Determination of the patch loading resistance of girders with corrugated webs using nonlinear finite element analysis

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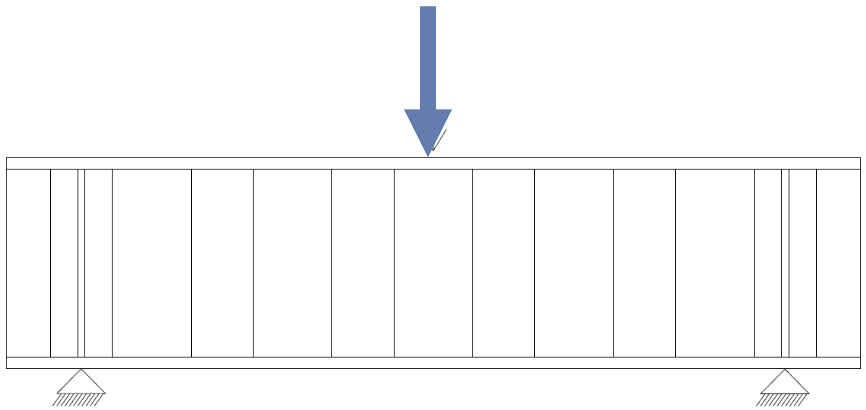
Patch loading tests

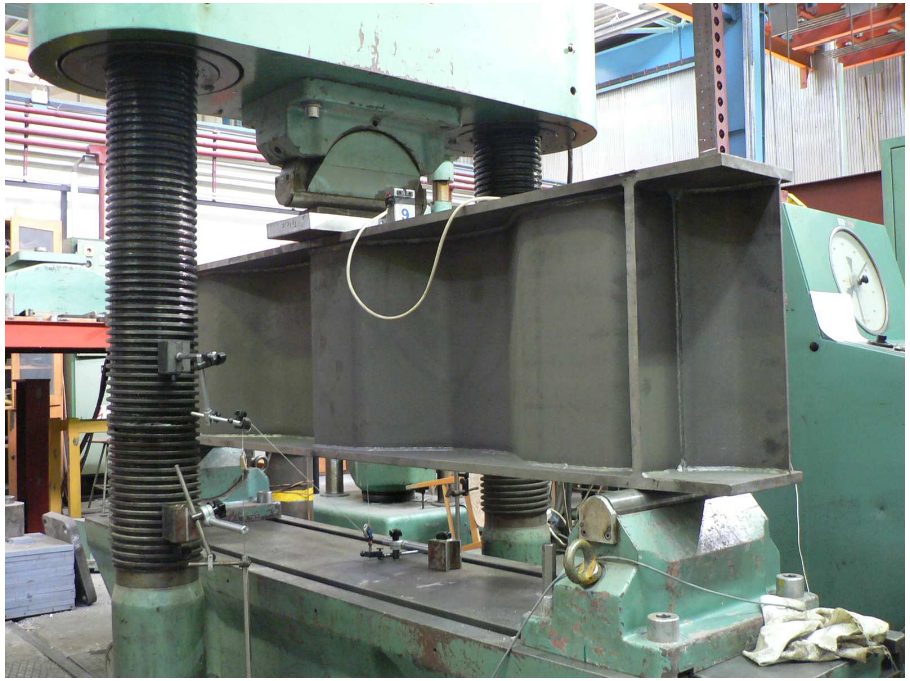
Experimental program 12 test specimens

Aims of the tests

1. Determination of the patch loading resistance for different geometrical arrangement.
2. Verification of the developed design method.
3. Development of FEM based design method.

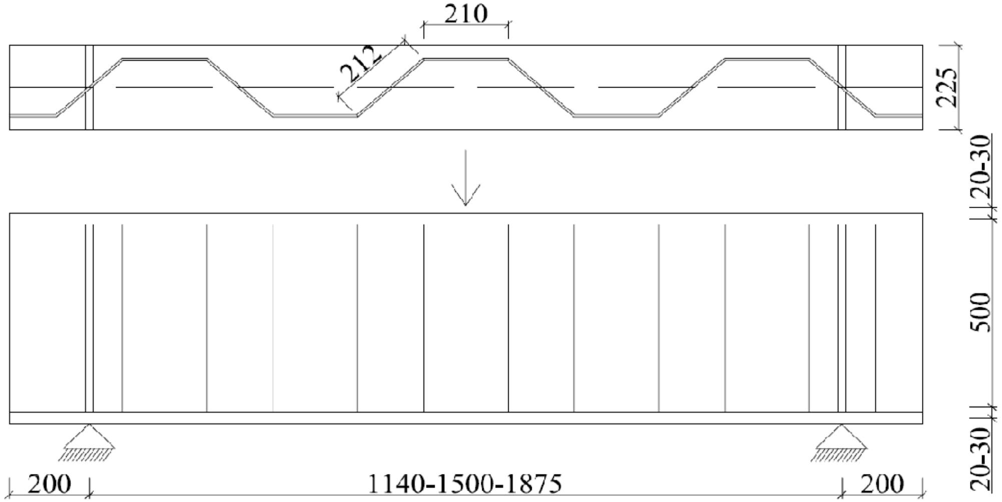
Test arrangement





Patch loading tests

Test specimens

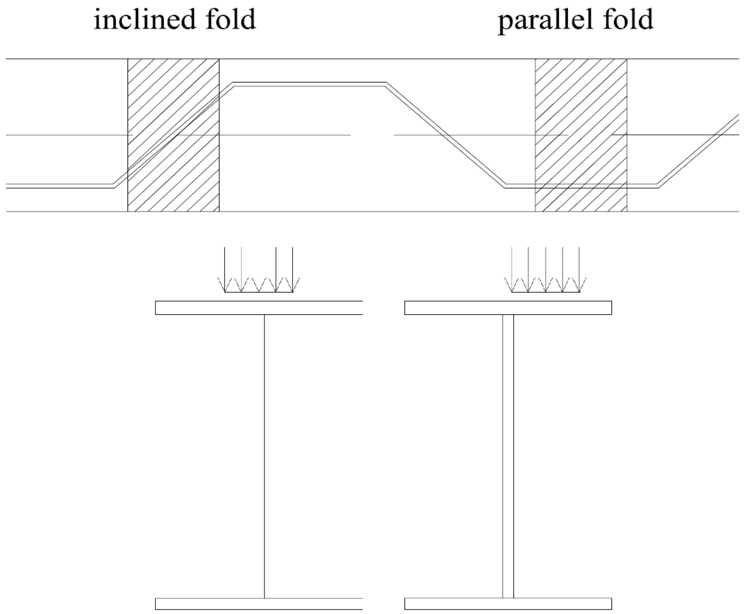


h_w=500mm
t_w=6mm
b_f=225mm
t_f=20mm; 30mm

alpha=39°
a_1=210mm
a_2=212mm

Analysed parameters

1. loaded fold (parallel, inclined, corner area)
2. loading length (90mm, 200mm, 380 mm)
3. span (1140mm, 1500mm, 1875 mm)
4. flange thickness (20mm, 30 mm)
5. loading eccentricity in tranverse direction



Patch loading tests

Failure modes - loading length
- loaded fold

loaded fold: parallel fold
loading length: 90mm

loaded fold: parallel fold
loading length: 200mm

FEM based design method

Research strategy

1. FE model development for all test specimens
2. Experimental patch loading resistance ⟷ numerical resistance
3. Experimental failure mode ⟷ numerical failure mode
4. Experimental load-displacement diagram ⟷ numerical analysis

5. Verification of the numerical model

6. Recommendations for equivalent geometric imperfection

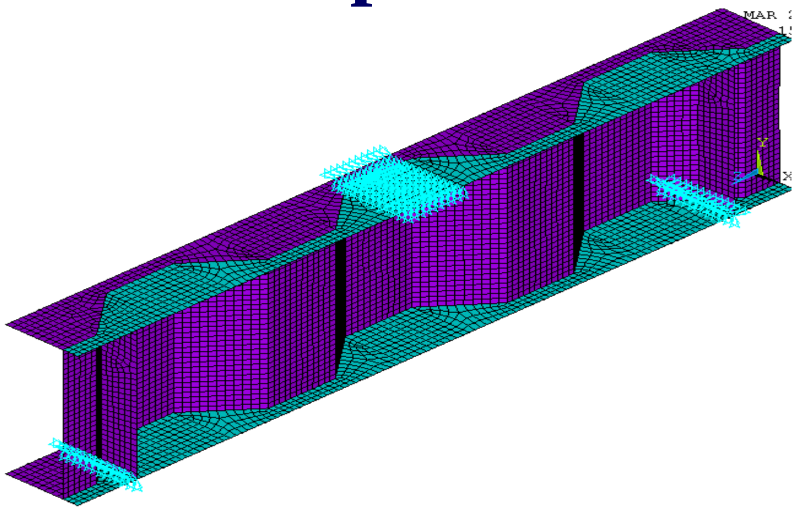
Aim: determination of the design value of the patch loading resistance by numerical simulation

