

Stronger Steels in the Built Environment

WP2: Plastic design of high strength frames

Leroy Gardner

Imperial College London

www.imperial.ac.uk/steel-structures

Outline

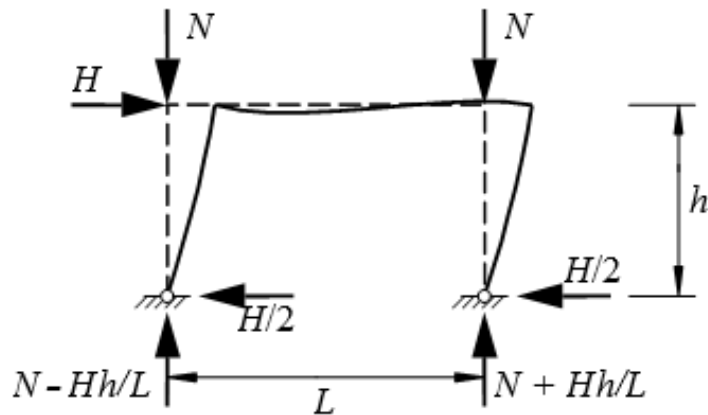
- Introduction to frame stability design
- Tests on HSS frames
- FE validation and parametric studies
- Plastic design of HSS frames
- Conclusions

Analysis types

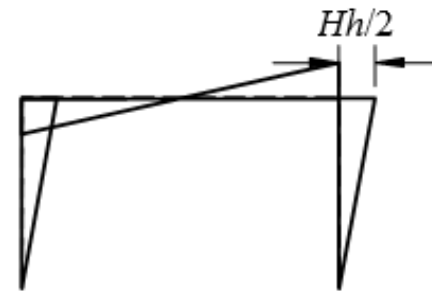
Analysis types:

- First order elastic
- Second order elastic
- First order plastic
- Second order plastic

Second order effects – $P\Delta$ and $P\delta$

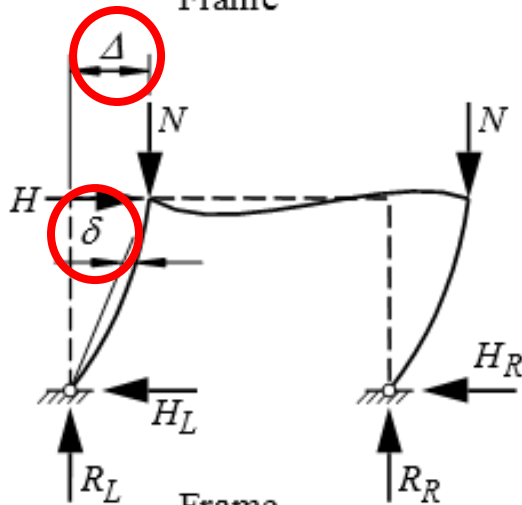


Frame

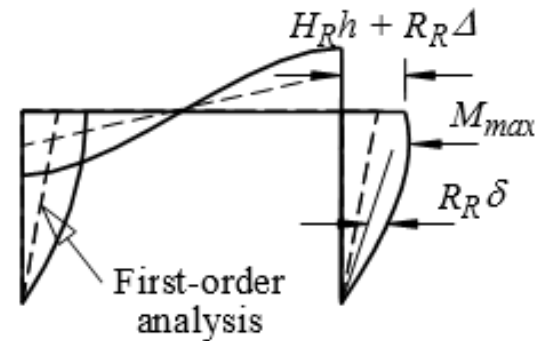


Bending moments

First order



Frame



Bending moments

Second order

Second order effects – $P\Delta$ and $P\delta$

$P\Delta$ effects are associated with global frame deformations. These effects are generally considered during the analysis of the structure (i.e. by performing a second order analysis, or amplifying the results of a first order analysis)

$P\delta$ effects are associated with member buckling. These are normally dealt with in the member design, since the buckling curves make allowance for these effects.

Effects of deformed geometry

EN 1993-1-1 Clause 5.2.1(2) states that deformed geometry (second order effects) shall be considered:

- if they increase the action effects significantly
- or modify significantly the structural behaviour

Limits for ignoring deformed geometry

For elastic analysis:

$$\alpha_{cr} = \frac{F_{cr}}{F_{Ed}} \geq 10$$

where

α_{cr} is the factor by which the design loading would have to be increased to cause elastic instability in a global mode. It may be determined by linear buckling analysis or approximated by considering deflections under equivalent horizontal forces

F_{Ed} is the design loading on the structure

F_{cr} is the elastic critical buckling load for global instability based on initial elastic stiffness.

Limits for ignoring deformed geometry

For plastic analysis:
$$\alpha_{cr} = \frac{F_{cr}}{F_{Ed}} \geq 15$$

Stricter limit for plastic analysis due to loss of stiffness associated with material yielding.

So, for $\alpha_{cr} \geq 10$ (or 15), the effects of deformed geometry may be ignored and a first order analysis will suffice

Analysis method and achievement

Distinguish between:

- **Analysis method** (1st or 2nd order)
- **Analysis achievement** i.e. can achieve 2nd order by:

1) 2nd order analysis

2) 1st order and amplified sway, with $k_{amp} = \frac{1}{1 - 1/\alpha_{cr}}$

3) 1st order and increased effective length.

Frame stability

Limits for treatment of second order effects depend on α_{cr} :

$$\alpha_{cr} = \frac{F_{cr}}{F_{Ed}}$$

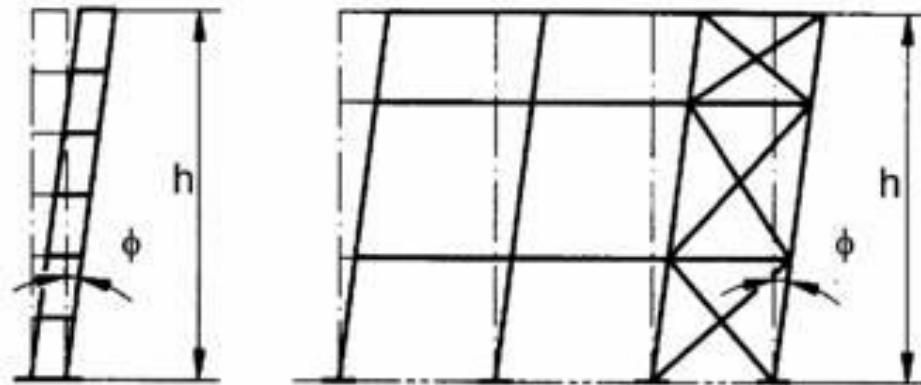
Limits on α_{cr}	Action	Achievement
$\alpha_{cr} > 10$	First order analysis	First order only
$10 > \alpha_{cr} > 3$	First order analysis + 1) Amplified sway method or 2) effective length method	Second order effects by approximate means
$\alpha_{cr} < 3$	Second order analysis	Second order effects more accurately

