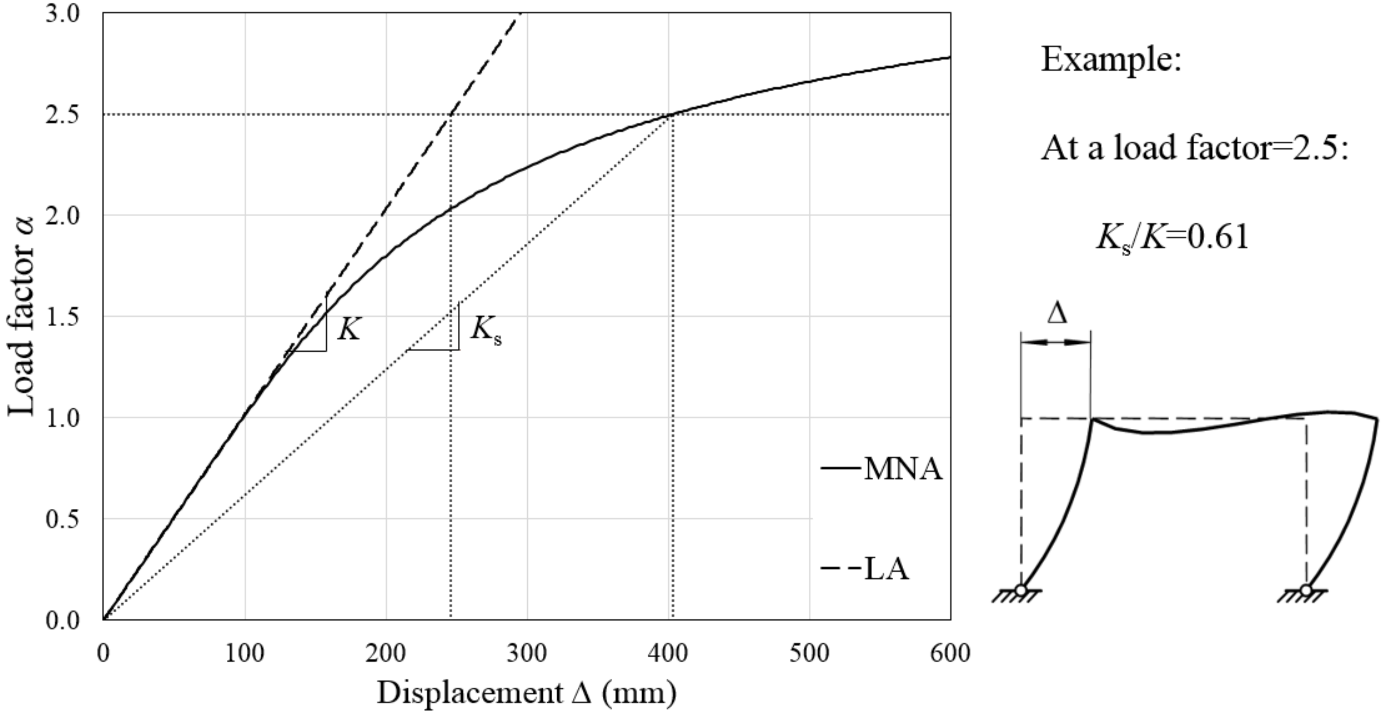
If material nonlinearity is considered, greater deflections ensue due to loss of material stiffness

By ignoring material nonlinearity, maximum second order forces and moments in the considered frames are underestimated

Reduction to sway stiffness of frame due to material nonlinearity

Material nonlinearity results in increased loss of stiffness.

'Average' reduction can be estimated through ratio of secant stiffness K_s to initial stiffness K from a first order plastic analysis (MNA)



Reduction to sway stiffness of frame due to material nonlinearity

Influence of material nonlinearity may be considered by defining a modified elastic buckling load factor $\alpha_{\mathrm{cr,mod}}$