Problem to be solved: → imperfection shape

→ imperfection scaling factor

Numerical model development

Finite element model

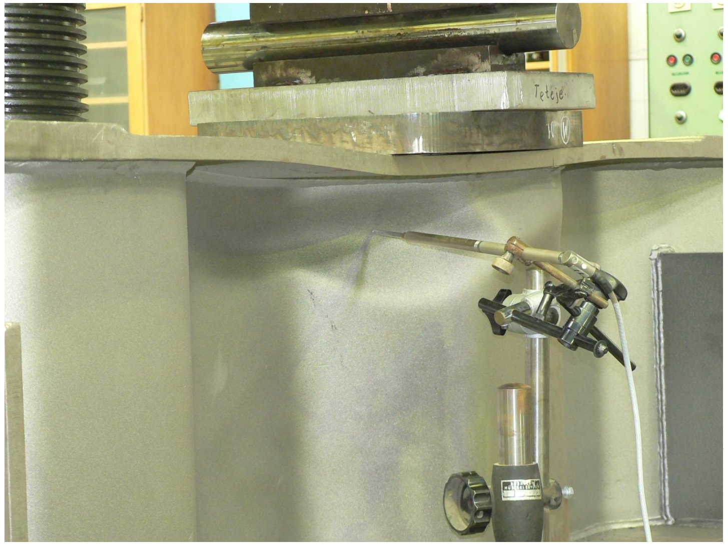


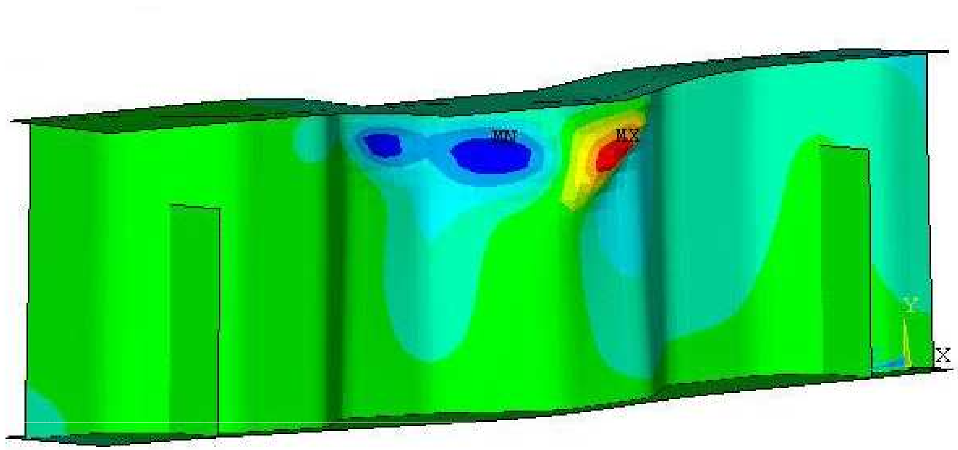
Experimental and numerical resistances

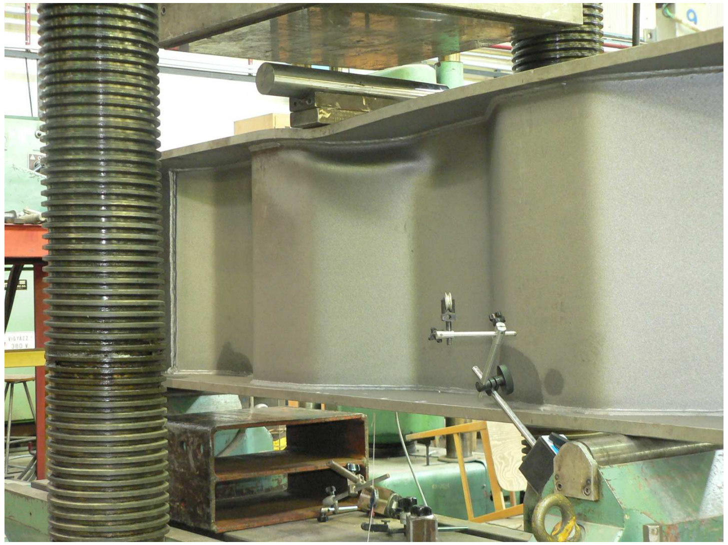
	R_{exp} [kN]	R_{num} [kN]	difference [%]
1. specimen	754,20	771,08	2,2
2. specimen	956,48	1044,18	9,2
3. specimen	764,75	769	0,6
4. specimen	949,02	969,054	2,1
5. specimen	1192,01	1201,24	0,8
6. specimen	1119,33	1155,901	3,3
7. specimen	1077,72	1093,58	1,5
8. specimen	1263,94	1285,4	1,7
9. specimen	1220,48	1250,34	2,4
10. specimen	1090,00	1120,4	2,8
11. specimen	1280,99	1314,078	2,6
12. specimen	772,39	781,05	1,1

