



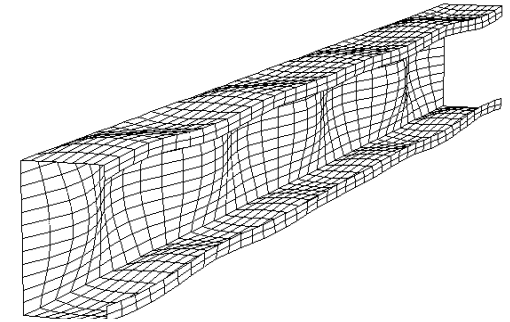
FEM based stability design of structures - 1

László Dunai

Stability phenomena

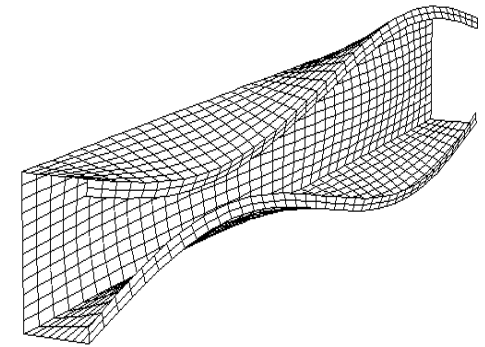
local plate buckling

axial, shear, transverse



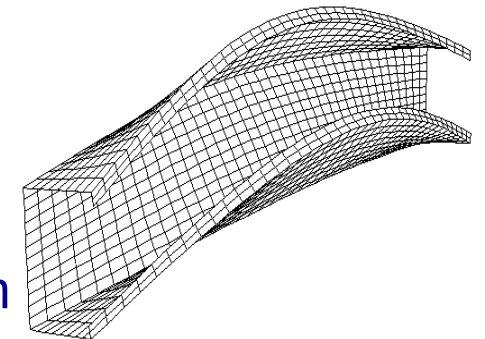
distortional buckling

stiffener buckling, cross-section distortion

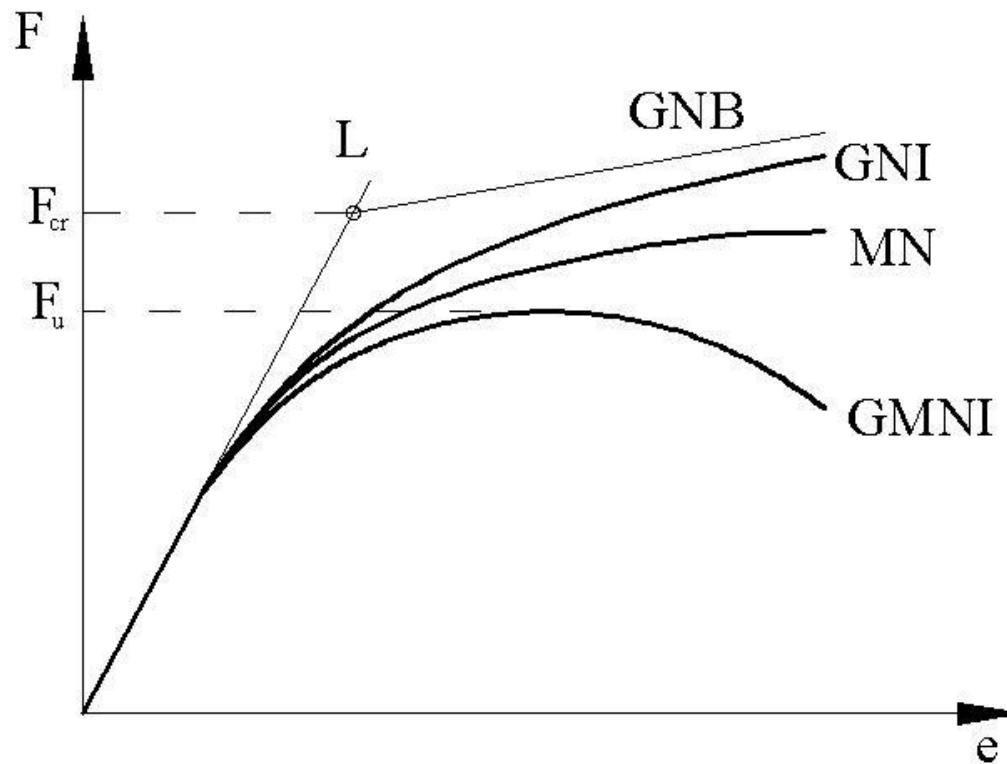


global buckling

flexural, torsional, flexural-torsional, lateral-torsion



Analysis types



Stability design – reduction factor

„traditional”

structural element + M, N, V



critical stress - slenderness

GNB analysis



Buckling curves

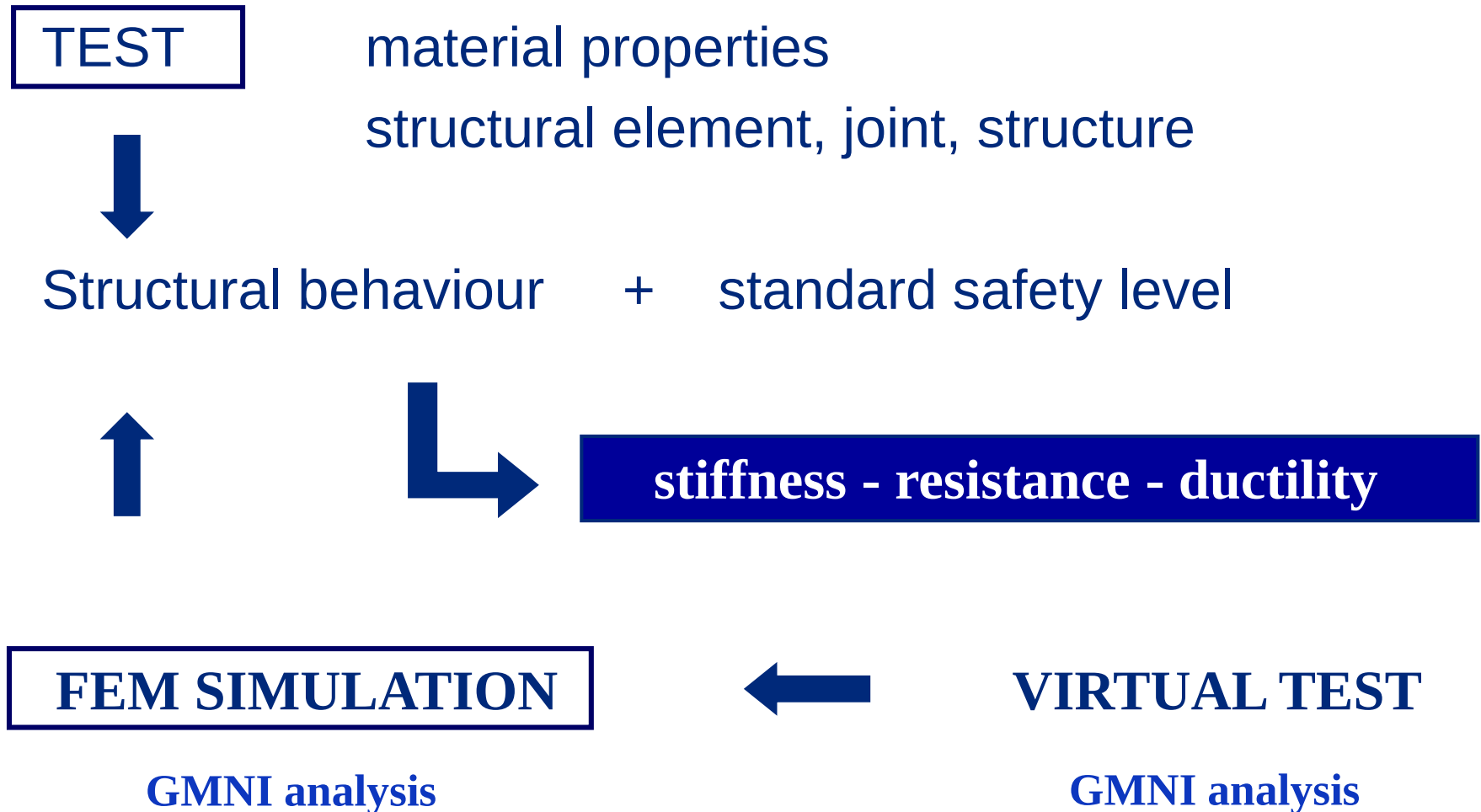


RESISTANCE

imperfections



Stability design – experiment, FEM



FEM model, analysis

- geometry - 3D
- material nonlinearity
- geometric nonlinearity
- imperfections „real” – geometric, residual stress
„equivalent” geometric



GMNI model and analysis
nonlinear solution technology

Stability analysis and design methods

GNB analysis and design – steel silo

GMNI analysis and design – steel frame

Combined design – steel cooling tower

Test + GNI analysis – design model validation

GMNI analysis and design – refurbishment

GNB analysis and design – steel silo



GNB analysis ↔ design

GNB — bifurcation stability limit state

$$\begin{array}{c} \downarrow \\ \sigma_{cr} \end{array} \rightarrow \bar{\lambda} = \sqrt{\frac{f_y}{\sigma_{cr}}} \rightarrow \chi$$

reduction factor method

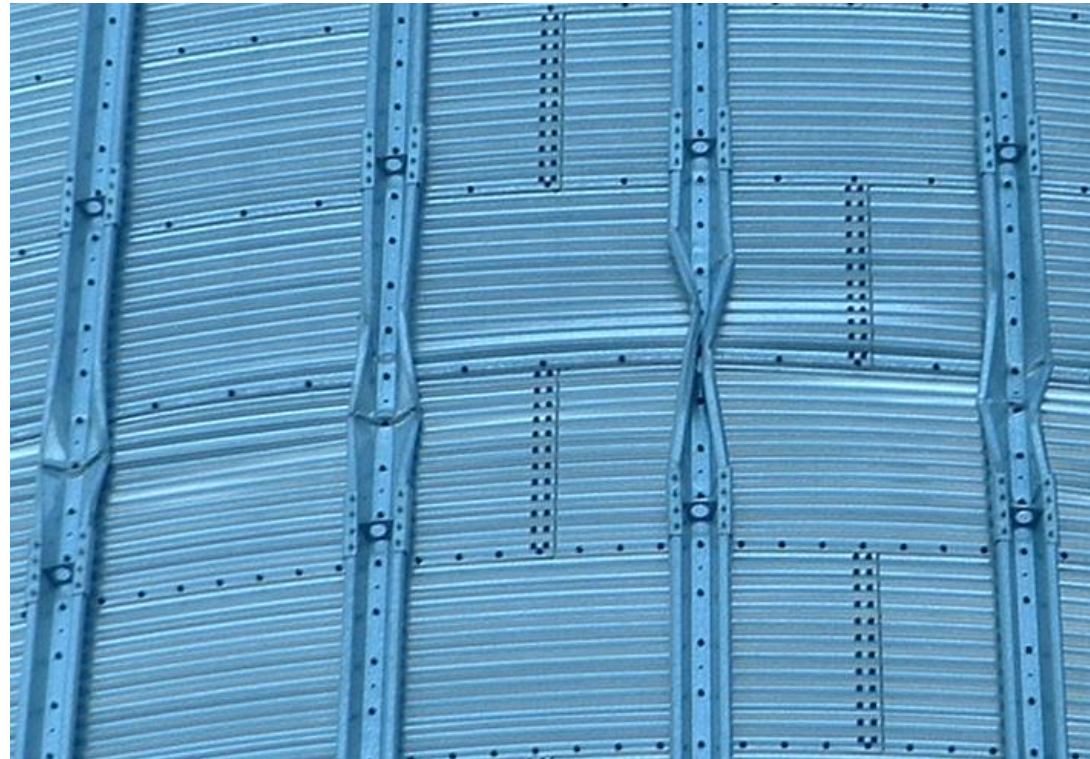
advanced model $\textcircled{\sigma_{cr}}$ — interpretation?

Column stability failure modes

Global buckling

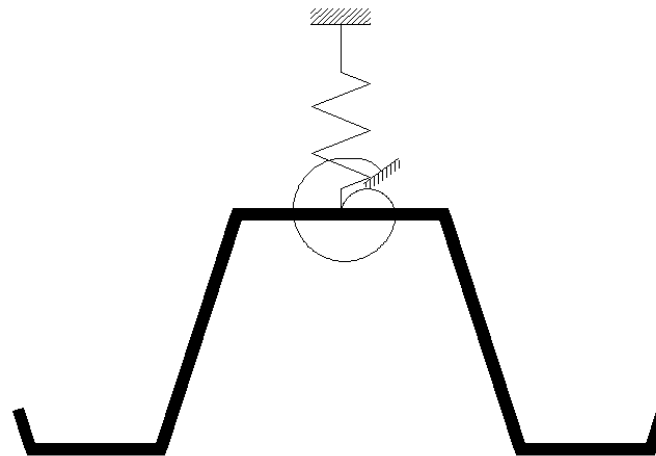
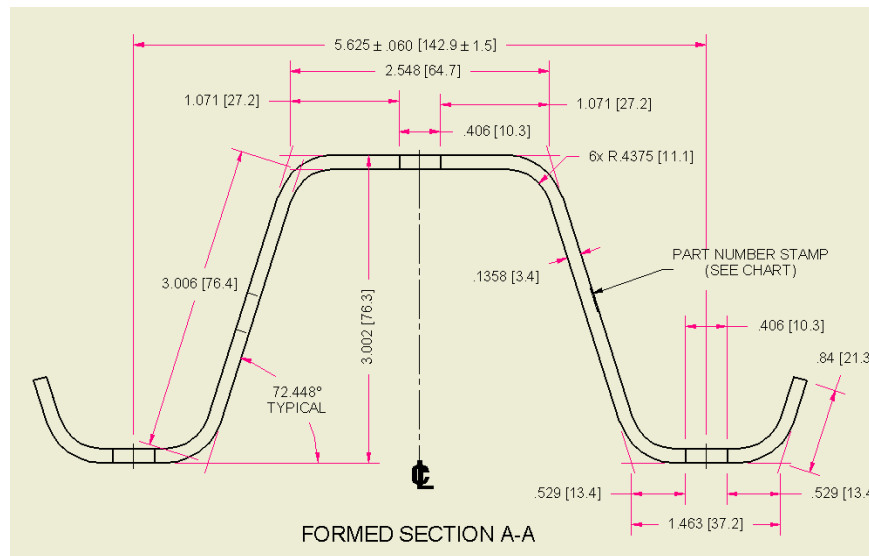


Distortional buckling



Hat-profile column – design model

Finite Strip Method – GNB analysis – design



Load

Save

Input

Properties

Analyze

Post

Z

R

Print

Copy

Reset

?

X

Plot Shape

?

separate window in-plane mode

☒ 2D ☐ 3D ☒ Undef. Scale 1

half-wavelength = 70

?

mode

1

?

file

0

?

loaded files:

Load another file

1 =

Plot Curve

?

dump to text

☒ minima ☒ log scale ☐ classify

modes

1

?

files to be plotted

1

?

