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

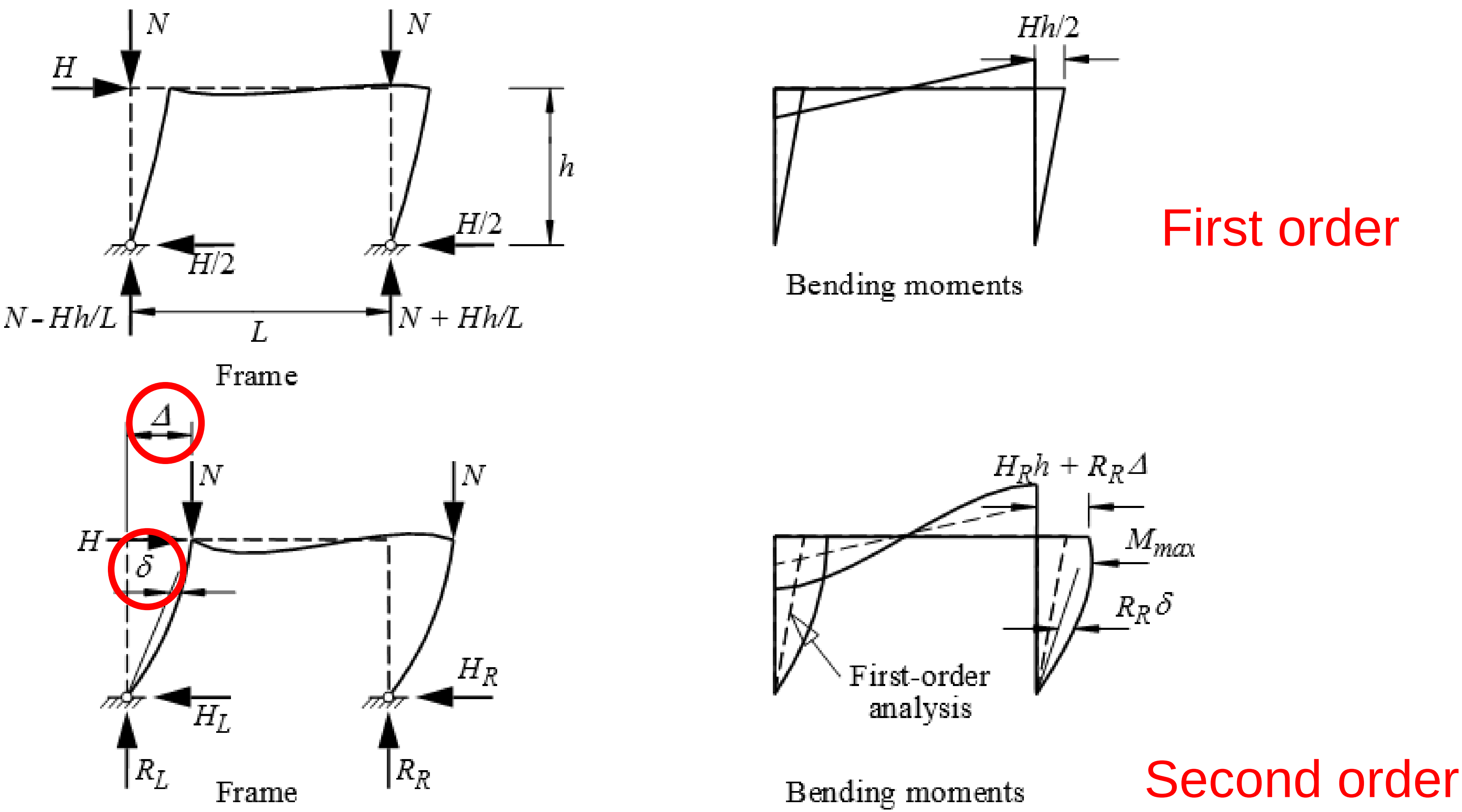
- Introduction to frame stability design
- Tests on HSS frames
- FE validation and parametric studies
- Plastic design of HSS frames
- Conclusions

Analysis types

Analysis types:

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

Second order effects – PΔ and Pδ



Second order effects – PΔ and Pδ

PΔ 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)