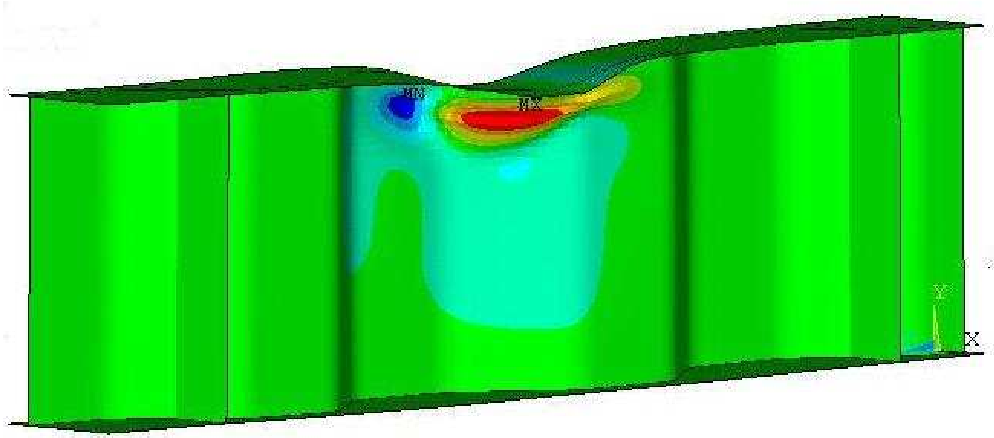
Numerical model verification

experimental failure mode ⟷ **numerical simulation**





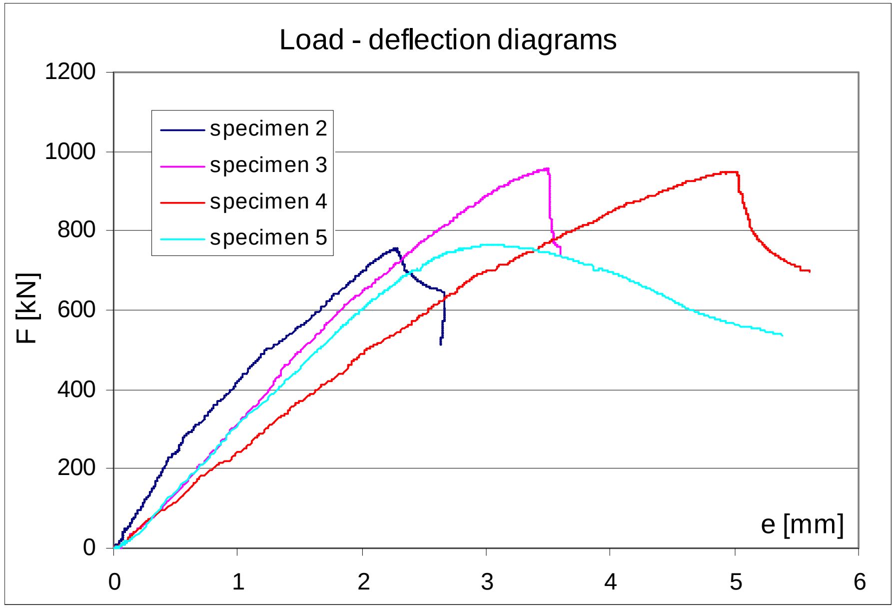




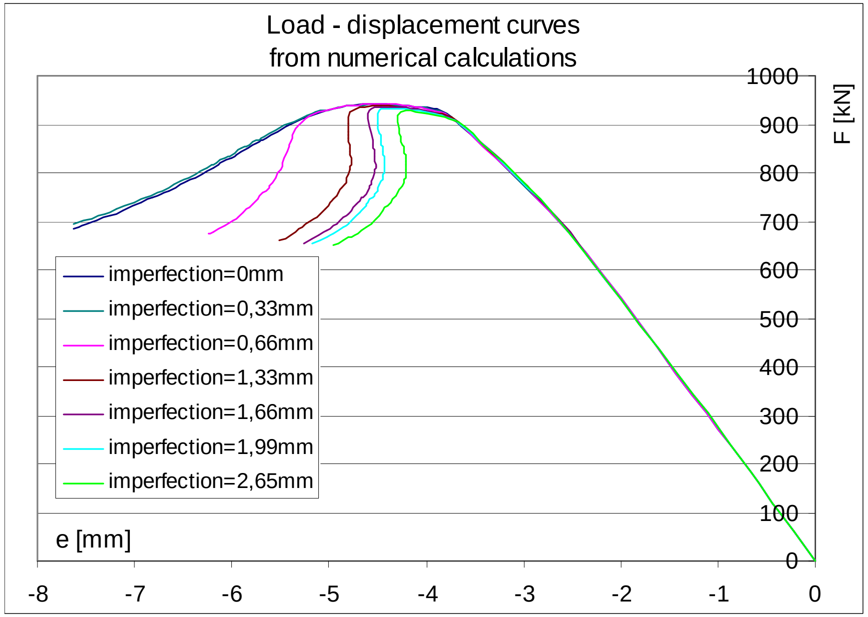
Numerical model verification

Observations in the experiments: different post-ultimate behaviours

Experimental load-displacement curves

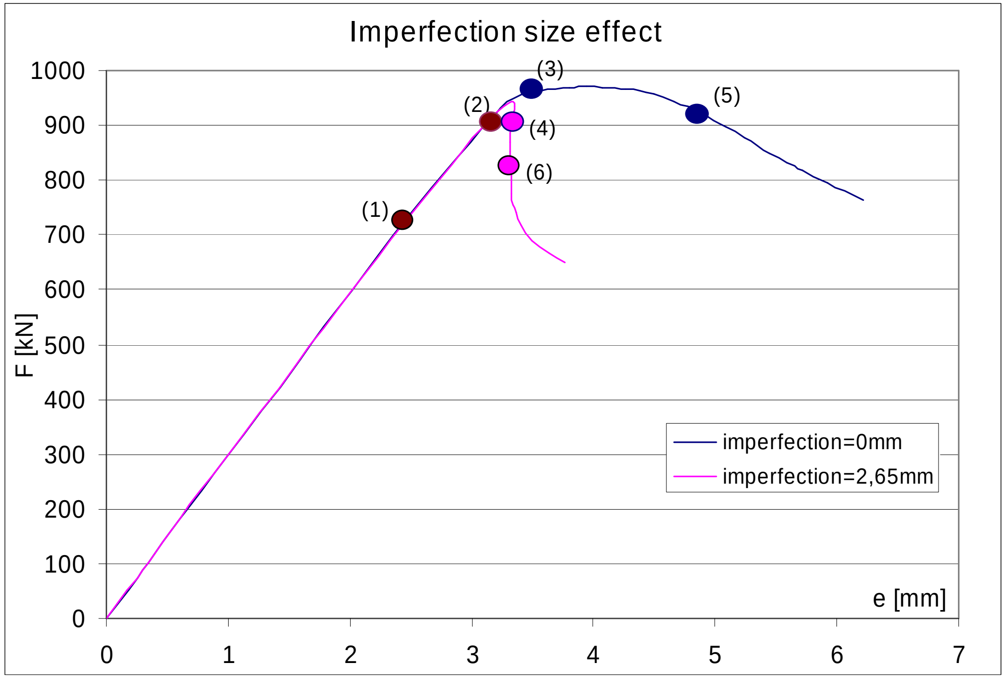


Numerical load-displacement curves

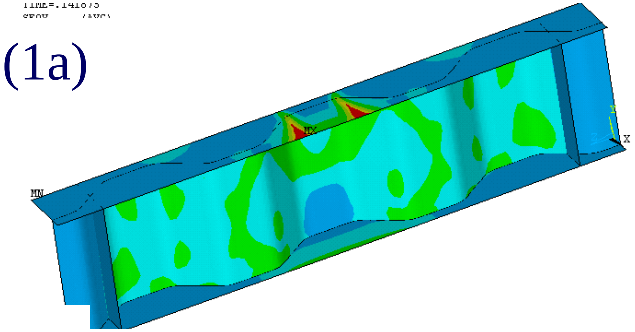


imperfections

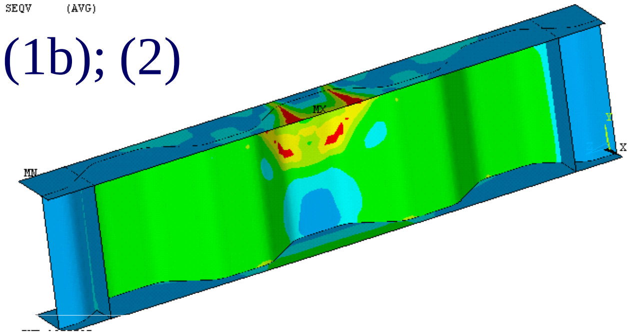
Numerical model verification



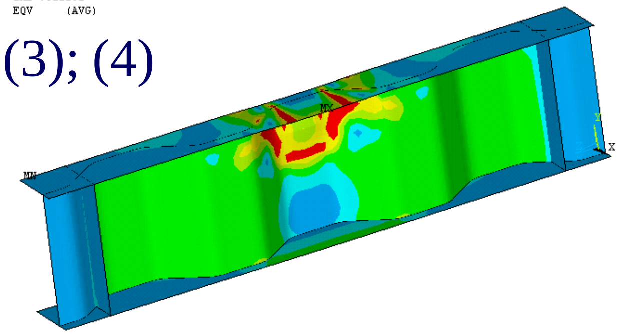
(1a)



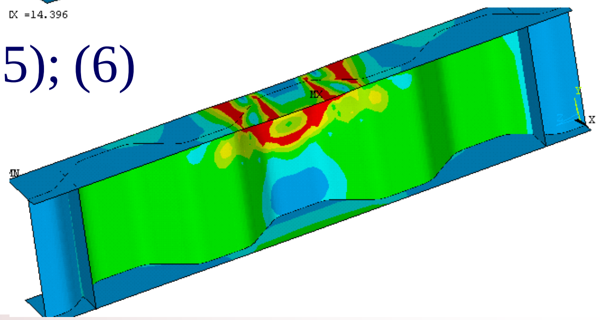
(1b); (2)



(3); (4)



(5); (6)



(1) a, First yielding in the flange (imp. = 0mm)
b, Yielding in the flange and web (imp. = 2,65mm)