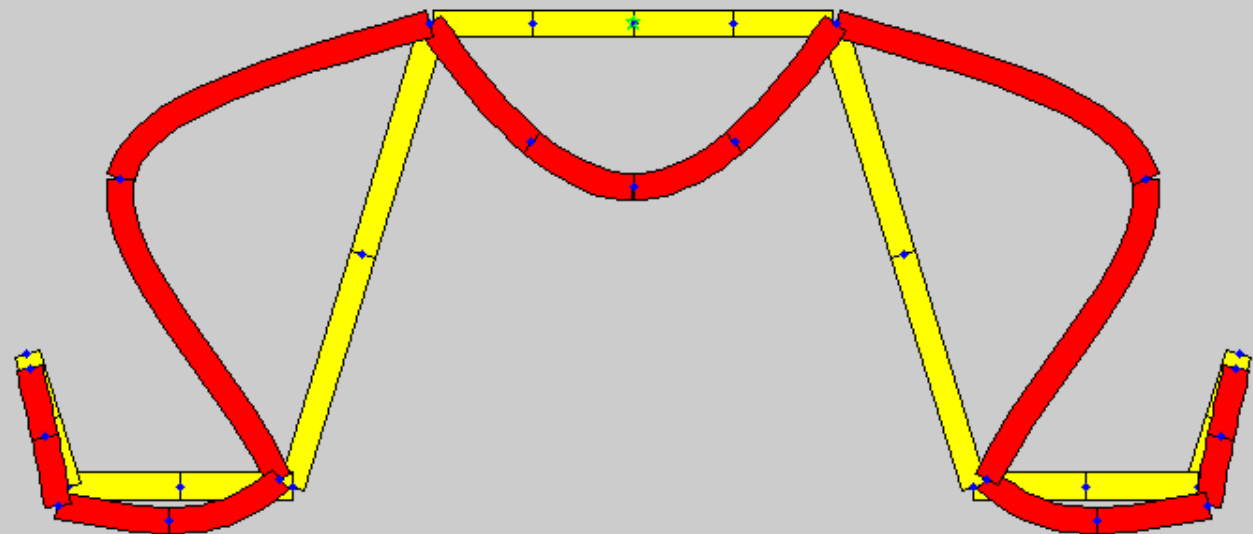
cFSM Modal Classification

Classify work norm

?

cFSM analysis is off

supplemental participation plot



Buckled shape for 0

half-wavelength = 70

load factor = 4009.3249

mode = 1

cFSM classification results: off

ymax

675.3587

load factor

ymin

0

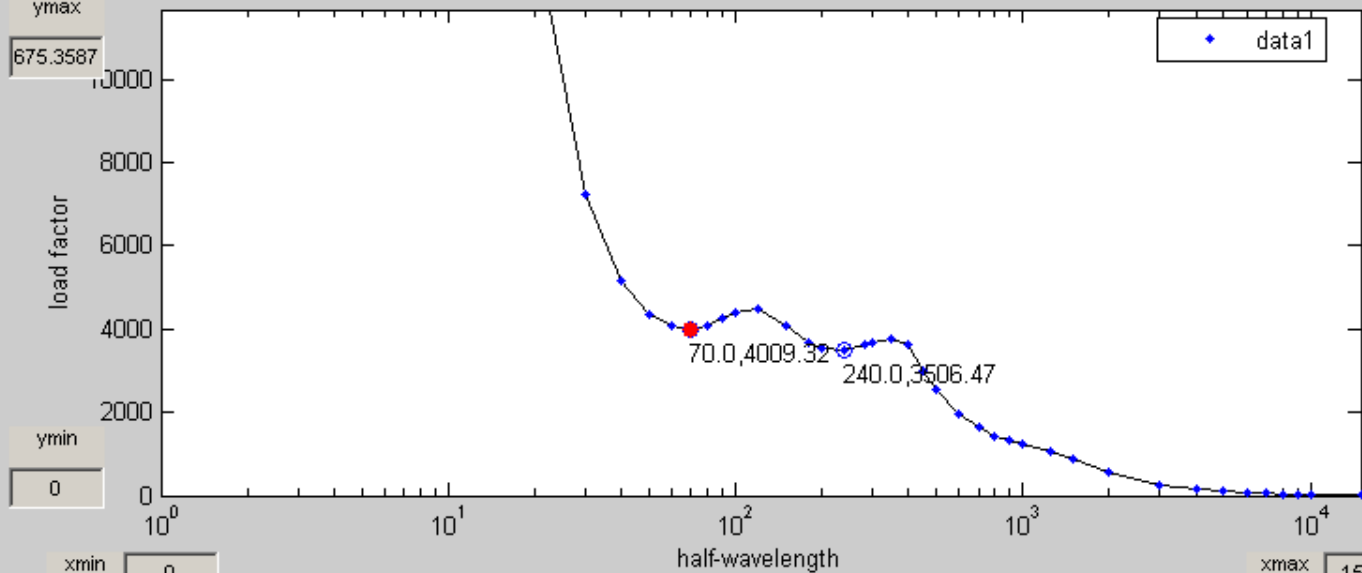
xmin

0

half-wavelength

xmax

15000



Load

Save

Input

Properties

Analyze

Post

Z

R

Print

Copy

Reset

?

X

Plot Shape

?

separate window in-plane mode

☒ 2D ☐ 3D ☒ Undef.

Scale

1

half-wavelength = 450

?

mode

1

?

file

0

?

loaded files:

Load another file

1 =

Plot Curve

?

dump to text

☒ minima ☒ log scale ☐ classify

modes

1

?

files to be plotted

1

?

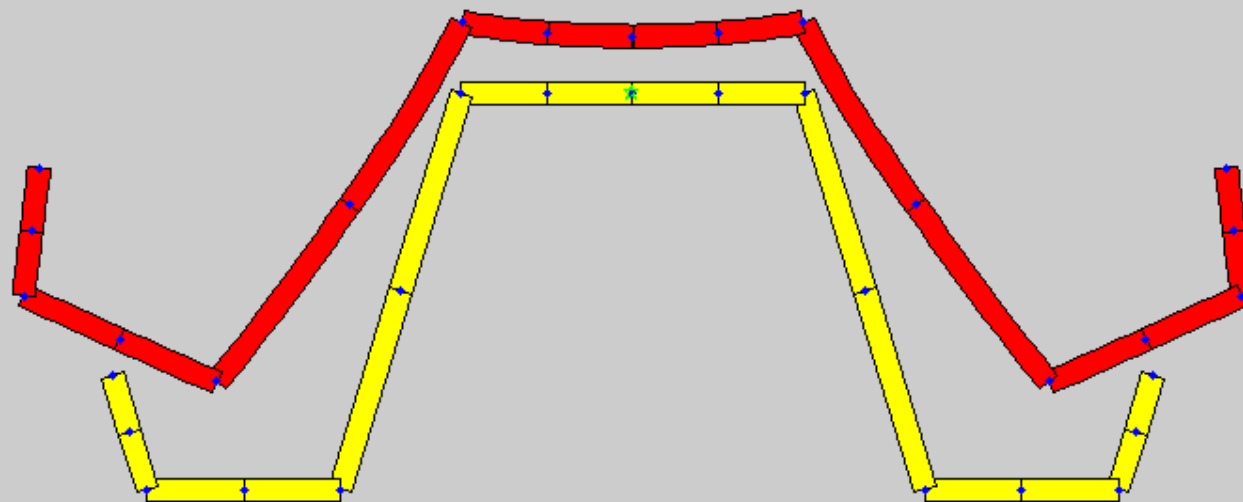
cFSM Modal Classification

Classify work norm

?

cFSM analysis is off

supplemental participation plot



Buckled shape for 0

half-wavelength = 450

load factor = 3013.0404

mode = 1

cFSM classification results: off

ymax

675.3587

load factor

ymin

0

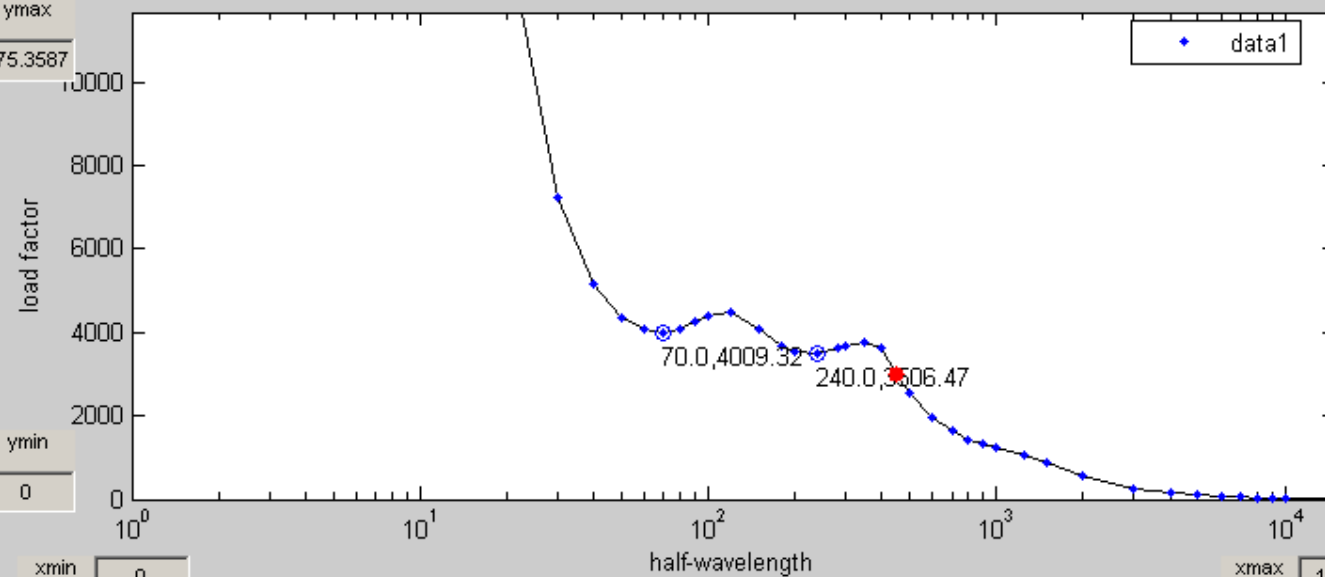
xmin

0

half-wavelength

xmax

15000



Load

Save

Input

Properties

Analyze

Post

Z

R

Print

Copy

Reset

?

X

Plot Shape

?

separate window in-plane mode

☒ 2D ☐ 3D ☒ Undef. Scale 1

half-wavelength = 1000

?

mode

1

?

file

0

?

loaded files:

Load another file

1 =

Plot Curve

?

dump to text

☒ minima ☒ log scale ☐ classify

modes

1

?

files to be plotted

1

?

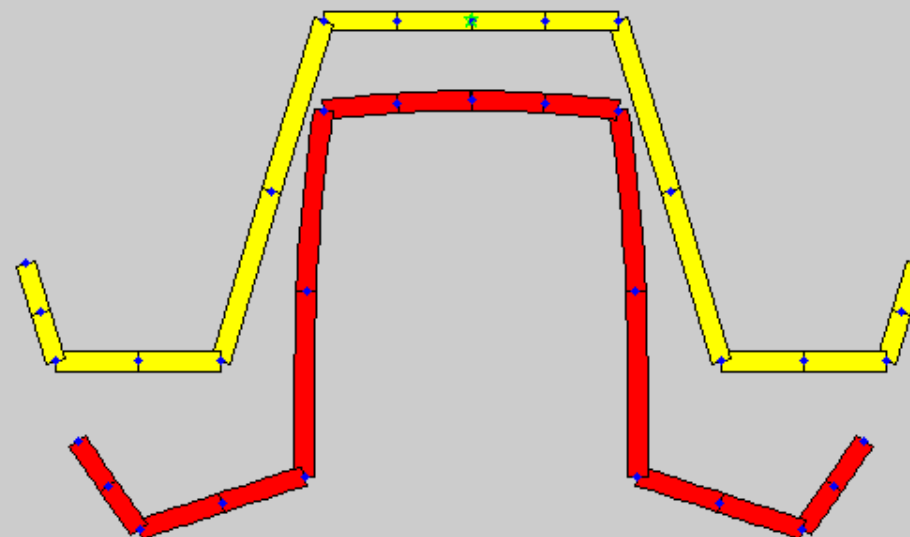
cFSM Modal Classification

Classify work norm

?

cFSM analysis is off

supplemental participation plot



Buckled shape for 0

half-wavelength = 1000

load factor = 1231.2465

mode = 1

cFSM classification results: off

ymax

675.3587

load factor

ymin

0

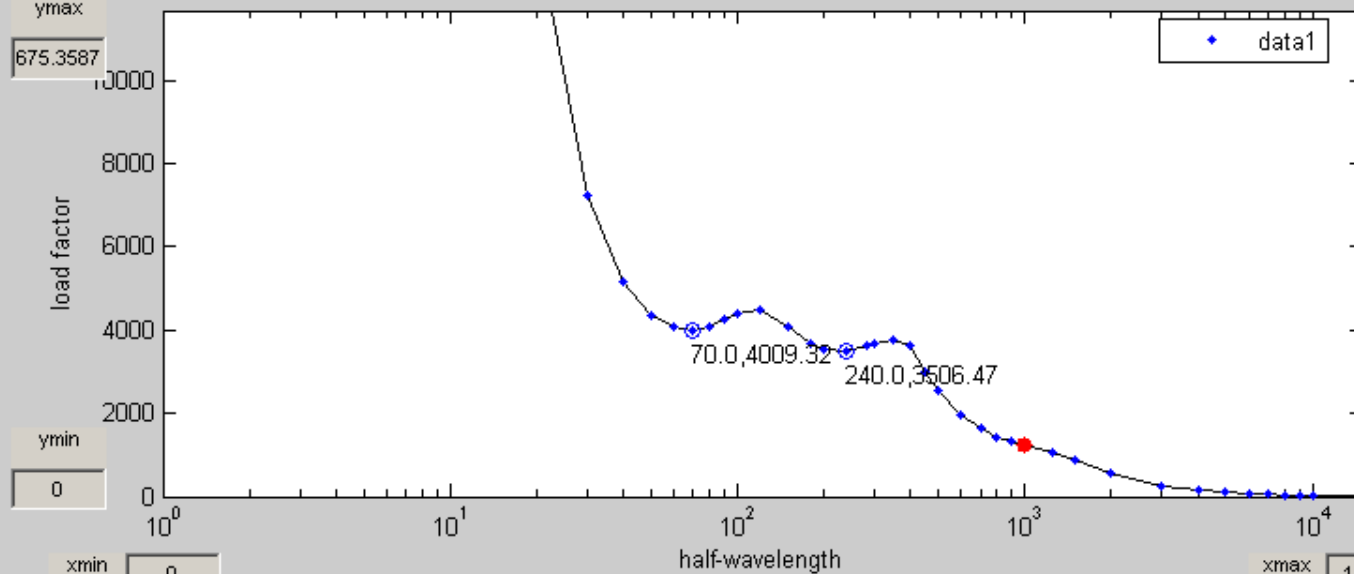
xmin

0

half-wavelength

xmax

15000



Load

Save

Input

Properties

Analyze

Post

Z

R

Print

Copy

Reset

?

X

Plot Shape

?

separate window in-plane mode

☒ 2D ☐ 3D ☒ Undef. Scale 1

half-wavelength = 3000

?

mode

1

?

file

0

?

loaded files:

Load another file

1 =

Plot Curve

?

dump to text

☒ minima ☒ log scale ☐ classify

modes

1

?

files to be plotted

1

?

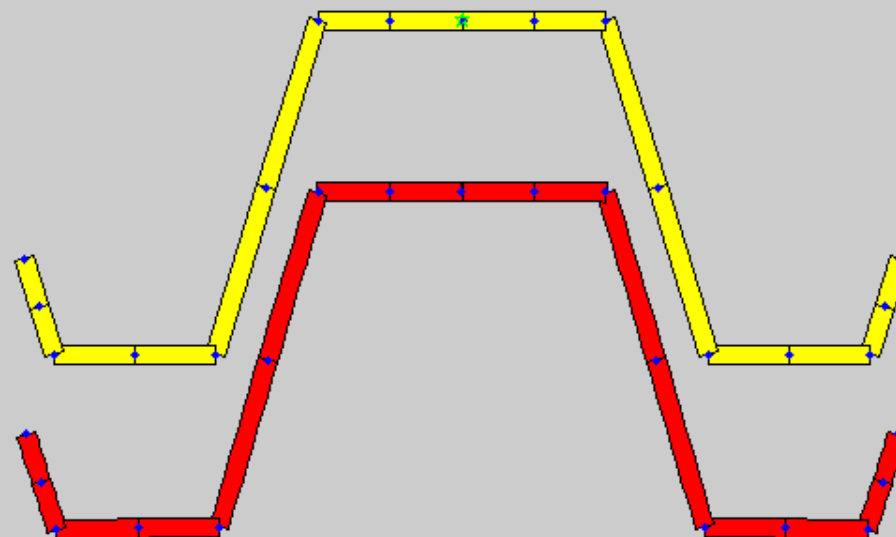
cFSM Modal Classification

Classify work norm

?