Global imperfections for frames

Global initial sway imperfections:

$$\phi = \phi_0 \alpha_h \alpha_m$$

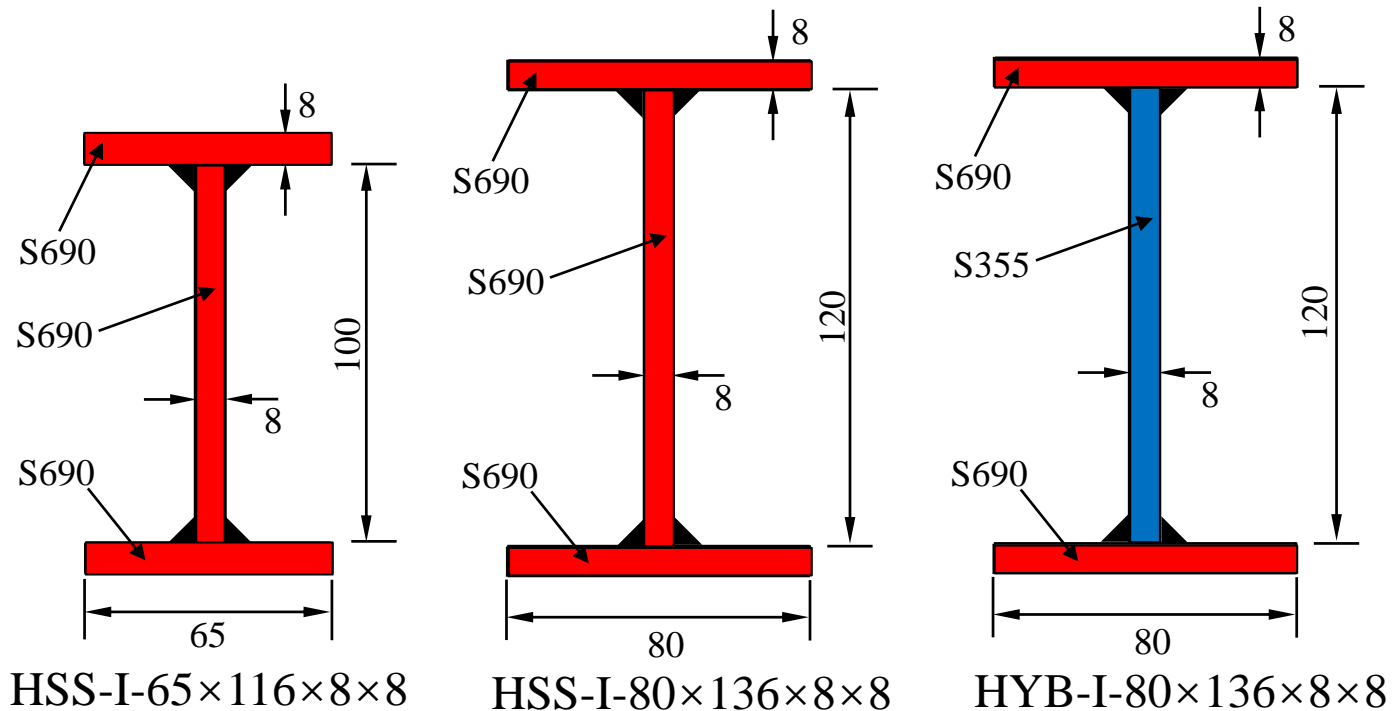
where ϕ_0 is the basic value = 1/200
 α_h and α_m are reduction factors



More conveniently, the effect of frame imperfections can be represented by a system of equivalent horizontal forces (or notional horizontal loads) equal to 1/200 (0.5%) of the vertical load at each storey

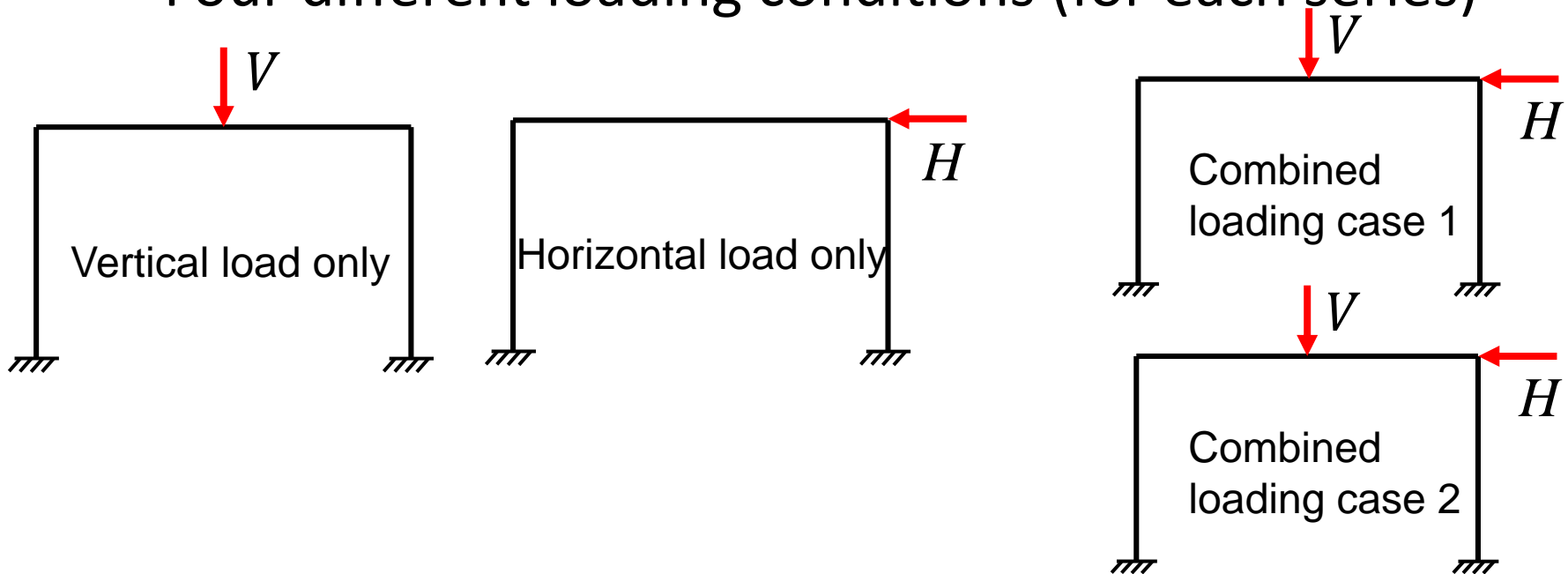
Overview of experimental study

- 12 tests on S690 and hybrid frames under different loading conditions including:
 - ✓ Three different cross-sections (three series)