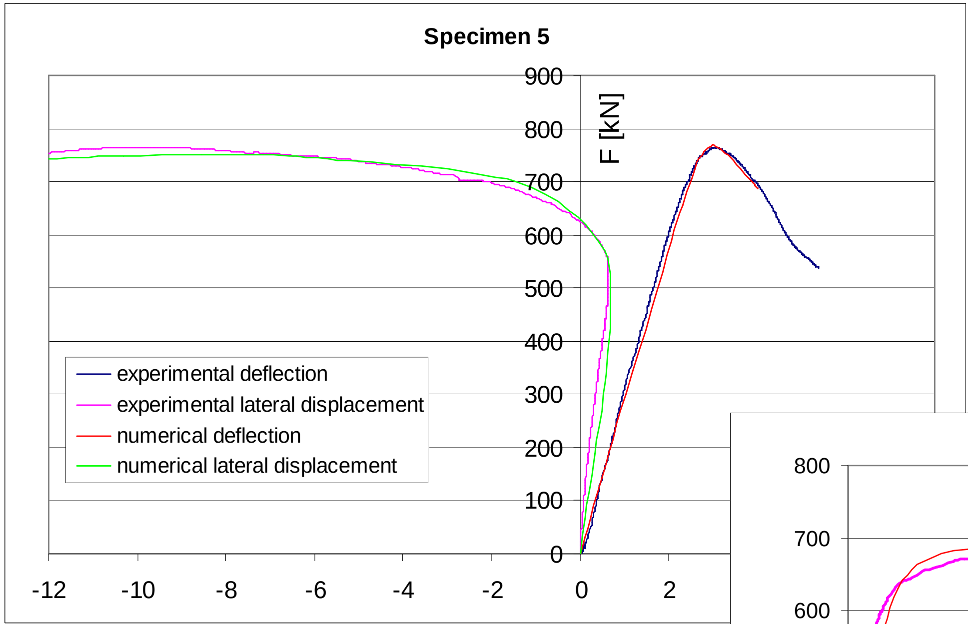
(2) First yielding in the web (imp. = 0mm)

(3) - (4) 2 plastic hinges in the flange

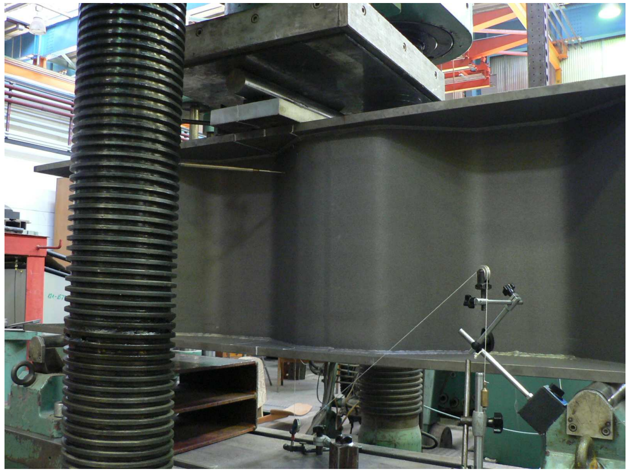
(5) - (6) 4 plastic hinges in the flange

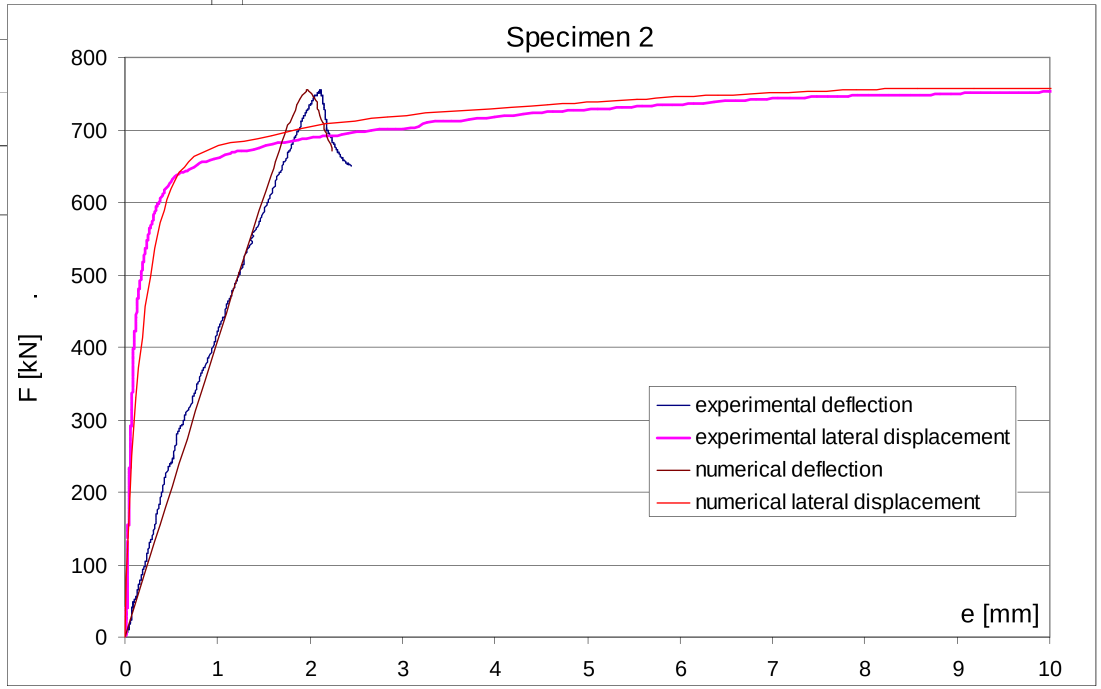
Numerical model verification

experimental load displacement diagram ↔ numerical model



measured: - deflection
- lateral displacement
- applied force





FEM based design method

No recommendations for imperfection of corrugated webs in EC3-1-5

Possible standardised imperfection types

Aims

Based on executed experiments the development of recommendations for equivalent geometric imperfections.

shape

scaling factor

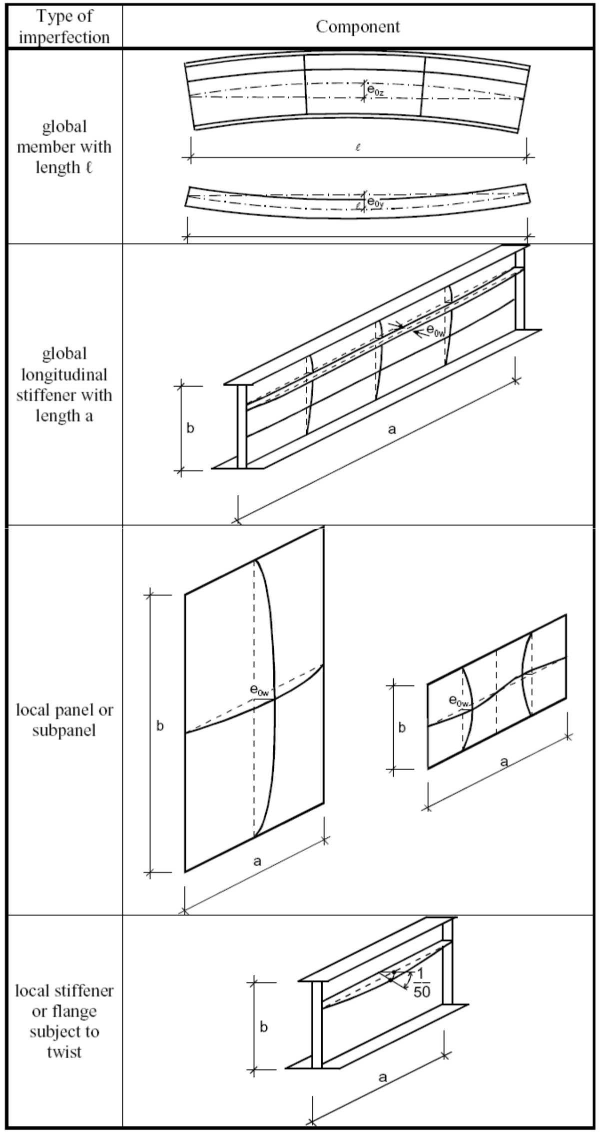
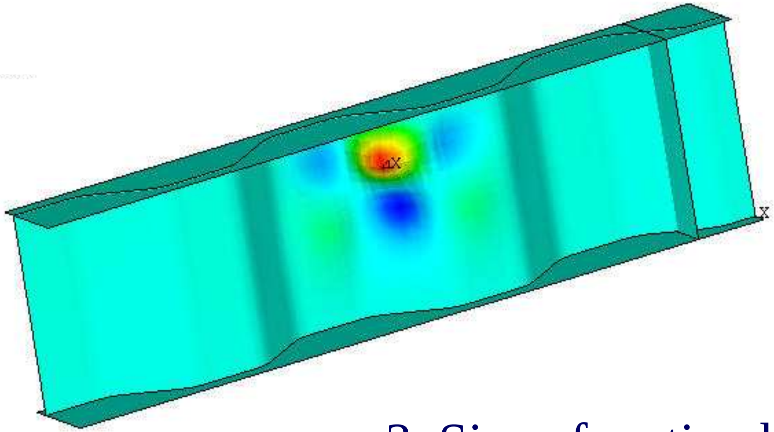