cFSM analysis is off

supplemental participation plot



Buckled shape for 0

half-wavelength = 3000

load factor = 258.2115

mode = 1

cFSM classification results: off

ymax

675.3587

load factor

ymin

0

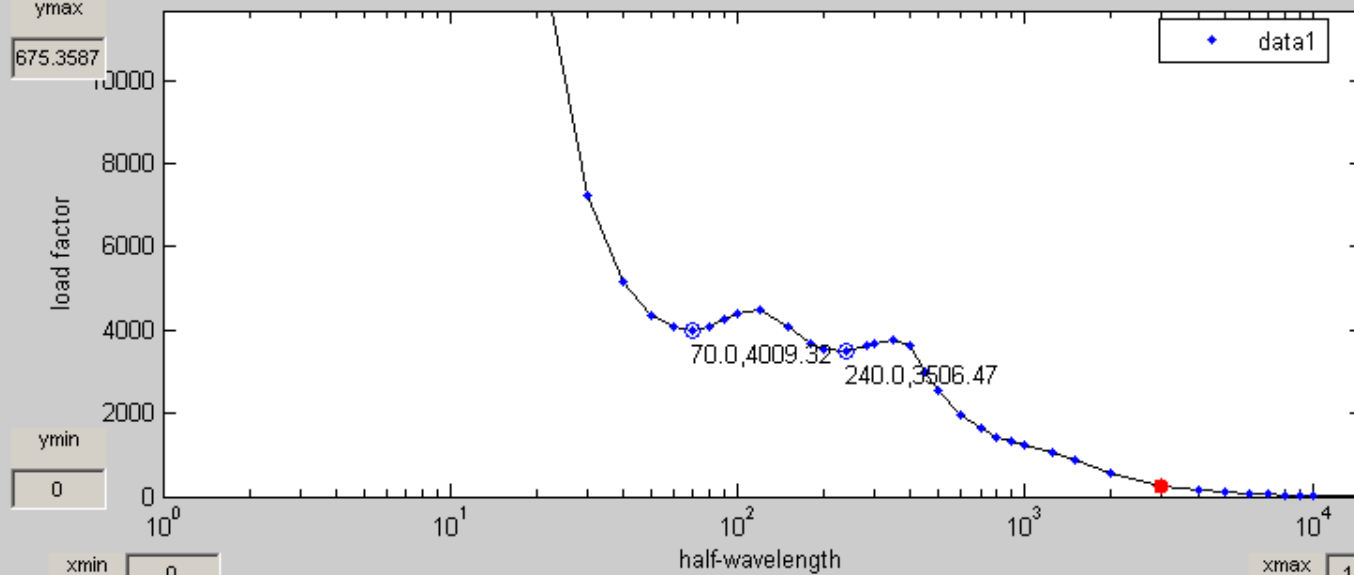
xmin

0

half-wavelength

xmax

15000



Design model – global buckling

Euler critical stress

$$\sigma_{G,cr}$$

slenderness

$$\bar{\lambda}_G = \sqrt{\frac{f_y}{\sigma_{G,cr}}}$$

column buckling
curves

$$\sigma_{G,cr} = \frac{\pi^2 EI}{A \cdot L_E^2}$$

$$\chi_G$$

reduction factor

$$N_{b,Rd} = A \chi_G f_y$$

global buckling
resistance

Design model – local buckling

plate buckling
critical stress

$$\sigma_{L,cr}$$

plate slenderness

$$\bar{\lambda}_L = \sqrt{\frac{f_y}{\sigma_{L,cr}}}$$

postcritical behaviour
Winter-formula

$$\frac{b_{eff}}{b} = \sqrt{\frac{\sigma_{L,cr}}{f_y}} \left(1 - 0.22 \sqrt{\frac{\sigma_{L,cr}}{f_y}} \right)$$

$$b_{eff}$$

$$A_{eff}$$

effective c-s

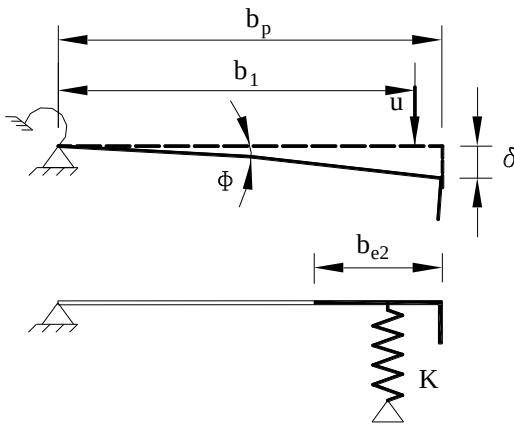
$$N_{c,Rd} = A_{eff} f_y$$

local buckling resistance

$$\sigma_{L,cr} = \frac{\pi^2 E}{12(1-\nu^2)} \left(\frac{t}{b} \right)^2 k$$

Design model – distortional buckling

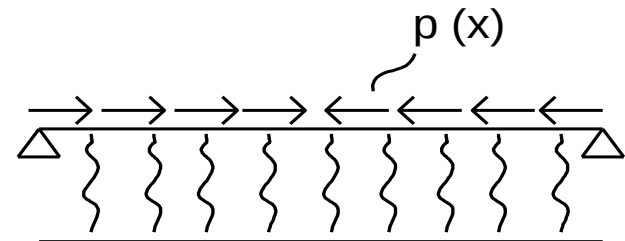
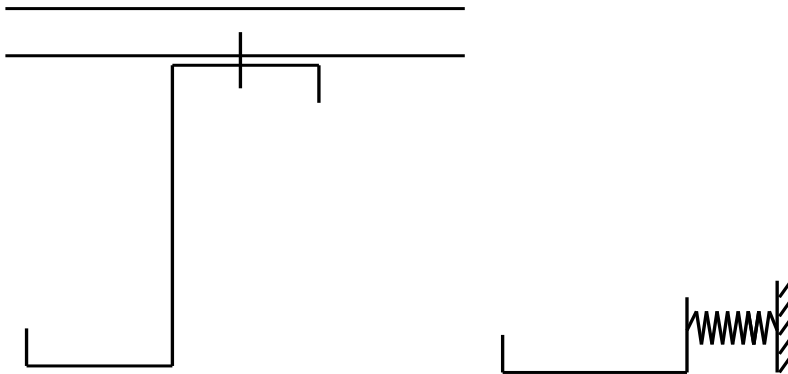
stiffener model: elastically supported axially loaded element



1, rigidity check – design rule

2, stiffener buckling

3, flange buckling



Design model – stiffener buckling

stiffener critical

stress

$$\sigma_{D,cr}$$

slenderness

$$\overline{\lambda}_D = \sqrt{\frac{f_y}{\sigma_{D,cr}}}$$

distort. buckling
curves

$$\sigma_{D,cr} = \frac{2\sqrt{K \cdot E \cdot I_{st}}}{A_{st}}$$

$$\chi_D \rightarrow t_{red}$$

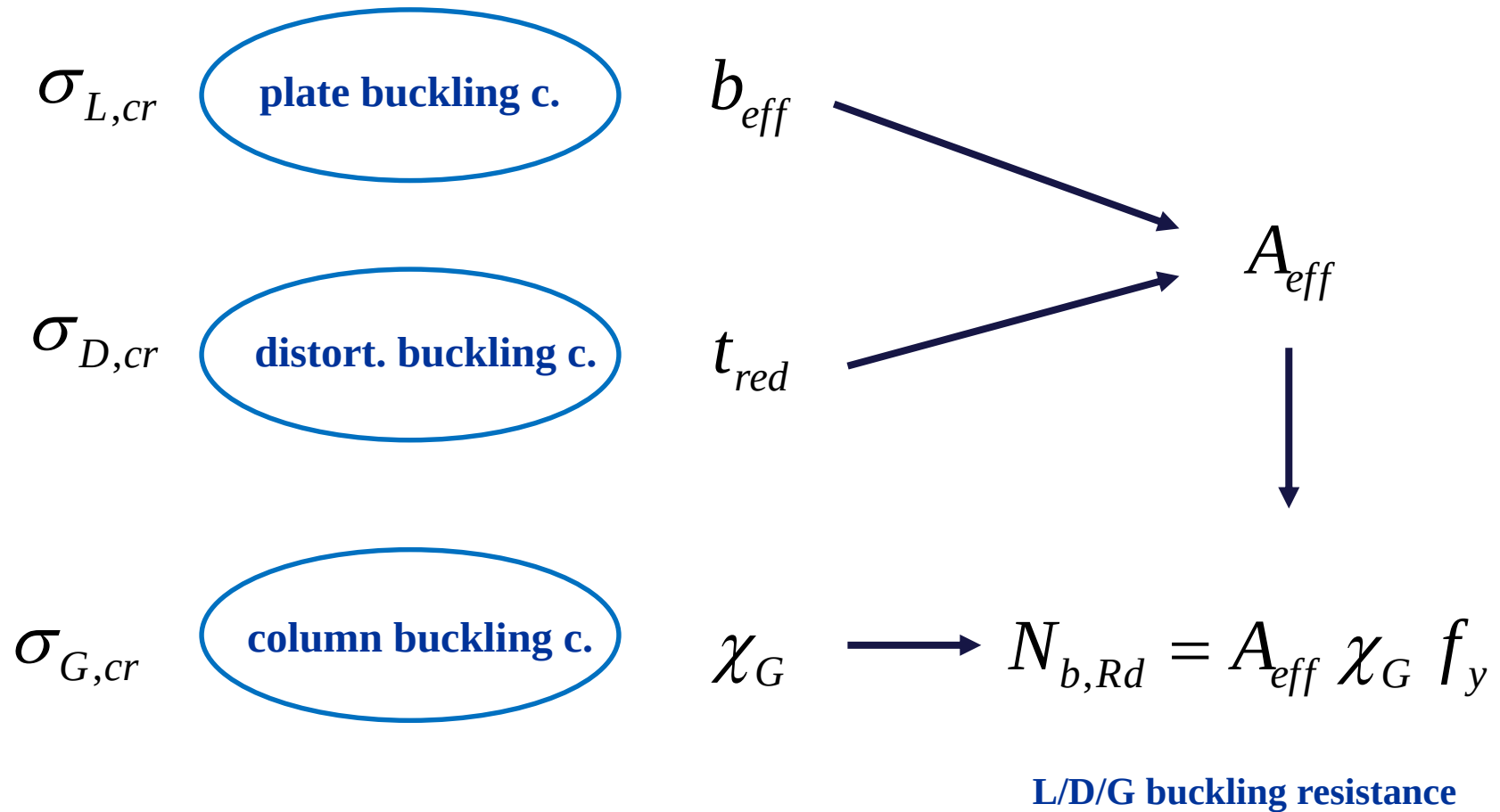
stiffener reduced
thickness

$$A_{eff}$$

$$N_{c,Rd} = A_{eff} f_y$$

local/dist. buckling resistance

Design model – L/D/G buckling 1

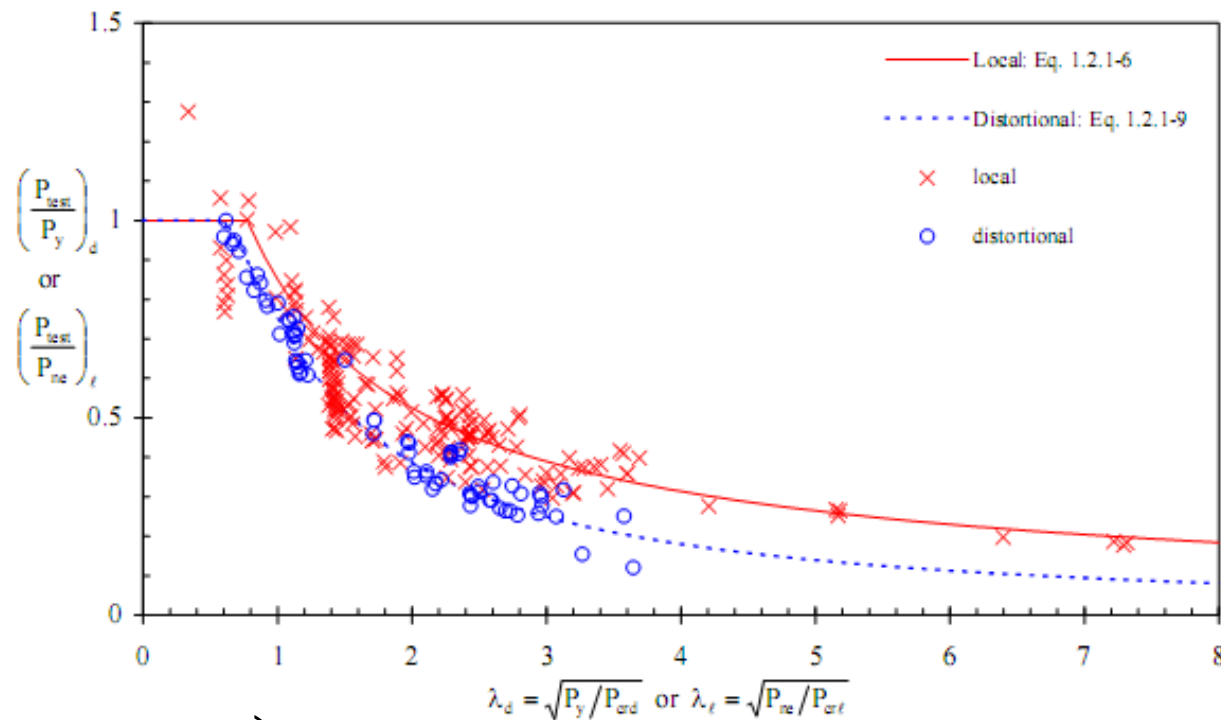


Design model – L/D/G buckling 2

$$\sigma_{L,cr} \quad \sigma_{D,cr} \quad \sigma_{G,cr}$$

Direct Strength Method – DSM

calibrated buckling curves

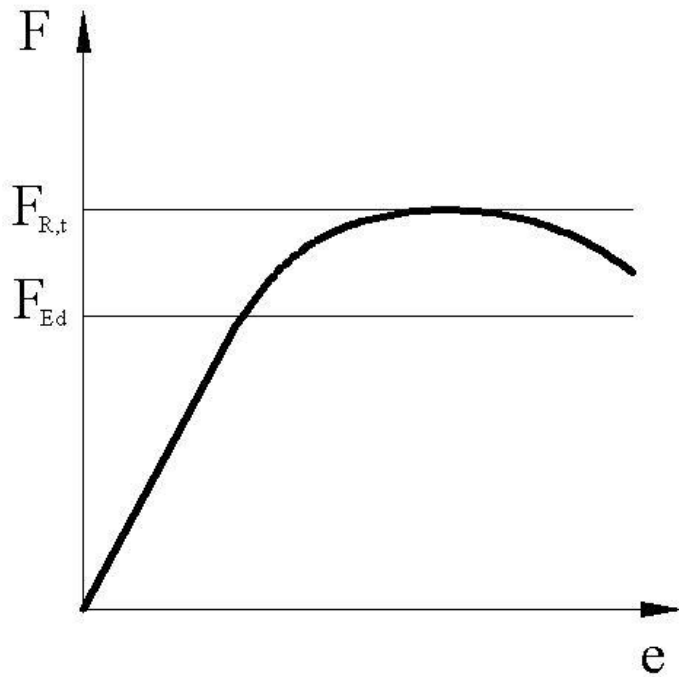


$$N_{b,Rd} = f(\sigma_{L,cr}, \sigma_{D,cr}, \sigma_{G,cr})$$

GMNI and design – steel frame



GMNI analysis – resistance



Design load F_{Ed}

Ultimate load by simulation $F_{R,t}$

$$\alpha_u = \frac{F_{R,t}}{F_{Ed}}$$

Safety against failure

$$\alpha_u \geq \alpha_1 \cdot \alpha_2$$

Reliability - accuracy of model

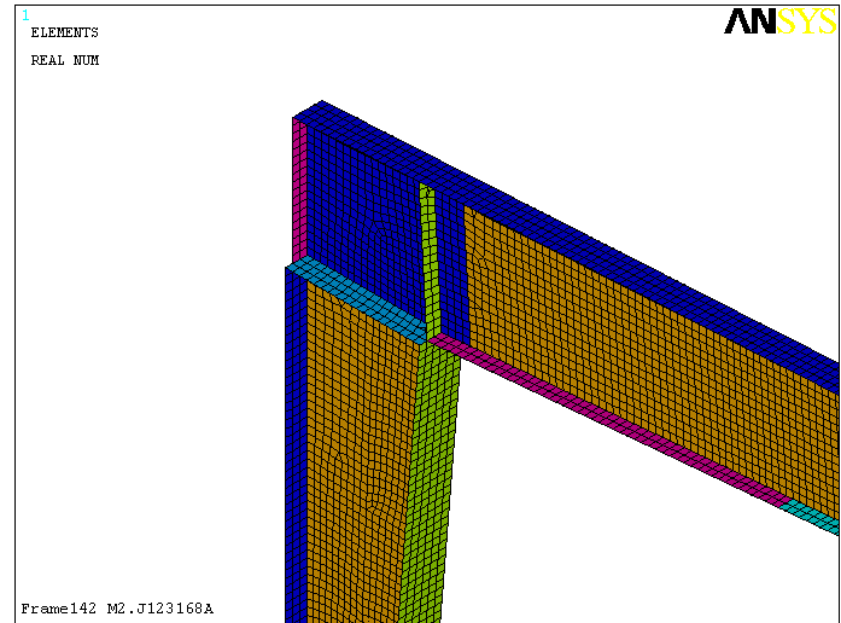
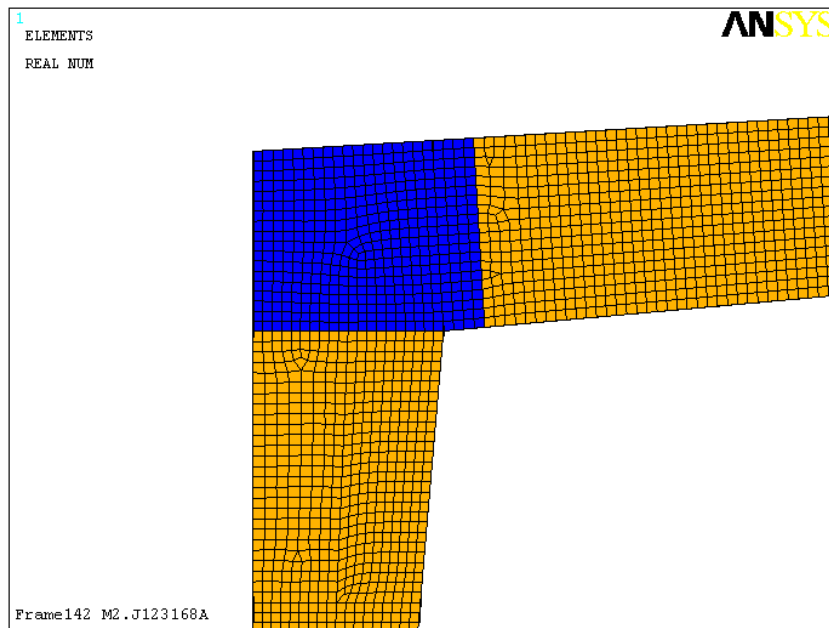
α_1

- failure mode

α_2

FE model

Geometric model – FE mesh verification!

