Imperfections for use with corrugated webs

Balázs Kövesdi

PhD Student

Supervisors:

Prof. Dr.-Ing. László Dunai
Prof. Dr.-Ing. Ulrike Kuhlmann

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Intoduction

- Previous research activity
  - Modified design method for patch loading resistance
  - Fatigue experiments on girders with corrugated webs
- Experimental investigations
  - Patch loading experiments on girders with corrugated webs
- Numerical investigations
  - FEM model development
  - Comparison of numerical simulations and tests
- FEM based desing method
  - Investigations for the equivalent geometric imperfections
  - Recommendation for possible imperfection shapes
  - Recommendation for imperfection scaling factor
- Summary

Previous research activity 1.

Patch loding resistance of girders with corrugated webs

Based on previous investigations from literature

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Numerical model development

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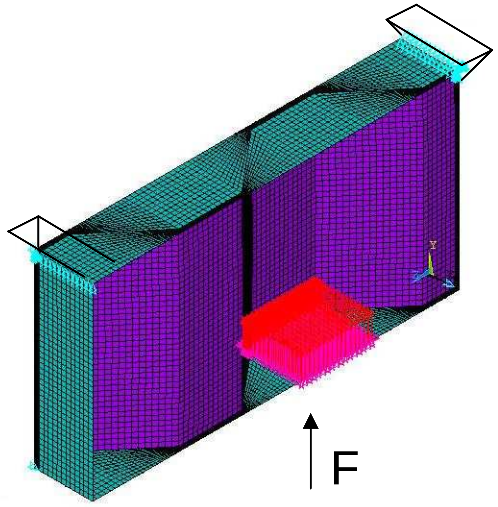
Numerical parametric study

(parameters having influence on the patch loading resistance)



Modified analitical design method

$$R = R_w + R_f =$$

$$\rho \cdot ss \cdot t_w \cdot f_{yw} \cdot k_\alpha + 2 \cdot \sqrt{4 \cdot M_{plf} \cdot \delta \cdot t_w \cdot f_{yw}}$$

Previous research activity 2.

Fatigue tests on girders with corrugated webs

Experimental program: 6 large scale specimens

(L=6750m; h_w=500mm; t_w=6mm; b_f=225mm; t_f=20-30mm)

Test arrangement: (3 and 4 point bending)

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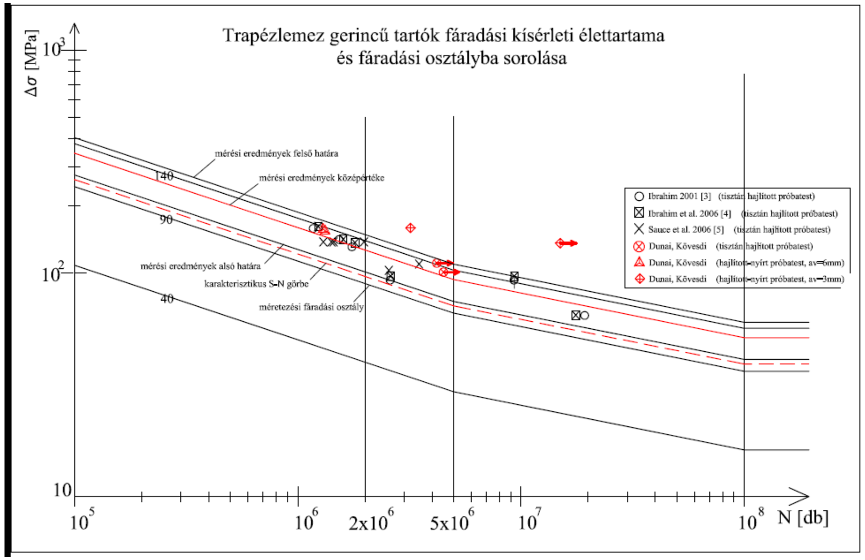
Fatigue class determination of the structural detail



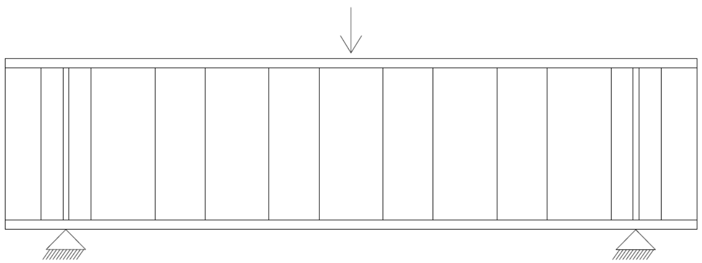
Patch loading tests

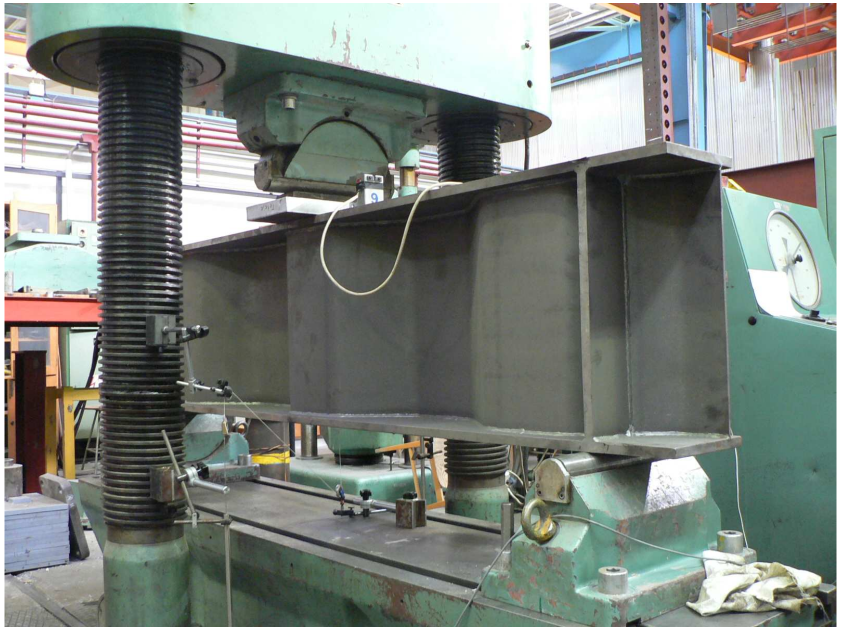
Experimental program: 12 test specimens

Aim of the tests:

1. Fatigue test girders could be used.
2. Determination of the patch loading resistance for different geometrical arrangement.
3. Verification of the previously developed modified design method.

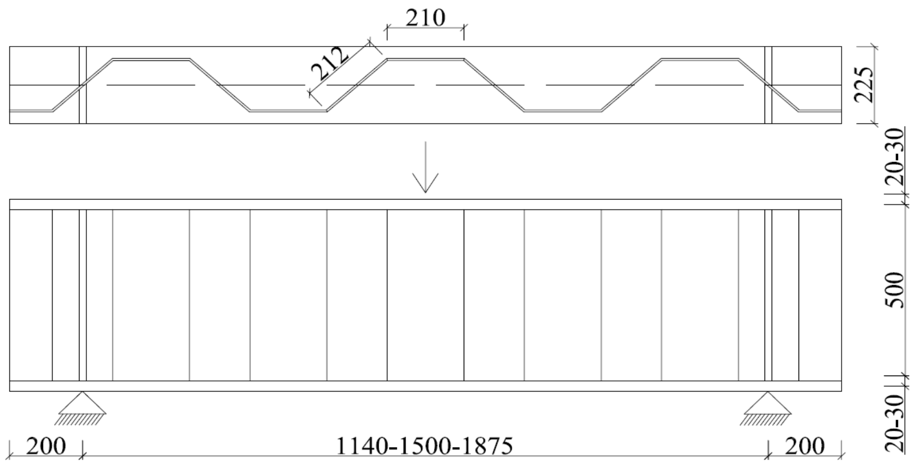
Test arrangement





Patch loading tests

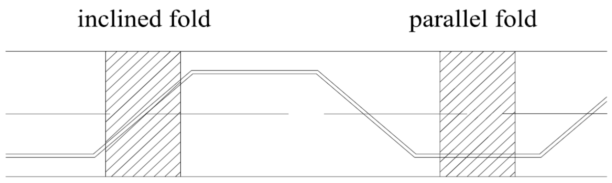
Test specimens



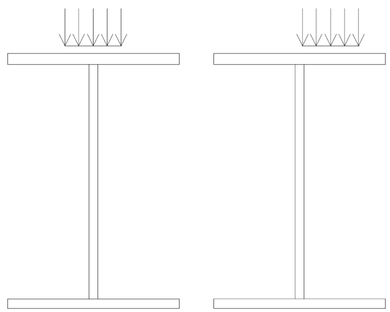
h_w=500mm
t_w=6mm
b_f=225mm
t_f=20mm; 30mm

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



Patch loading tests

<u>Failure modes:</u>
- loading length
- loaded fold

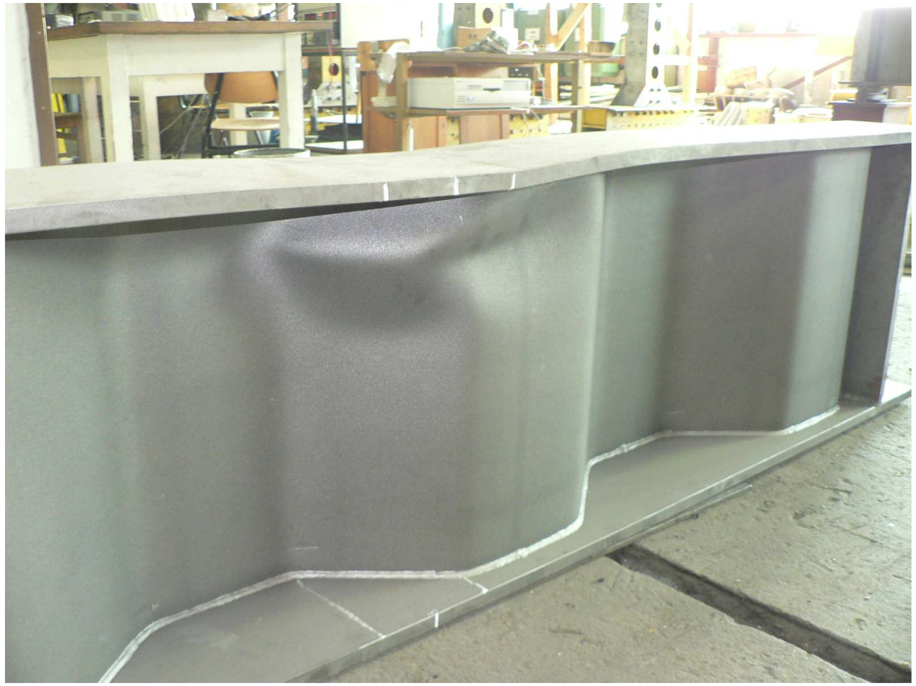
loaded fold: parallel fold
loading length: 90mm

loaded fold: parallel fold
loading length: 200mm

Patch loading tests

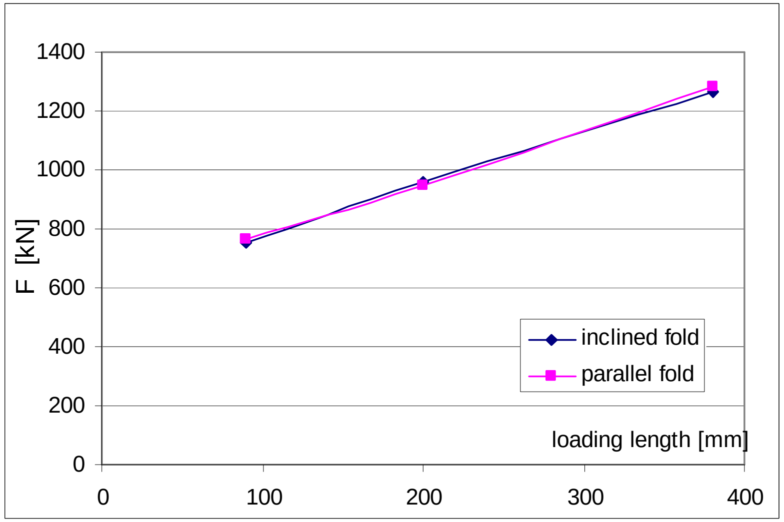
loaded fold: inclined fold
loading length: 90mm