$$\alpha_{\mathrm{cr,mod}} = \alpha_{\mathrm{cr}} \frac{K_{\mathrm{s}}}{K}$$

$$k_{\mathrm{amp,mod}} = \frac{1}{1 - \dfrac{1}{\alpha_{\mathrm{cr,mod}}}}$$

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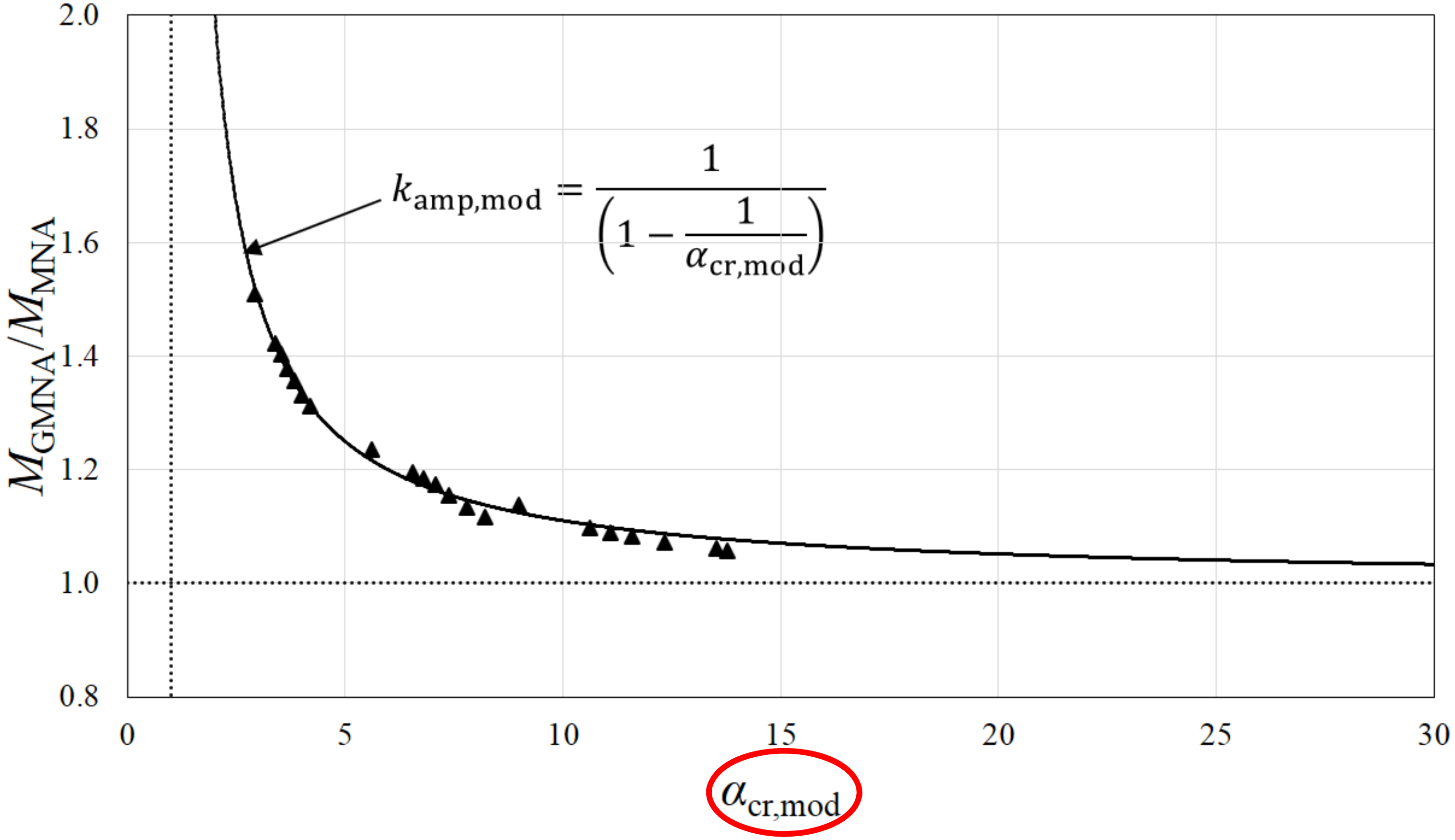

The $\alpha_{\mathrm{cr,mod}}$ captures the reduced stiffness and represents the behaviour of the frame after a certain degree of plastification

Assessment of design approaches

Assessment of design approaches

- Both EN 1994-1-4 and CSM design approaches evaluated.
- Second order effects may be neglected when $\alpha_{\mathrm{cr}} \geq 10$ for elastic analysis and $\alpha_{\mathrm{cr}} \geq 15$ for plastic analysis.
  - Limit of 15 for plastic analysis recognises the fact that frames have reduced stiffness following plasticity so greater second order effects
  - More consistent approach is to determine increased degree of flexibility on frame by frame basis, as with the proposed $\alpha_{\mathrm{cr,mod}}$ approach