Pδ 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

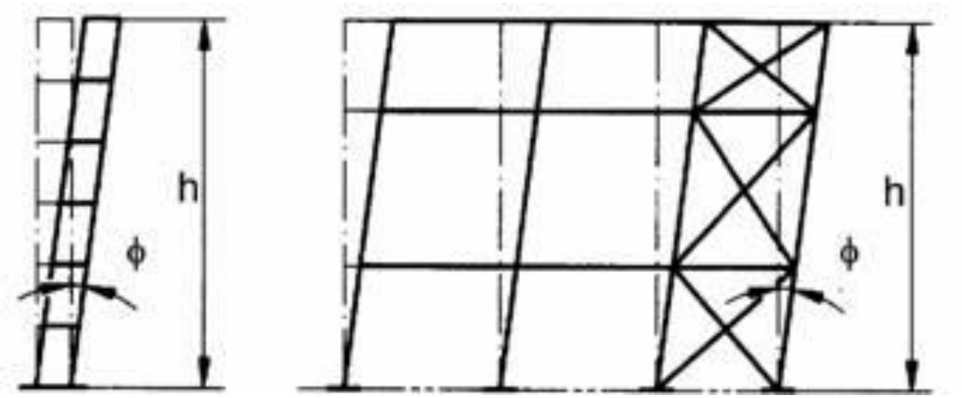
Global imperfections for frames

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

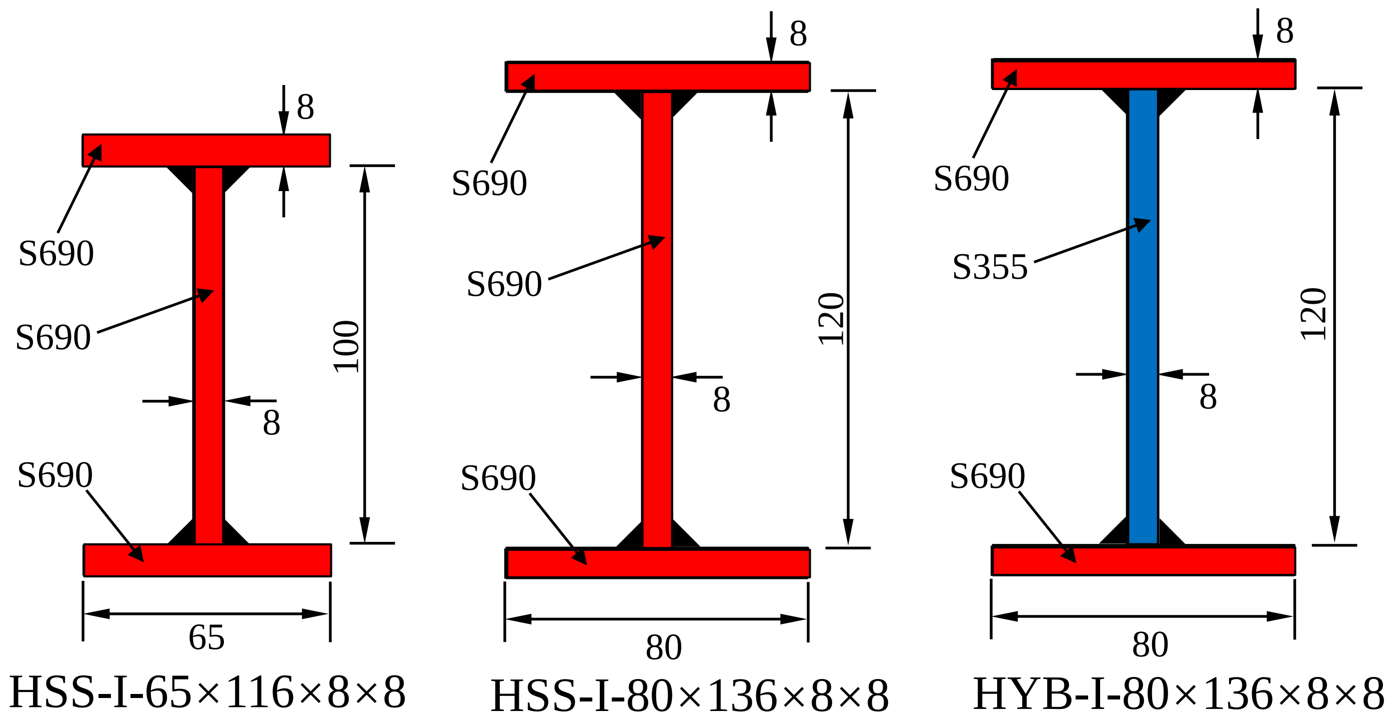


More conveniently, the effect of frame imperfections can be represented by a system of equivalent horizontal forces (or notional horizontal loads) equal to 1/200 (0.5%) of the vertical load at each storey

Overview of experimental study

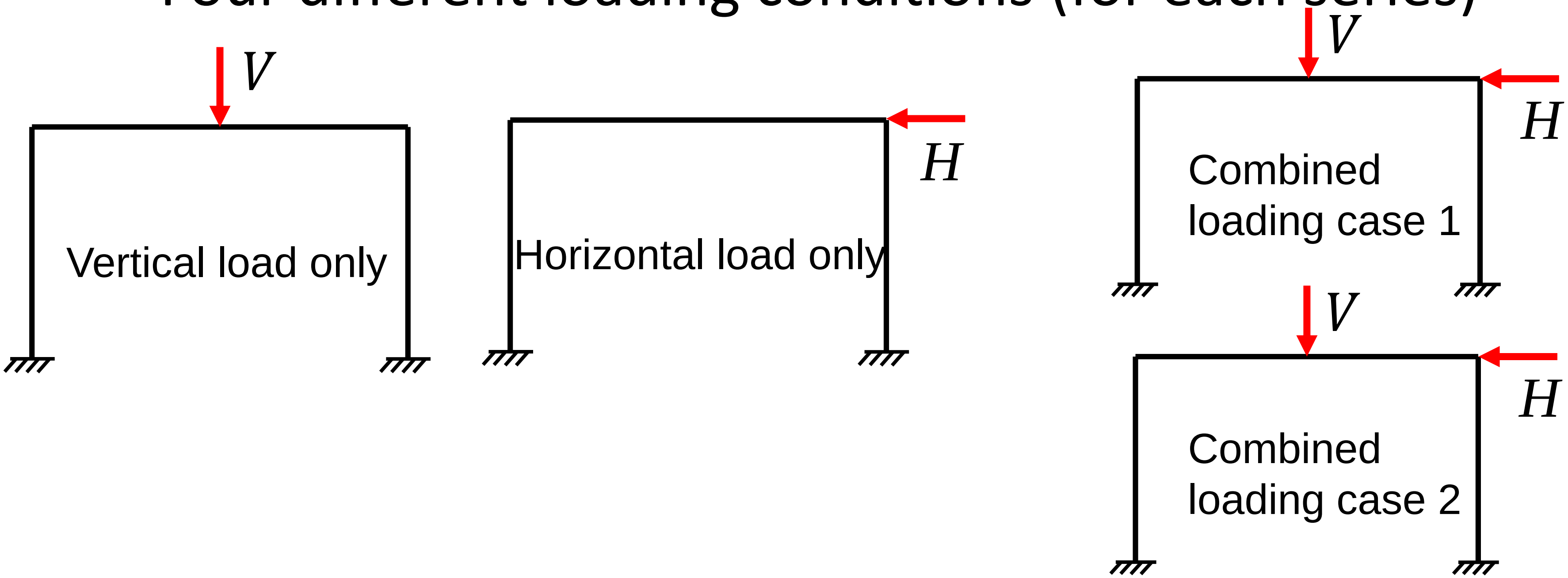
- 12 tests on S690 and hybrid frames under different loading conditions including:

✓ Three different cross-sections (three series)