loaded fold: inclined fold
loading length: 200mm

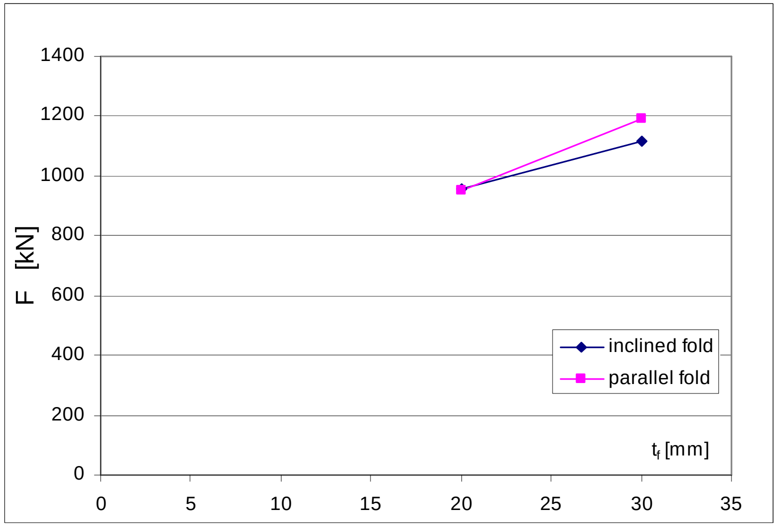


Test results

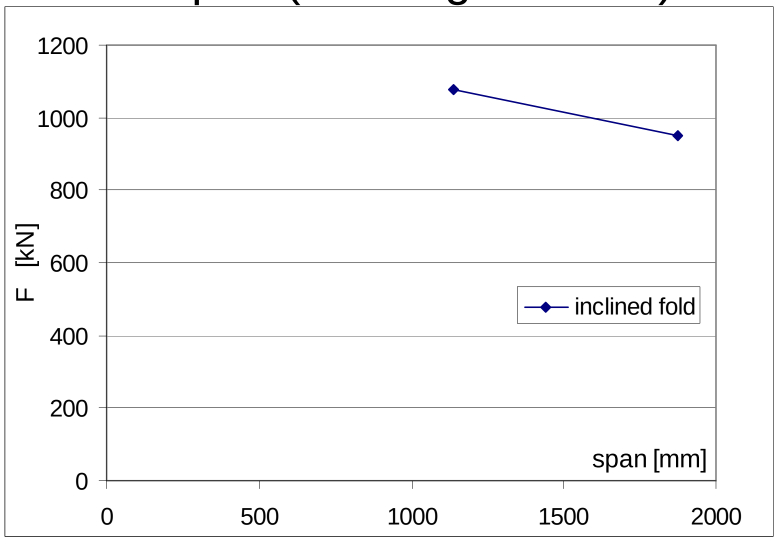
loading length



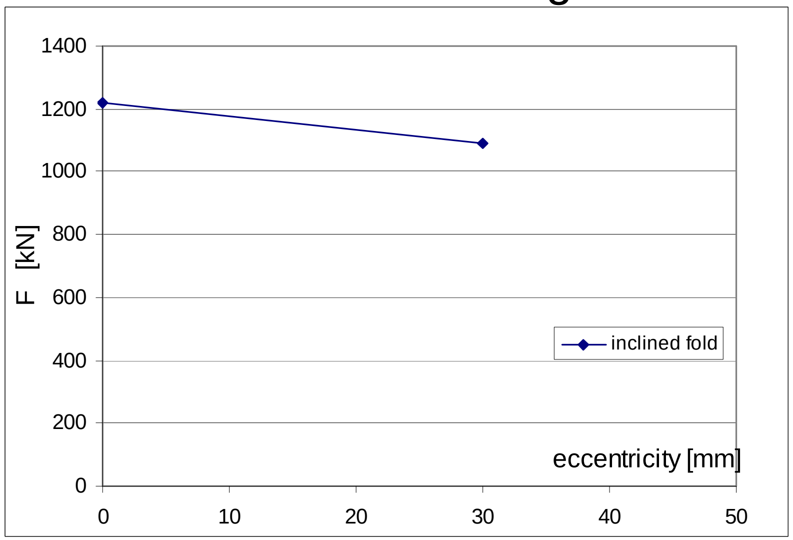
flange thickness



span (bending moment)



eccentric loading



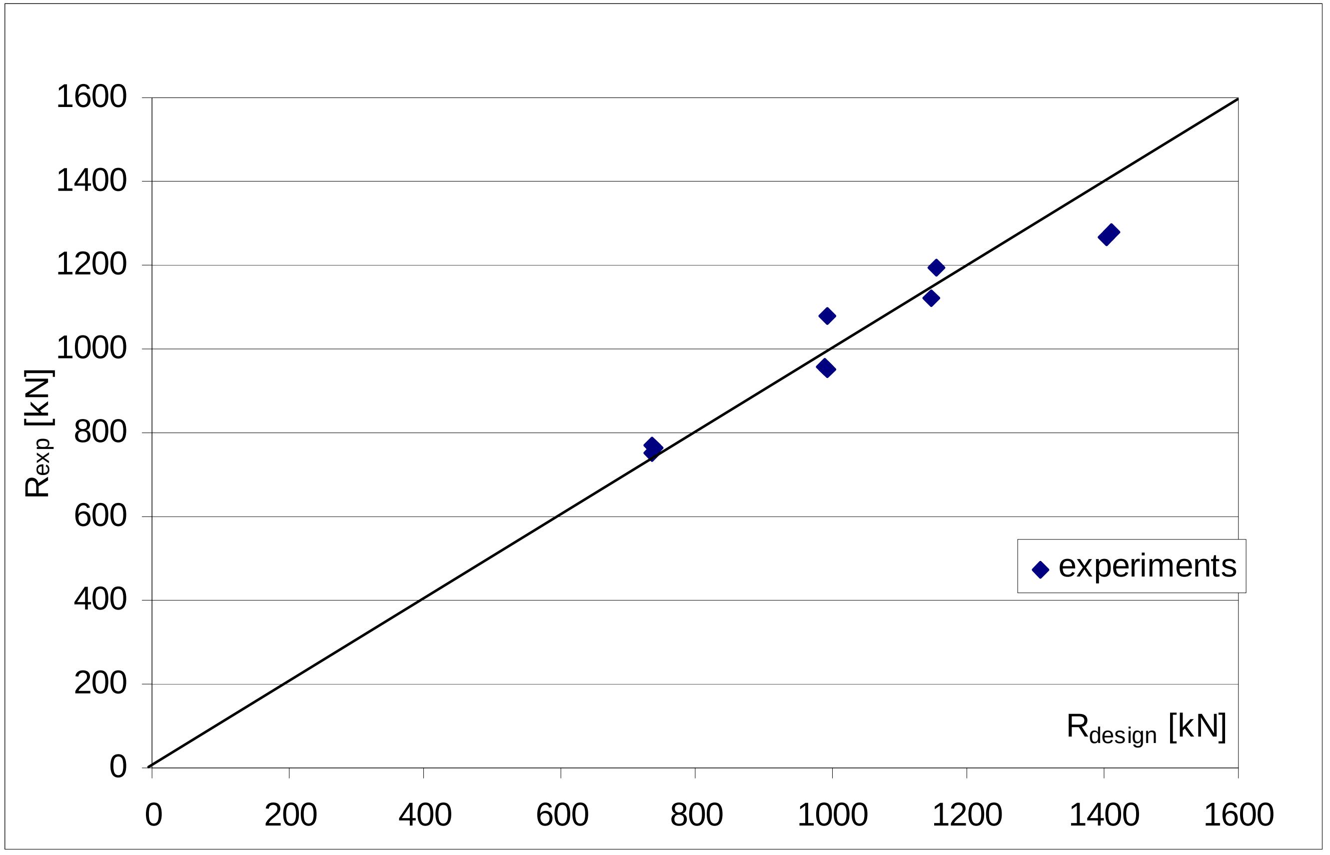
Comparison of test results and design method

Developed design method: $R = R_w + R_f =$

$$\rho \cdot ss \cdot t_w \cdot f_{yw} \cdot k_\alpha + 2 \cdot \sqrt{4 \cdot M_{plf} \cdot \delta \cdot t_w \cdot f_{yw}}$$

↕

Test results



FEM based design method

Research strategy:

1. FE model development for all test specimens
2. Experimental patch loading resistance ⟷ numerical calculations
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

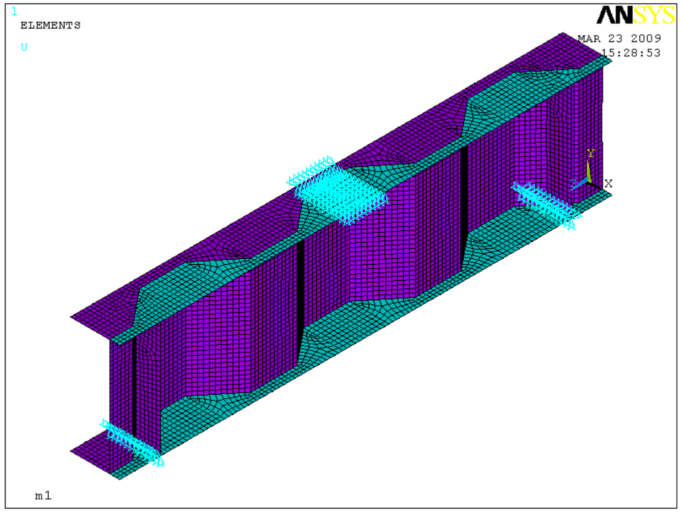
Aim: Determination of the design value of the patch loading resistance by numerical simulation

Problem by FE calculations : → imperfection form
→ imperfection scaling factor

→ Recommendations developed

FEM based design method

1. Numerical model

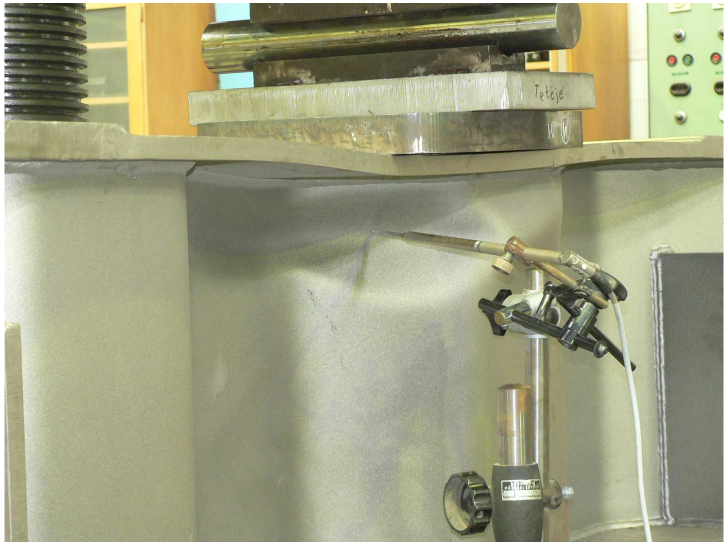


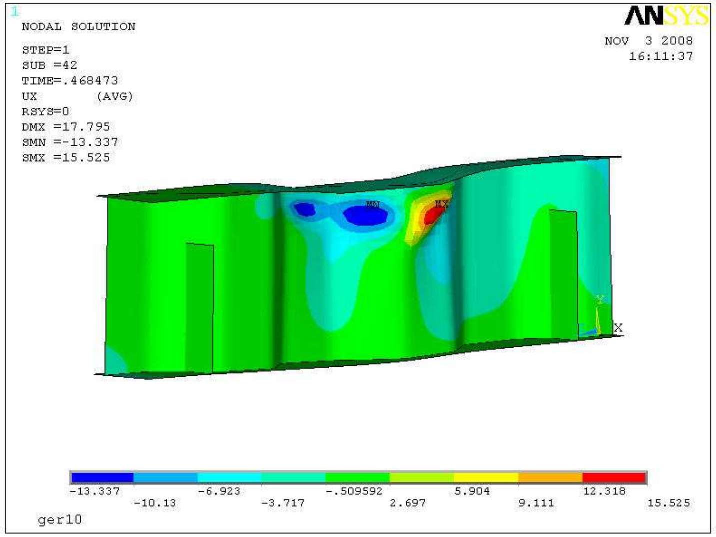
2. Comparison of test results and numerical calculations