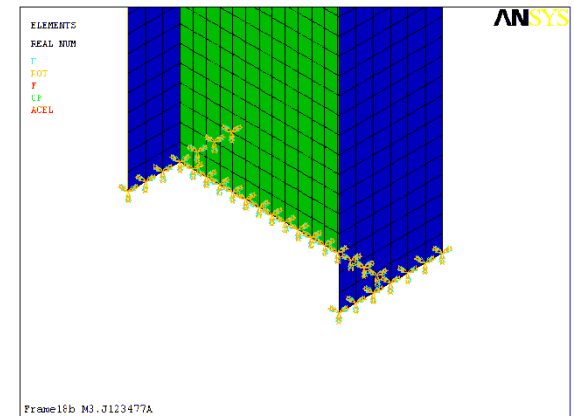
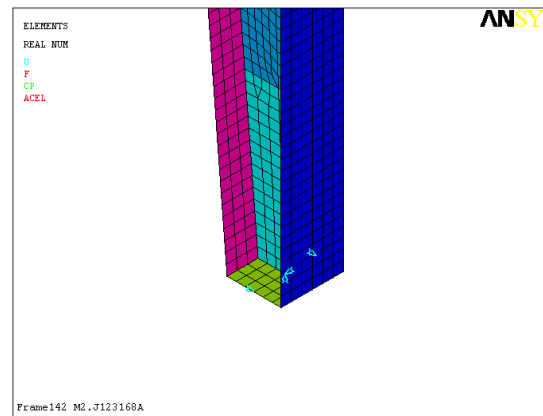


FE model

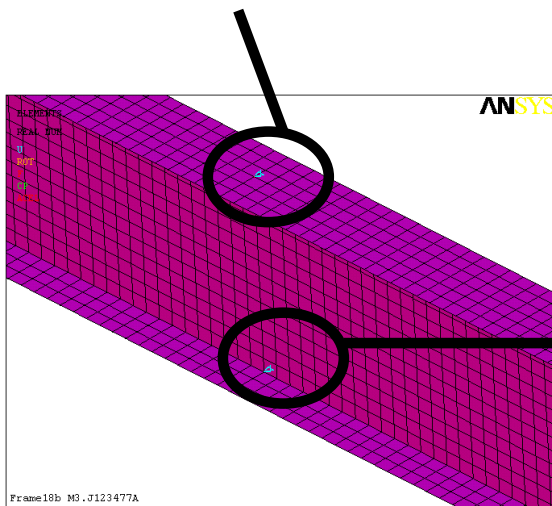
Support – structural arrangement --- behaviour

hinged

fixed



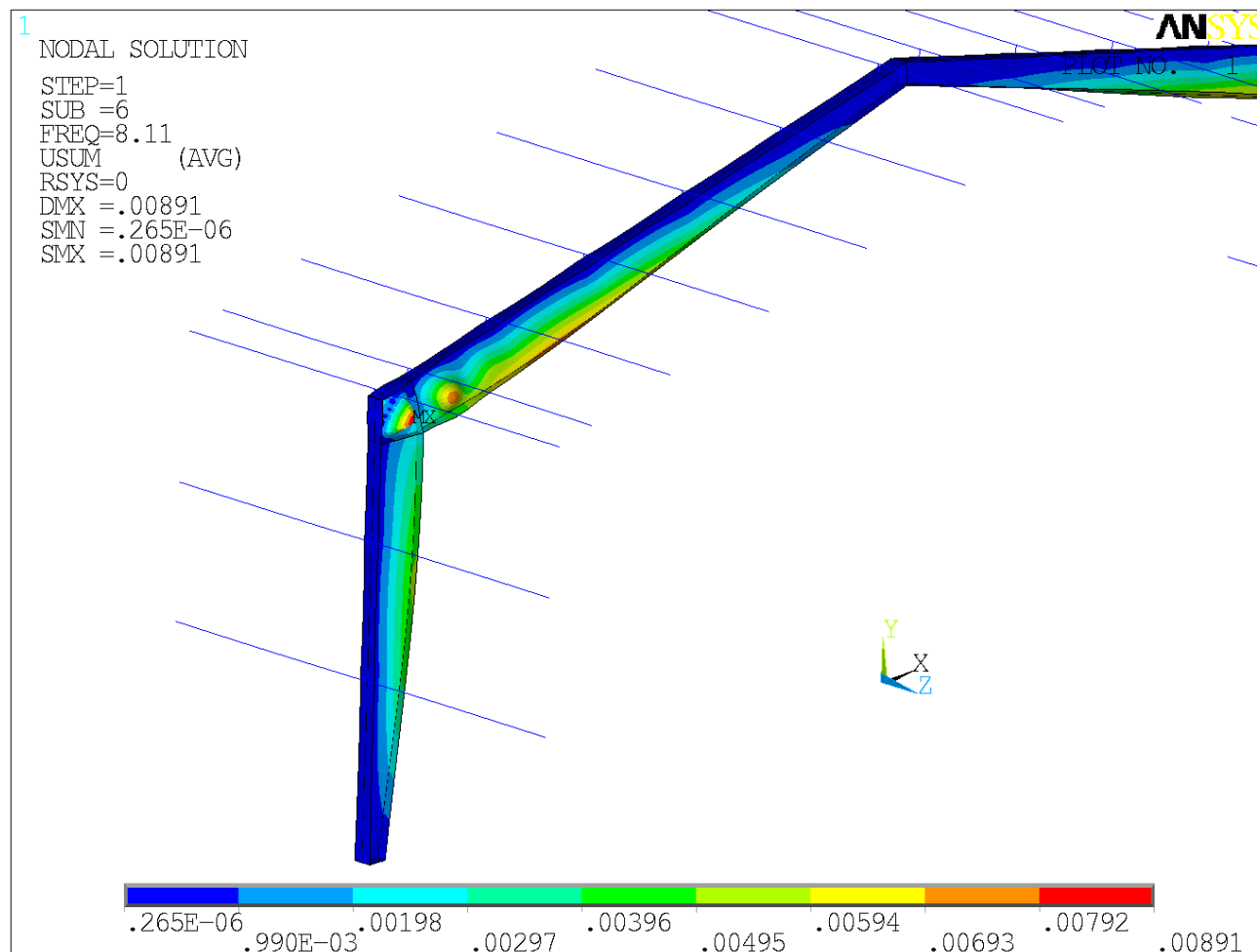
lateral support 1



lateral support 2

GNB analysis

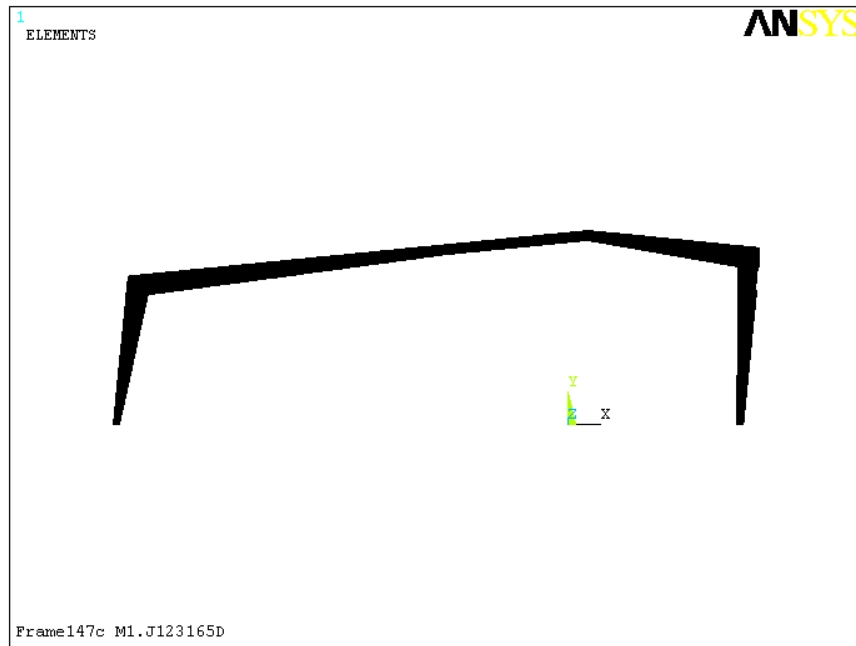
Interaction of different stability phenomena