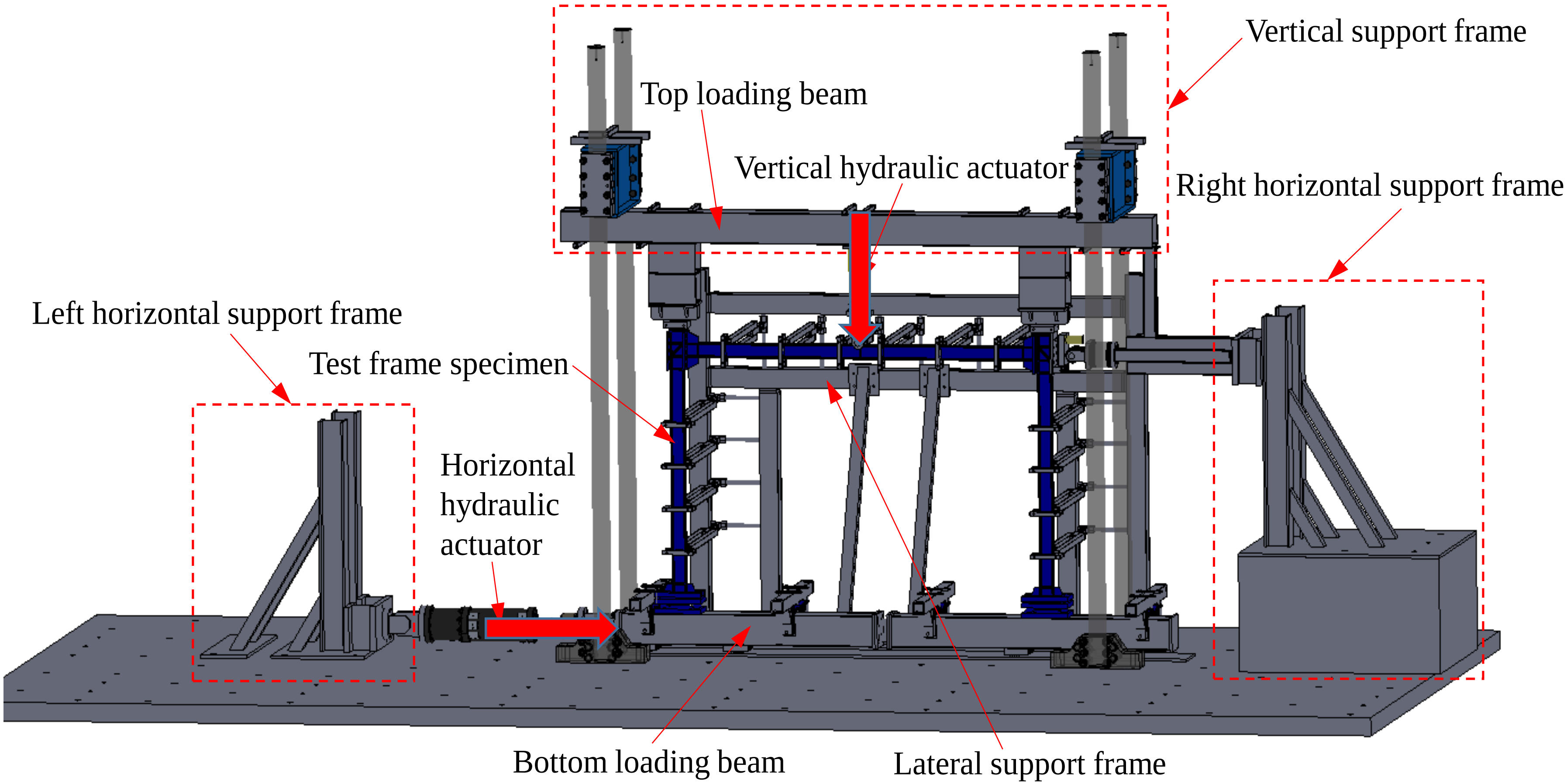


Overview of experimental study

- 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)