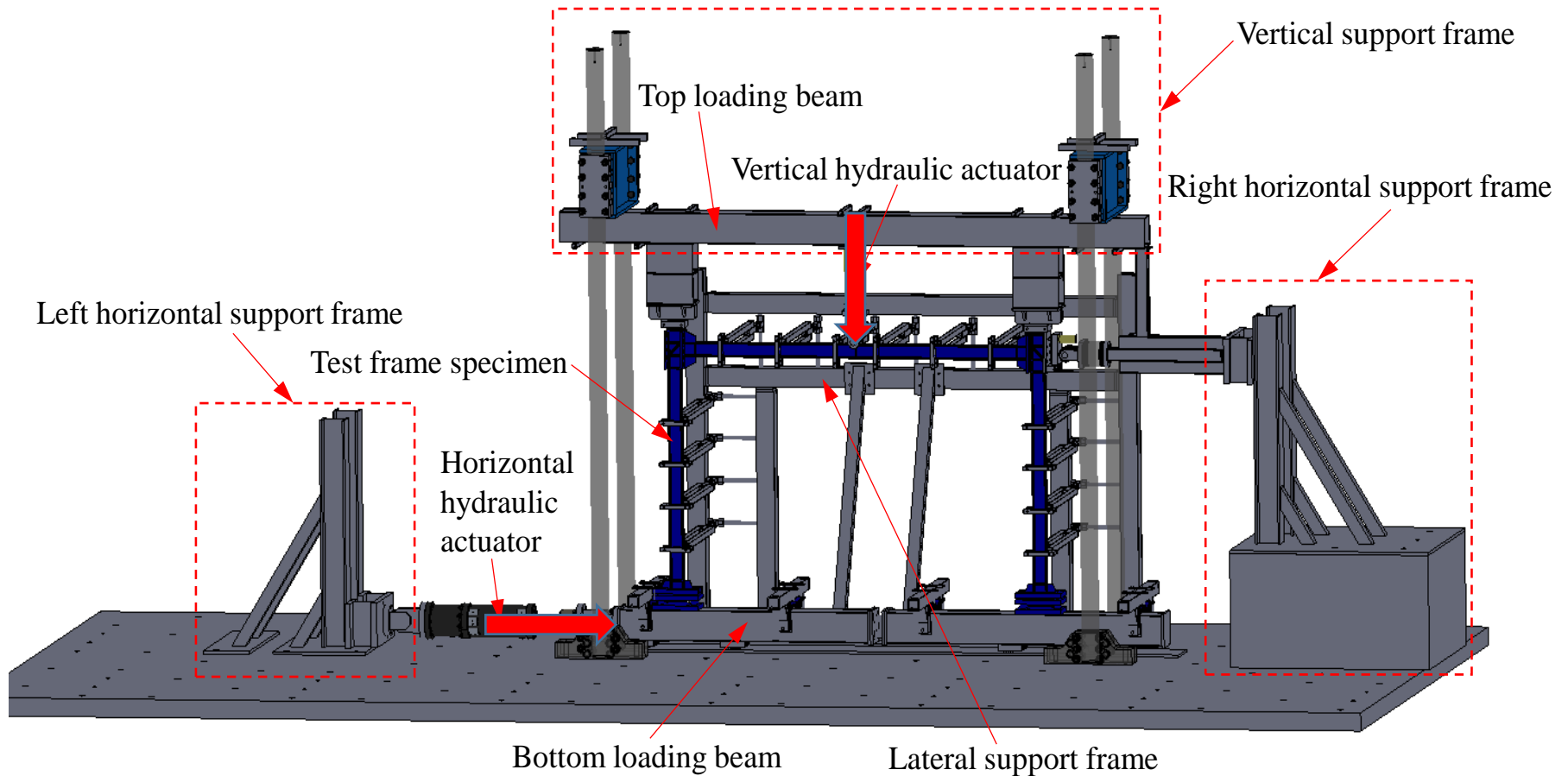


Overview of experimental study

- 12 tests on S690 and hybrid frames under different loading conditions including:
 - ✓ Three different cross-sections (three series)
 - ✓ Four different loading conditions (for each series)

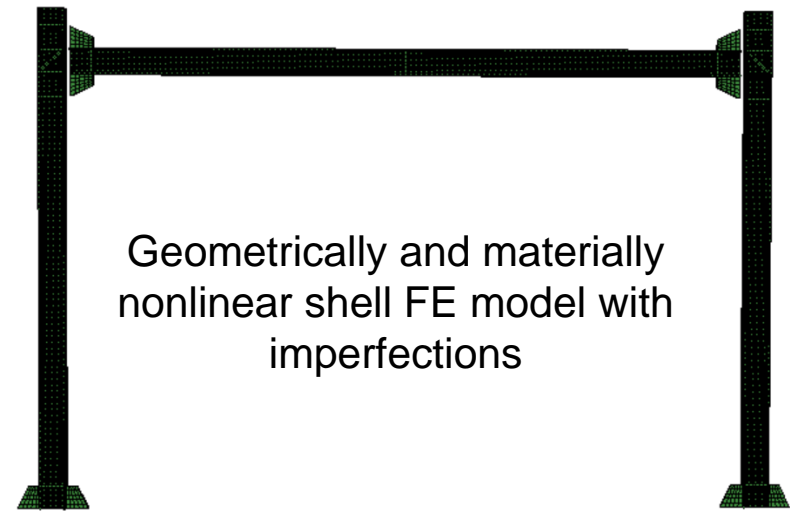
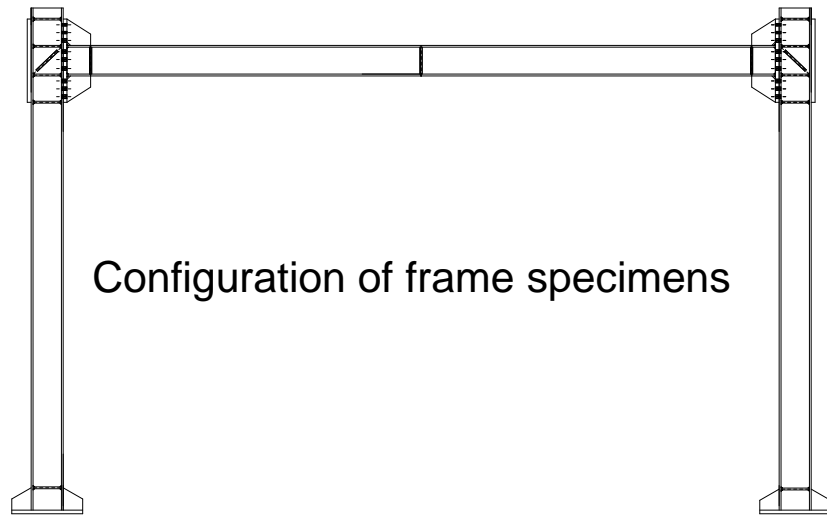