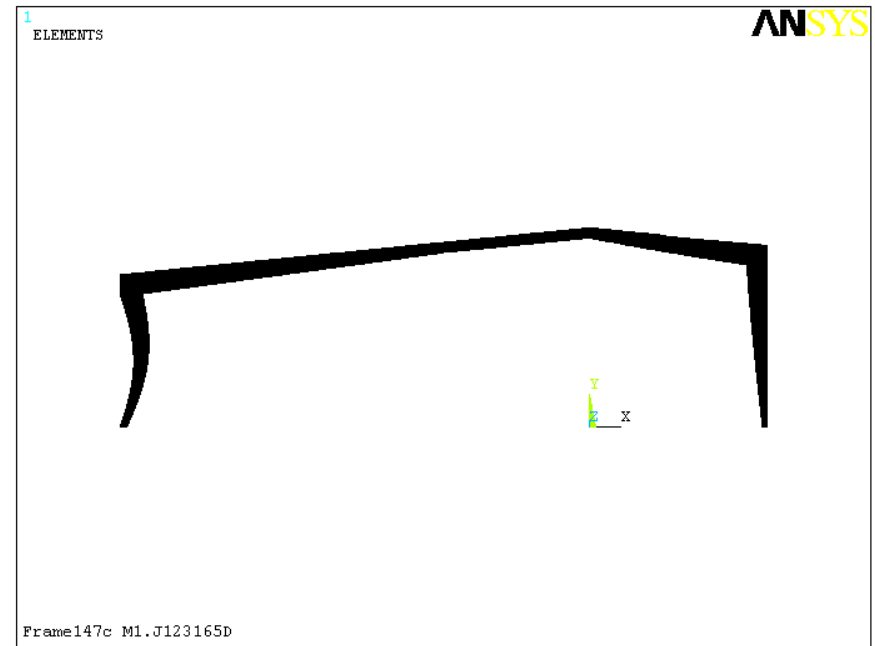
Imperfections 1

Combination of all possible stability failure modes

Global – frame

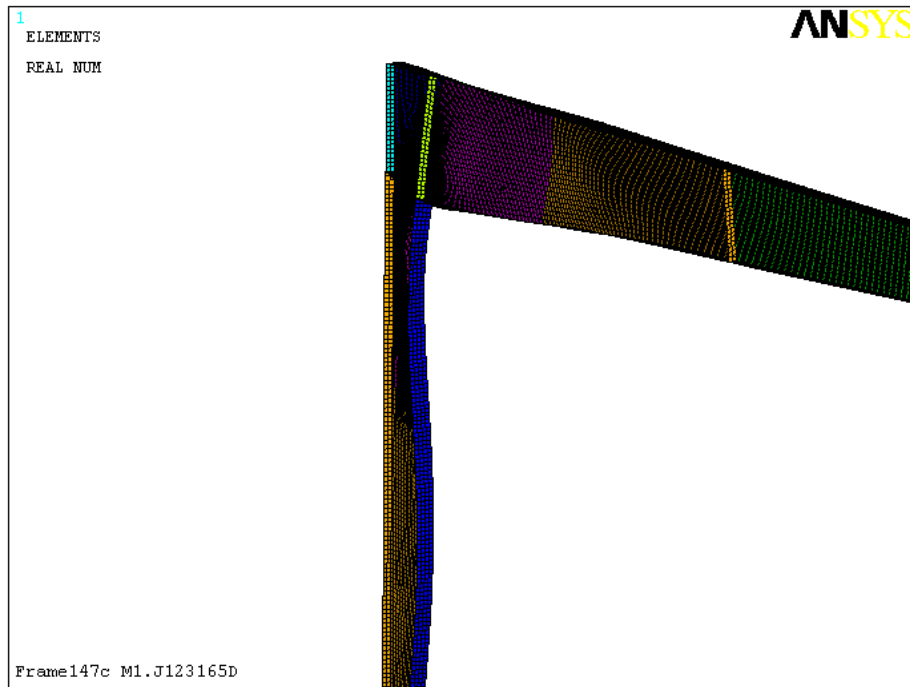


Local – structural element
1



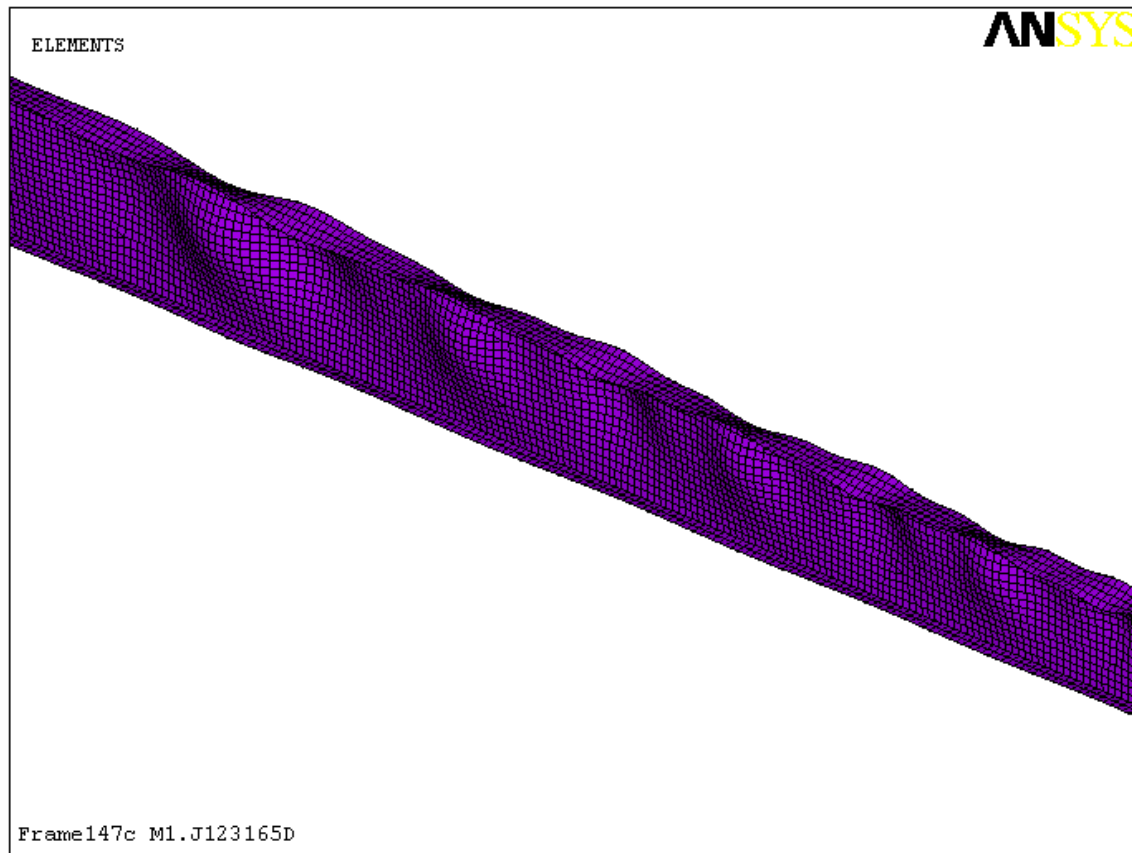
Imperfections 2

Local – structural
element 2



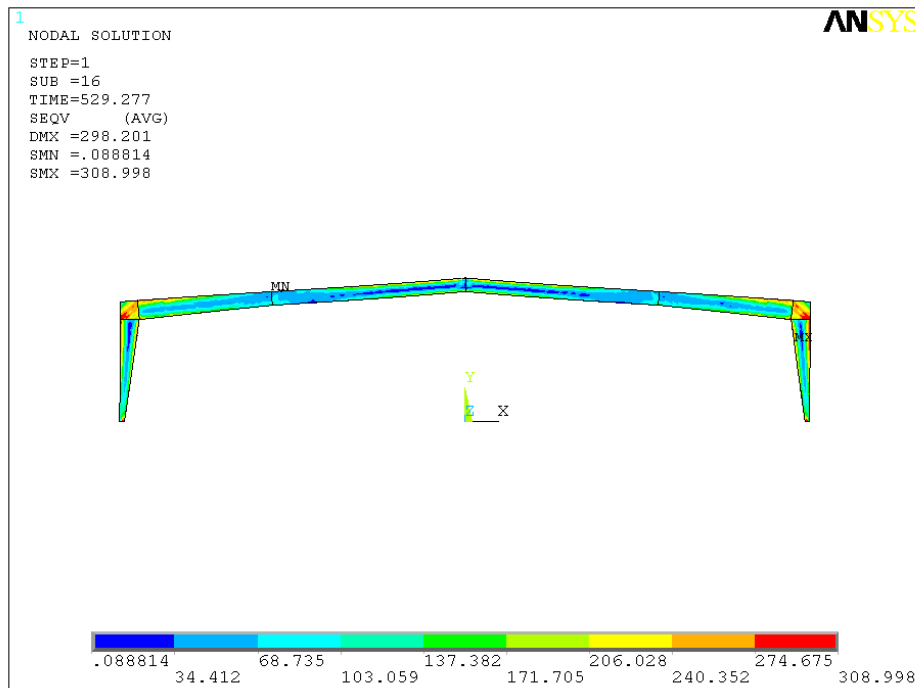
Imperfections 3

Local – plated cross-section

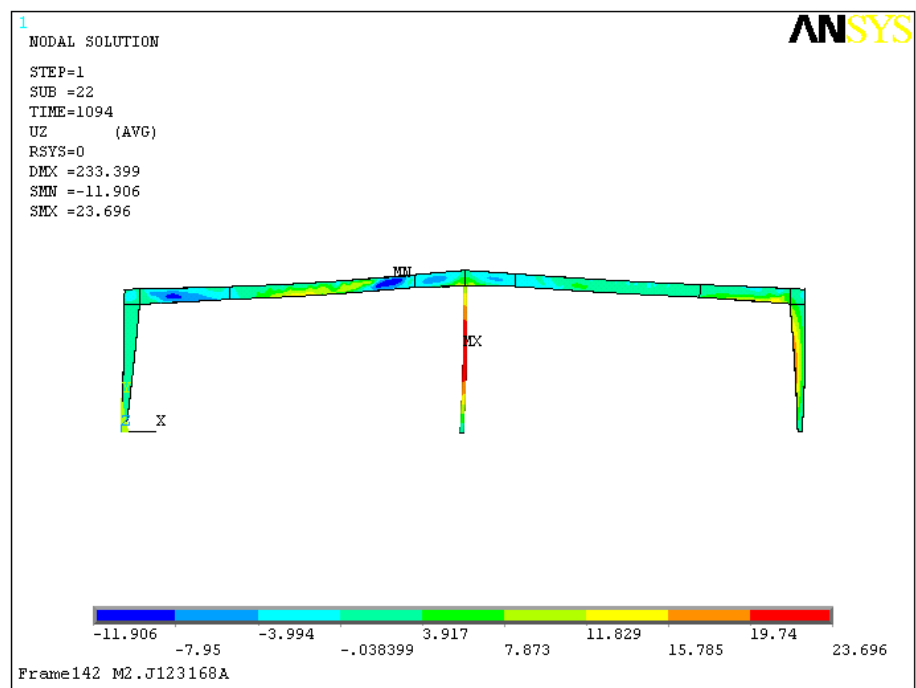


GMNI analysis – failure modes

plastic failure



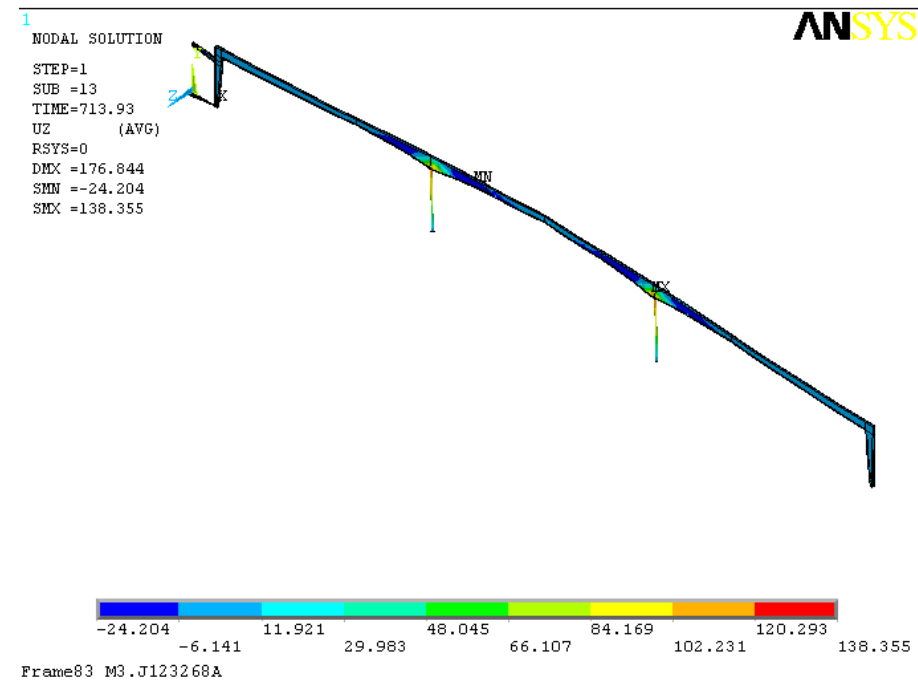
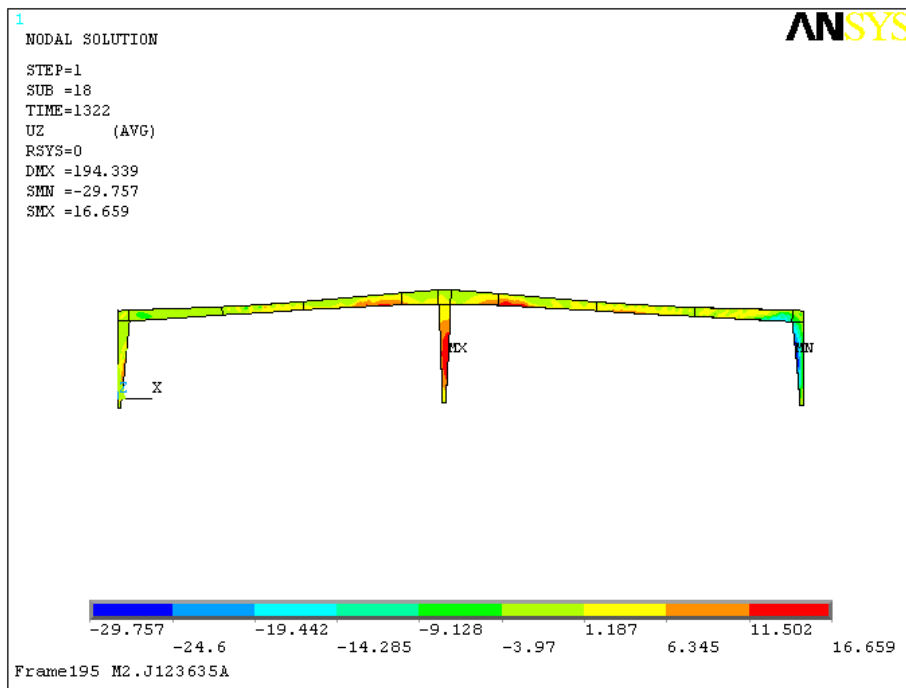
column buckling



GMNI analysis – failure modes

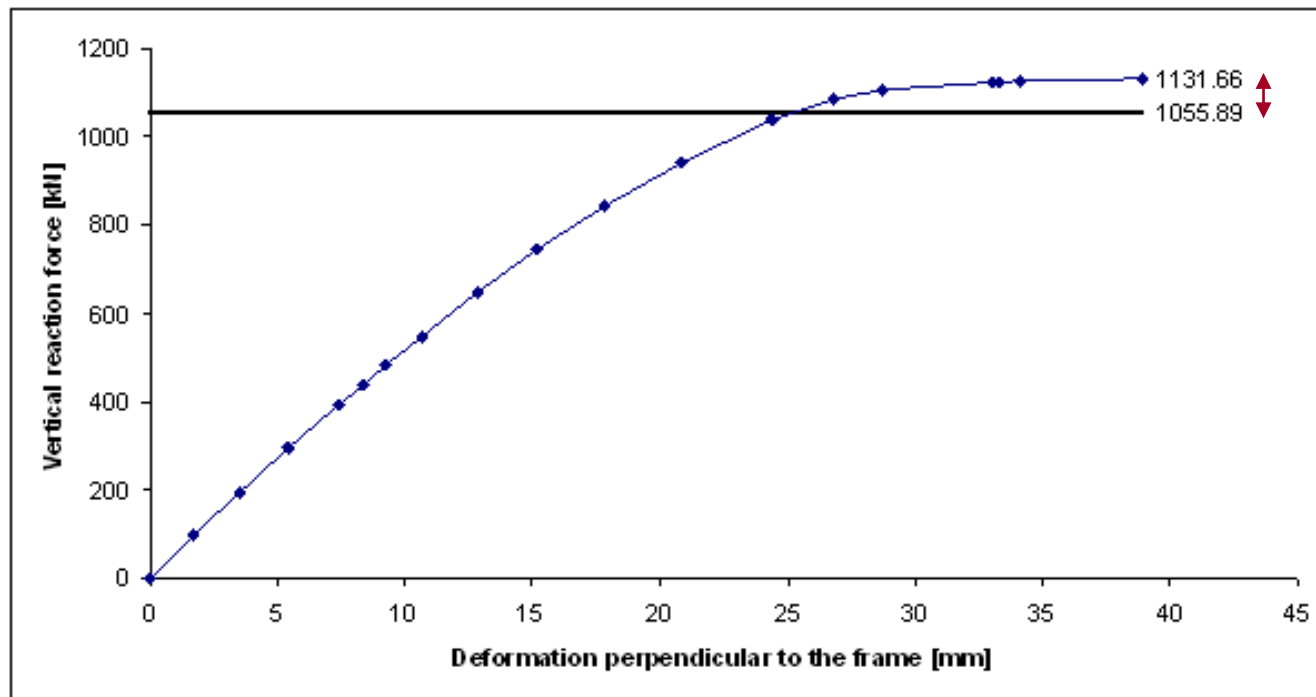
lateral torsional buckling

combination of column
buckling and LTB



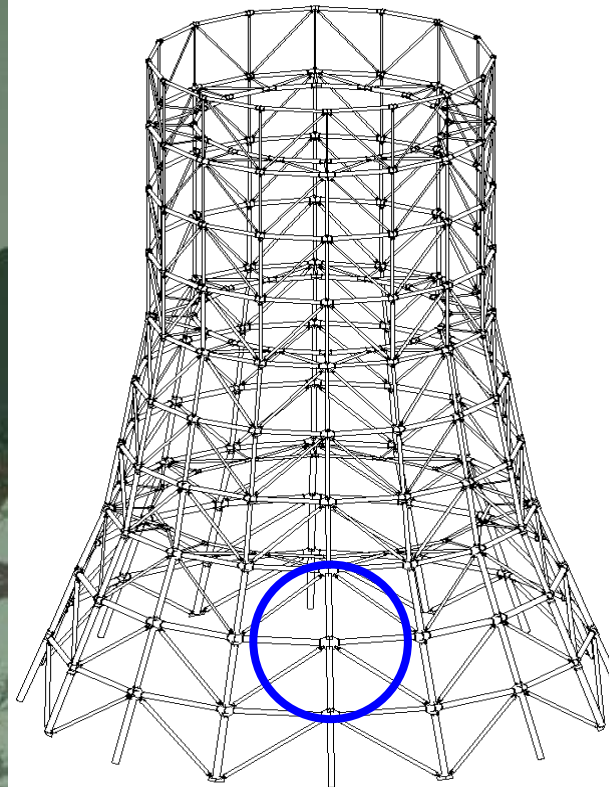
GMNI analysis – resistance

Representing load – displacement diagram

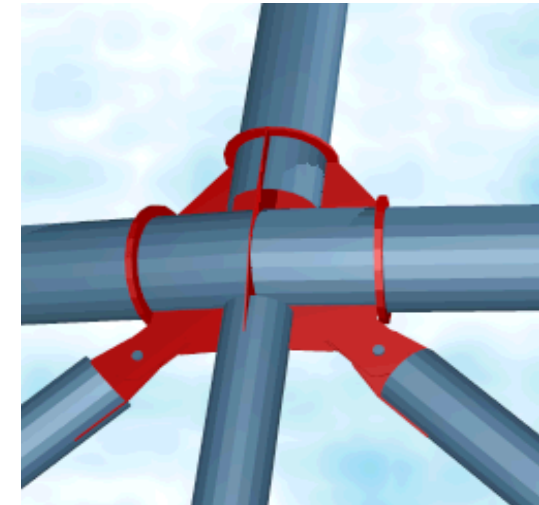


Standard resistance:
$$\alpha_u = \frac{\text{FE resistance}}{\text{Total load}} \geq \alpha_1 \alpha_2$$

Combined design – steel cooling tower

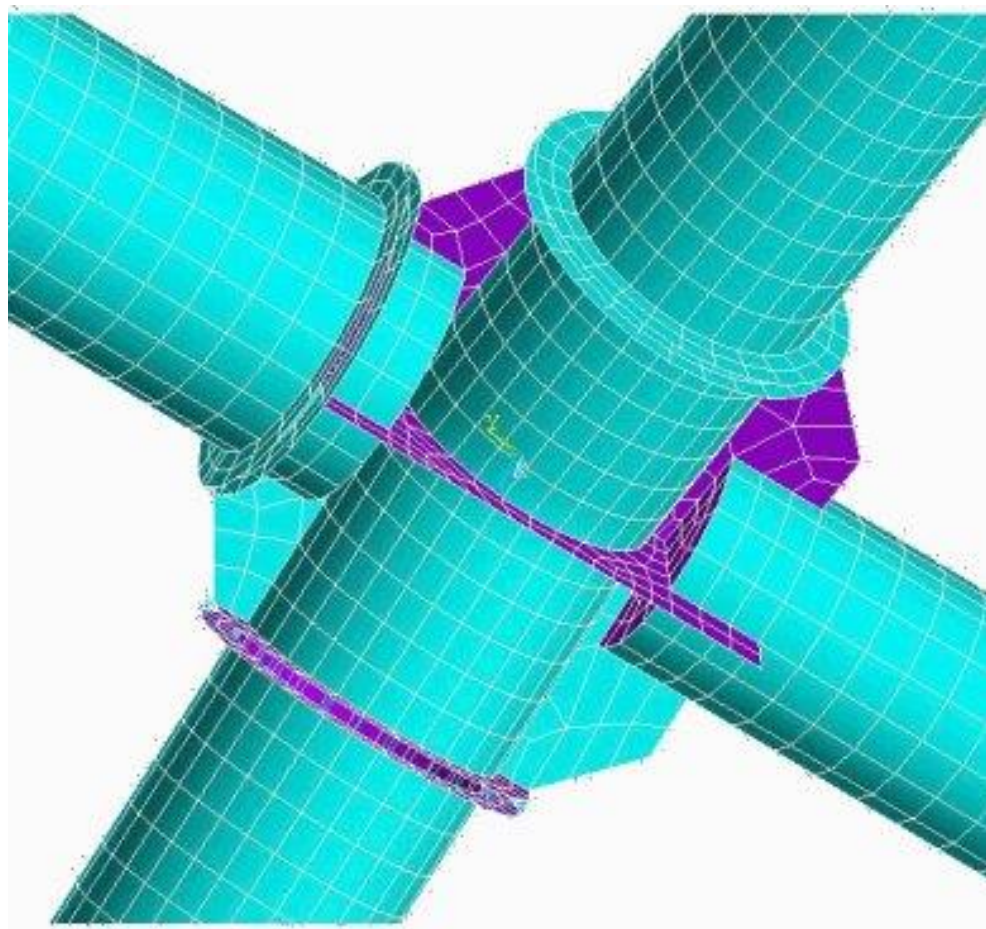
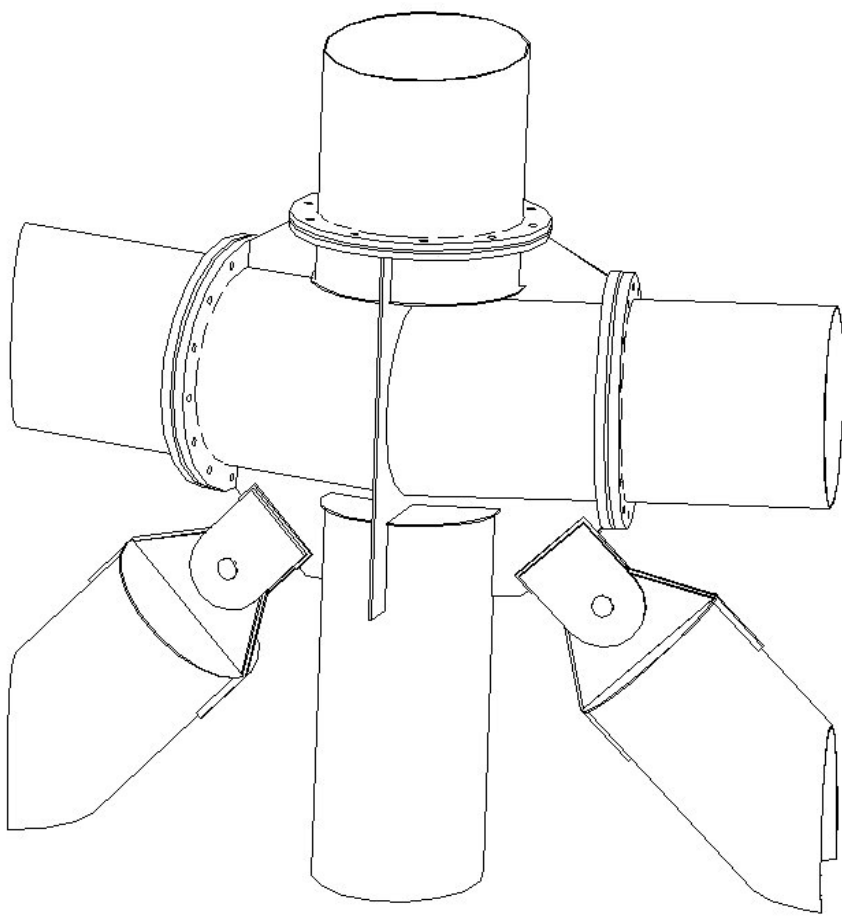