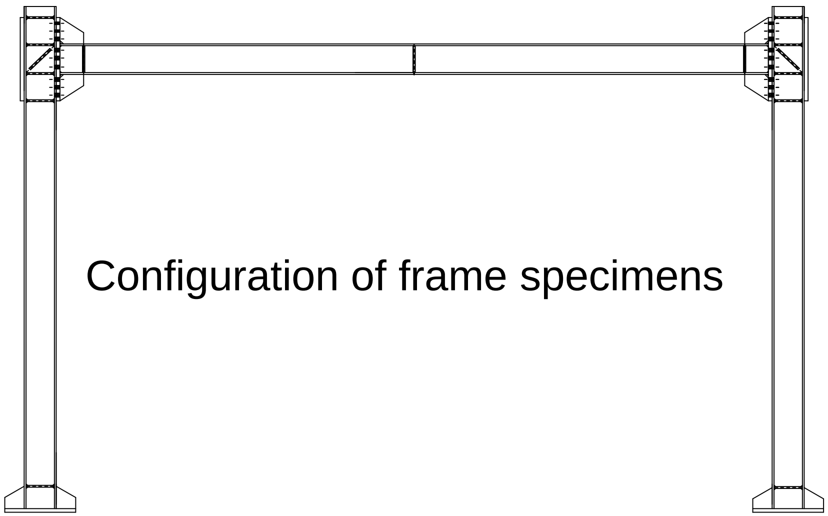


Overview of experimental study

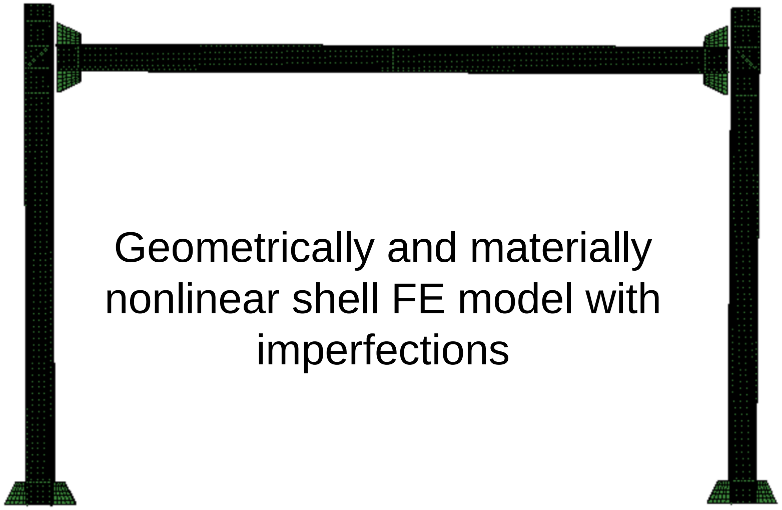


Frame test setup

FE validation and parametric study



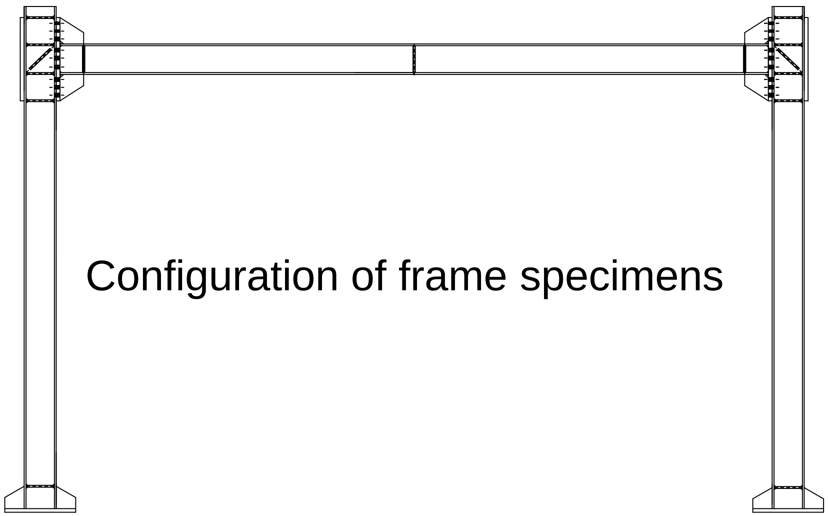
Configuration of frame specimens



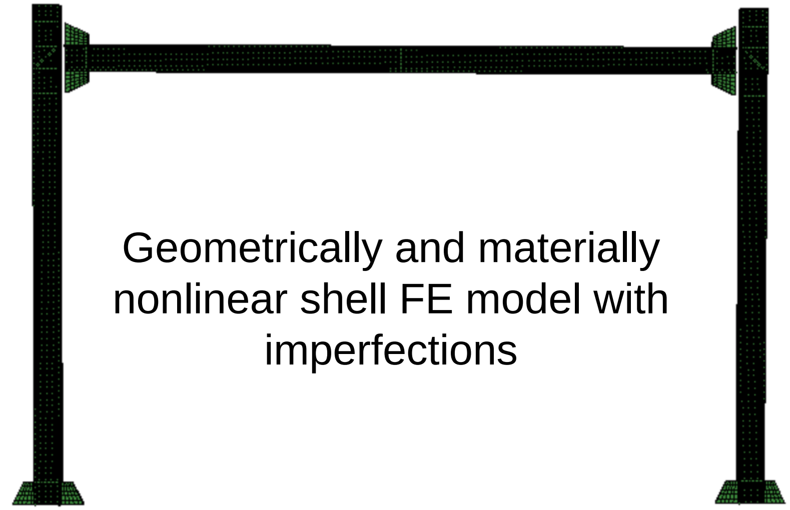
Geometrically and materially nonlinear shell FE model with imperfections