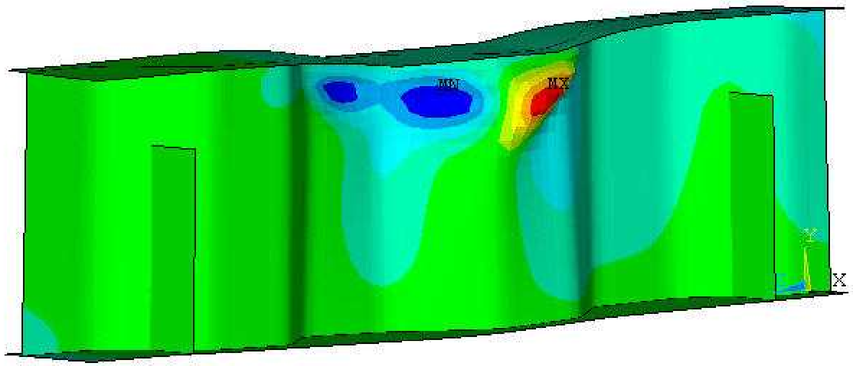
Figure C.1: Modelling of equivalent geometric imperfections

Equivalent geometric imperfection shape

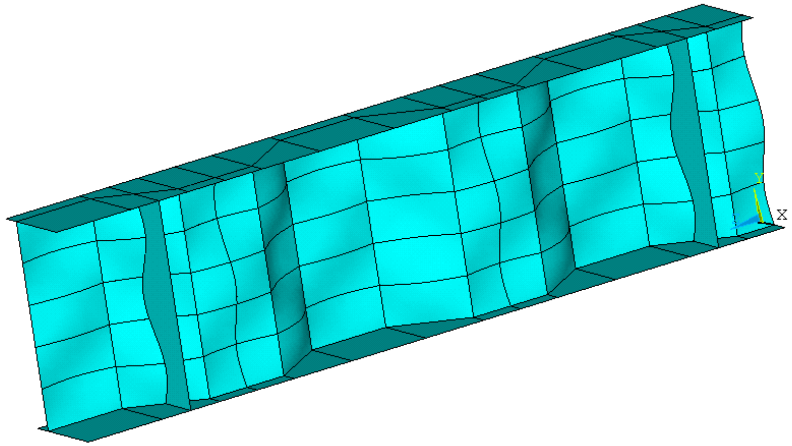
1. buckling mode



2. ultimate shape



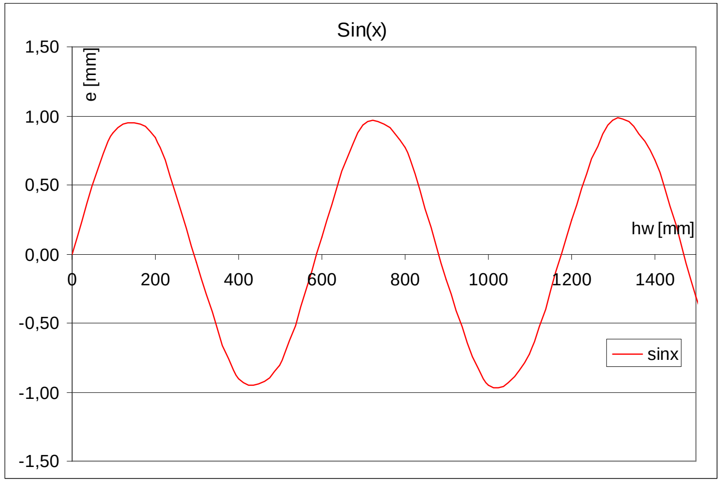
3. Sinus function based on EC3 subpanel



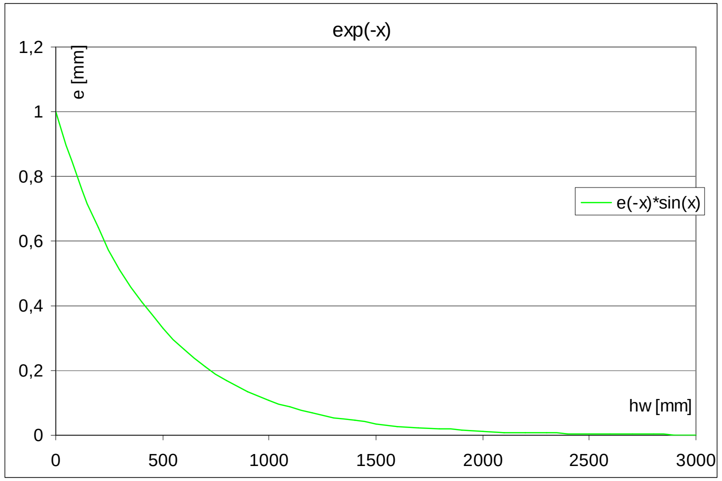
Equivalent geometric imperfection shape

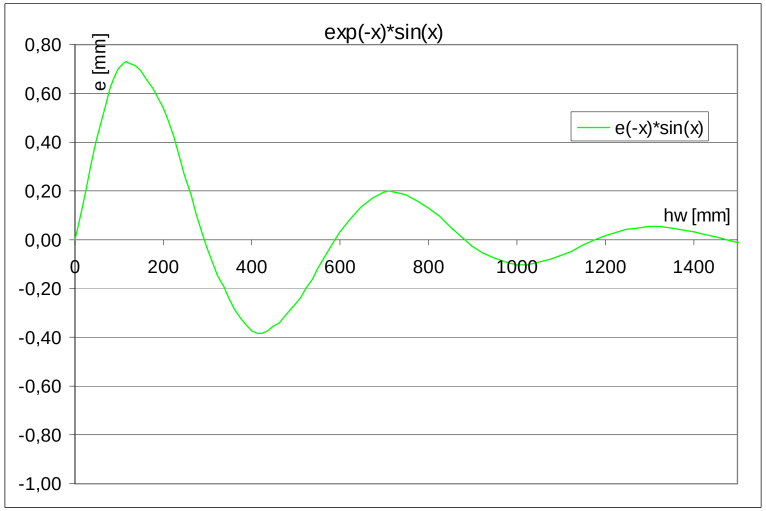
4. numerical approach of the buckling mode:

$$f(x) = e^{-\frac{1}{L \cdot m} x} \cdot \sin\left(\frac{1}{L} \cdot k \cdot \pi \cdot x\right)$$



x





k: distance between null points

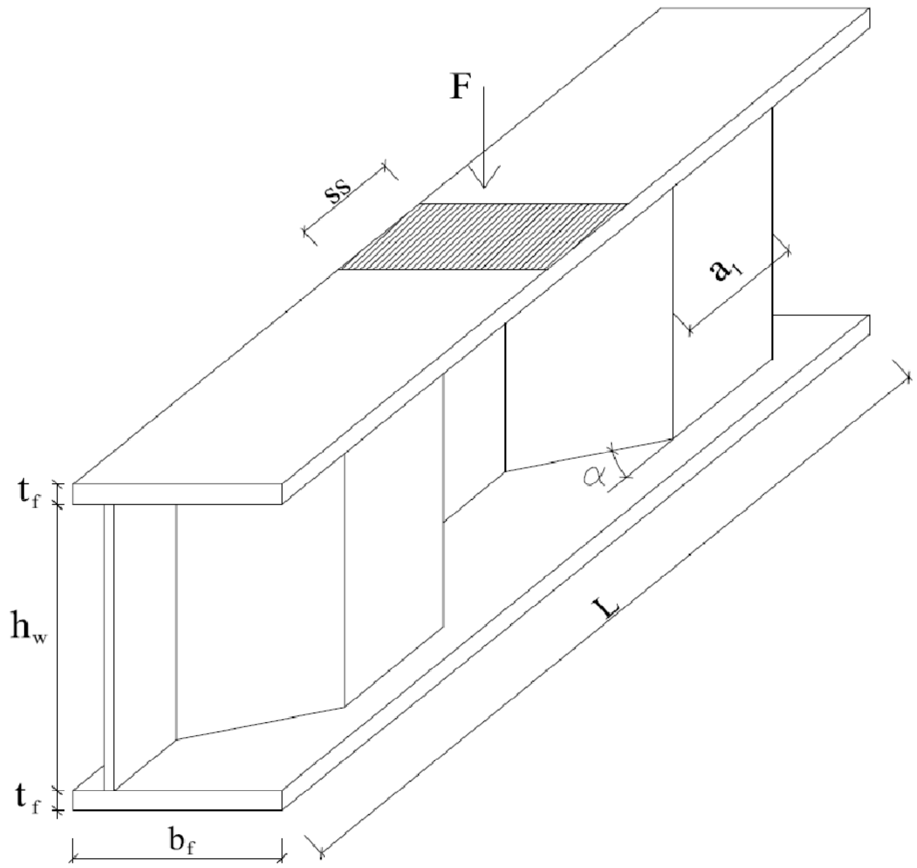
m: falloff rate

Equivalent geometric imperfection shape

Parameter study → influence of geometric parameters on the m and k

parameters	**m**	**k**
h_w	yes	yes
t_w	no	no
b_f	no	no
t_f	no	no
L	no	no
a_i	yes	yes
a	no	no
ss	yes	yes