global model

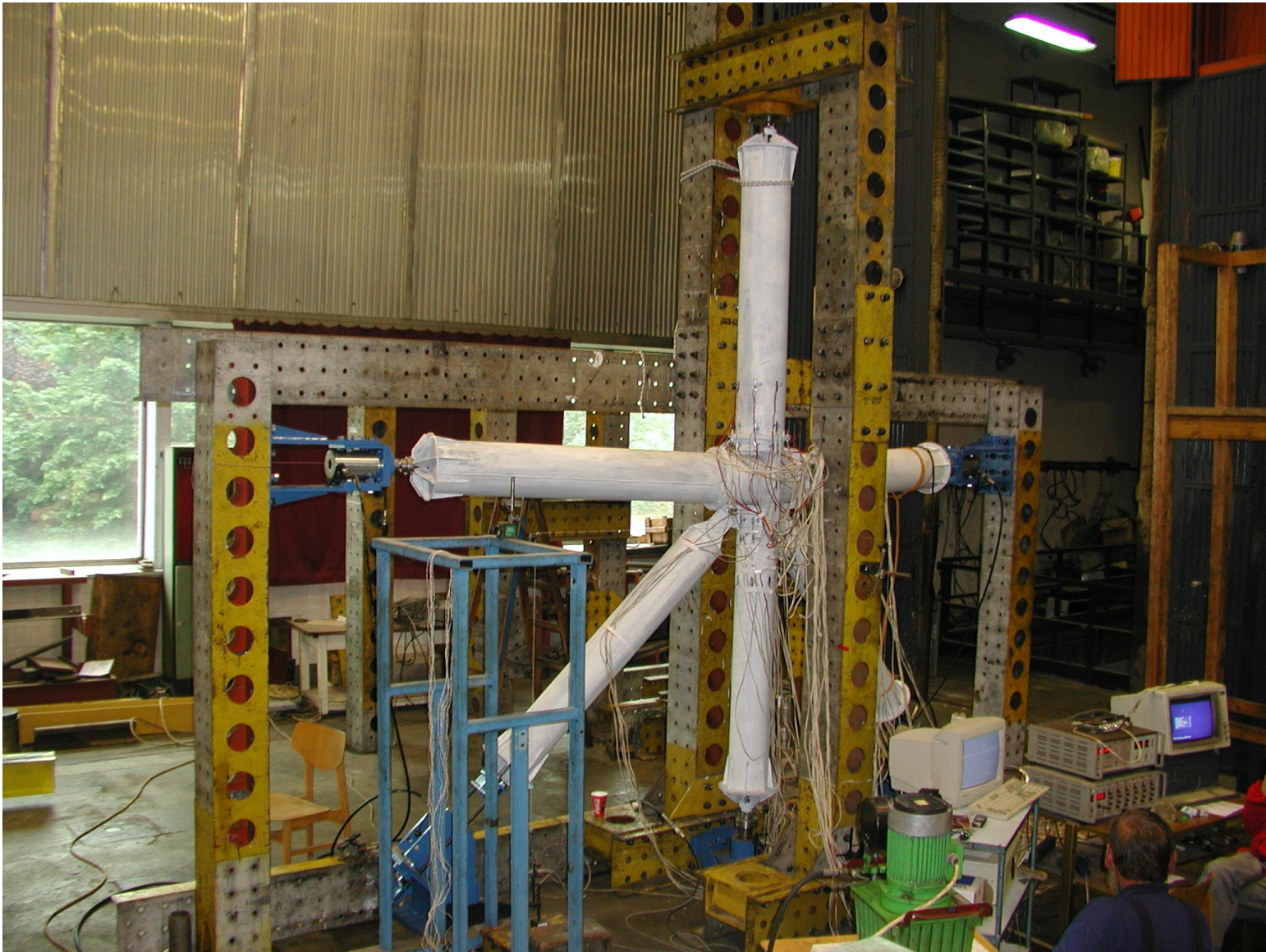


3D joint model

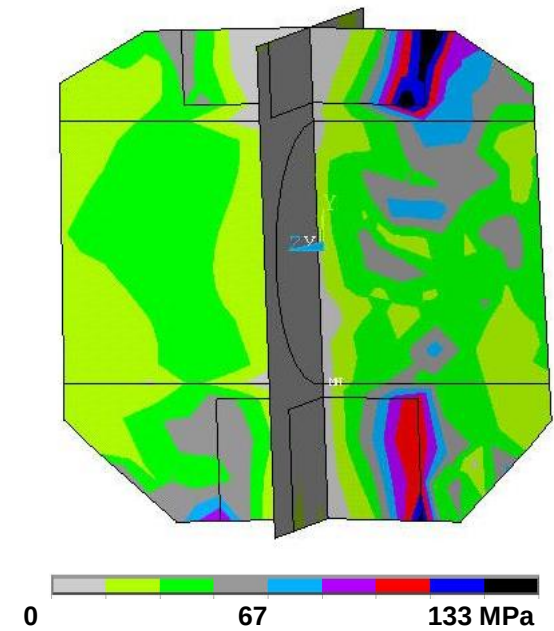
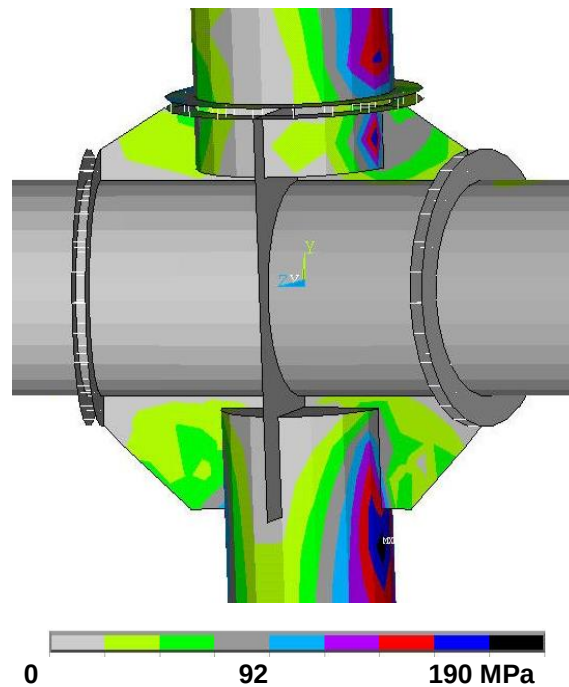
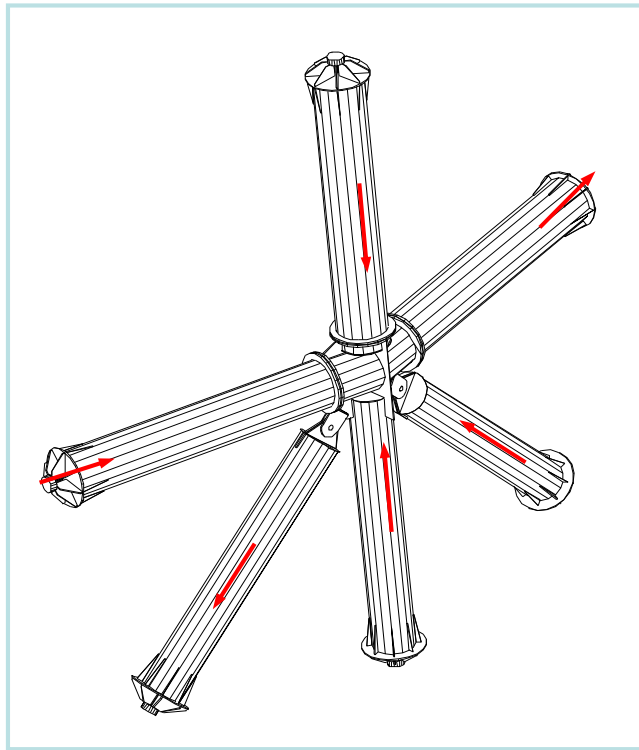
3D joint model



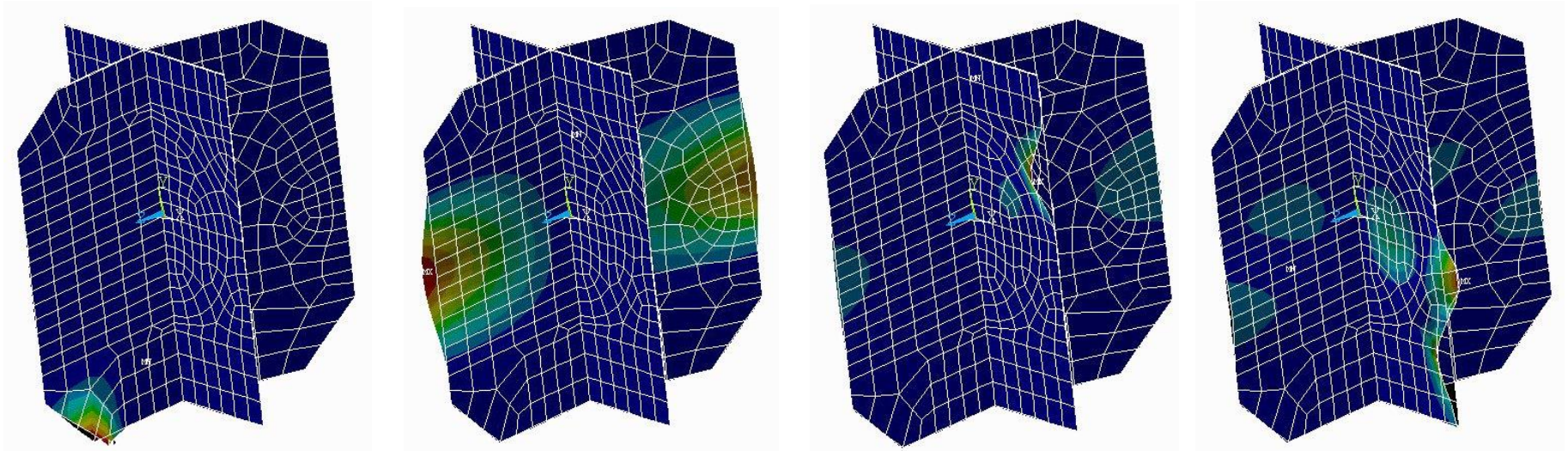
Experiment – prototype test 1:3



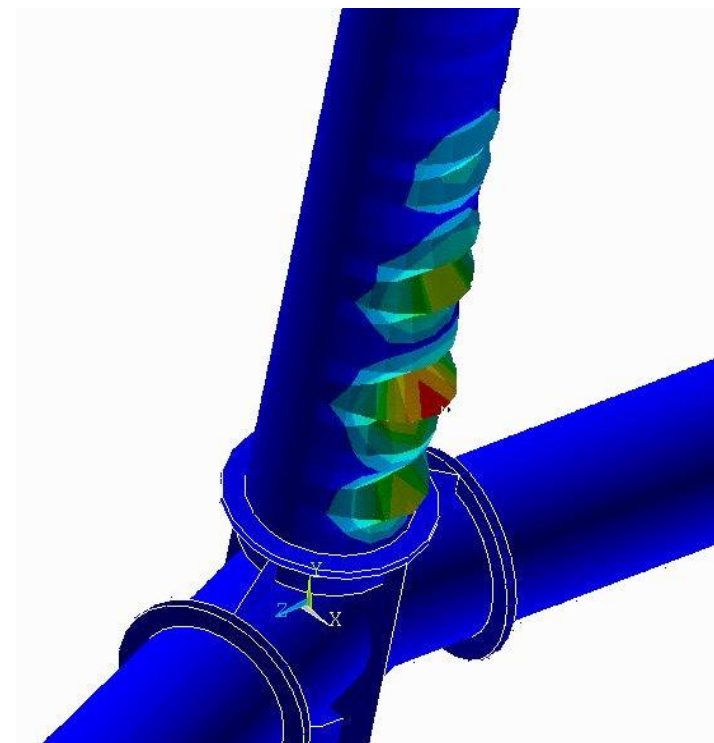
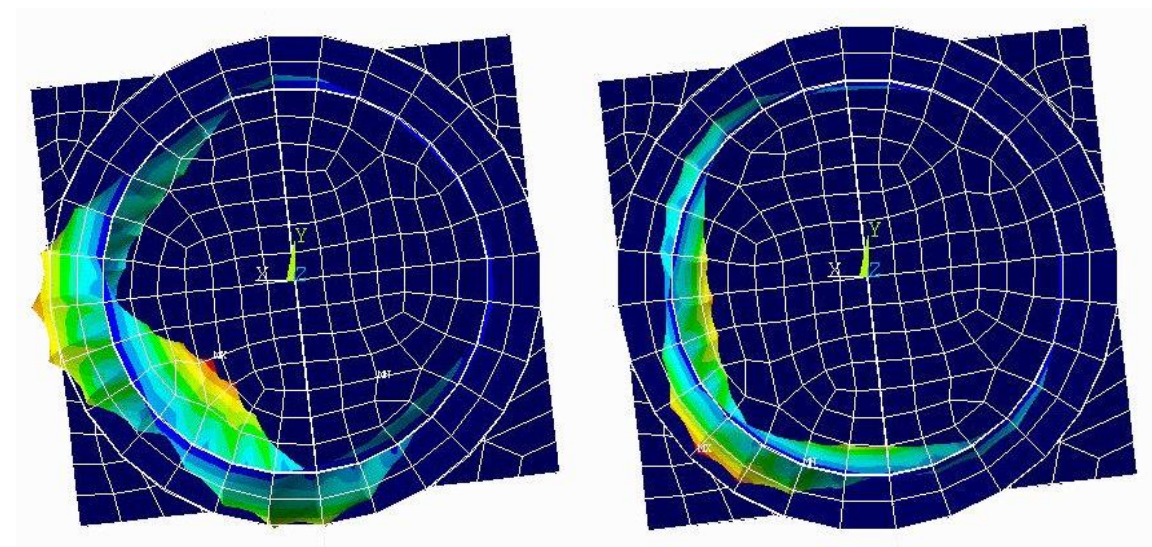
L analysis – stress distribution