- ✓ 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

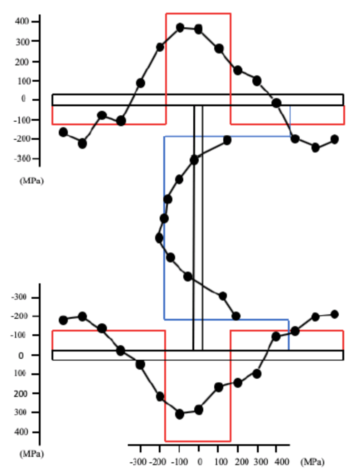


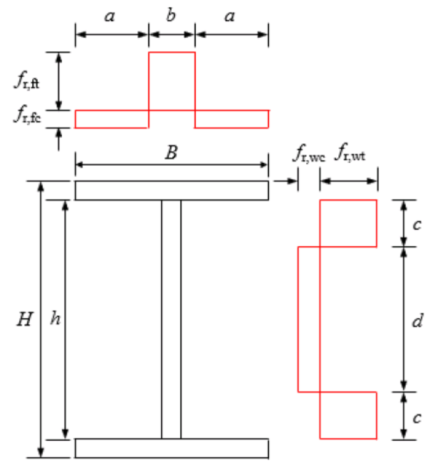
Configuration of frame specimens



Geometrically and materially nonlinear shell FE model with imperfections

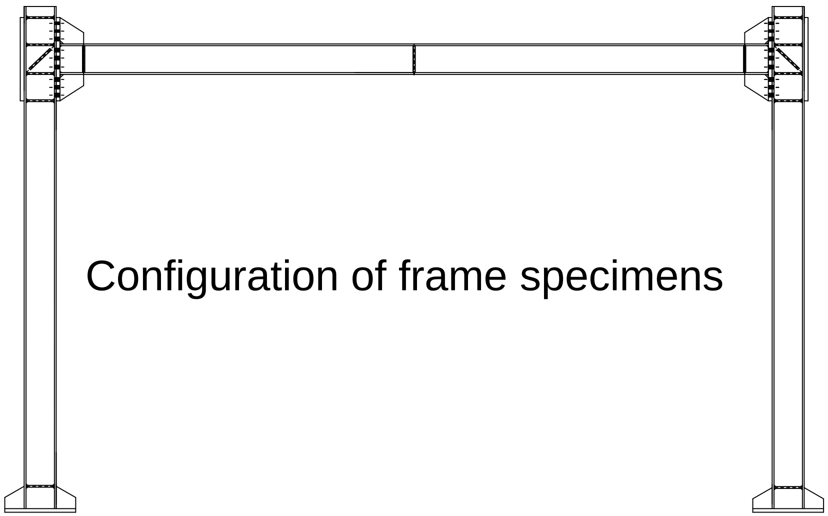
- ✓ Residual stress pattern



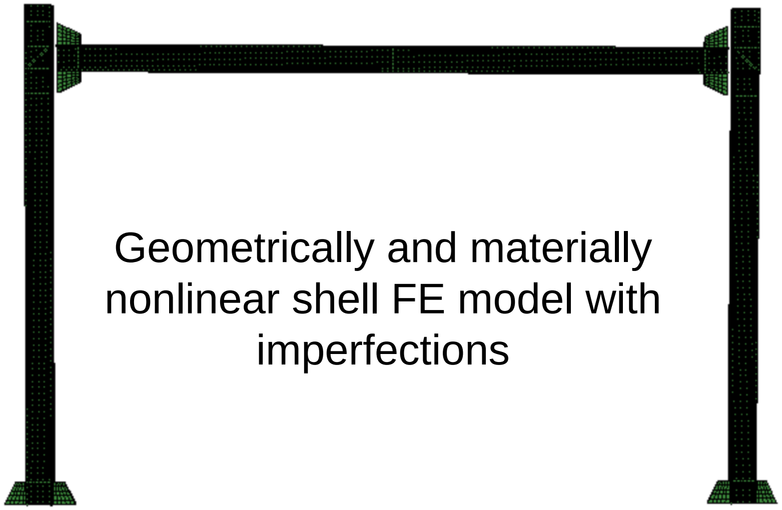


Proposed residual stress pattern according to experimental results

FE validation and parametric study

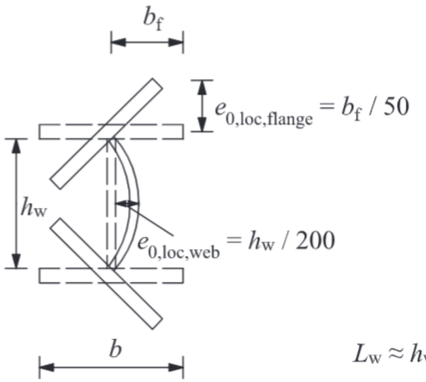


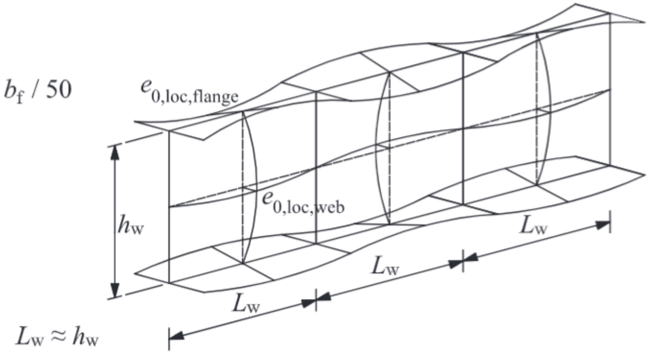
Configuration of frame specimens



Geometrically and materially nonlinear shell FE model with imperfections

- ✓ Local imperfections

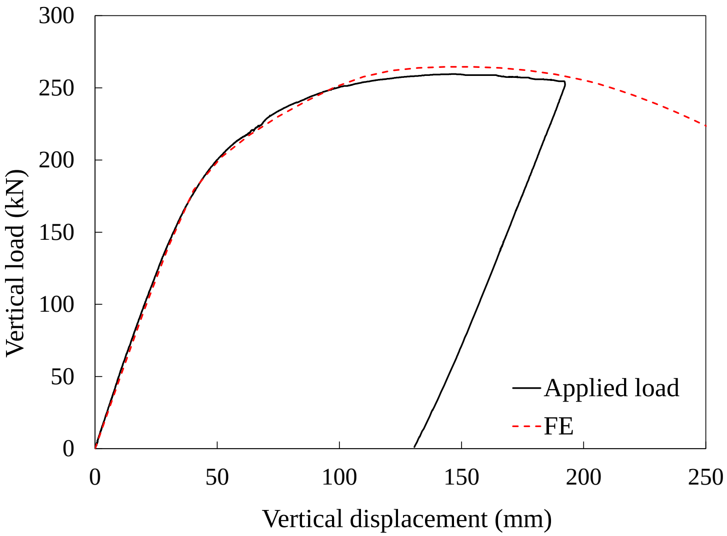




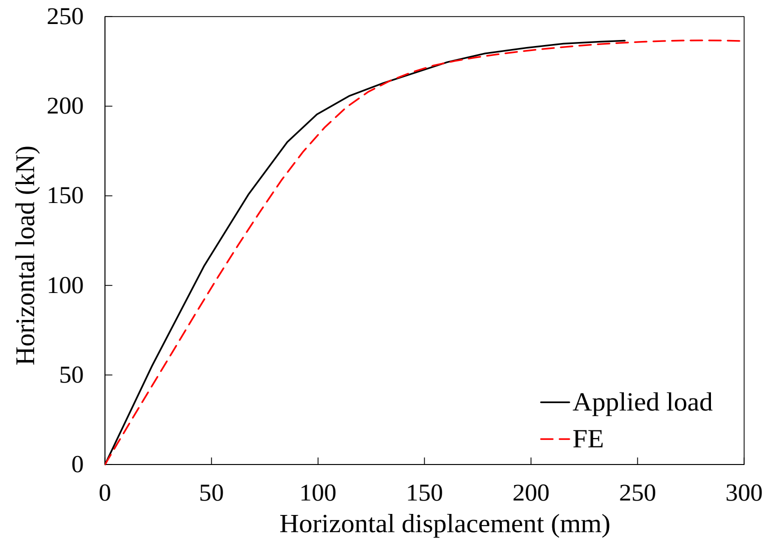
FE validation and parametric study

Validation results

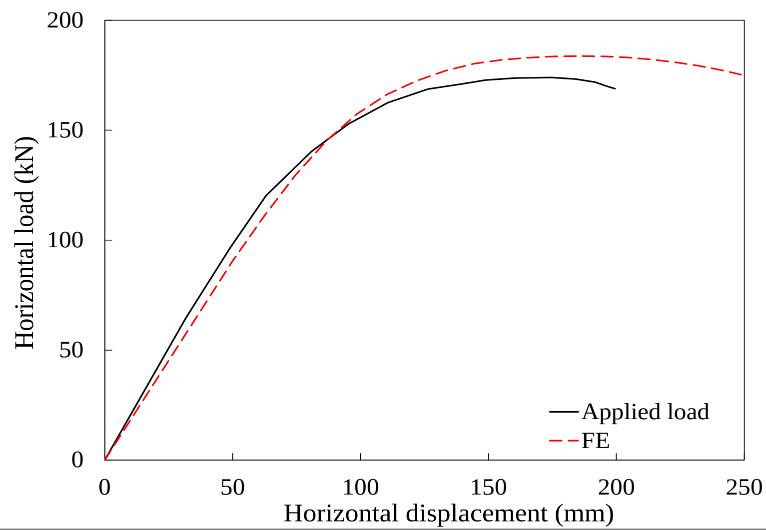
- ✓ Load-displacement curves



