Optimal Design of Steel Towers

Advances in Wind Turbine Towers

3nd International Conference

Swissôtel Bremen, Bremen, Germany

Milan Veljkovic,

26 August 2014.

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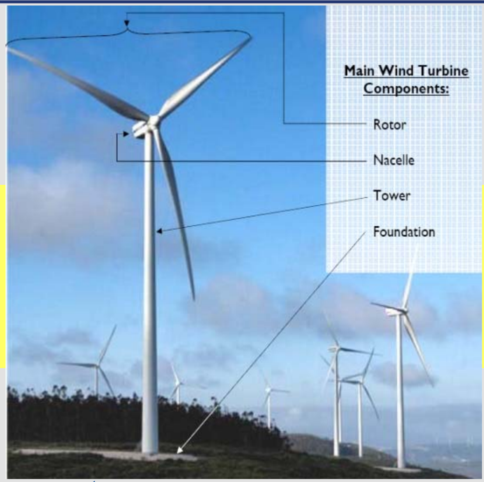
Agenda

- **Market opportunities.**
  - **Position of steel sector and competitors.**
  - **Technical barriers and trends.**
- **On-going research projects.**
    - Stability of polygonal vs. circular tubular towers.
    - Bolted connection in modular steel tower.
    - Door openings, are stiffeners necessary?
    - How to design flangeless connection?
    - How to manufacture competitive flanges?
- **Conclusions.**

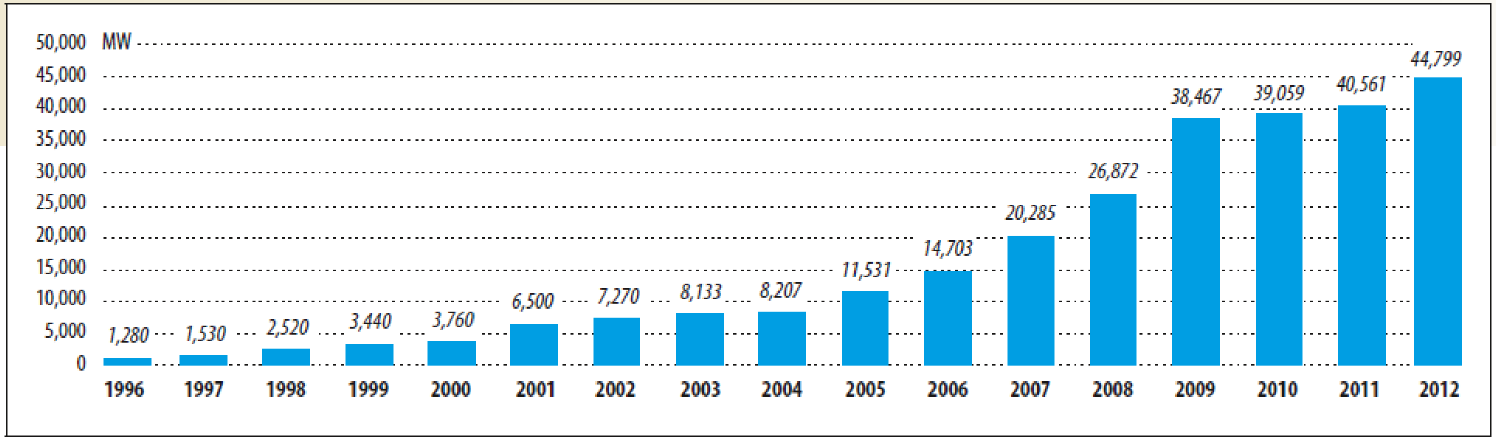
Economics of Wind Power
UK experience

Element	On-shore Cost as % of total	Offshore Cost as % of total
•Turbine	•33%	•21%
•Blades	•22%	•15%
•Tower	•20%	•13%
•Foundation	•9%	•21%
•Grid connection	•6%	•21%
•Design & Management	•10%	•9%
•Total cost per MW	•€1.5 - 2 million	•€2.5 – 3.5 million
	•300-400 k€	325-455 k€

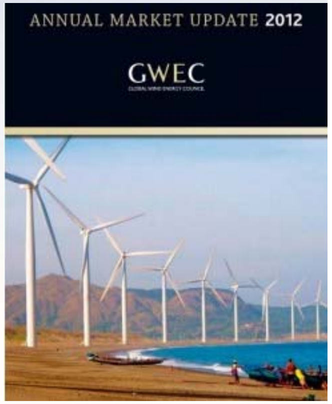


Market opportunities for wind towers

Global Annual Installed Wind Capacity 1996-2012



Source: GWEC



Cost assumptions

- Steel towers are 15 to 25 % of installation costs
- If 80% towers are made of steel for the cost of 250 k€/MW)