GNB analysis – plate buckling

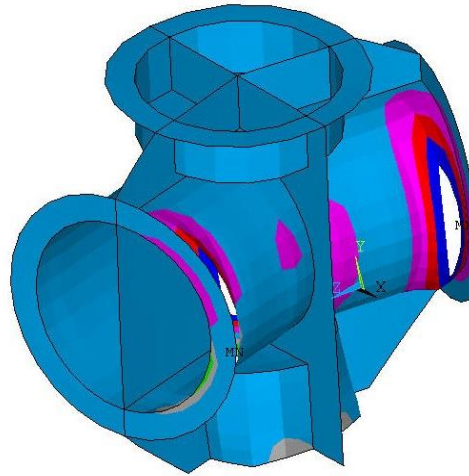
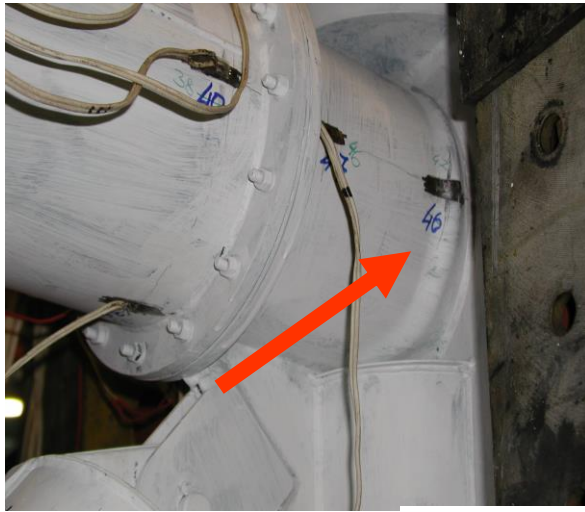


GNB analysis – shell buckling

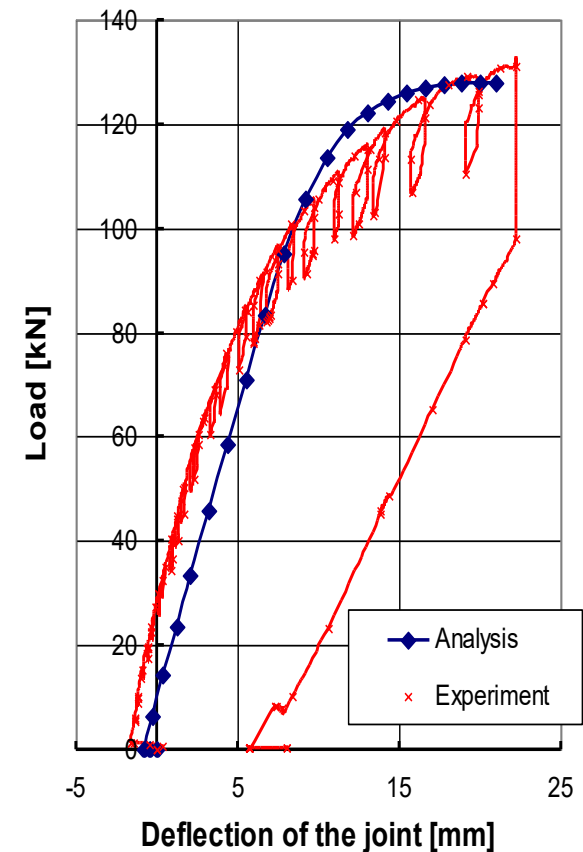
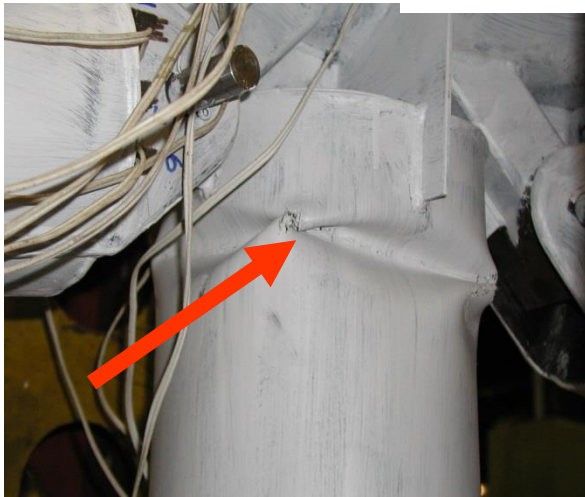


GMNI analysis – simulation + virtual test

elephant foot buckling



diamond shape buckling



Design methods

	model	analysis	design
1,	shell	GNB	L/D/G 1
	numerical buckling analysis for any of the buckling modes		
2,	shell	GNB	L/D/G 2
	numerical buckling analysis for all of the buckling modes		
3,	shell	GMNI	L/D/G 3
	numerical material geometrical nonlinear analysis with imperfections		
4,	specimen + shell	exp. + GMNI	test-based
	complicated complex structures, elements, joints, details		

Test + GNI analysis design model validation



Model test



Arch stability

in-plane (N,M)

out-of-plane (N)



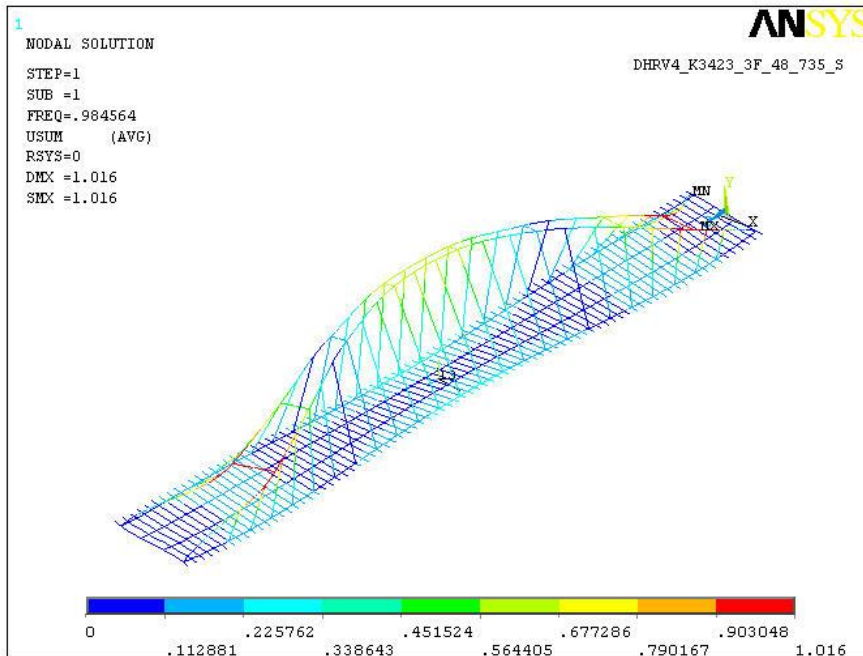
design method



validation

Model design – GNB analysis

Model, beam model, $M = \sim 1:34$



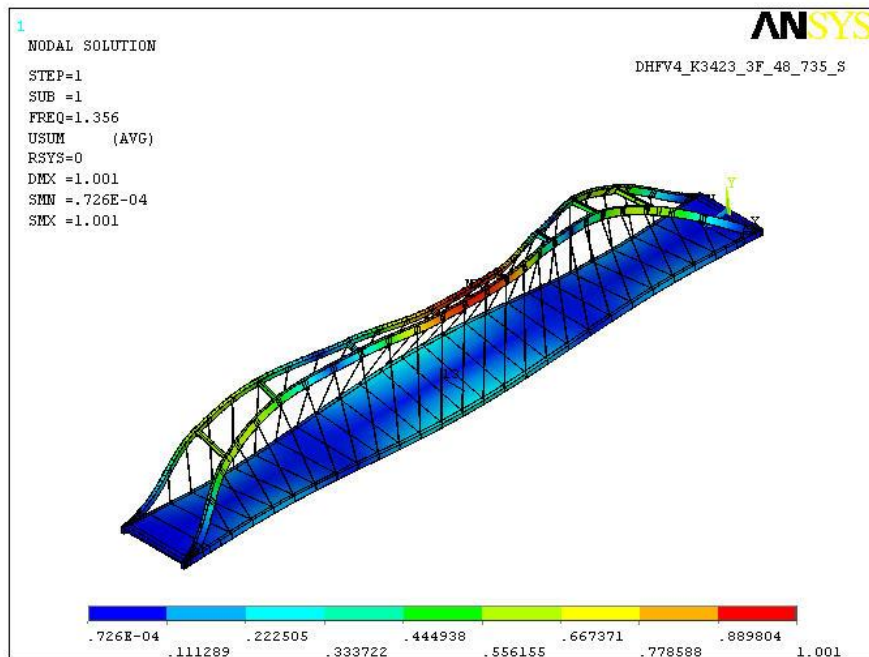
Critical multiplier: 0.984

Slenderness: 81.88

Relative slenderness: 0.880

Model design – GNB analysis

Model, shell model, $M = \sim 1:34$



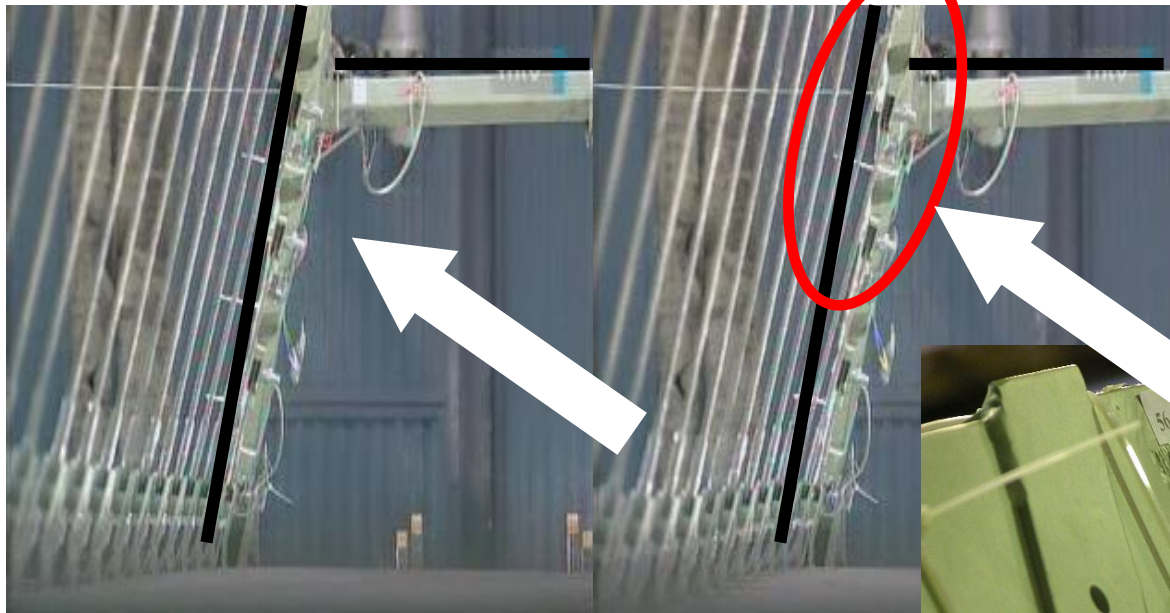
Critical multiplier: 1.356

Slenderness: 74.80

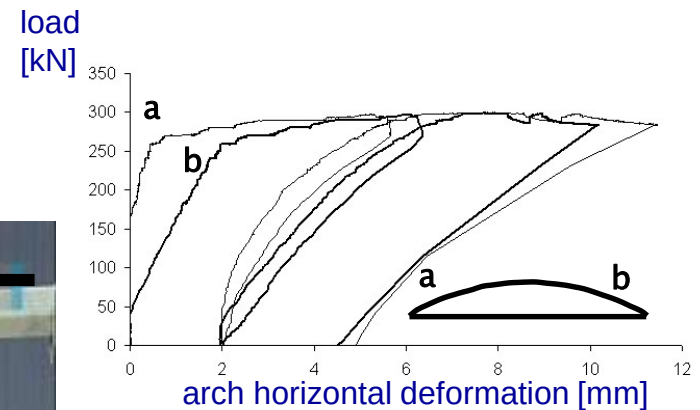
Relative slenderness: 0.804

Test – failure mode – total load

ultimate load: 320 kN



out-of-plane buckling of the arch

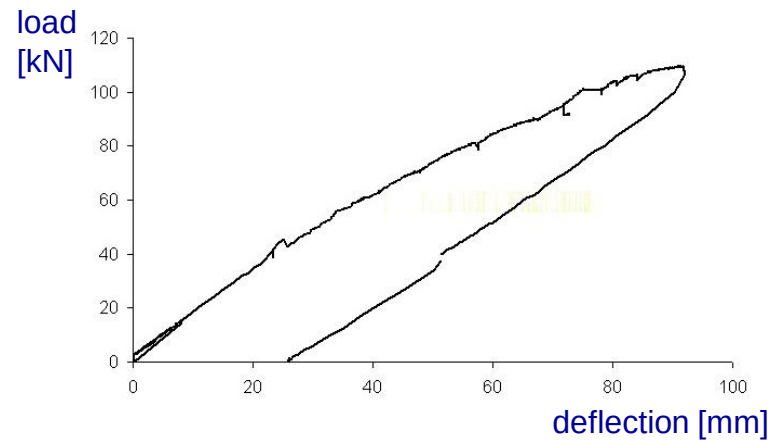


local plate buckling

Test – failure mode – partial load

ultimate load: 110 kN

in-plane buckling of the arch

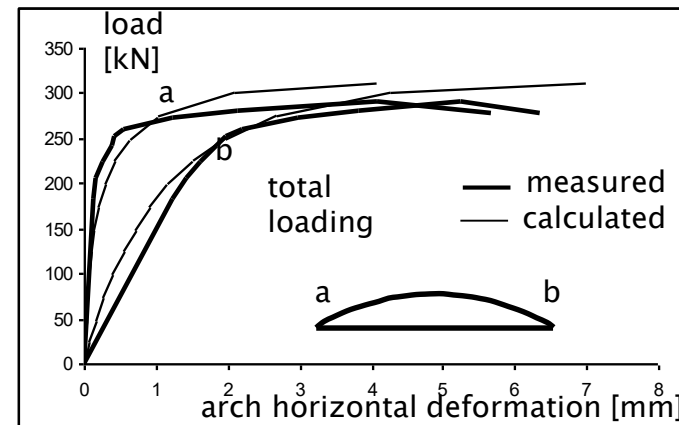
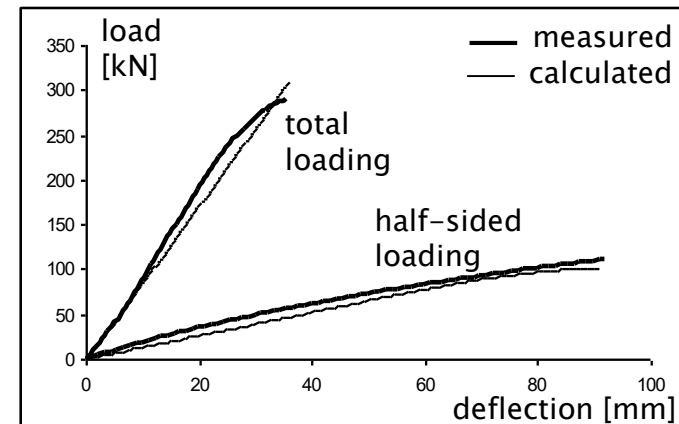
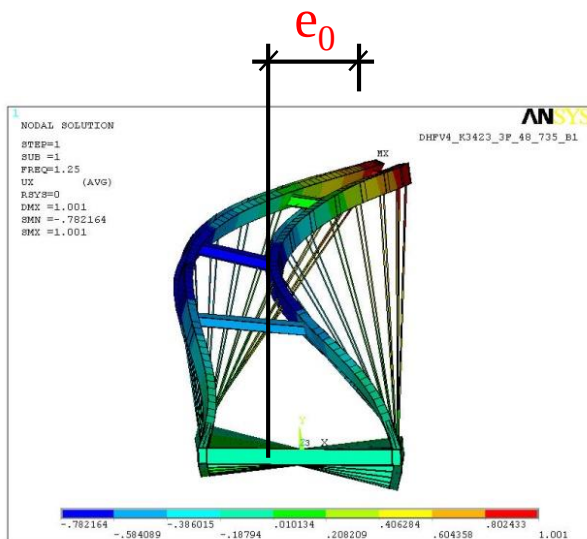


Model verification

material and geometrical nonlinearity

imperfection: $e_0 = 2$ mm

on the half side of the model $\Rightarrow$
non-symmetrical behaviour



Design method validation

Hungarian Standard:

HS

$$(1) \quad \frac{N}{N_e} + \psi_y \frac{M_y}{M_{e,y}} + \psi_z \frac{M_z}{M_{e,z}} \leq 1$$

strength check

+

$$(2) \quad \frac{N}{N_{ke,z}} \leq 1$$

buckling check

Japanese Standard:

JSHB

$$(3) \quad \frac{N}{N_{ke,z}} + \psi_y \frac{M_y}{M_{e,y}} + \psi_z \frac{M_z}{M_{e,z}} \leq 1$$

linear interaction

Eurocode:

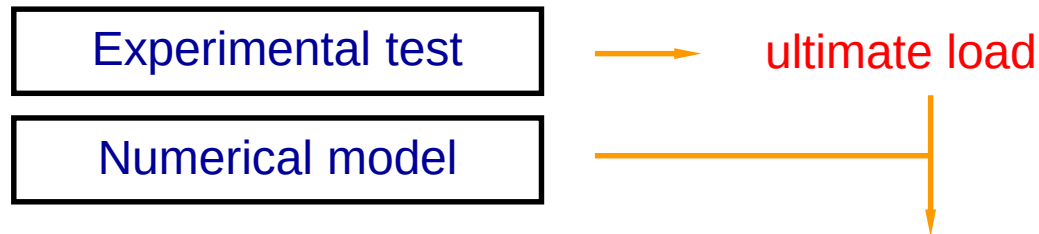
EC3

$$(4) \quad \frac{N}{N_{ke,y}} + k_{yy} \frac{M_y}{M_{e,y}} + k_{yz} \frac{M_z}{M_{e,z}} \leq 1$$

$$(5) \quad \frac{N}{N_{ke,z}} + k_{zy} \frac{M_y}{M_{e,y}} + k_{zz} \frac{M_z}{M_{e,z}} \leq 1$$

} combined
interaction

Safety level?