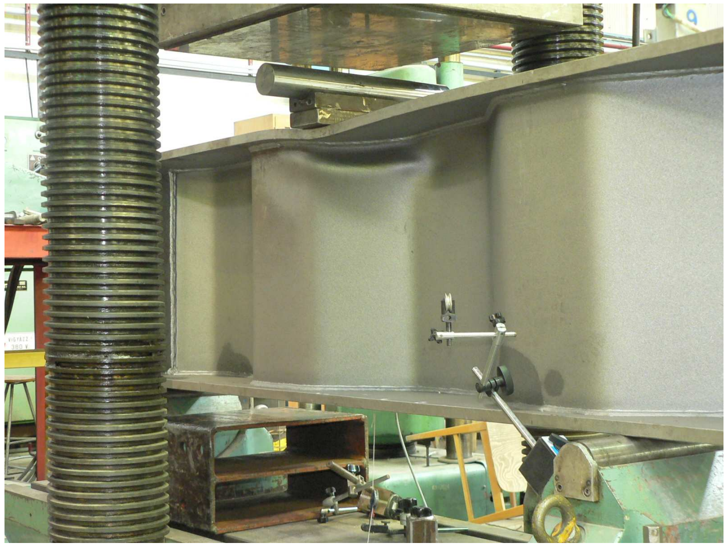
	R_{exp} [kN]	R_{num} [kN]	difference [%]
1. specimen	754,20	771,08	2,2
2. specimen	956,48	1044,18	9,2
3. specimen	764,75	769	0,6
4. specimen	949,02	969,054	2,1
5. specimen	1192,01	1201,24	0,8
6. specimen	1119,33	1155,901	3,3
7. specimen	1077,72	1093,58	1,5
8. specimen	1263,94	1285,4	1,7
9. specimen	1220,48	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