- 12,7 GW of new turbines in Europe (2012)
  - 15 billion € (total value of new installed eq. 1,2 mil €/ 1MW
    - Tower costs 250 k€/MW 3,2 billion €

GEWC-Europe
1,0-1.3 mil €/ MW

Sweden 1,6 mil €/ MW

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Wind farms

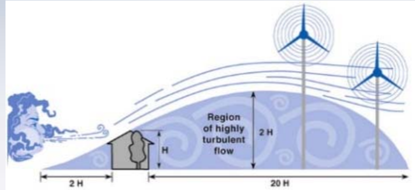
World's largest onshore wind farms

Wind farm	Current capacity (MW)	Country
Alta (Oak Creek-Mojave)	1020	USA
Buffalo Gap Wind Farm	523.3	USA
Capricorn Ridge Wind Farm	662.5	USA
Dabancheng Wind Farm	500	China
Fowler Ridge Wind Farm	599.8	USA
Horse Hollow Wind Energy Center	735.5	USA
Jaisalmer Wind Park	1,064	India
Meadow Lake Wind Farm	500	USA
Panther Creek Wind Farm	458	USA
Roscoe Wind Farm	781.5	USA
Sweetwater Wind Farm	585.3	USA

- wind speed of 16 km/h or greater.
- constant flow of non-turbulent wind.
- access to local demand or transmission capacity.

Dragaliden Wind Farm, Norrbotten, Sweden © *Svevind*

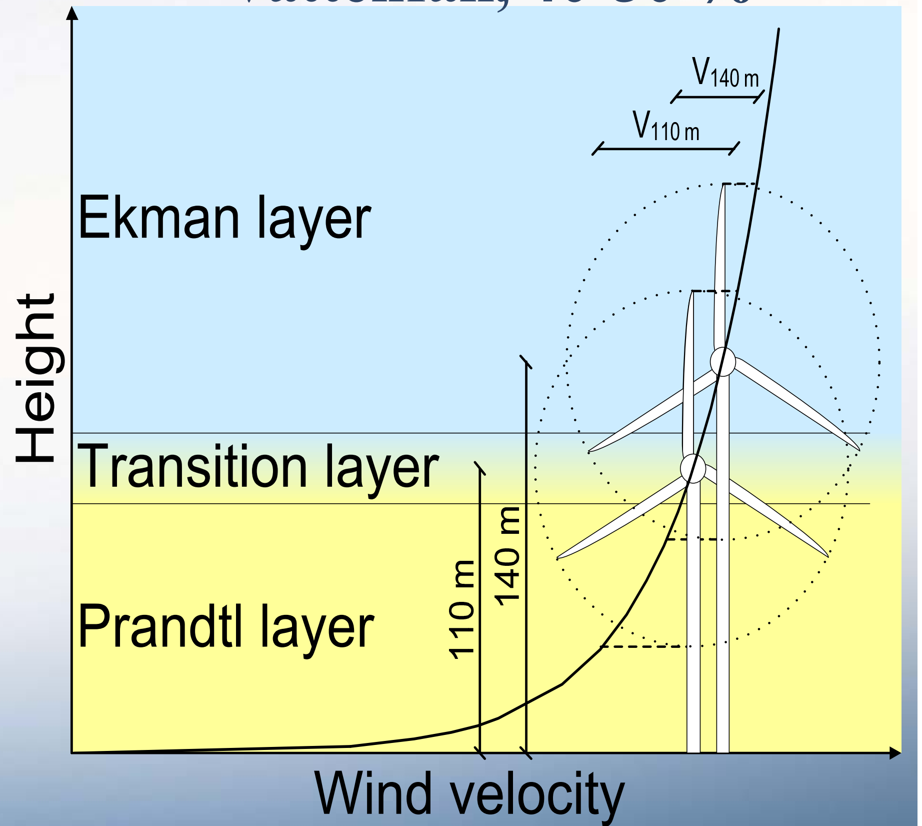
Onshore challenges
Height and Foundation



Vattenfall, 40-50 %

Matthias Schubert, former CTO at the REpower Systems:
"By raising the hub height from 93m to 143m, the company expects an increase in yield of up to a whopping 50% in low-wind locations."