Overview of experimental study



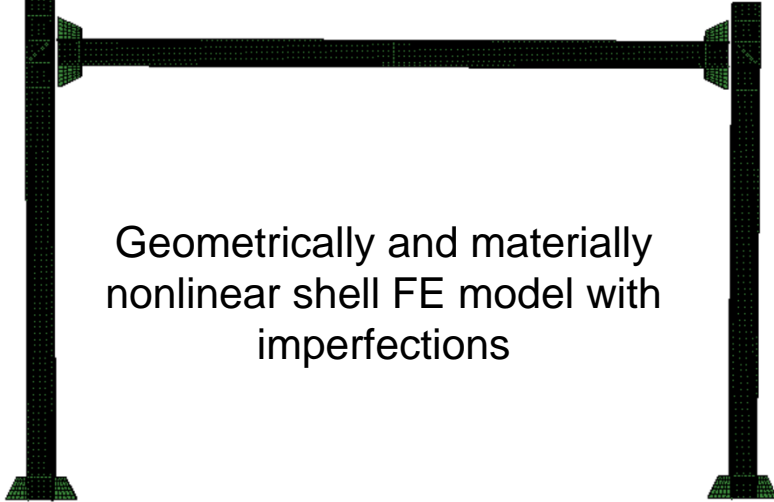
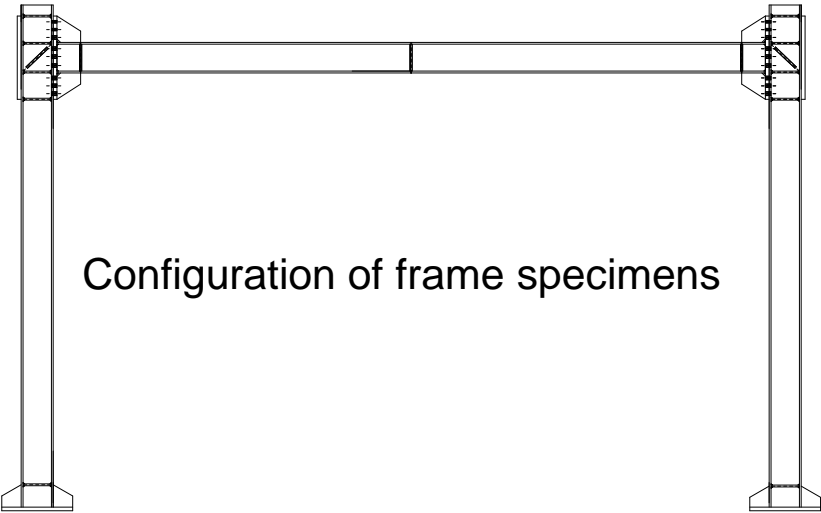
Frame test setup

FE validation and parametric study

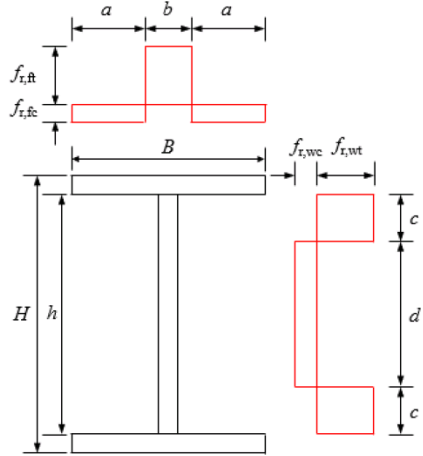
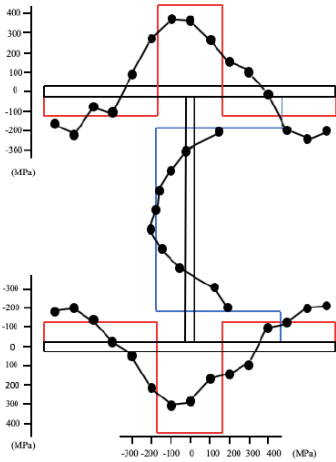


- ✓ Member out-of-straightness using the form of a half-sine wave with $L/1000$
- ✓ Out-of-plumbness of $1/200$ of the frame height

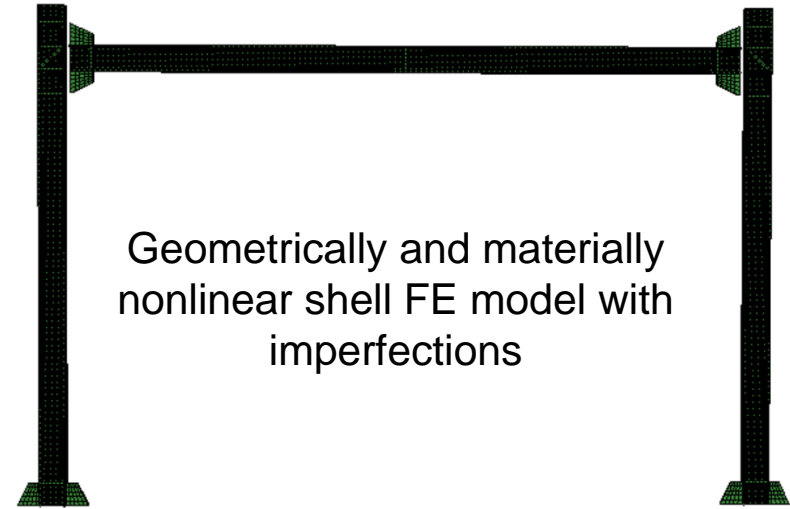
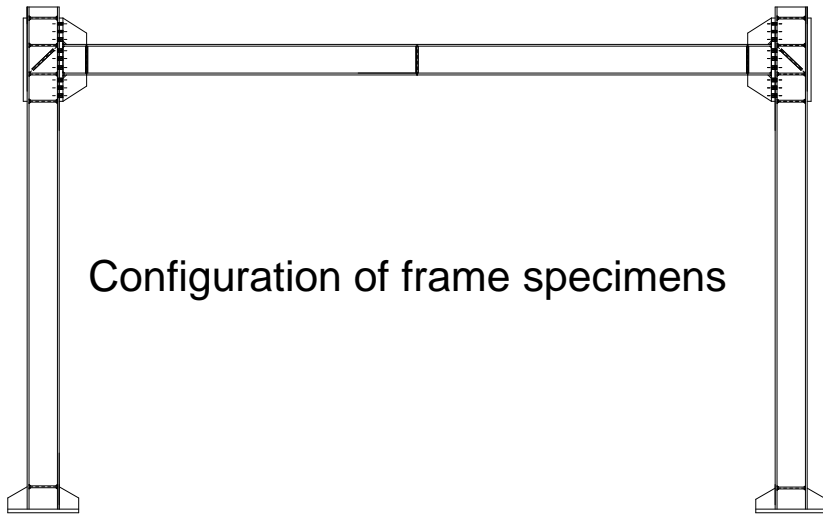
FE validation and parametric study