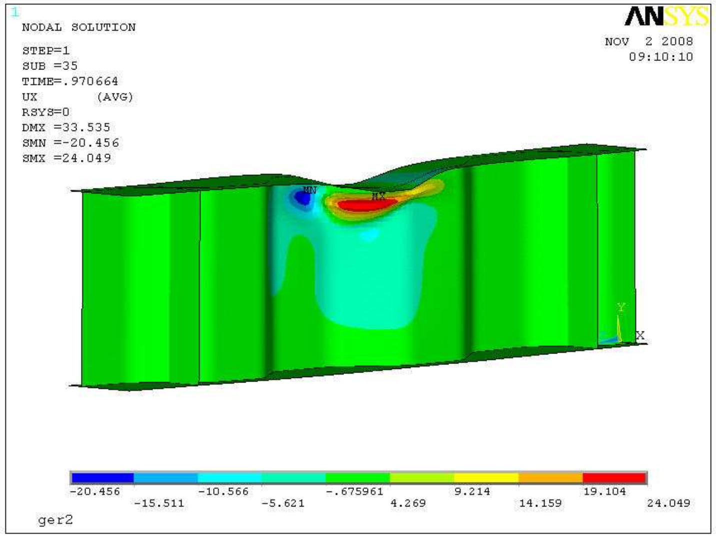
FEM based design method

3. Experimental failure mode ⟷ numerical model



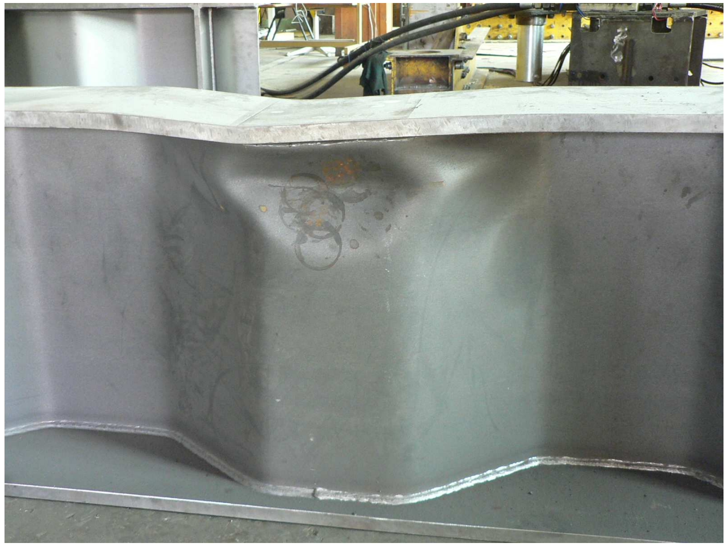


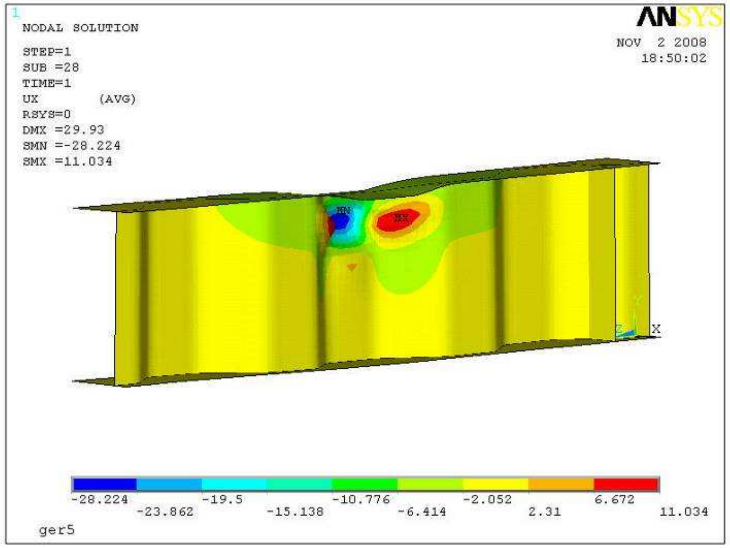


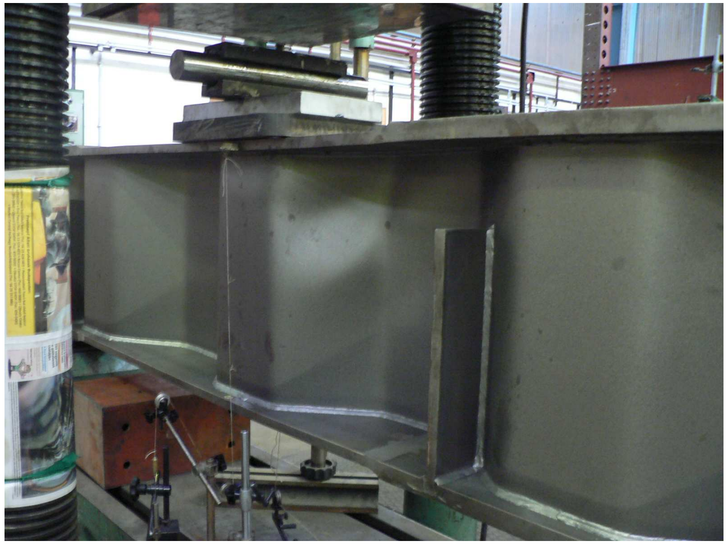


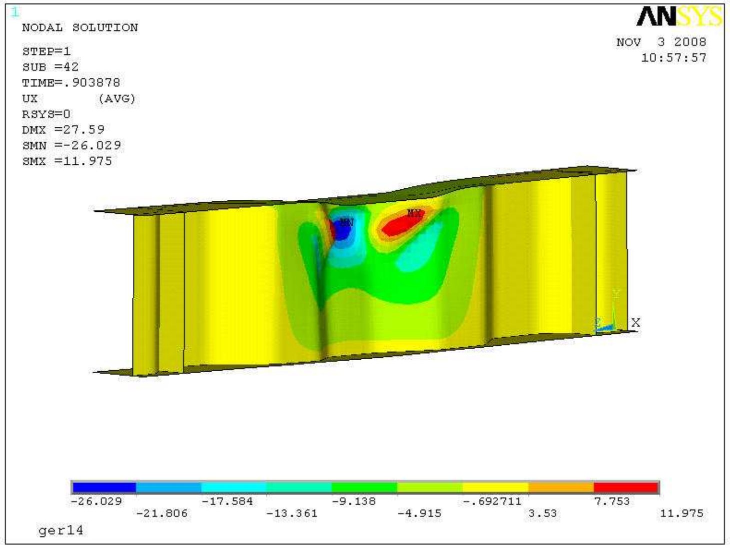
FEM based design method

3. Experimental failure mode ⟷ numerical model



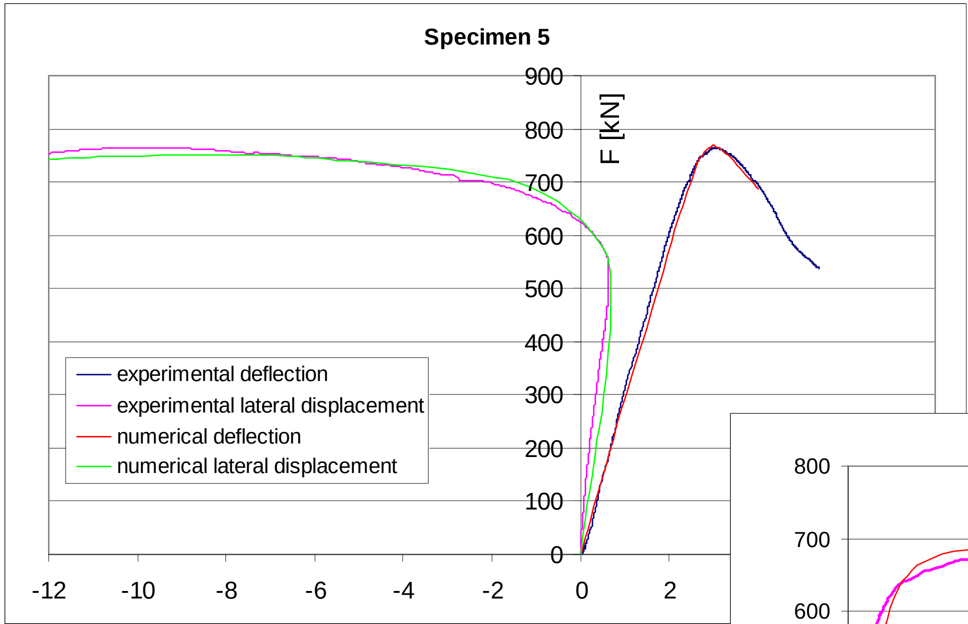




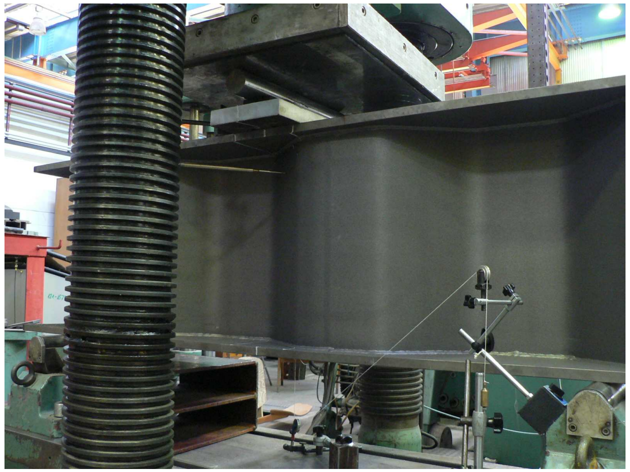


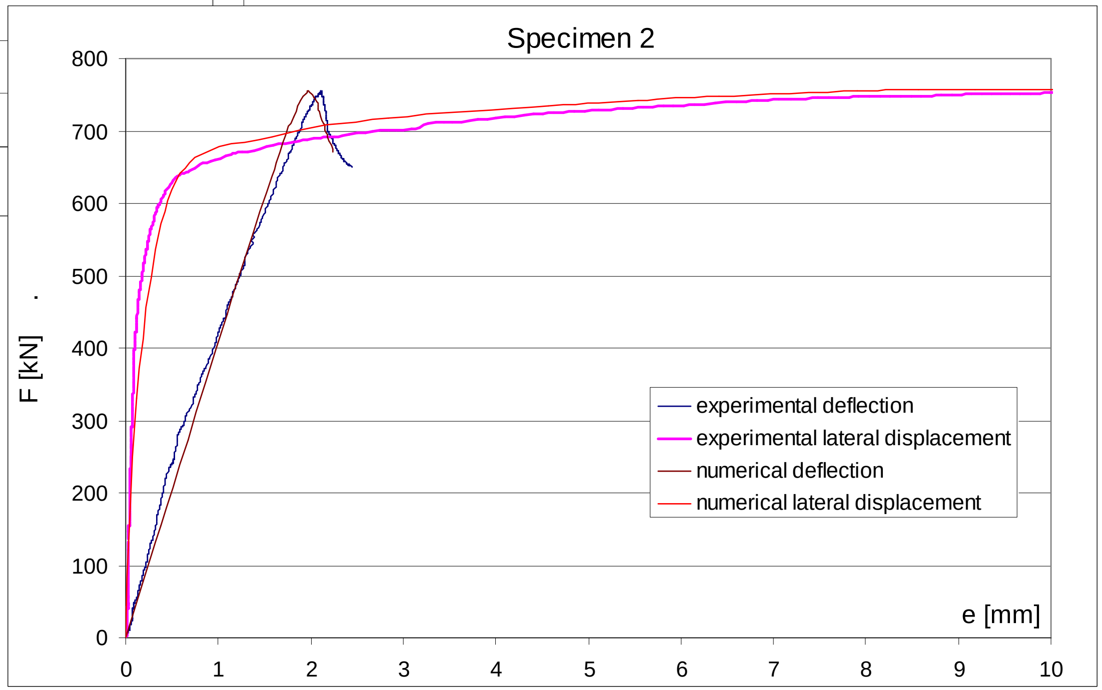
FEM based design method

4. Experimental load displacement diagram ⟷ numerical model



measured: - deflection
- lateral displacement
- applied force

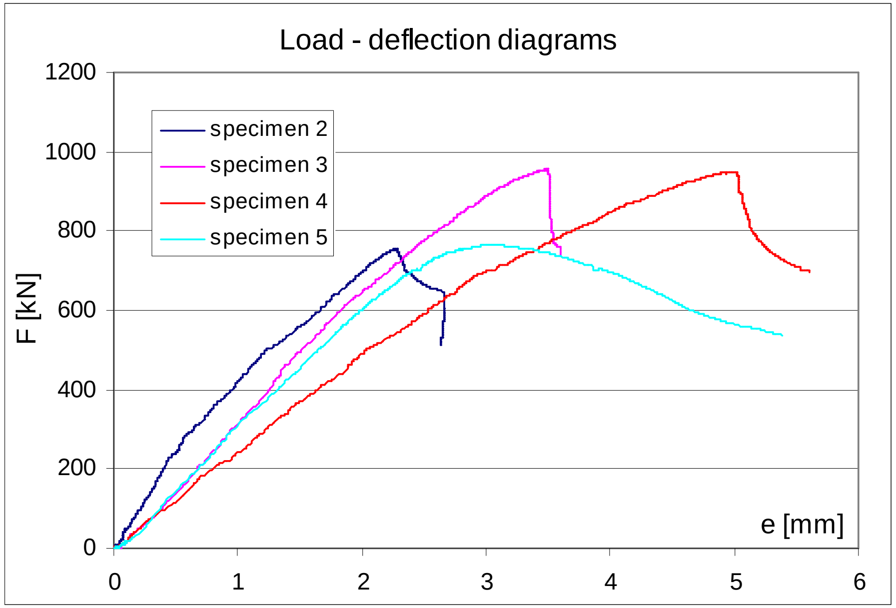




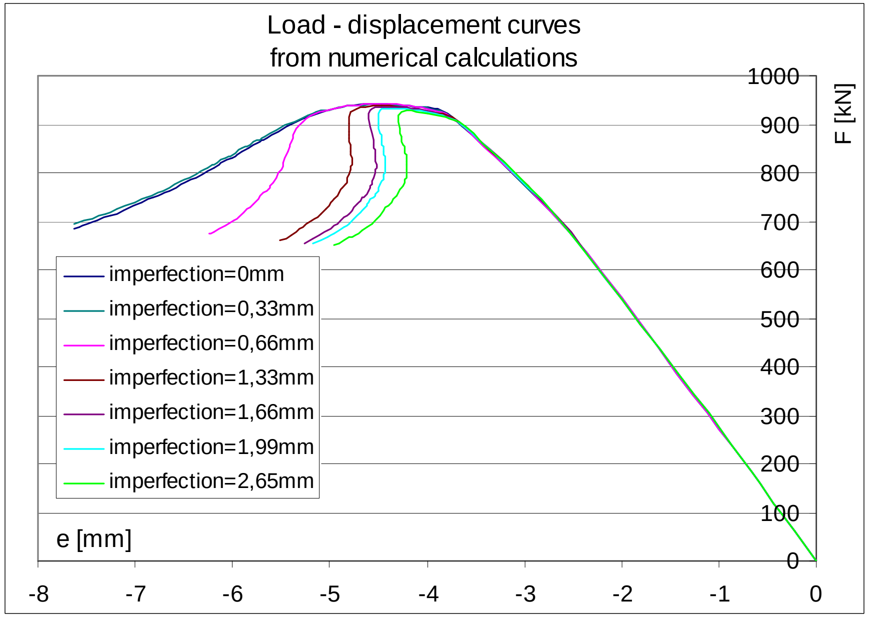
FEM based design method

Observations in the experiments: Different post-ultimate behaviours

Experimental load-displacement curves

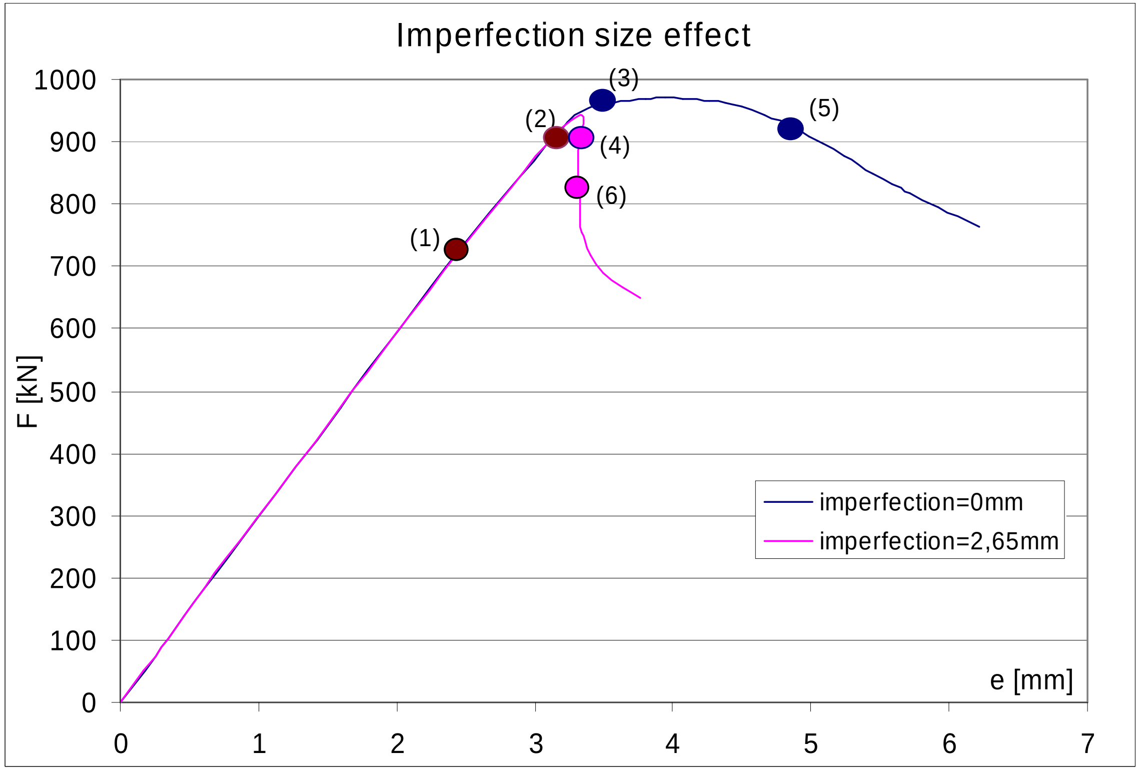


Numerical load-displacement curves



Reason: Imperfections

FEM based design method



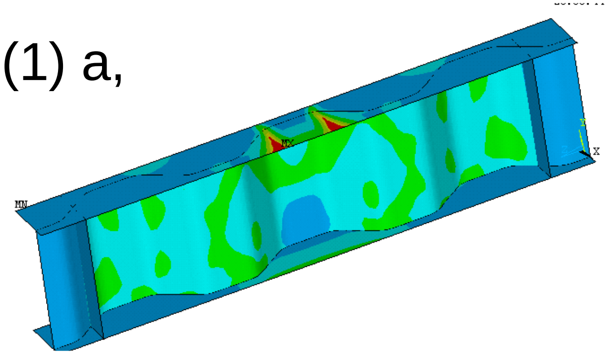
(1) a, First yielding in the flange (if imperfection size = 0mm)
b, Simultaneous yielding in the flange and web (if imperfection size = 2,65mm)

(2) First yielding in the web (if imperfection size = 0mm)

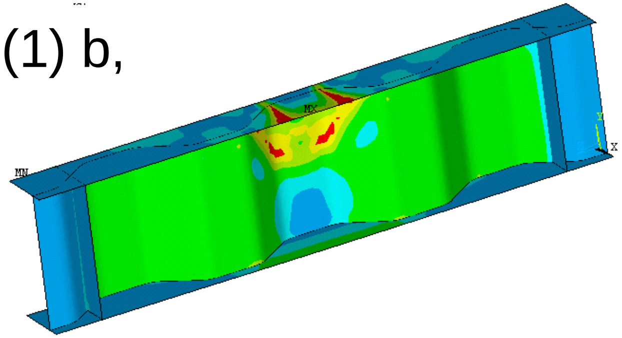
(3) - (4) 2 plastic hinges in the flange

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

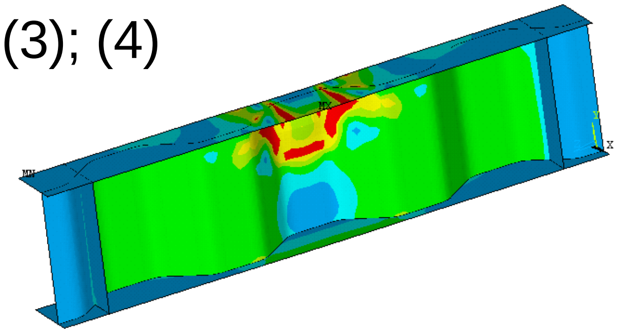
(1) a,



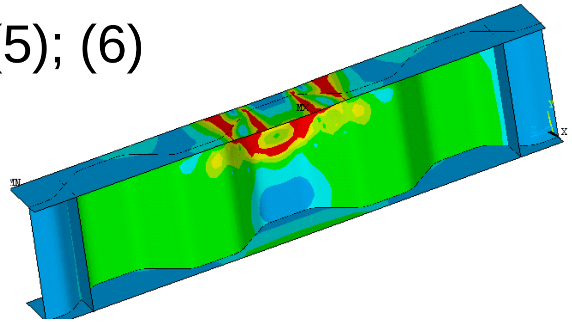
(1) b,



(3); (4)



(5); (6)