HSS-I-80×136-V



HSS-I-80×136-H

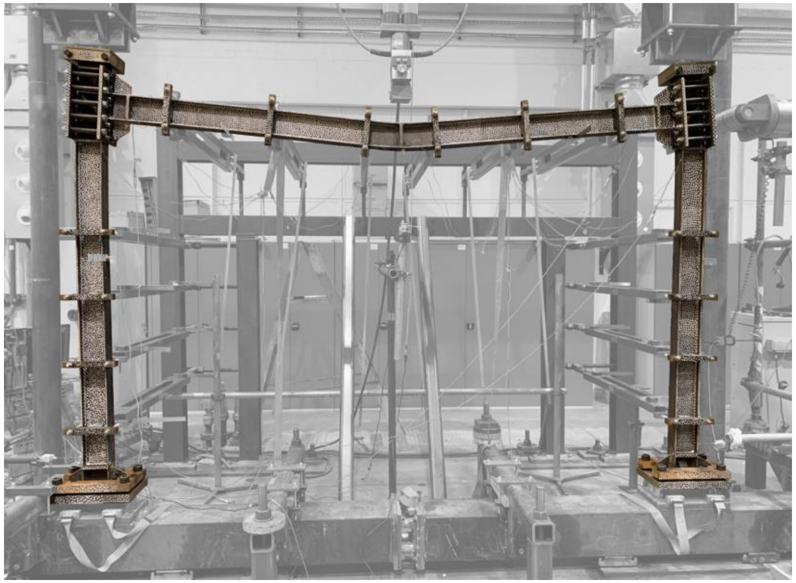


HSS-I-80×136-V&H1

FE validation and parametric study

Validation results

✓ Failure modes



Test

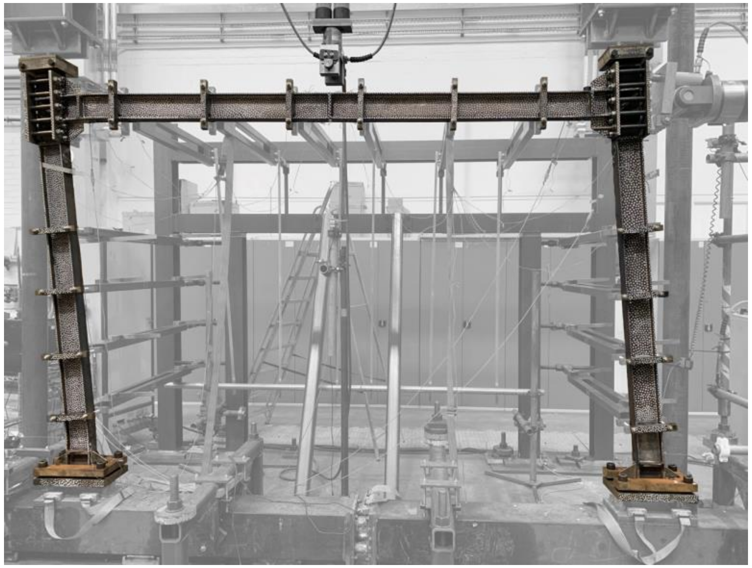
FE

HSS-I-80×136-V
(Beam mechanism)

FE validation and parametric study

Validation results

✓ Failure modes



Test

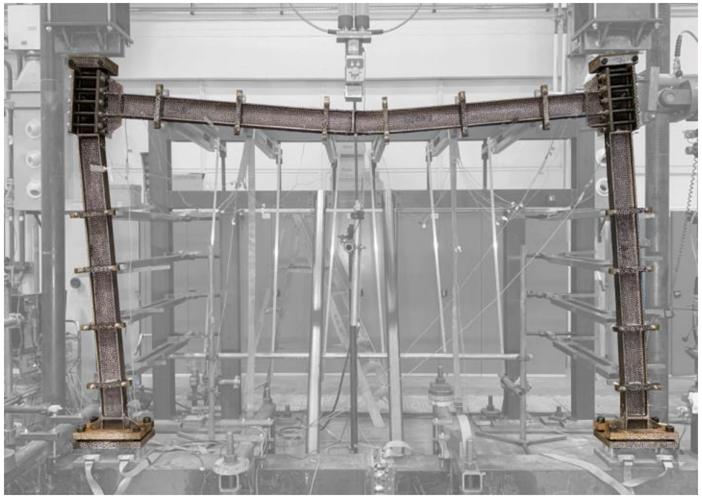
FE

HSS-I-80×136-H
(Sway mechanism)

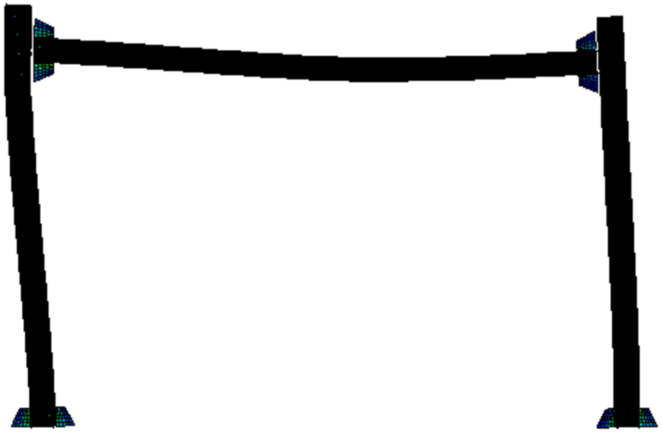
FE validation and parametric study

Validation results

✓ Failure modes



Test



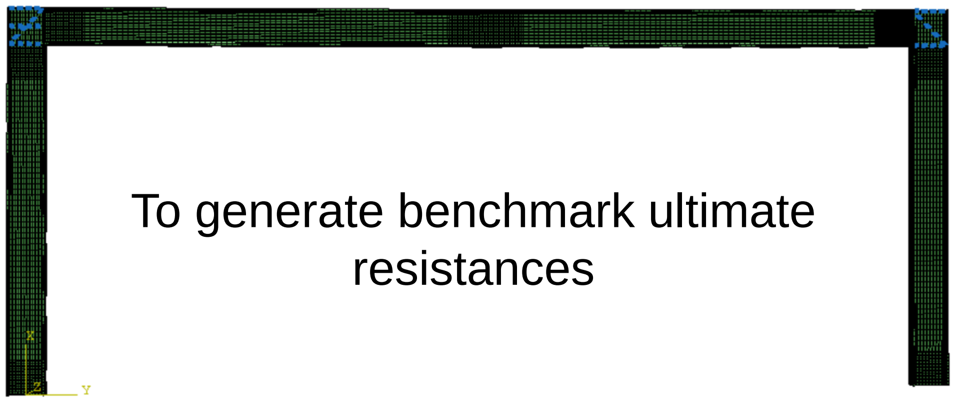
FE

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

FE validation and parametric study

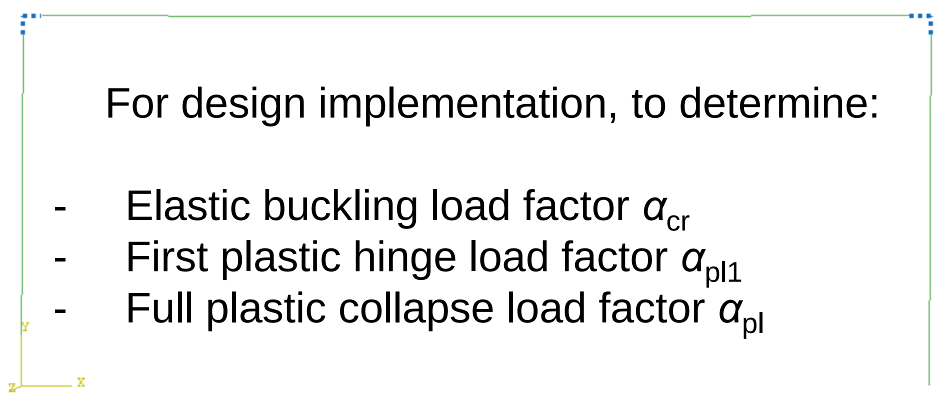
Parametric study

- Shell FE models



To generate benchmark ultimate resistances

- Beam FE models



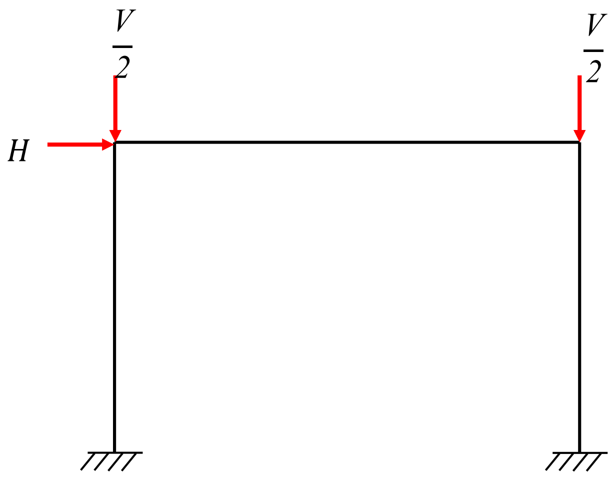
For design implementation, to determine:

- Elastic buckling load factor α_{cr}
- First plastic hinge load factor α_{pl1}
- Full plastic collapse load factor α_{pl}

FE validation and parametric study

Parametric study

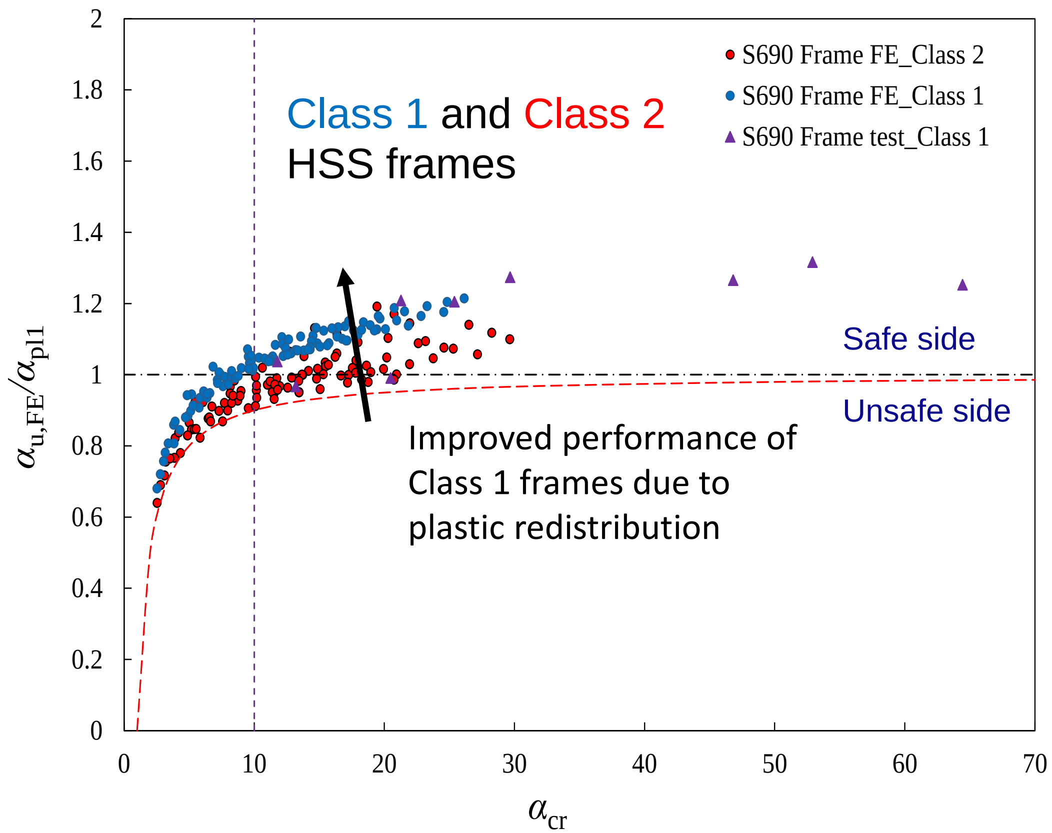
- Material: S355 and S690
- Two Class 1 cross-sections and two Class 2 cross-sections
- Loading conditions: H = 0.1/0.3/0.5/0.7/0.9 V



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

Current design rules – no plastic redistribution

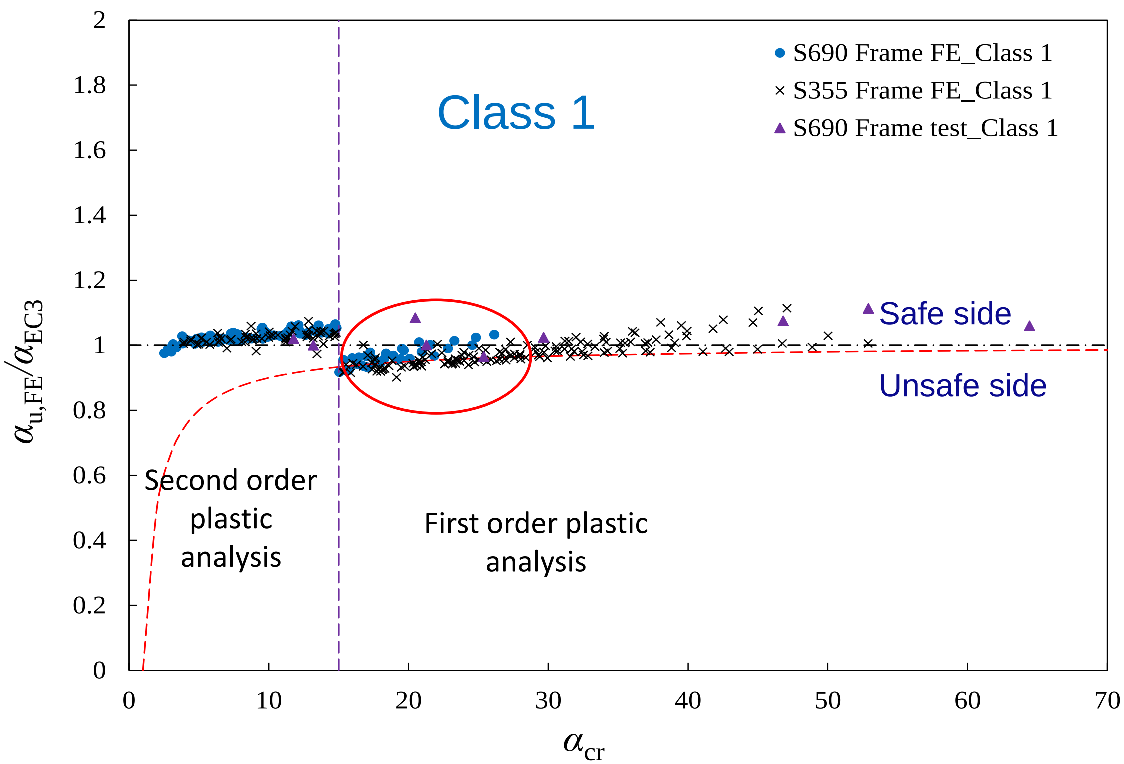
- Currently, plastic design is not allowed for HSS
- Frame ultimate load factors are therefore normalised by load level at first plastic hinge α_{pl1} obtained from first order analysis
- Clear difference in performance between HSS frames with Class 1 and 2 sections, indicating that disallowing plastic 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