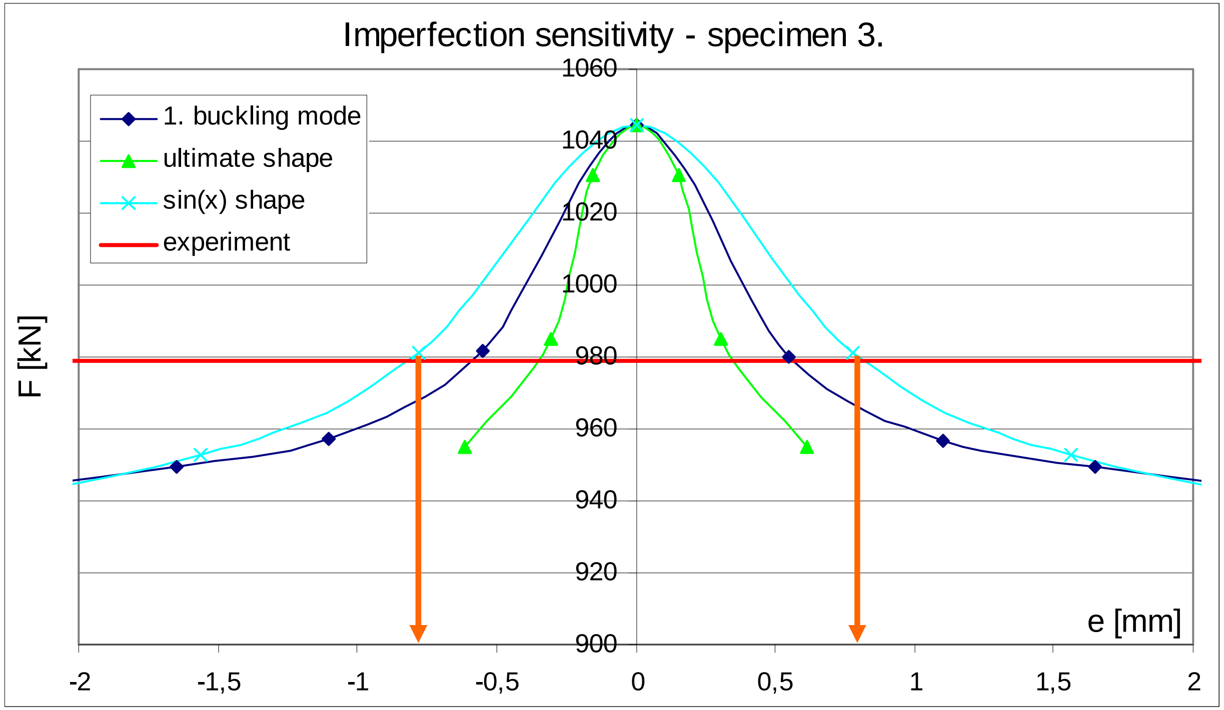
$k = f(h_w/a_i, ss/a_i)$ $m = f(h_w/a_i, ss)$



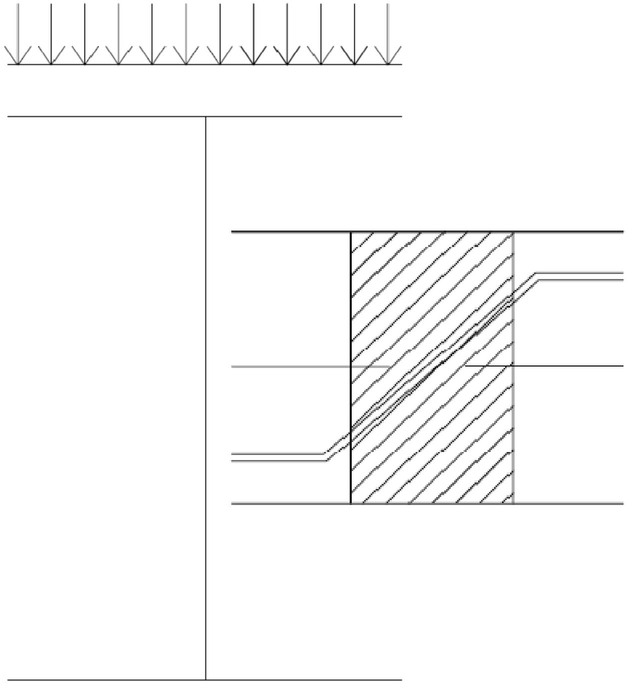
Equivalent geometric imperfection magnitude

Scaling factor determination for:
1. first buckling mode
2. ultimate shape
3. sin(x) wave shape

Experimental background: → Imperfection sensitivity for all three imperfection shapes.