Equivalent geometric imperfection

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

Possible standardised imperfection types

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

shape

scaling factor

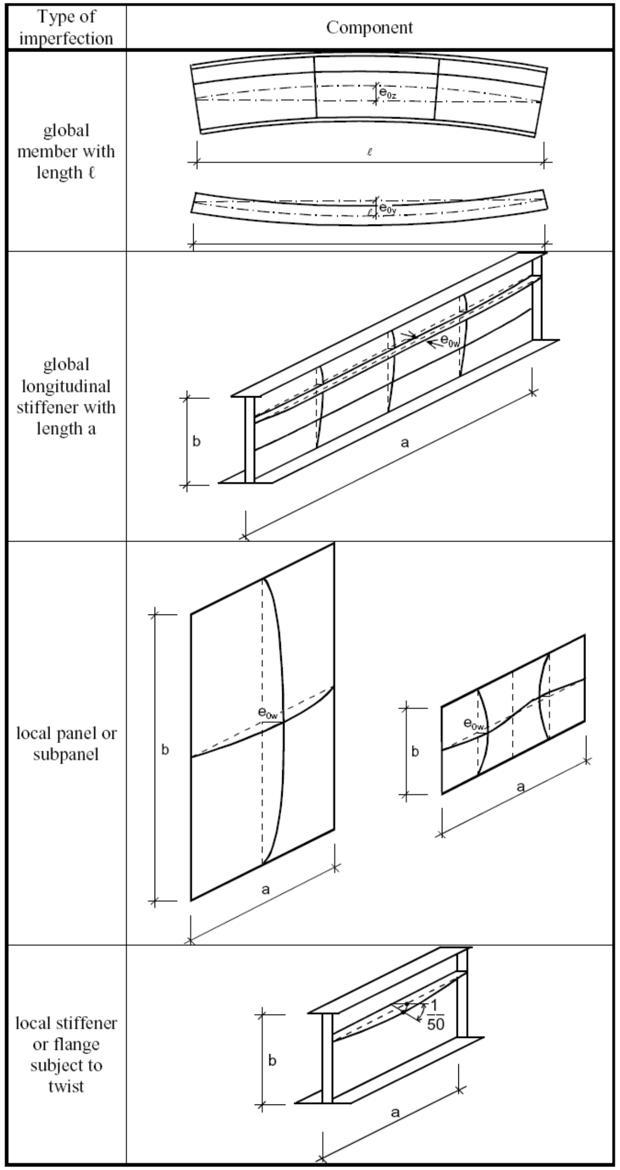
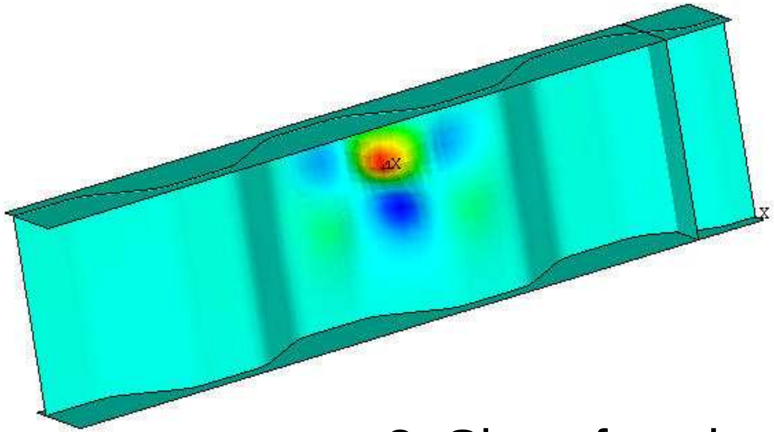


Figure C.1: Modelling of equivalent geometric imperfections

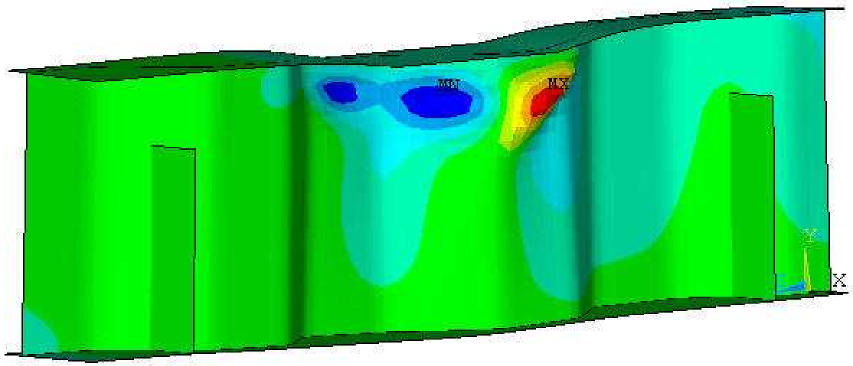
Equivalent geometric imperfection

Possible shapes

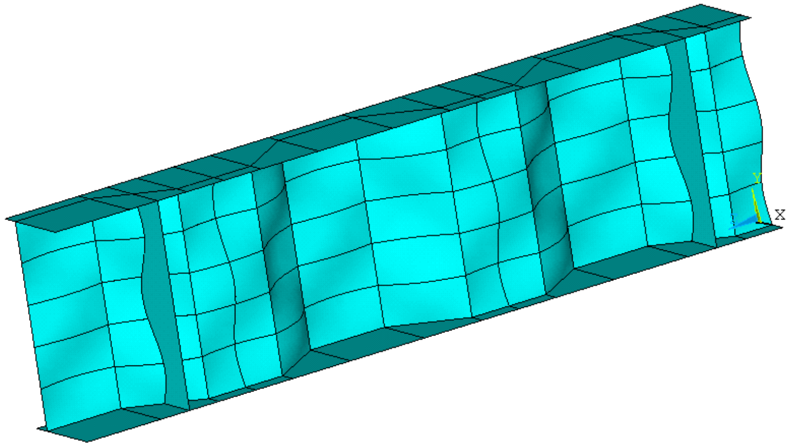
1. buckling mode



2. ultimate shape

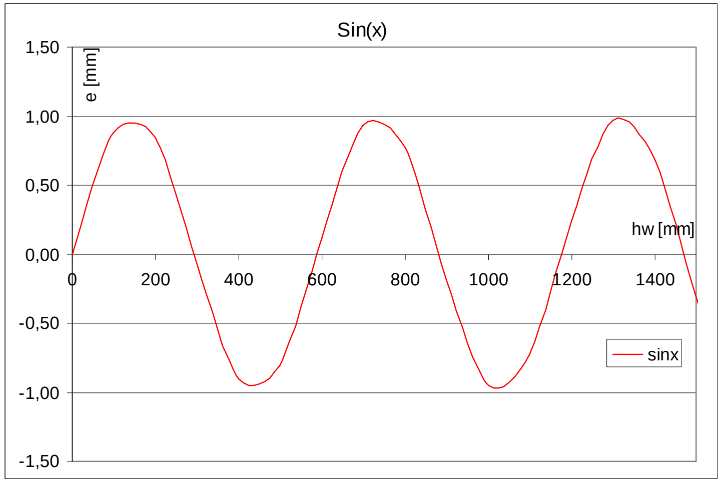


3. Sinus function based on EC3 subpanel

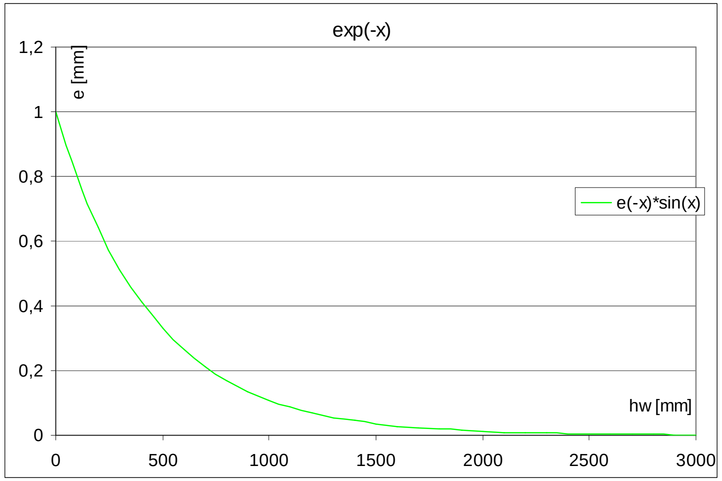


Equivalent geometric imperfection

4. numerical approach of the buckling mode: $f(x) = e^{-\frac{1}{L \cdot m} \cdot x} \cdot \sin(\frac{1}{L} \cdot k \cdot \pi \cdot x)$



x



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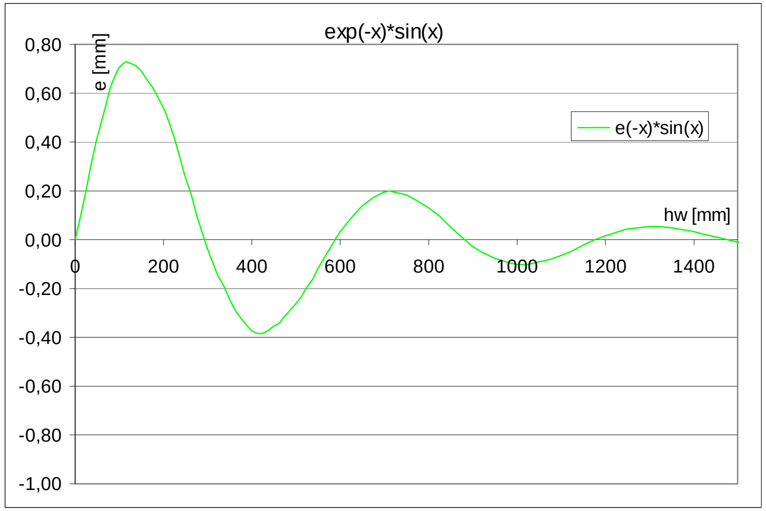