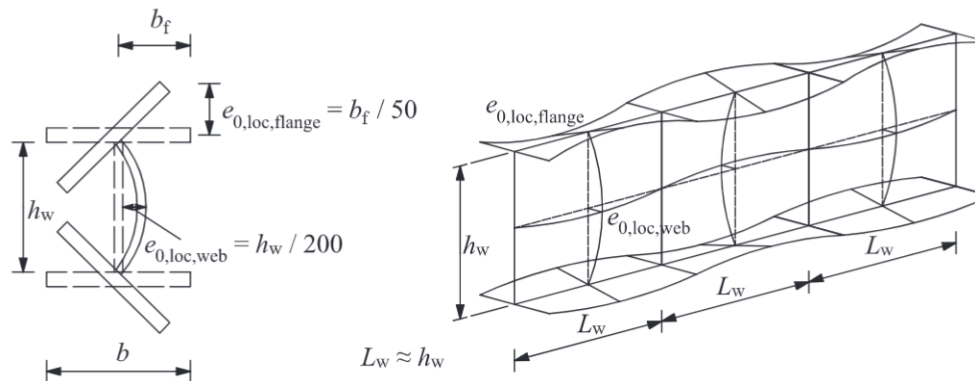
✓ Residual stress pattern



FE validation and parametric study



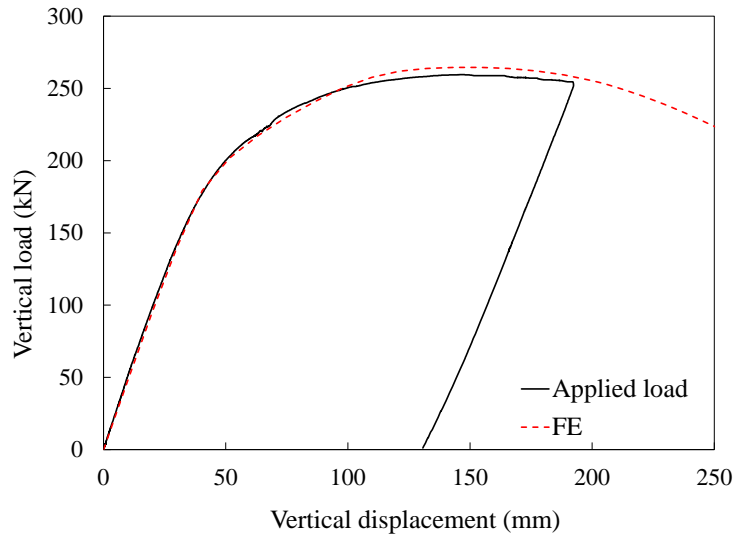
✓ Local imperfections



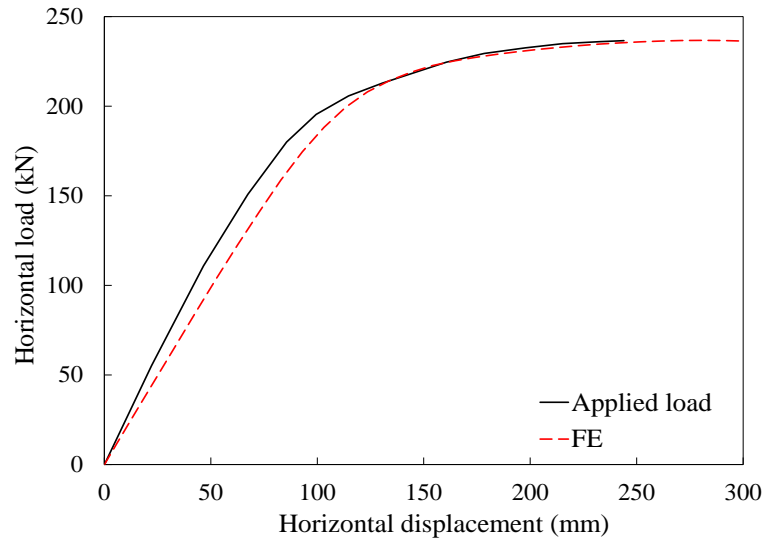
FE validation and parametric study

Validation results

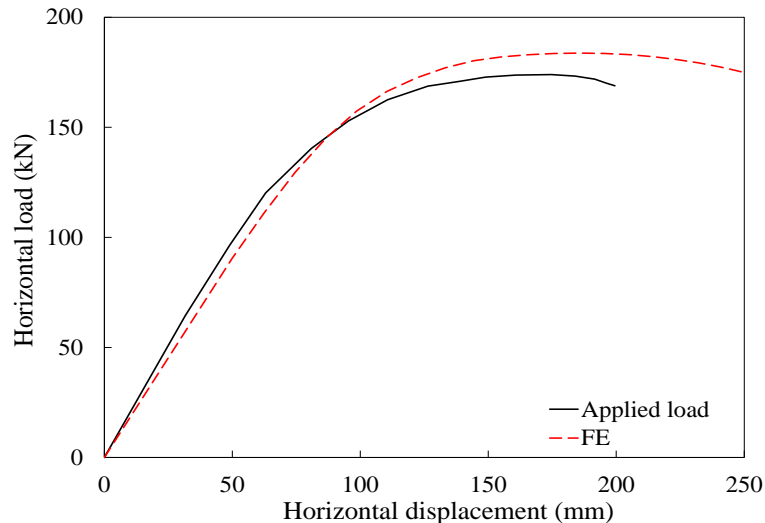
- ✓ Load-displacement curves



HSS-I-80×136-V



HSS-I-80×136-H

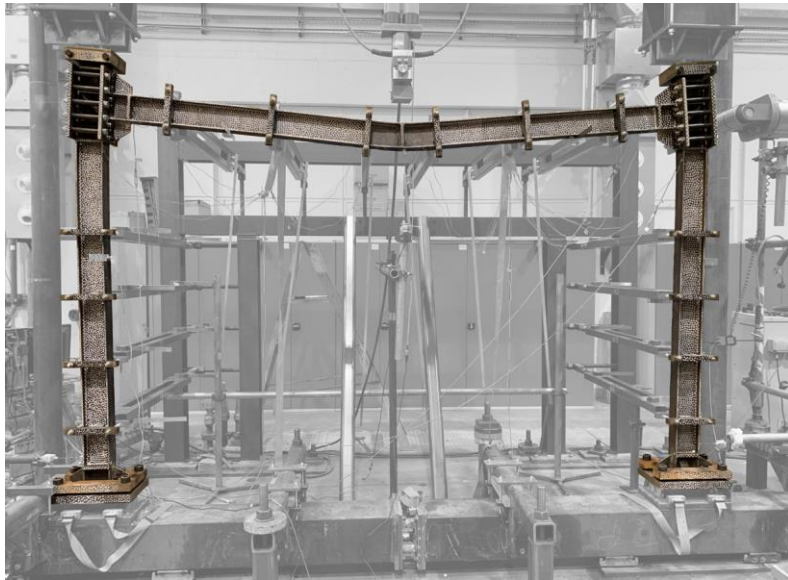


HSS-I-80×136-V&H1

FE validation and parametric study

Validation results