3.2-MW turbine
http://www.windpowerengineering.com/



1st problem: Transport for onshore towers

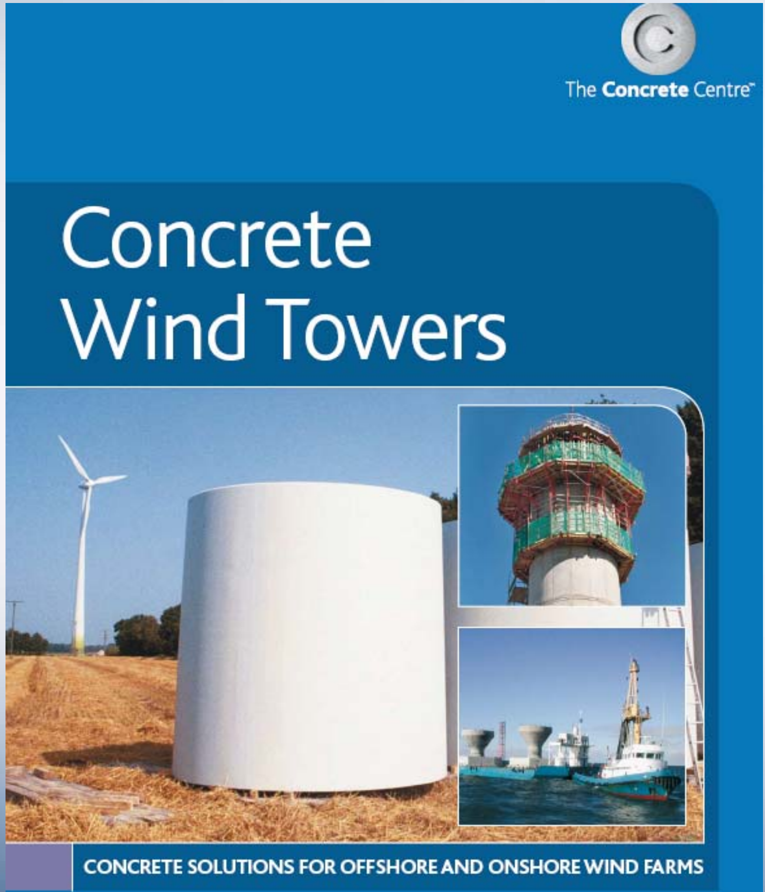
www.awea.org

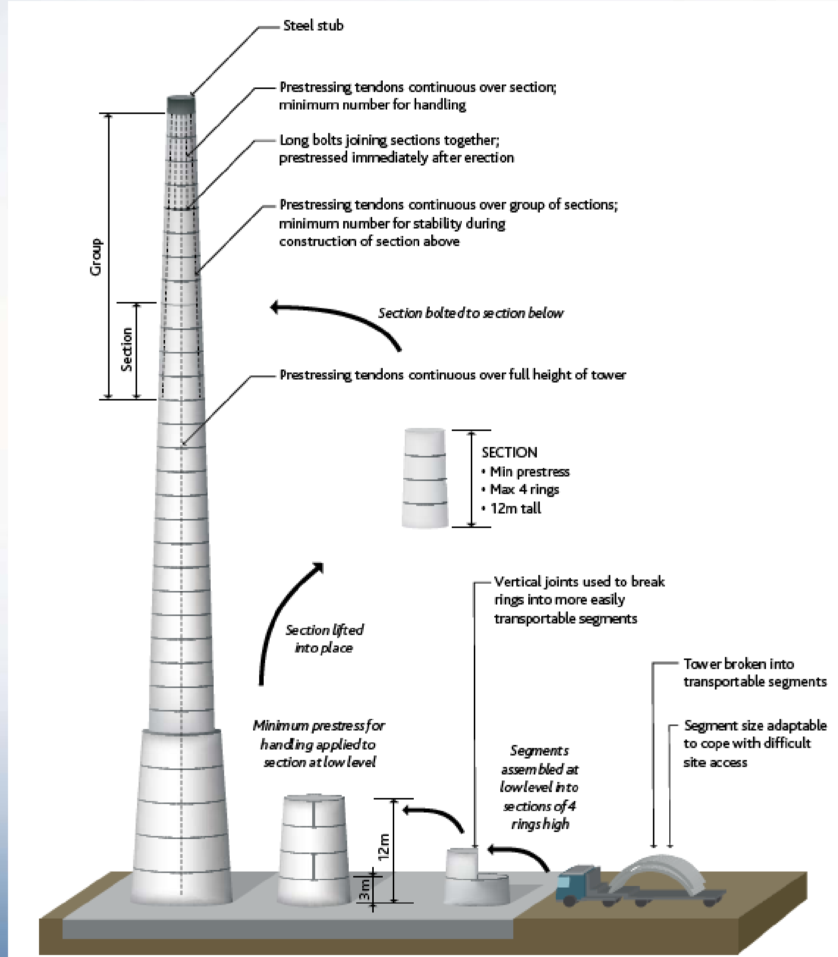
Diameter: 4,5 m

Length: 36 m

Weight: 70 t

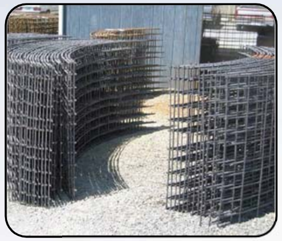
Concrete Tower

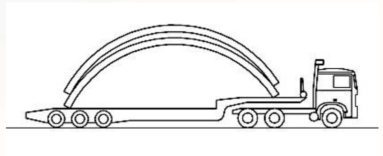




Pre-stressed concrete tower

Production, transport and assembling, but also dismantling.