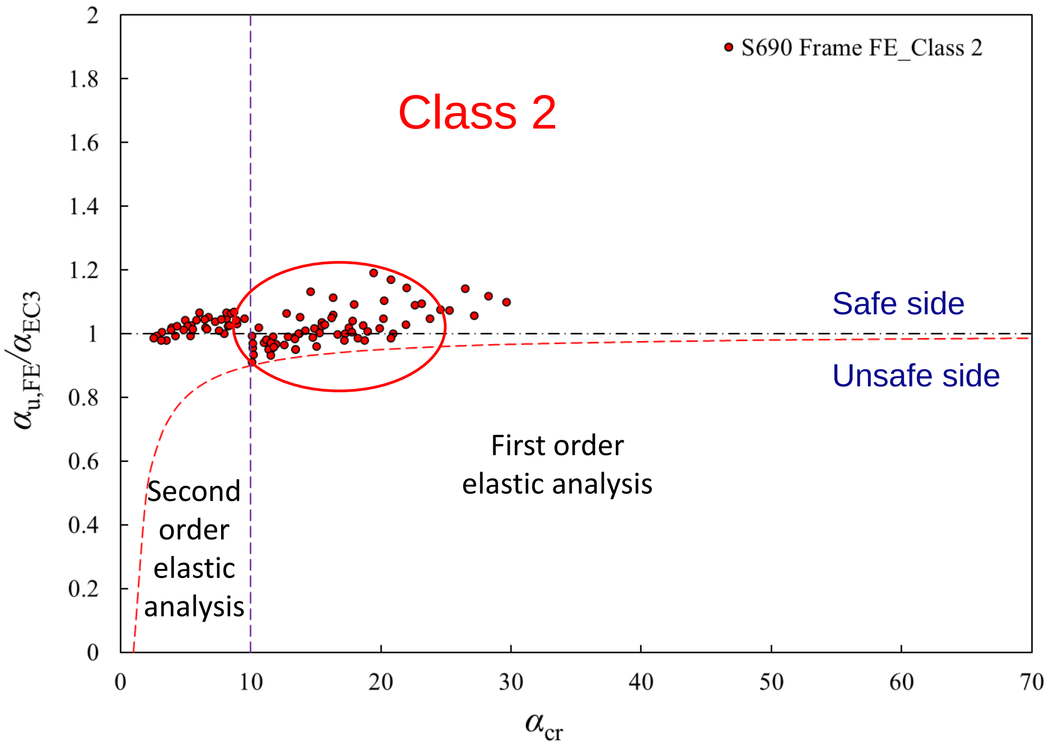
- Here, ultimate load factors for frames with Class 1 sections are normalised by full plastic collapse load α_{pl}:
  - First order plastic analysis for $\alpha_{cr} \geq 15$,
  - Second order plastic analysis for $\alpha_{cr} < 15$
- HSS and NSS frames generally follow the same trend and are generally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

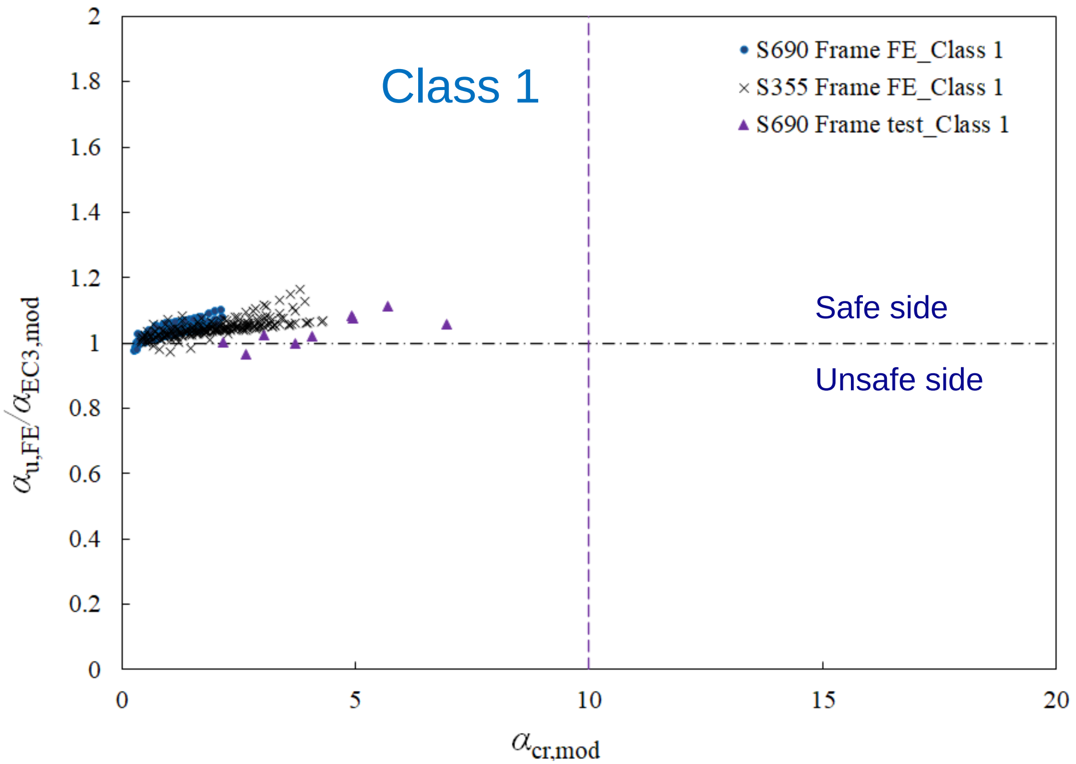
- Here, ultimate load factors for frames with Class 2 sections are normalised by first plastic hinge load level α_{pl1}:
  - First order elastic for $\alpha_{cr} \geq 10$,
  - Second order elastic for $\alpha_{cr} < 10$
- i.e. this is following the current design rules, and the results are generally 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