- ✓ Failure modes



Test



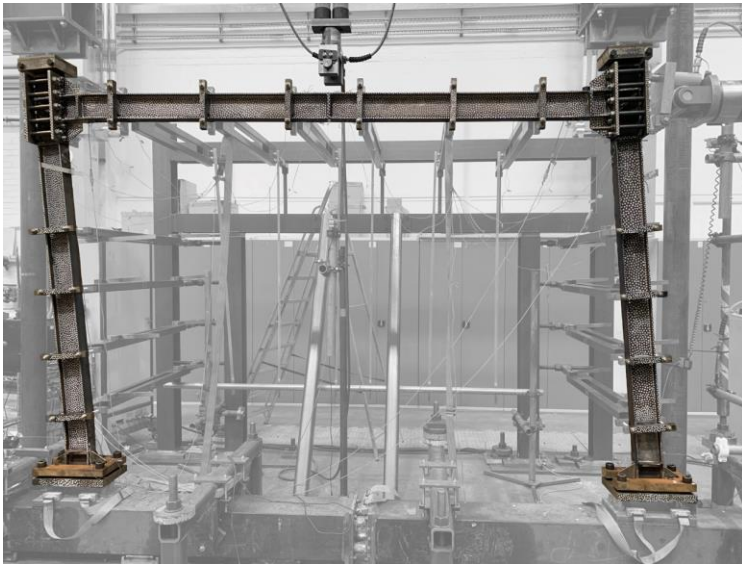
FE

HSS-I-80×136-V
(Beam mechanism)

FE validation and parametric study

Validation results

- ✓ Failure modes



Test



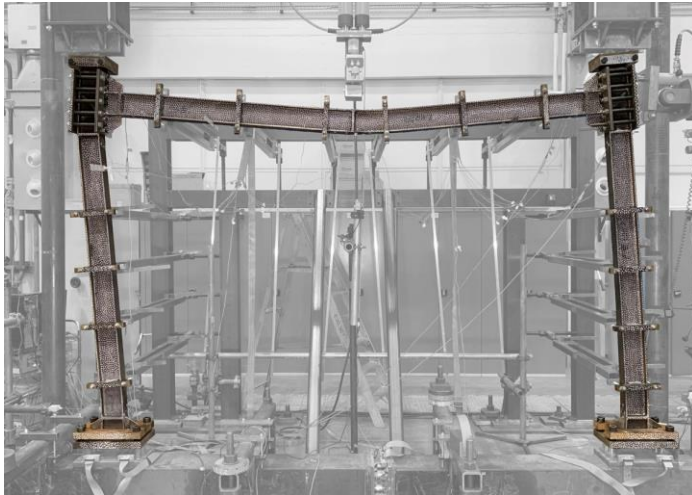
FE

HSS-I-80×136-H
(Sway mechanism)

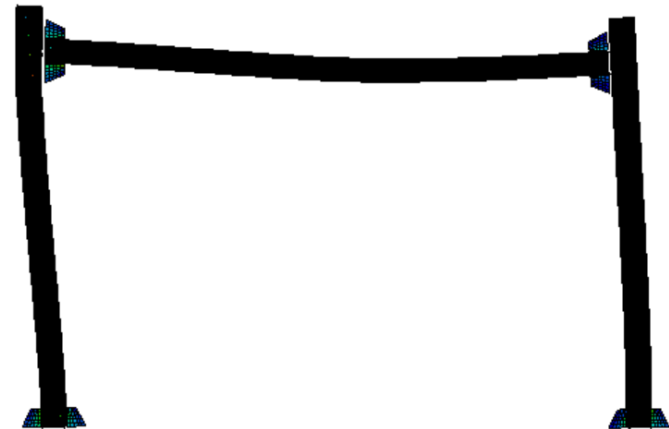
FE validation and parametric study

Validation results

- ✓ Failure modes



Test



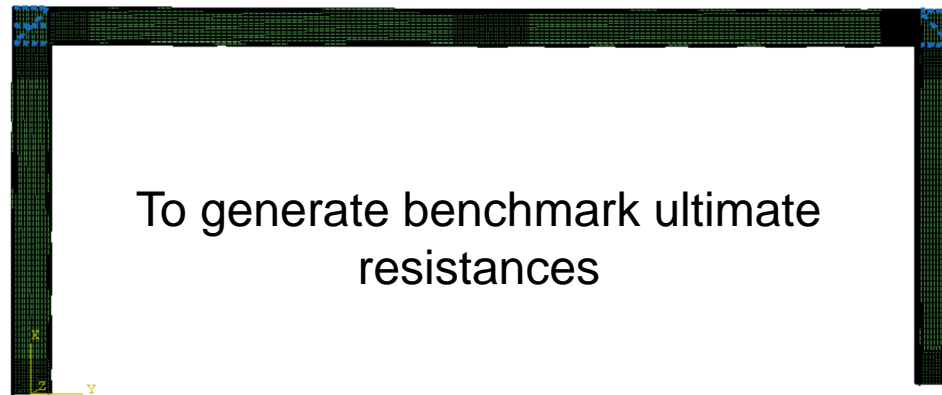
FE

HSS-I-80×136-V&H1
(Combined mechanism)