Internal forces: N , M_y , M_z from analyses:

1. linear + second order modification factor
2. geometrically nonlinear – equivalent imperfection 1
3. geometrically nonlinear – equivalent imperfection 2

standard ultimate load



experimental ultimate load

Safety

Equivalent imperfection – 1

Eurocode 3 – Part 1.1:

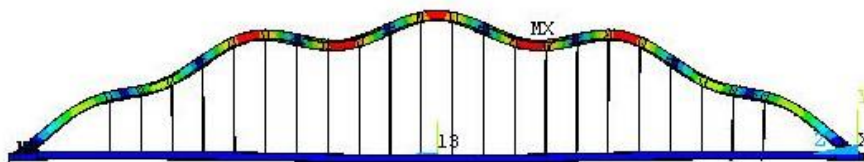
shape of the elastic critical buckling mode: η_{cr}

$$e_{0,d} = \alpha(\bar{\lambda} - 0.2) \frac{M_{Rk}}{N_{Rk}} \frac{1 - \chi \bar{\lambda}^2}{1 - \chi \bar{\lambda}^2} \frac{\gamma_{M1}}{\gamma_{M1}}$$

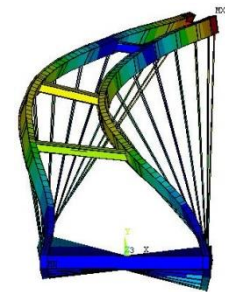
$$\eta_{init} = \frac{e_{0,d}}{\bar{\lambda}^2} \frac{N_{Rk}}{EI \eta''_{cr,max}} \eta_{cr}$$

second order analysis

in-plane buckling mode:



out-of-plane buckling mode:



In-plane	Out-of-plane
3.44 mm	17.30 mm

Equivalent imperfection – 2

Eurocode 3 – Part 2:

(Design of bridges)

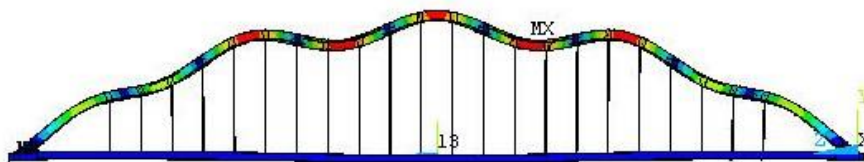
$$\eta_{0,z} = \frac{l}{500}$$

in-plane

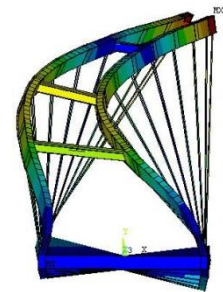
$$\eta_{0,y} = \frac{l}{250}$$

out-of-plane

in-plane buckling mode:



out-of-plane buckling mode:



In-plane	Out-of-plane
17.98 mm	35.96 mm

Safety levels

L analysis

	total load	half-sided load
HS	2.25	3.06
JSHB	3.07	3.28
EC3	2.20	1.87

Linear + GNI analyses

	total load	half-sided load
EC3 – linear	2.20	1.87
EC3 – eqv. geom. imp. 1	1.45	1.84
EC3 – eqv. geom. imp. 2	2.29	2.15

GMNI analysis and design refurbishment

**Hungarian Railway Co.
locomotive repair shop**



**Hungarian State Opera House
workshop and rehearsal center**

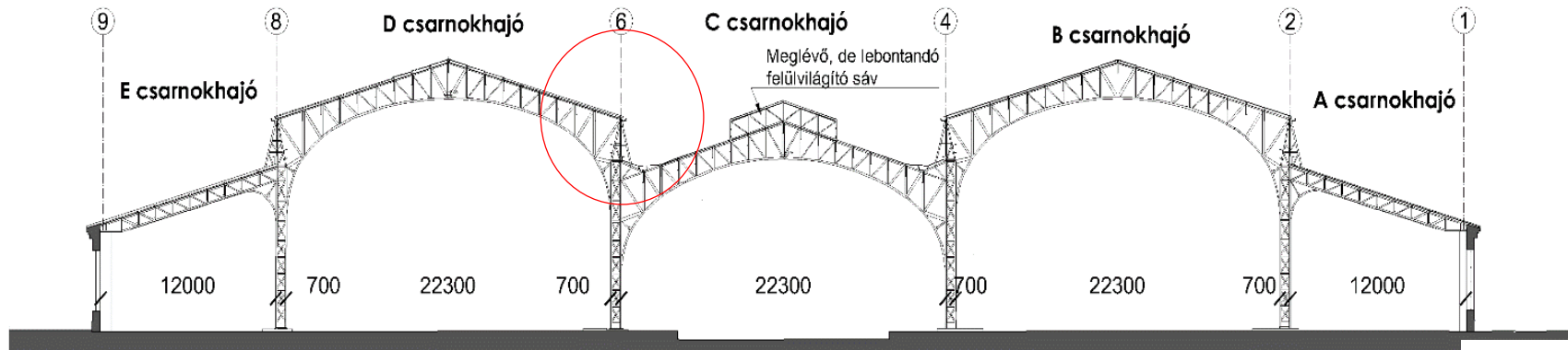


Eiffel-hall 1885; $L = 110$ m, $H = 220$ m

Budapest, 26-30.06.2017

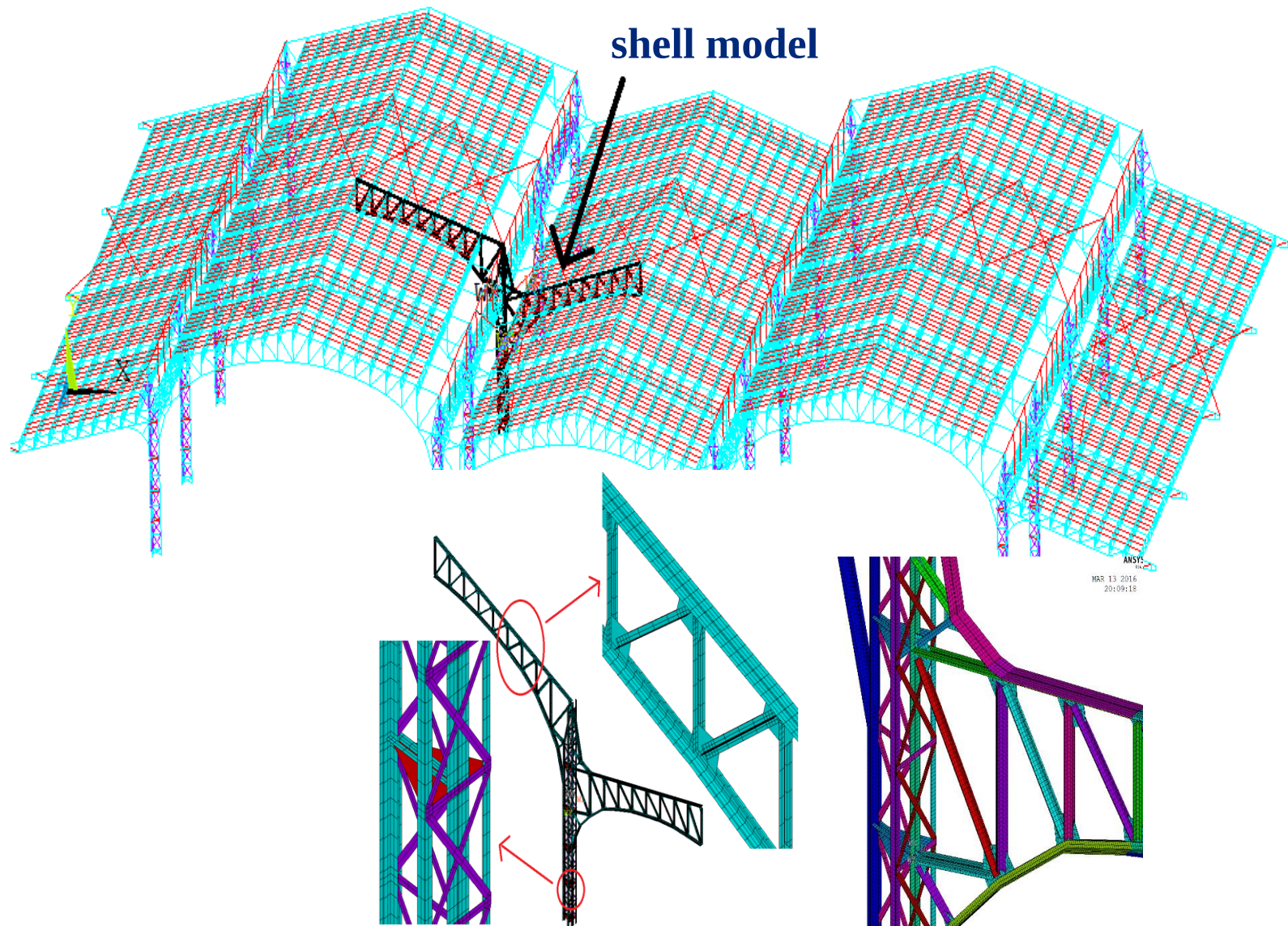
Trussed frame stability

structural damages – novel functions/loads – design of strengthening

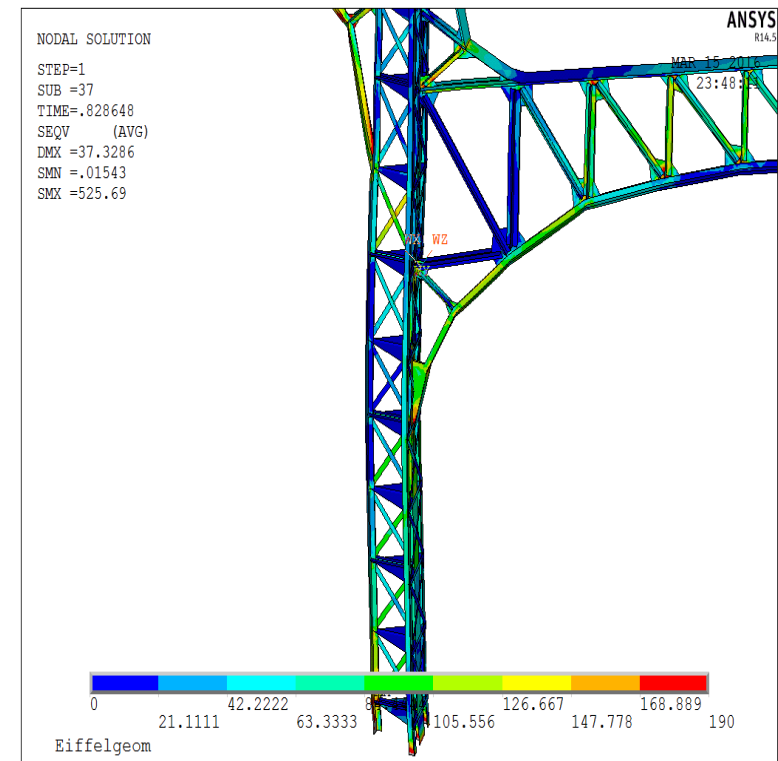
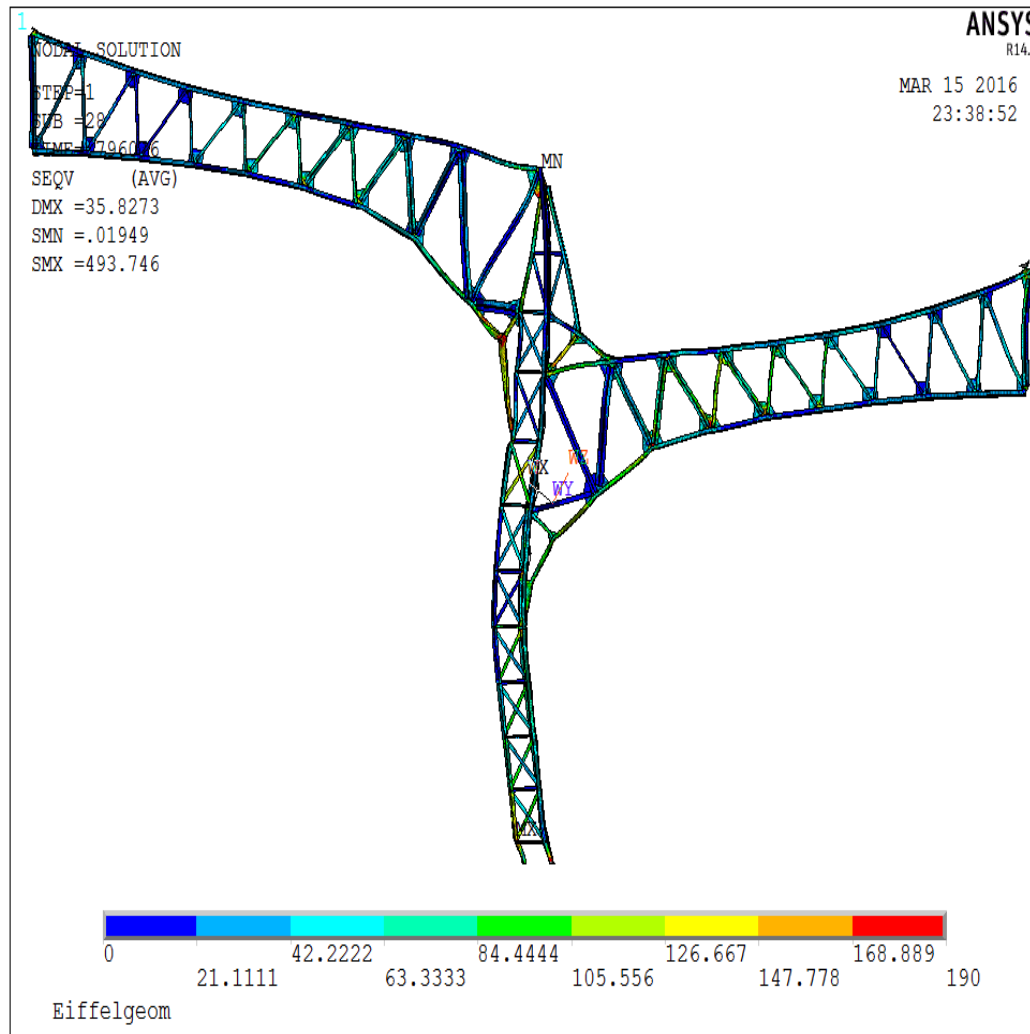


damages – site inspection

Muliti-level FE modelling – damages



GMNI analysis – design resistances





PhD course program

	Monday	Tuesday	Wednesday	Thursday	Friday
9:00 - 10:30	Computational structural design methodology (László Dunai)	Advanced fatigue assessment and design of bridges (Balázs Kövesdi)	Improvement methods for Eurocode based design - parametric study and test evaluation (Balázs Kövesdi)	Lecture (Prof. Morgenthal)	Advanced techniques for fabrication simulations - Welding simulation (Néző J.)
10:45 - 12:15	FEM based stability design of structures - 1 (László Dunai)	Finite element modelling of cold formed steel members in fire situation (Nuno Lopez)	Design and solutions for bridge monitoring systems + loading test of bridges (Balázs Kövesdi)	Lecture (Prof. Morgenthal)	Modelling of the people induced vibrations of structures and vice versa (Uni Osijek)
12:15 - 13:15	Lunch	Lunch	Lunch	Lunch	Lunch
13:15 - 14:45	FEM based stability design of structures - 2. / Bridges (Balázs Kövesdi)	Fatigue assessment of a steel bridge deck - evaluation of measured database - (Project work pres.)	Project work preparation	Lecture (Tajammal Abbas)	Presentation of project work
15:00 - 16:30	Modern bridge erection methods and their improvements and modelling (Lecture)	Bridges on the Danube (László Dunai)	Project work preparation	Finite element technologies for nonlinear solids and structures (Jose Korlec)	
		Guided ship tour - bridges in Budapest			



Thank you for your attention!