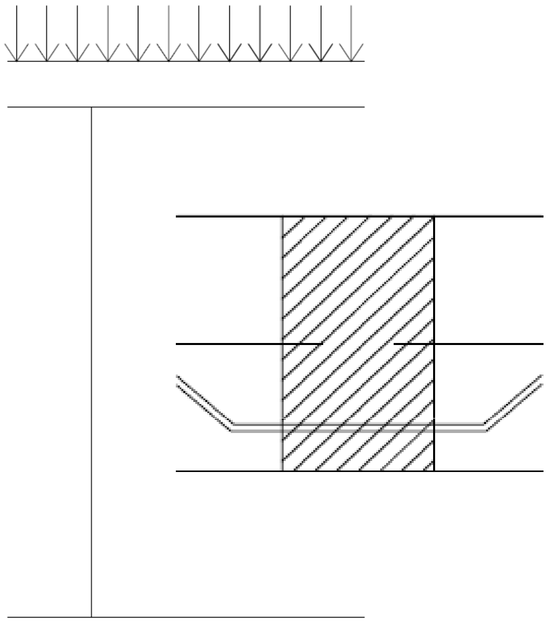


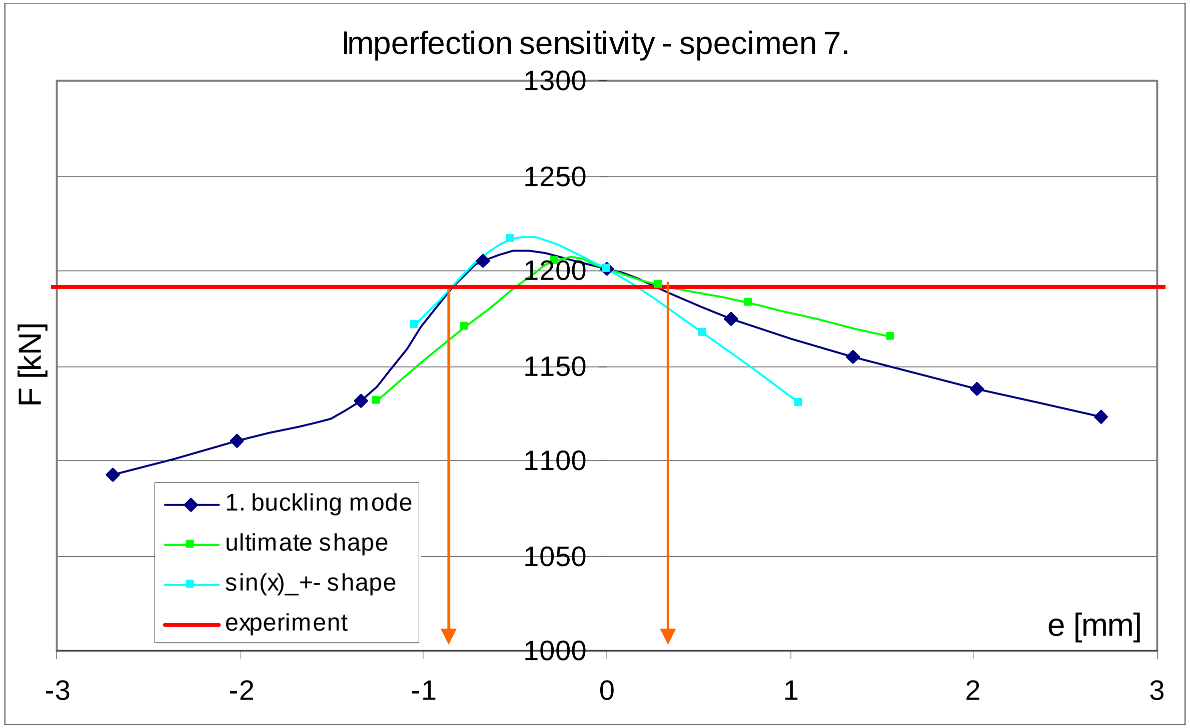
loaded fold: inclined



Equivalent geometric imperfection magnitude

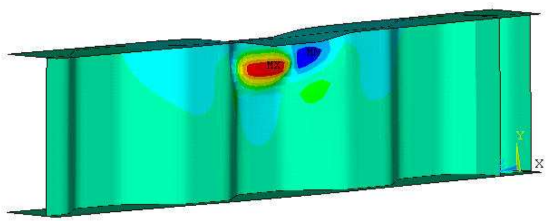
loaded fold: parallel



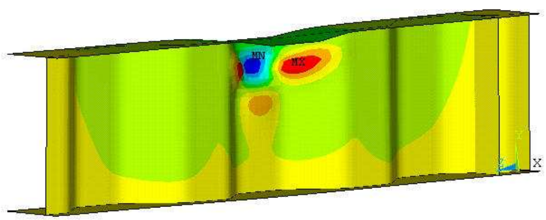


asymetrical behaviour

negative value

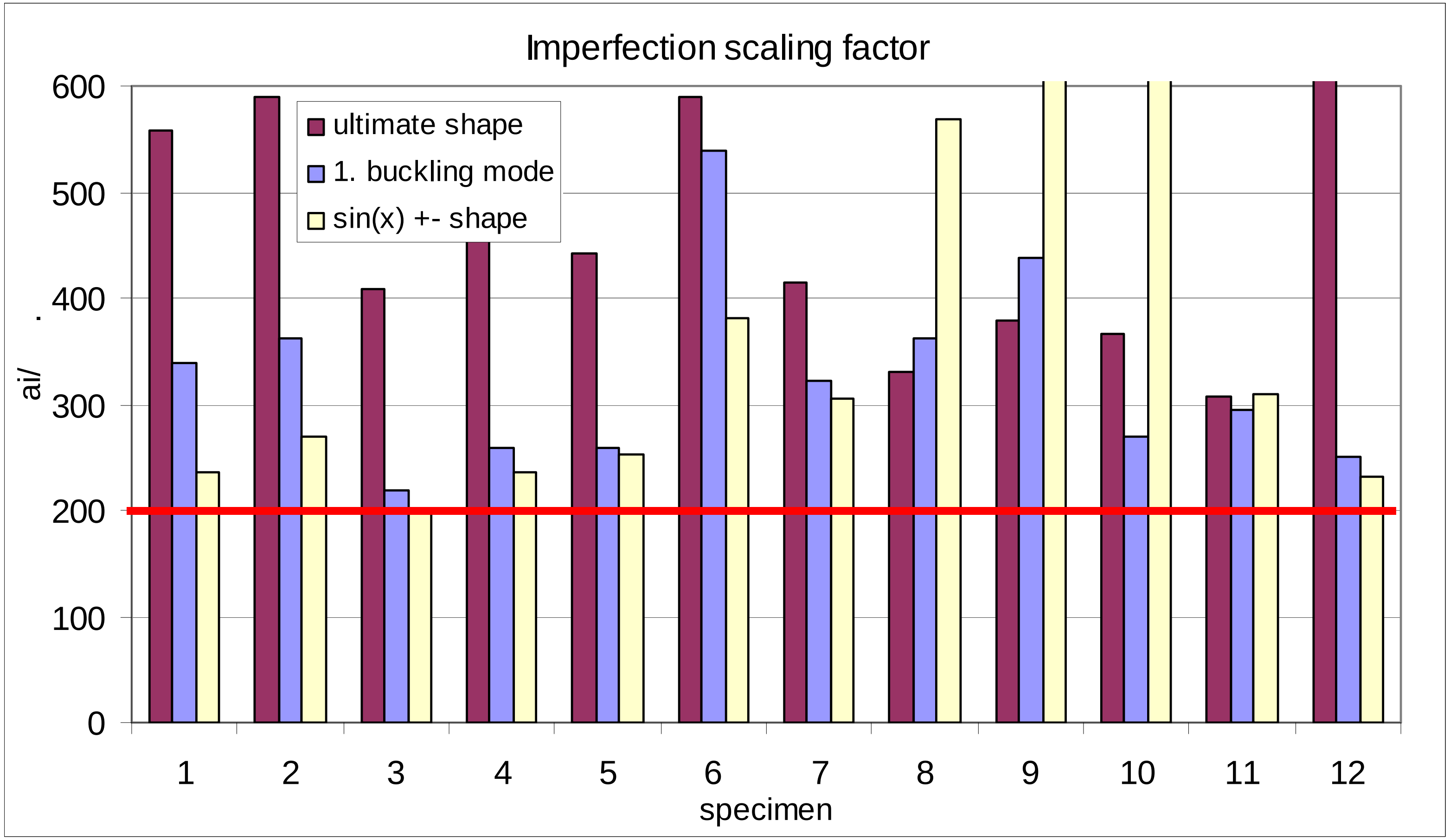


positive value



Compared to all tests results → imperfection scaling factors

Equivalent geometric imperfection magnitude

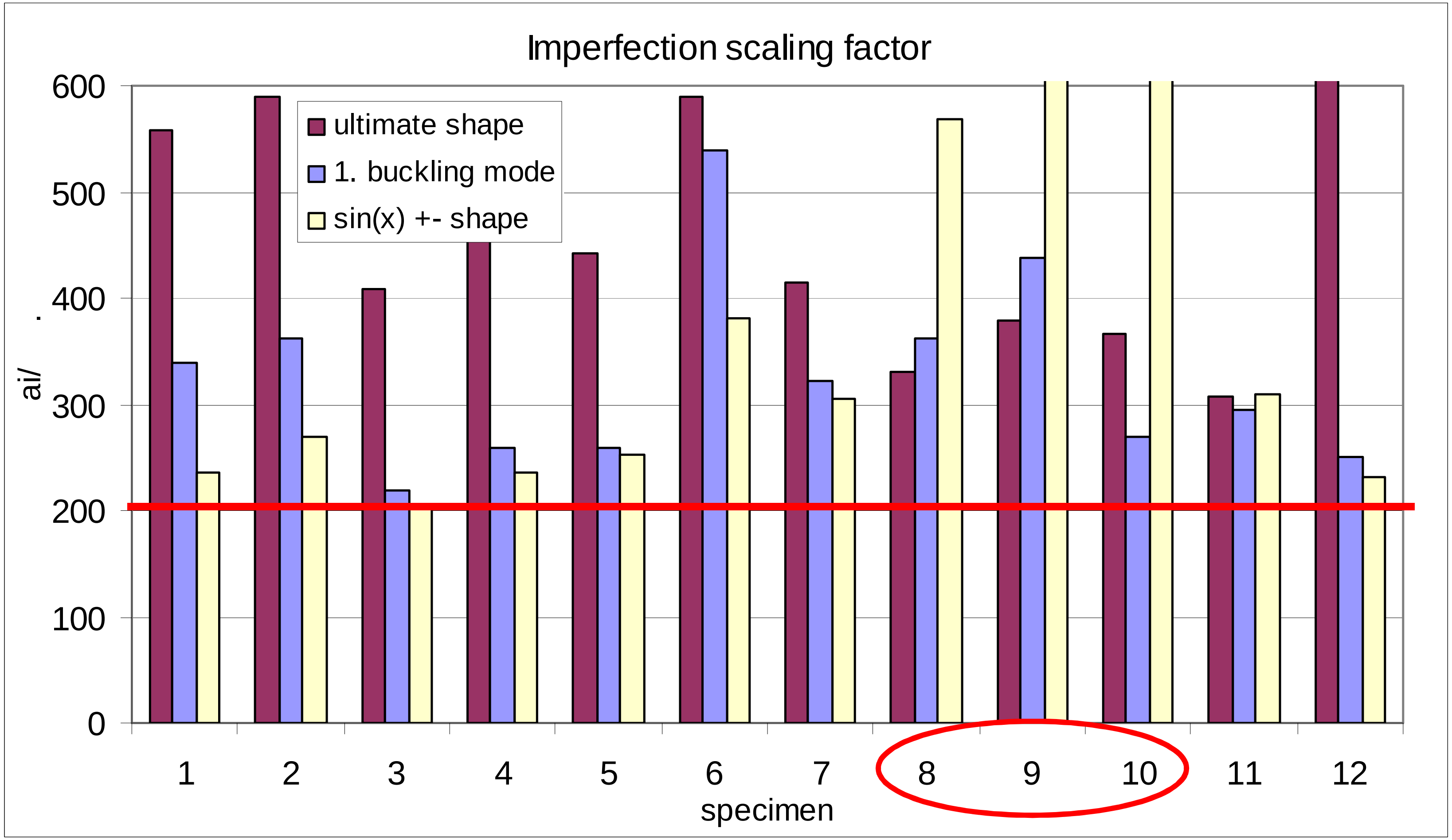


Imperfection scaling factor recommendations:

sin(x) shape imperfection: $a_i/200$

local buckling mode imperfection: $a_i/200$

Equivalent geometric imperfection magnitude

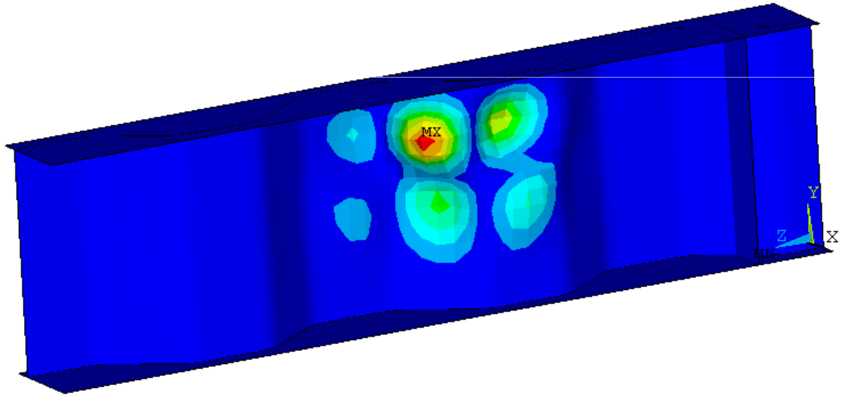


contradictions

Evaluation
of ultimate shape imperfection

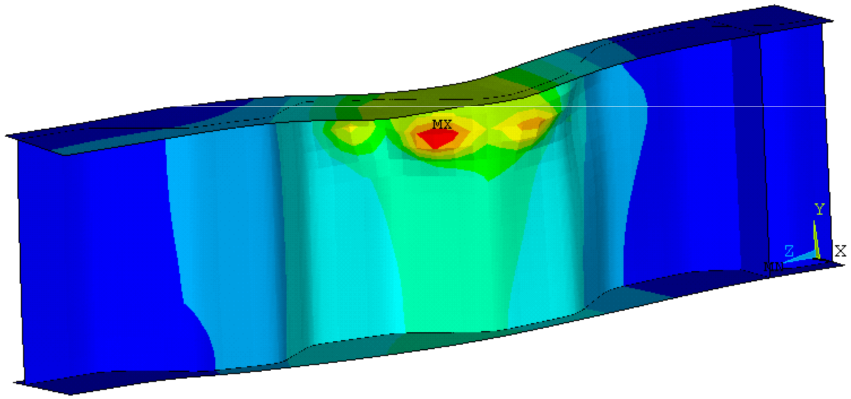
Unexpected cases: ultimate shape imperfection gives the largest resistance