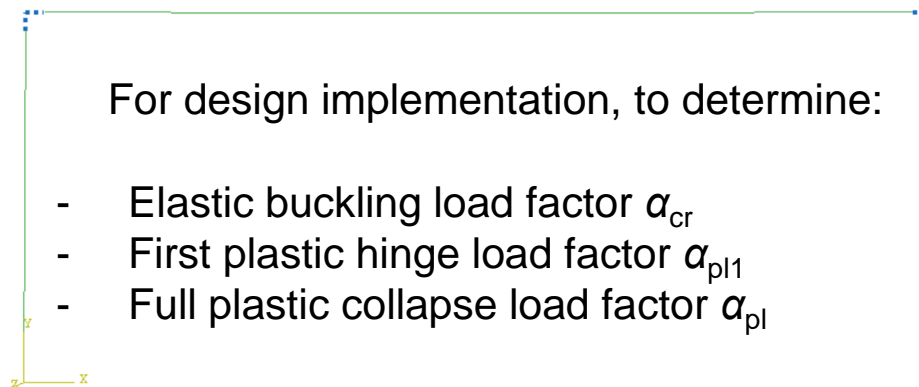
FE validation and parametric study

Parametric study

- Shell FE models



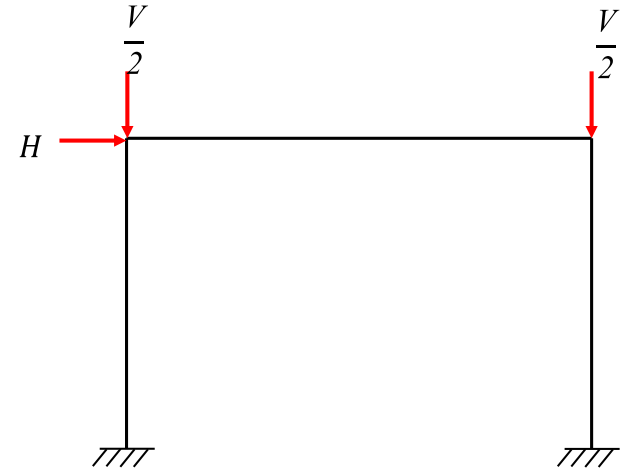
- Beam FE models



FE validation and parametric study

Parametric study

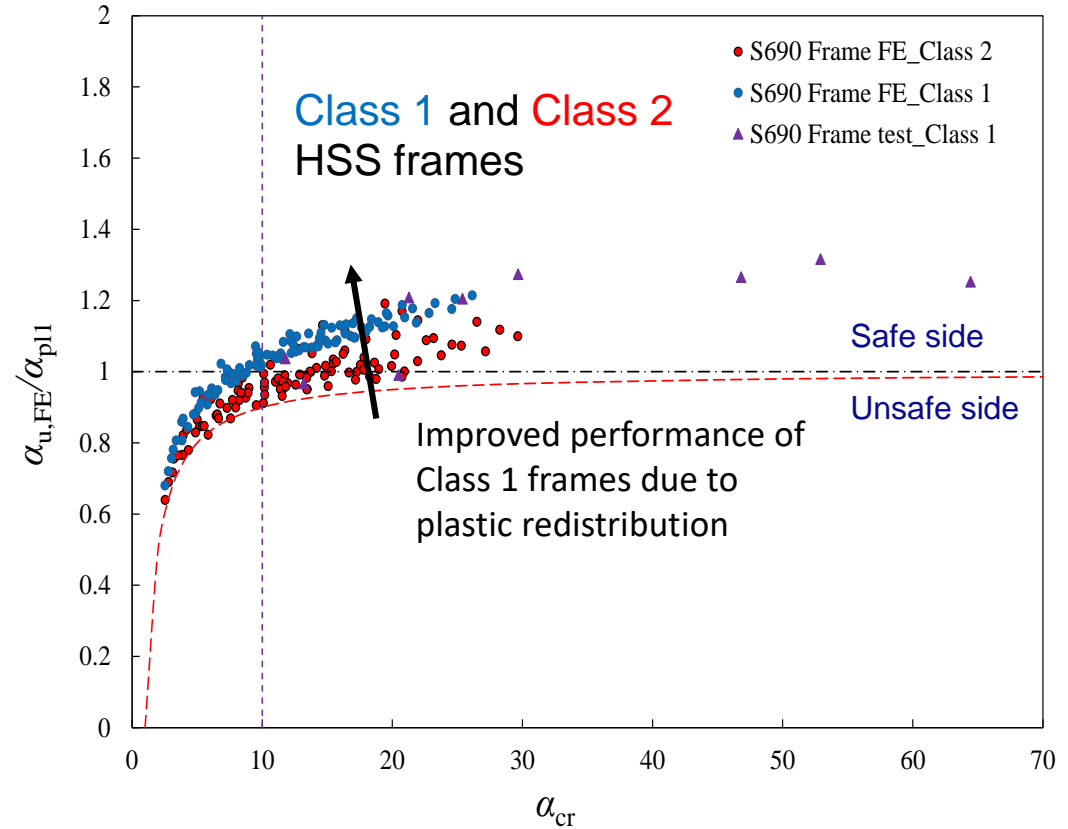
- Material: S355 and S690
- Two Class 1 cross-sections and two Class 2 cross-sections
- Loading conditions: $H = 0.1/0.3/0.5/0.7/0.9 V$



A total of 200 S355 frames and 200 S690 frames has been investigated.

Current design rules – no plastic redistribution

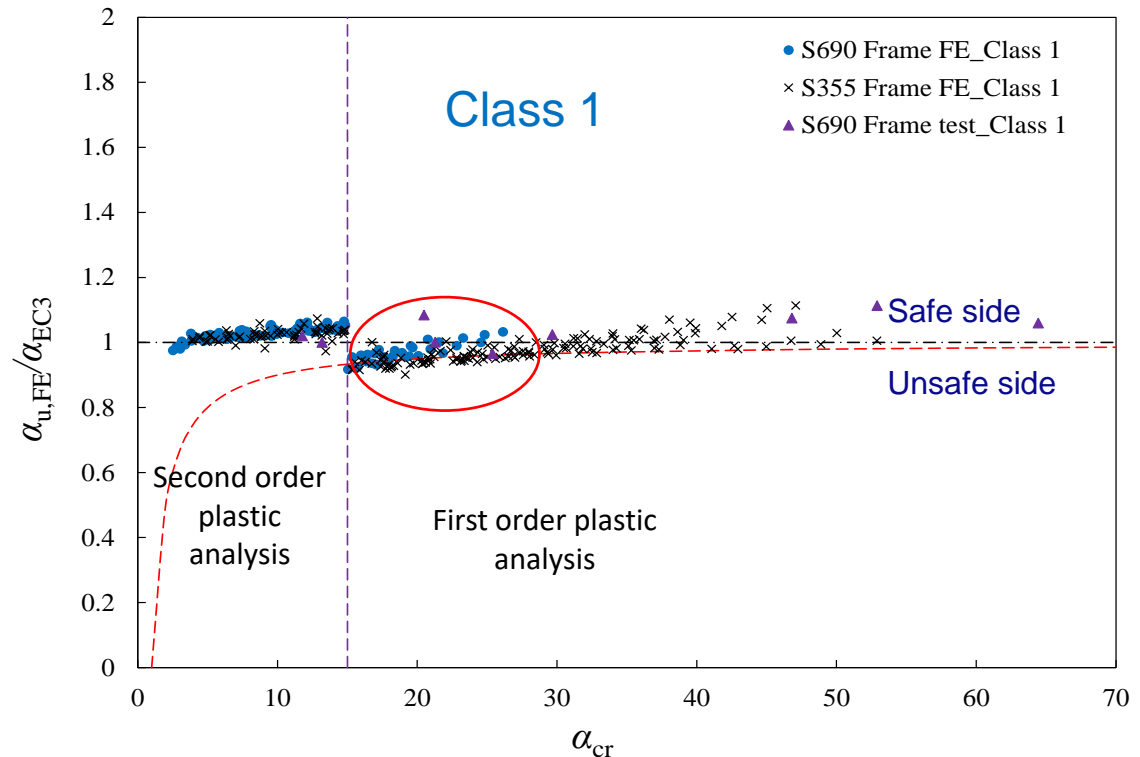
- Currently, plastic design is not allowed for HSS
- Frame ultimate load factors are therefore normalised by load level at **first plastic hinge** α_{p1} obtained from **first order analysis**
- **Clear difference in performance between HSS frames with Class 1 and 2 sections, indicating that disallowing plastic design for HSS is overly-conservative**