k: distance between null points

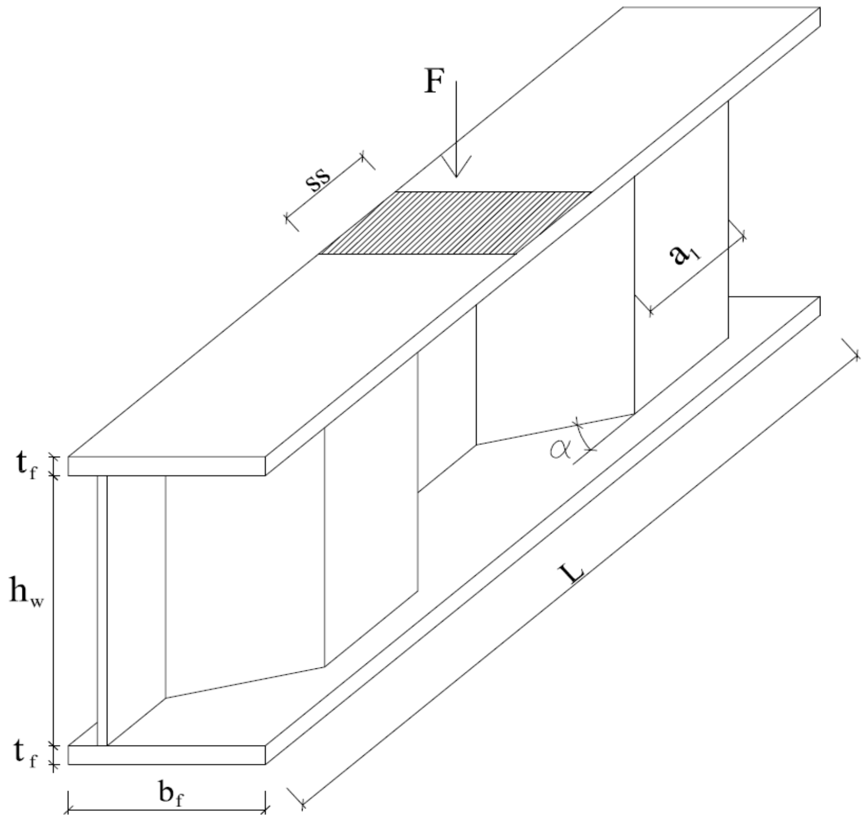
m: falloff rate

Equivalent geometric imperfection

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
α	no	no
ss	yes	yes

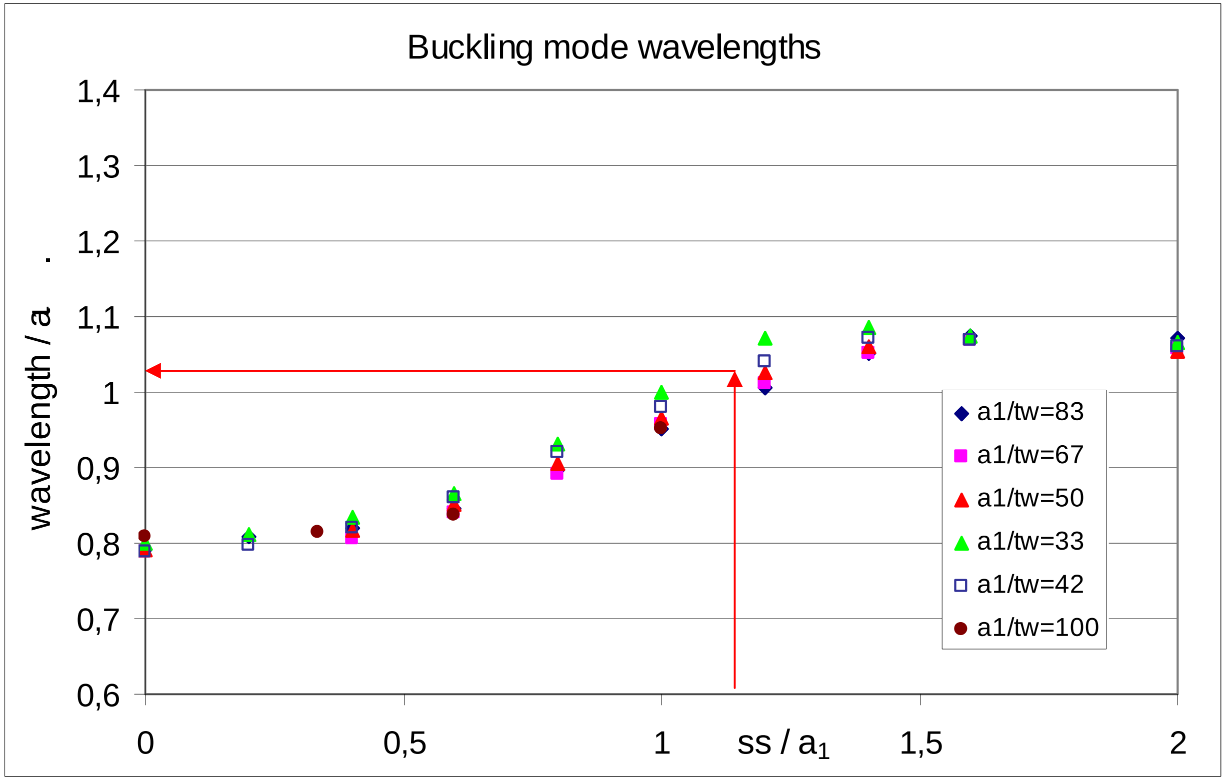
$k = f(h_w/a_i, ss/a_i)$ $m = f(h_w/a_i, ss)$

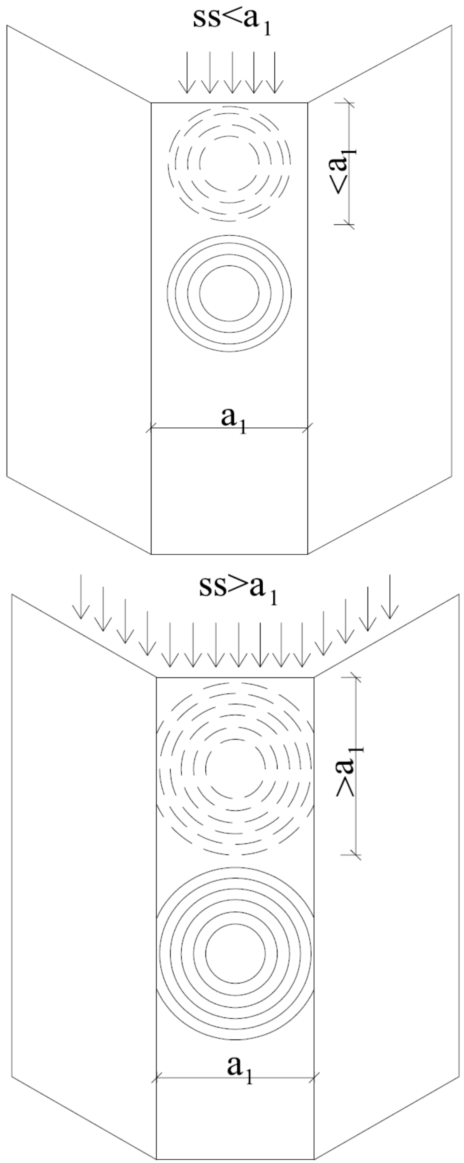


Equivalent geometric imperfection

Wavelength:

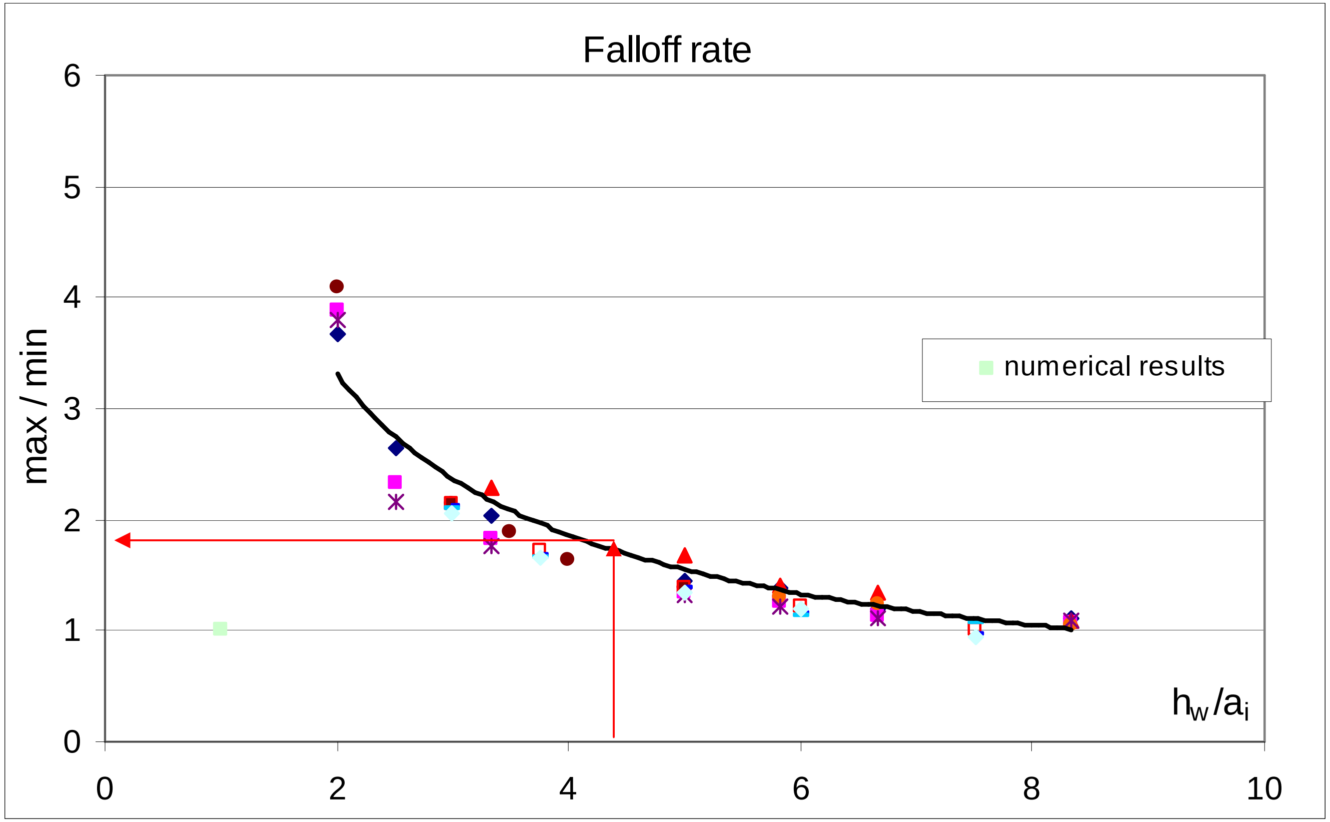
$$k = \frac{h_w}{a_i} \cdot f\left(\frac{ss}{a_i}\right)$$





Equivalent geometric imperfection

Falloff rate:



m and k are determined

4. imperfection shape:

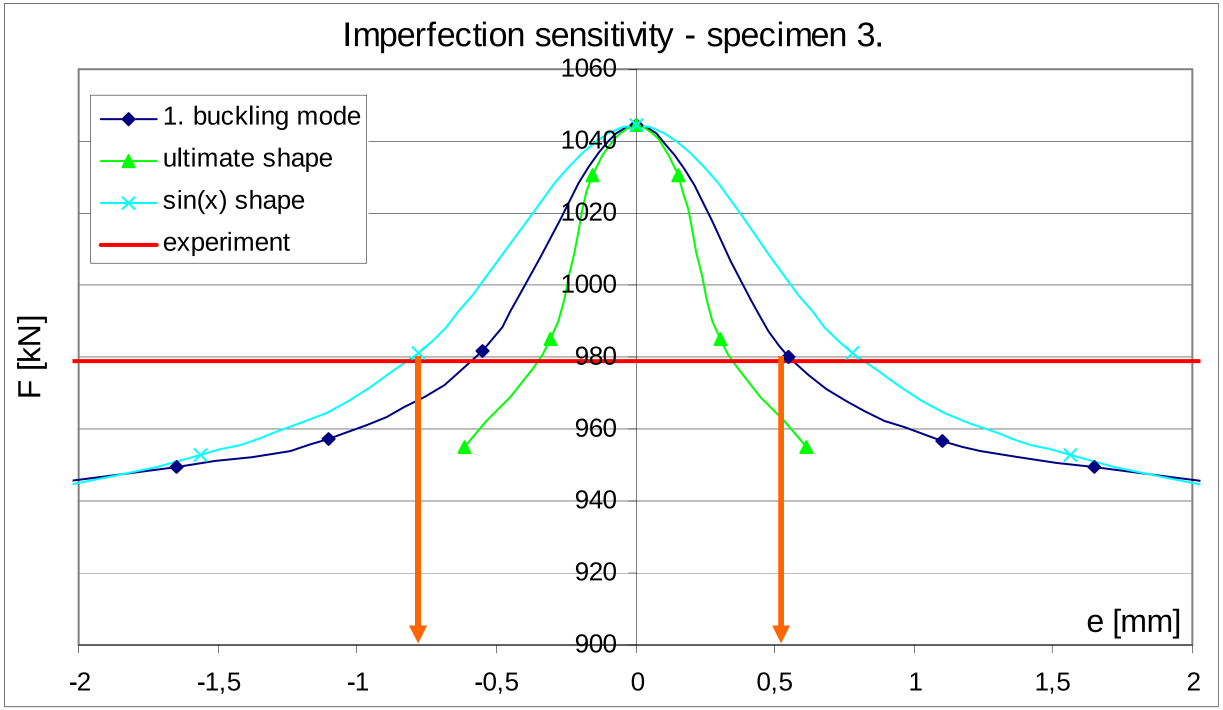
$$f(x) = e^{-\frac{1}{L \cdot m} \cdot x} \cdot \sin\left(\frac{1}{L} \cdot k \cdot \pi \cdot x\right)$$

Equivalent geometric imperfection

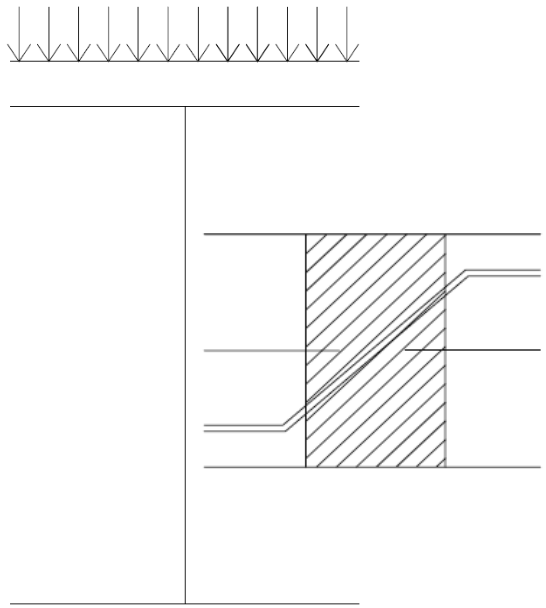
Scaling factor determination for:

1. first buckling mode
2. ultimate shape
3. sin(x) wave shape

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

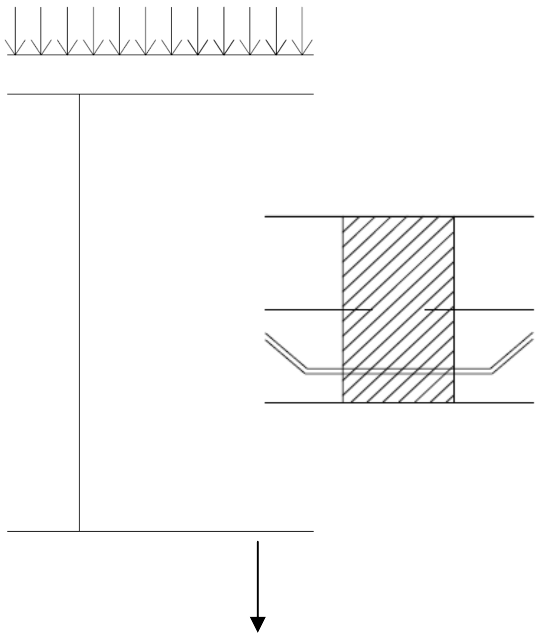


loaded fold: inclined

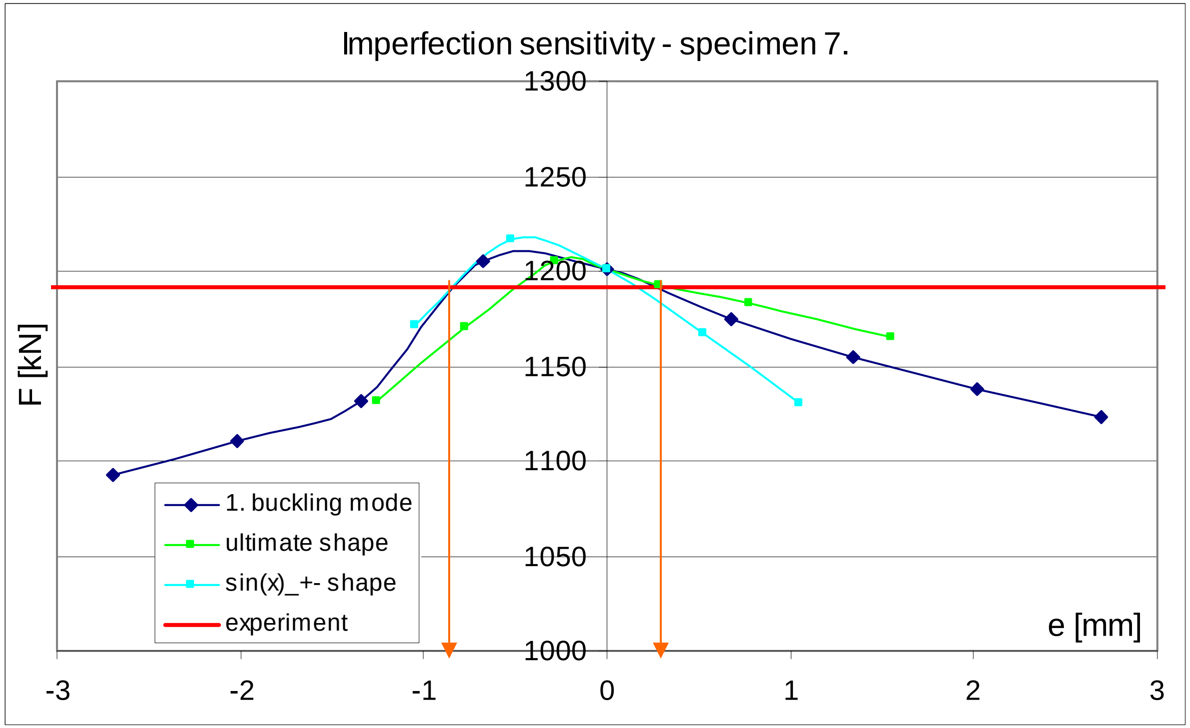


Equivalent geometric imperfection

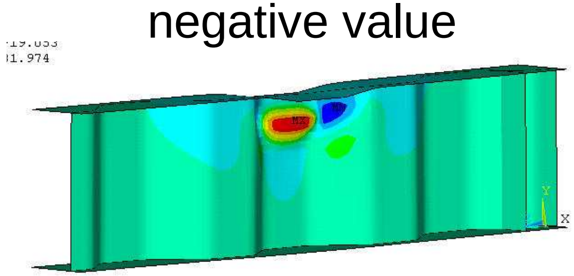
loaded fold: parallel



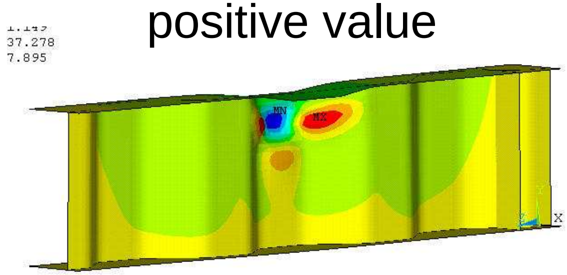
asymetrical behaviour



negative value

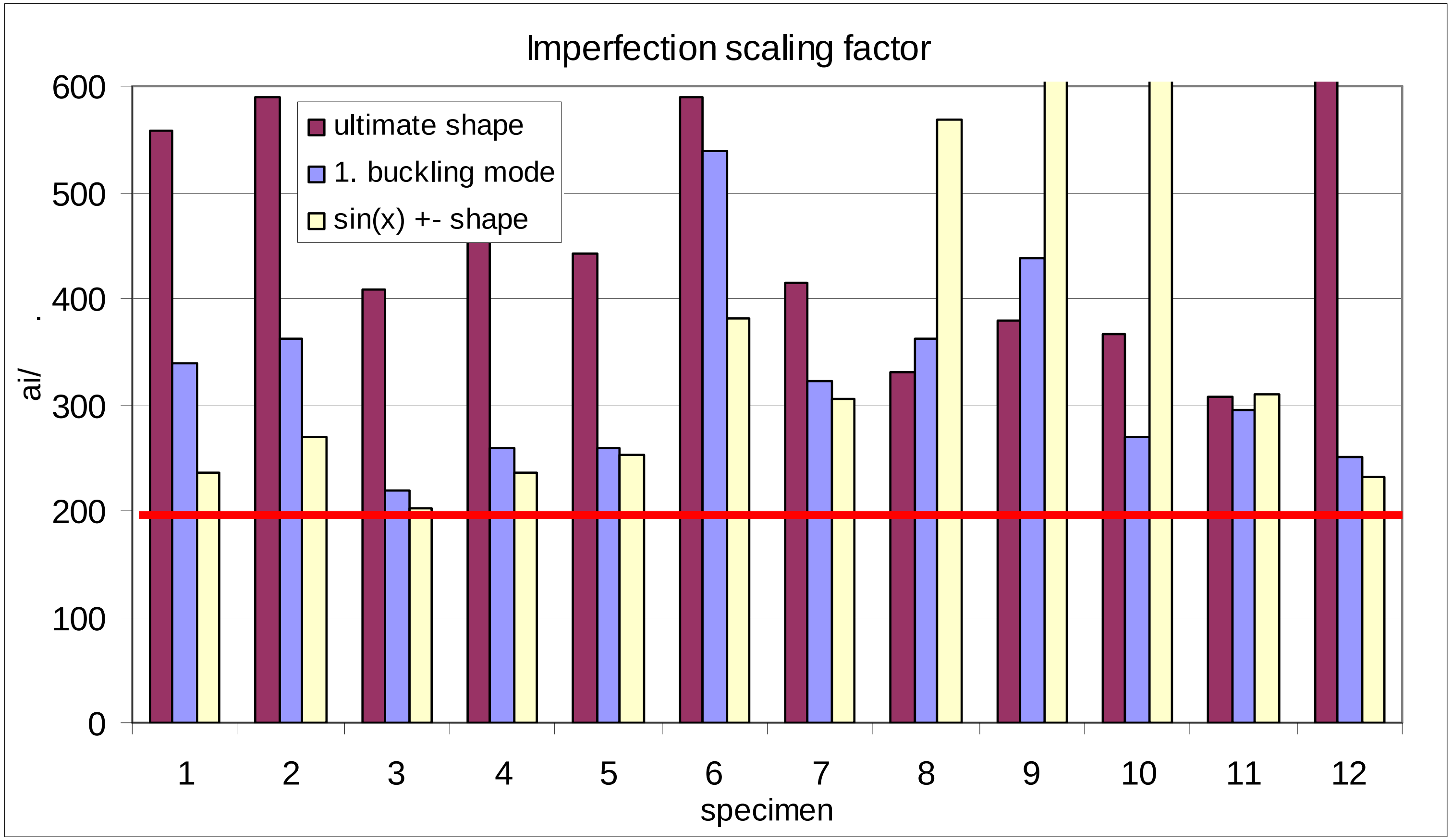


positive value



Compared to all tests results → Necessary imperfection scaling factor

Equivalent geometric imperfection

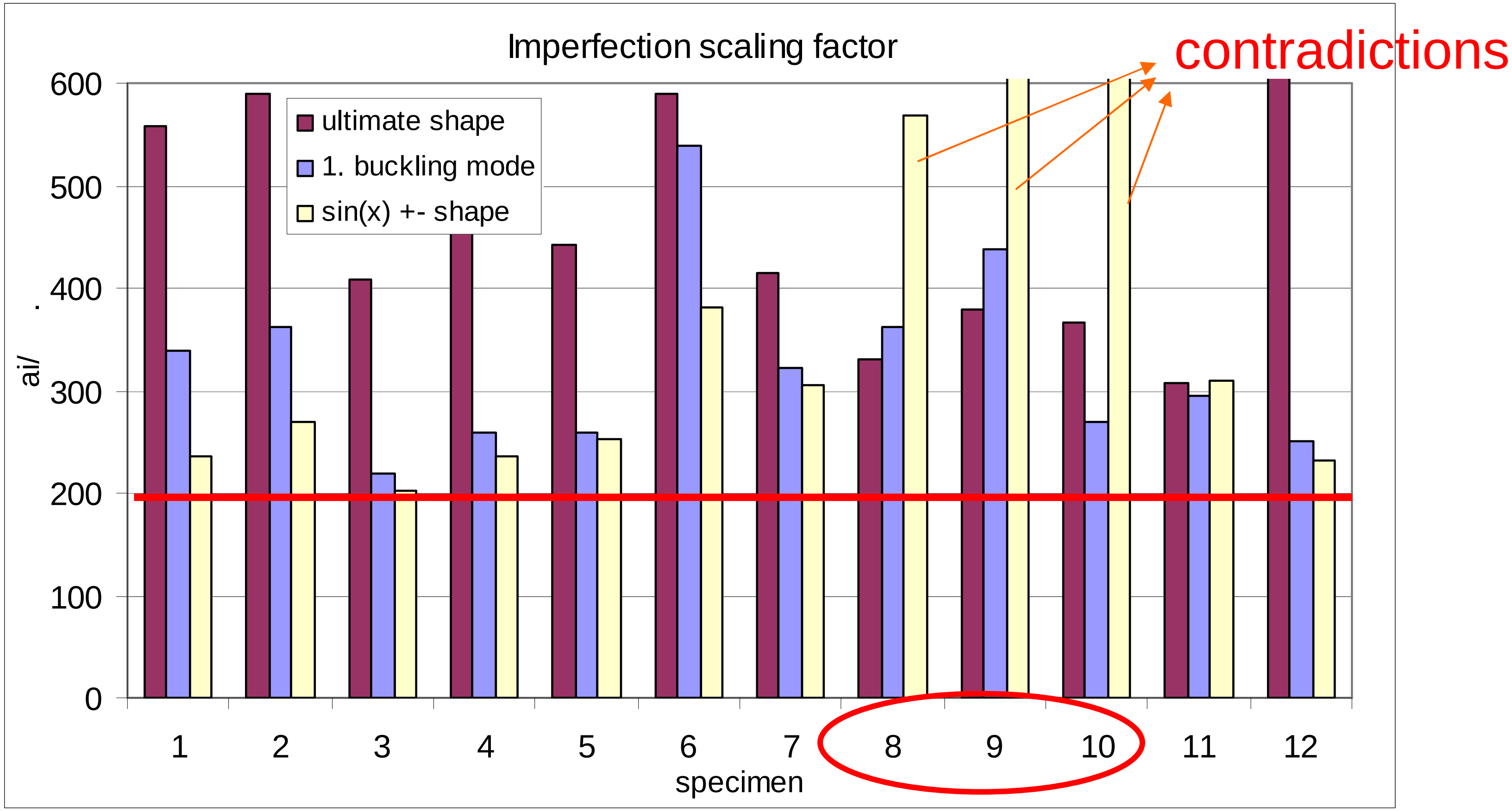


Imperfection scaling factor recommendations:

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

buckling mode imperfection: $a_i/200$

Equivalent geometric imperfection



Imperfection scaling factor recommendations:

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

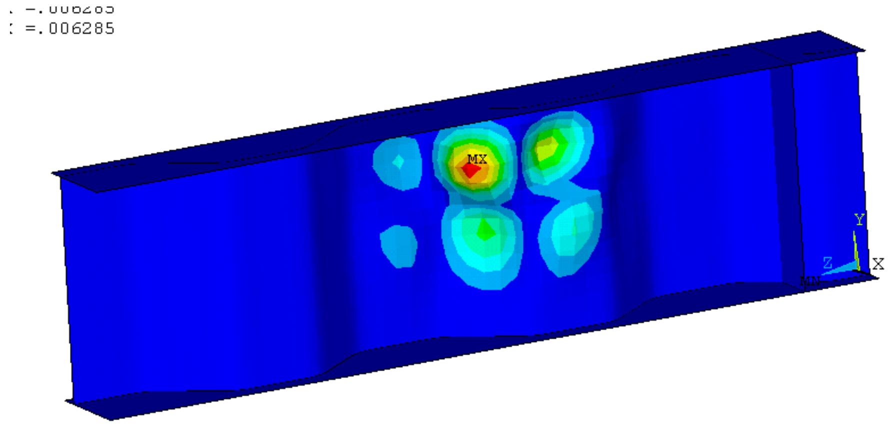
buckling mode imperfection: $a_i/200$

Evaluation

of ultimate shape imperfection

Unexpected cases: Ultimate shape imperfection gives the largest resistance.

First buckling mode



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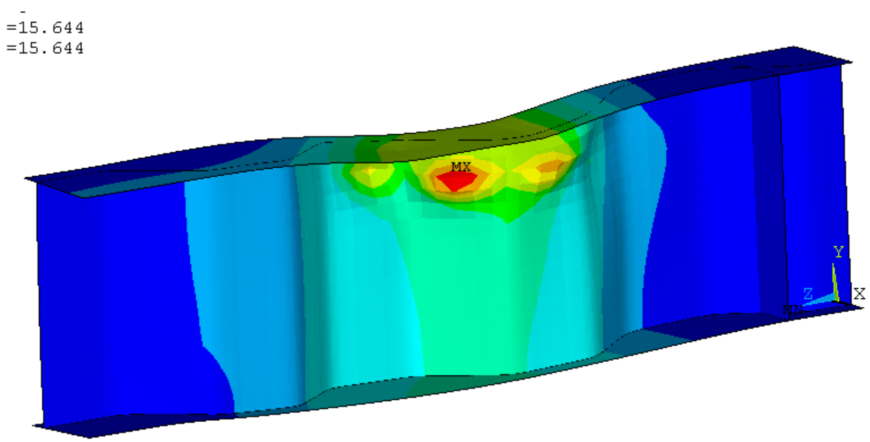
Imperfection in more waves

Ultimate shape



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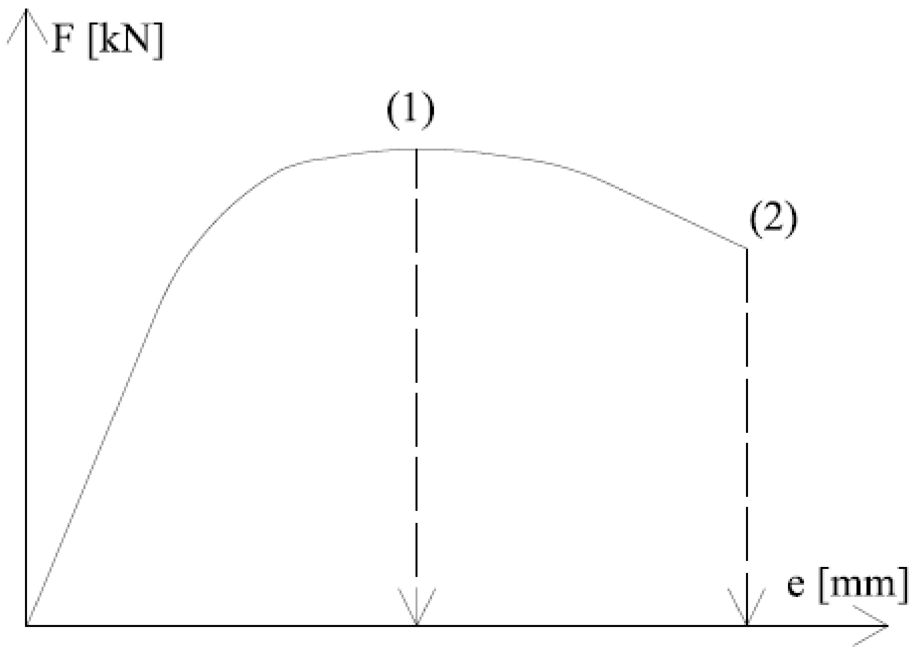
Imperfection only in 1 wave

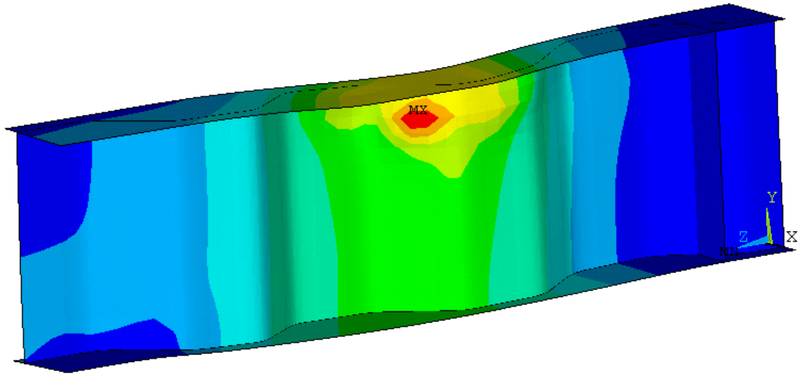
Evaluation

of ultimate shape imperfection

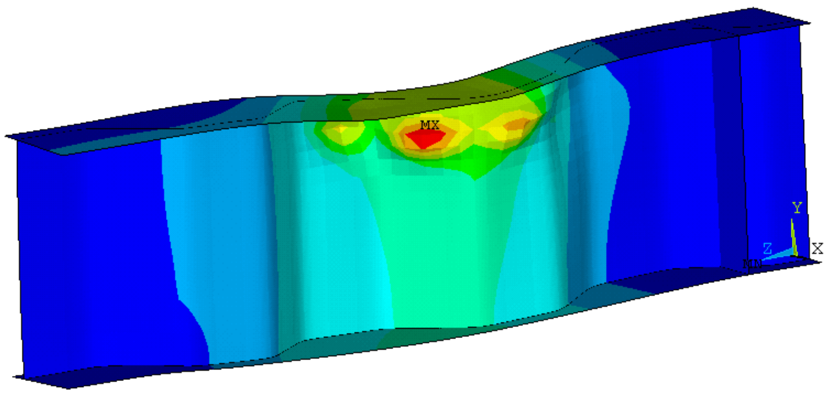
Ultimate shape in different load steps:



Shape by point (1):



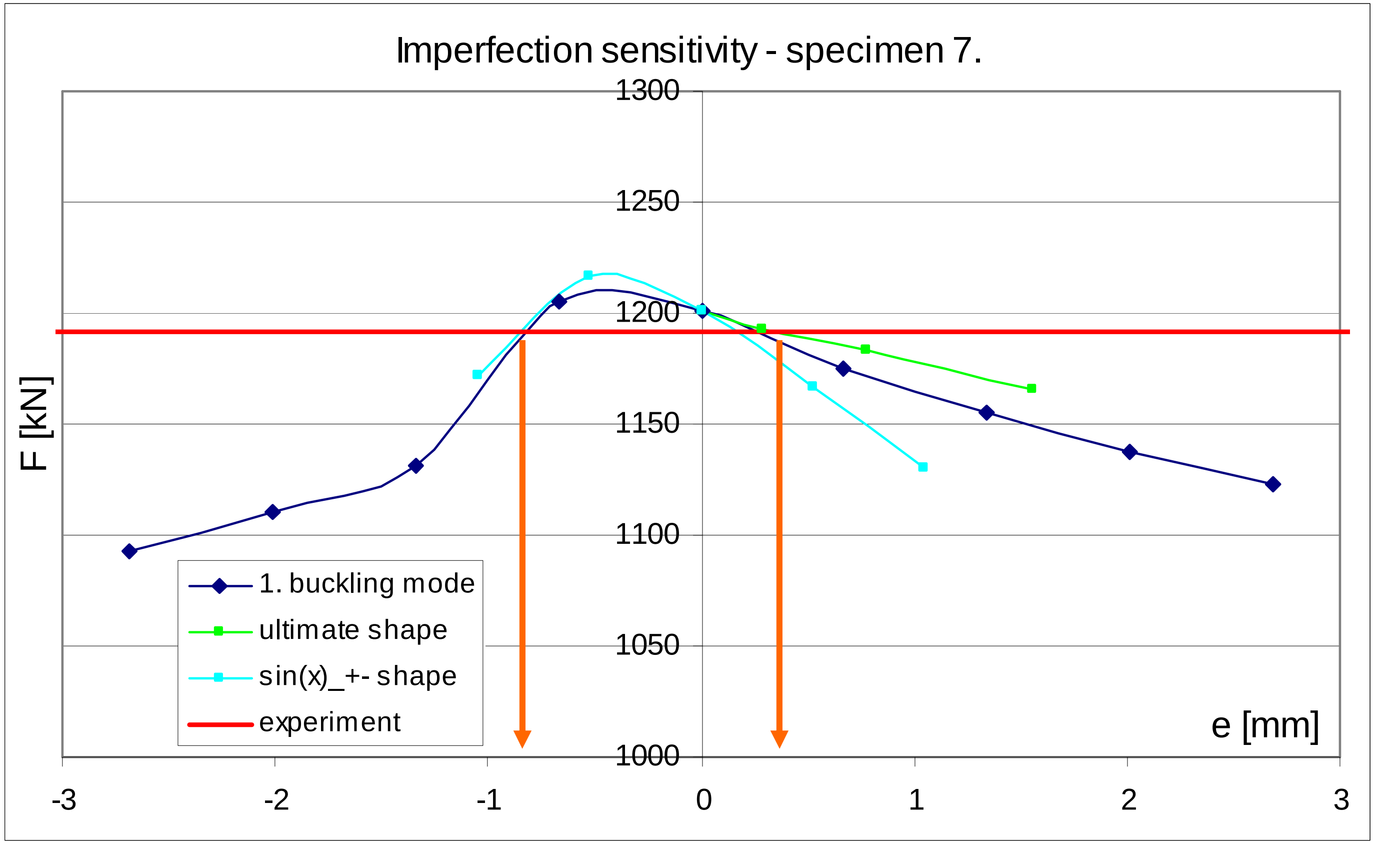
Shape by point (2):



Evaluation

of ultimate shape imperfection

scaling factors are not always comparable



Summary

1. Patch loading tests (12 tested specimens)

2. Numerical model development for all test speciments

3. Model verification (comparison of numerical model ⟷ test results)

4. Development of imperfections for patch loading of corrugated webs

    4.1. 3 imperfections shape analysis

    4.2. Imperfection sensitivity for different shapes

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Imperfection shape and scaling factor determination

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Proposal for FEM based design method

Thank you for your attention!