Different design approaches considered

No.	Name	Analysis type	Limit	Material model	Imperfections	Cross-section check	Member check	GMNIA/Design resistance (α_u/α_d)				
								No. of frames	Mean	Min.	Max.	COV
1	LA	First order	$\alpha_{cr} \geq 10$	Elastic	Sway	EN 1993-1-4	EN 1993-1-4	10	1.55	1.38	1.71	0.06
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5	GMNIA	Second order	-	Plastic	Sway + bow + R.S.	EN 1993-1-4	-	28	1.08	1.00	1.26	0.07
6	LA	First order	$\alpha_{cr} \geq 10$	Elastic	Sway	CSM	EN 1993-1-4 with k_{CSM} and M_{CSM}	10	1.09	1.02	1.16	0.03
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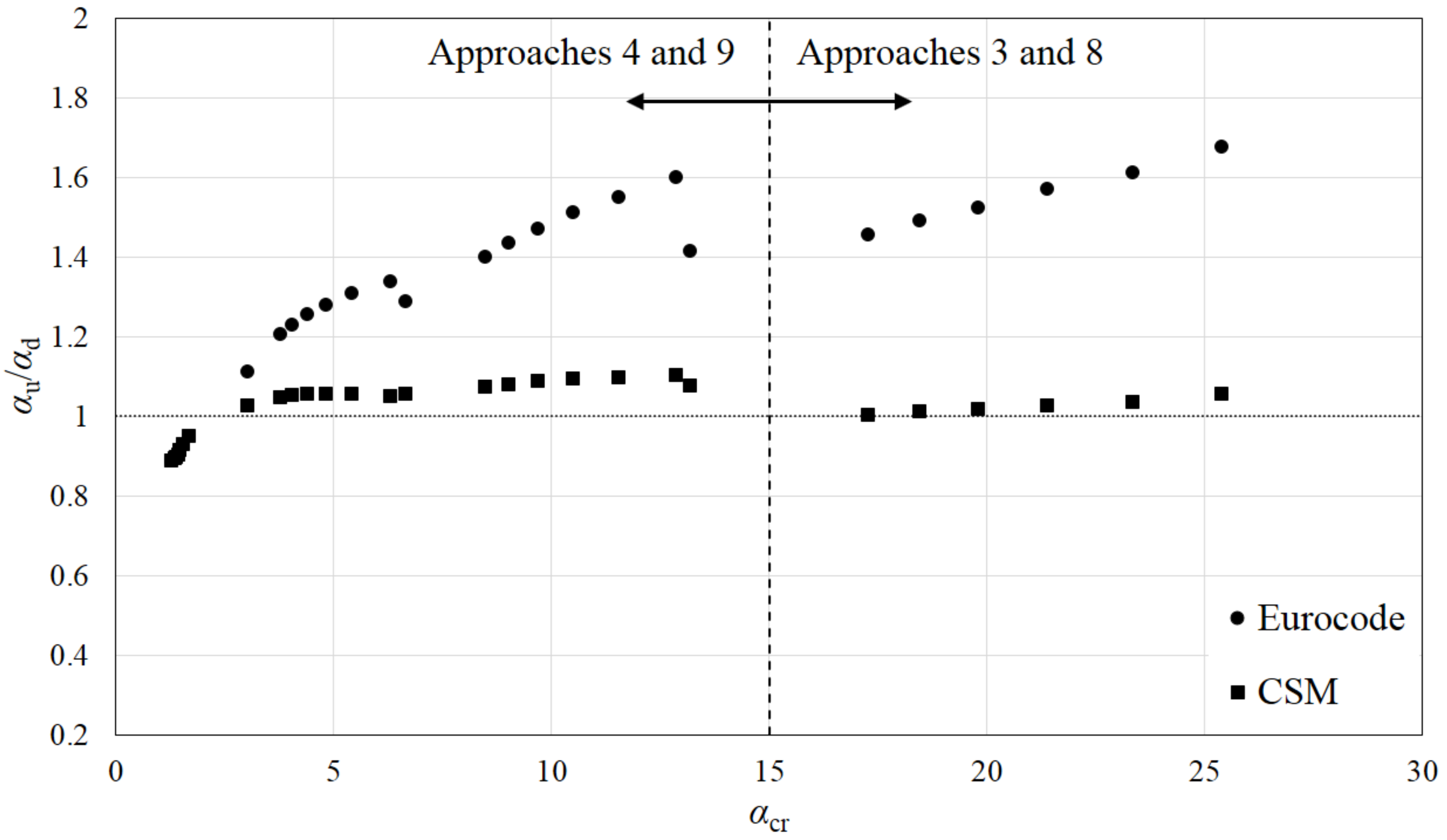
EN 1993-1-4 versus CSM – plastic analyses



For very low α_{cr} values both design approaches lead to results on the unsafe side – such flexible frames are unlikely to be encountered in practice

Different design approaches considered

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Most accurate and consistent design predictions achieved by always employing a plastic analysis with CSM checks

No.	Name	Analysis type	Limit	Material model	Imperfections	Cross-section check	Member check	No. of frames	Mean	Min.	Max.	COV
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Conclusions

- A plastic global analysis should always be employed for stainless steel frames to capture accurately the increased stiffness degradation
- First order analysis when $\alpha_{\mathrm{cr}} \geq 15$ and second order analysis when $\alpha_{\mathrm{cr}} < 15$
- Proposal taking account of increased degree of flexibility - First order analysis when $\alpha_{\mathrm{cr,mod}} \geq 10$ and second order analysis (or first order with amplification $k_{\mathrm{amp,mod}}$) when $\alpha_{\mathrm{cr,mod}} < 10$ – more consistent frame by frame approach
- The Continuous Strength Method results in significantly more accurate strength predictions compared with EN 1993-1-4

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