Second order effects become dominant for frames with low α_{cr} as usual

Applying plastic design to Class 1 HSS frames with current α_{cr} rules

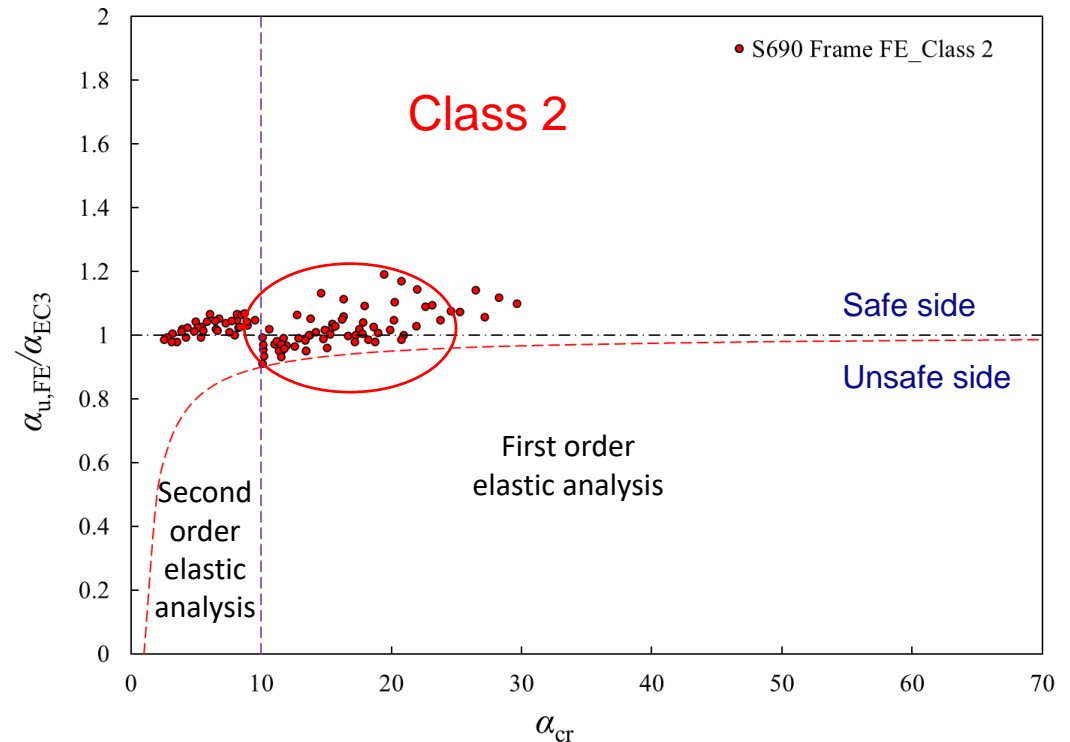
- Here, ultimate load factors for frames with **Class 1** sections are normalised by **full plastic collapse load α_{pl}** :
 - First order plastic analysis for $\alpha_{cr} \geq 15$,
 - Second order plastic analysis for $\alpha_{cr} < 15$
- HSS and NSS frames generally follow the same trend and are generally on the safe side for $\alpha_{cr} < 15$



Results slightly on unsafe side for $15 \leq \alpha_{cr} < 30$ for both S355 and S690 because we are ignoring second order effects, but they still have some influence (up to around 10%)

First hinge design for Class 2 HSS frames (currently allowed)

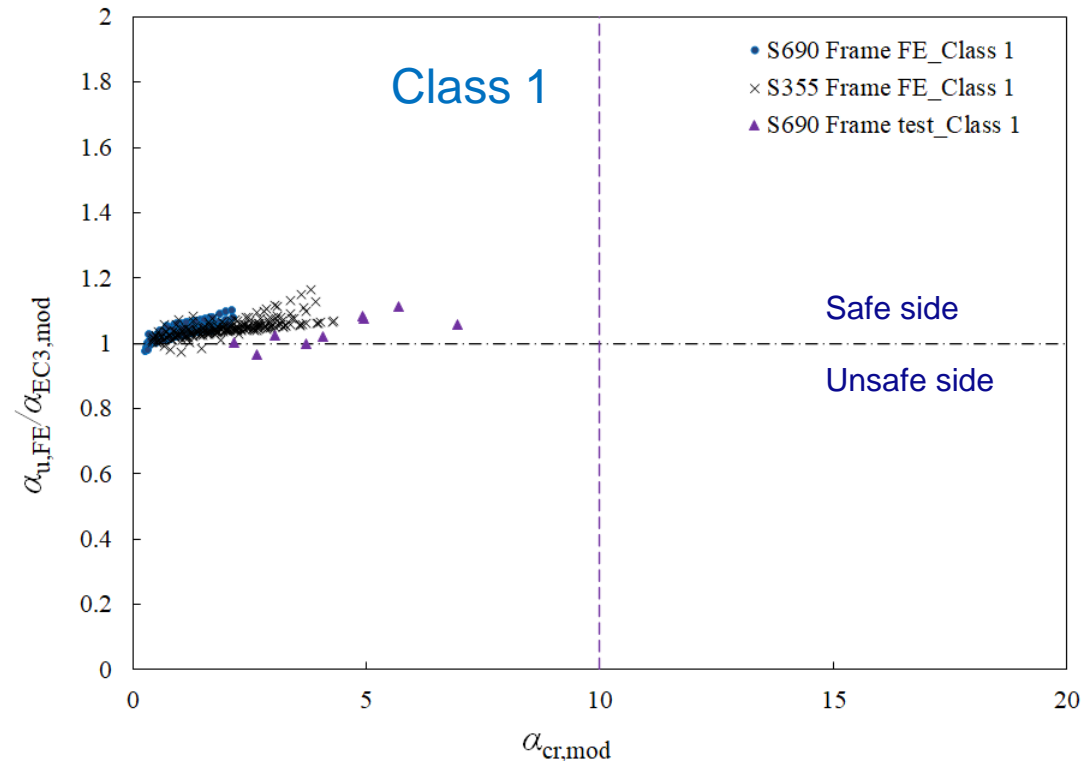
- Here, ultimate load factors for frames with **Class 2** sections are normalised by **first plastic hinge load level** α_{p1} :
 - First order elastic for $\alpha_{cr} \geq 10$,
 - Second order elastic for $\alpha_{cr} < 10$
- i.e. this is following the **current design rules**, and the results are generally good



Similarly to before, results slightly on unsafe side for $10 \leq \alpha_{cr} < 20$ because we are ignoring second order effects, but they still have some influence (up to around 10%)

Plastic design for HSS frames with new prEN α_{cr} rules

- In **prEN 1993-1-1**, for plastic design, α_{cr} is calculated based on a frame with hinges at the locations of the plastic hinges formed at the design load level
- Limit on α_{cr} for plastic analysis changes from 15 to 10 i.e. consistent with elastic analysis
- Frames, rightly, considered to be more flexible in plastic regime and second order plastic analysis is needed in far more cases



Results that were slightly on the unsafe side for $10 \leq \alpha_{cr} < 20$ in EN 1993-1-1 are now safely predicted through use of second order plastic analysis

Conclusions

- Plastic design is not allowed for HSS in current design provisions
- HSS beams and frames shown to behave similarly to NSS beams and frames, but with slightly reduced ductility
- Slightly stricter slenderness limits proposed to eliminate this problem for HSS
- Application of plastic design to HSS frames provides safe-sided results; inclusion in next revision of EC3 will depend on code committee decisions
- New prEN 1993-1-1 α_{cr} rules will eliminate slightly unsafe-sided results due to second order effects for both NSS and HSS frames