First buckling mode



Imperfection in more waves

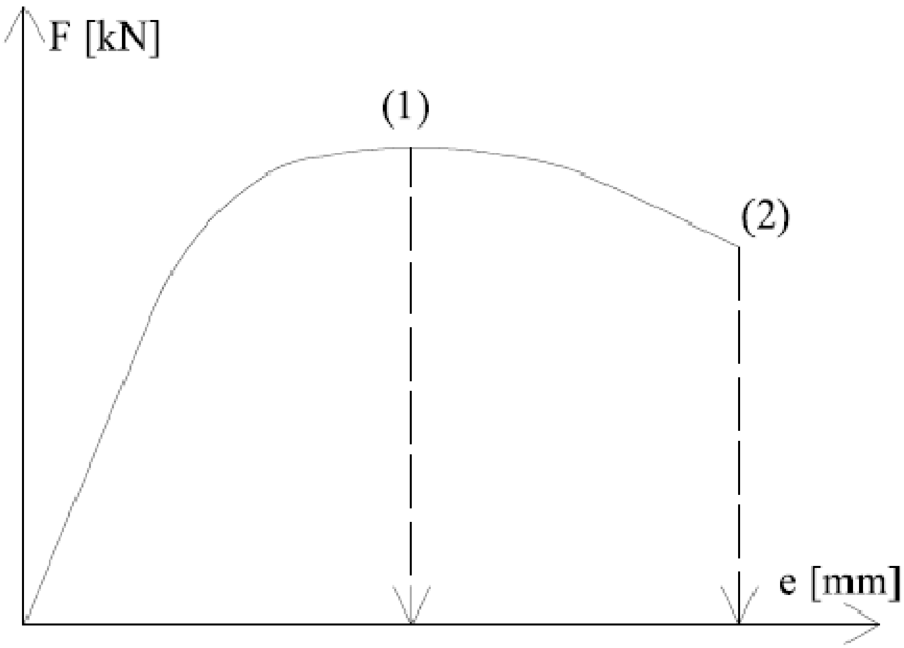
Ultimate shape



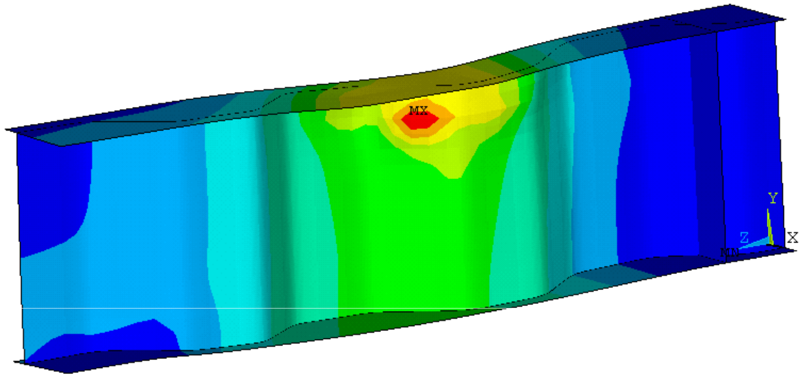
Imperfection only in 1 wave

Evaluation of ultimate shape imperfection

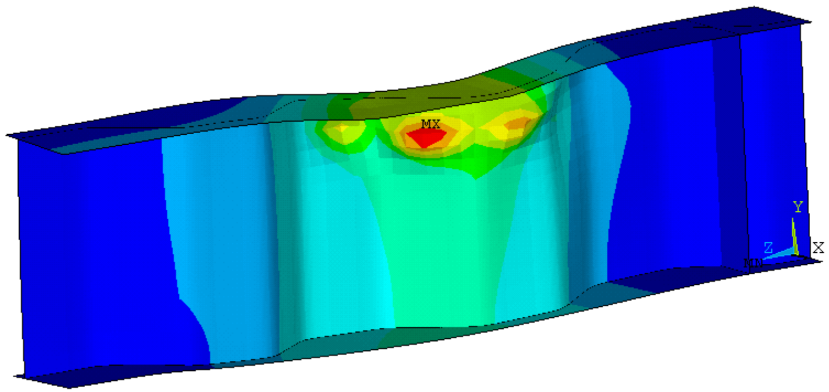
Ultimate shape in different load steps:



Shape by point (1):



Shape by point (2):



Conclusions

Test results (12 large scale test specimens)

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Numerical model development and verification

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three investigated imperfections shapes + buckling shape prediction

↓

Imperfection sensitivity analysis for different imperfection shapes

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Imperfection shape and scaling factor determination

↓

Proposal for FEM based design method

Thank you for your attention!