NO TRANSPORT CONSTRAINTS

Hybrid Tower


ATS, May 2009 Grevenbroich 2,3 MW

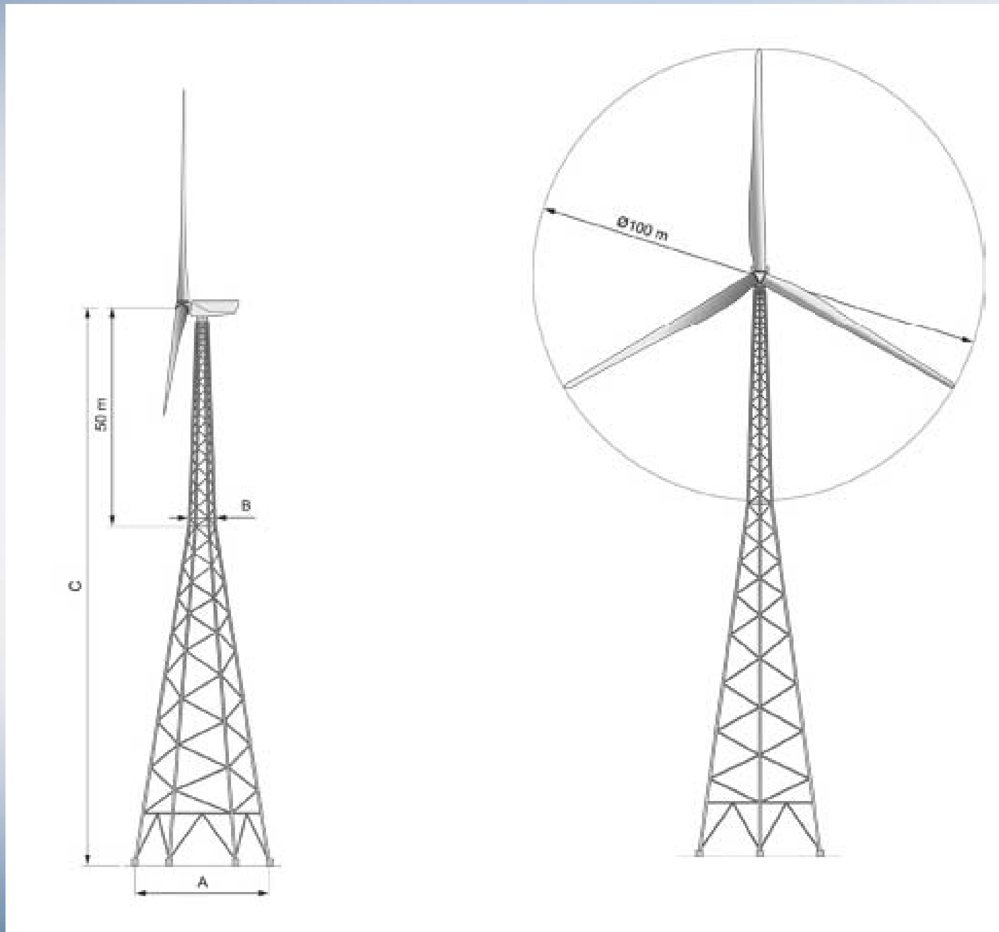
Lattice tower

near Antwerpen, 111m 1,5 Mw, 2006

SeeBA 160-m-Gittermast Laasow Lausitz Brandenburg
Foto: Jan Oelker, 2006 jan.oelker@gmx.de

Lattice tower –L profiles

Lattice tower



ruukki
more with metals

Lattice tower

Tubular tower: Alternative
Bolted polygonal shell tower

http://andresen-towers.com

2nd problem: Lifting technology

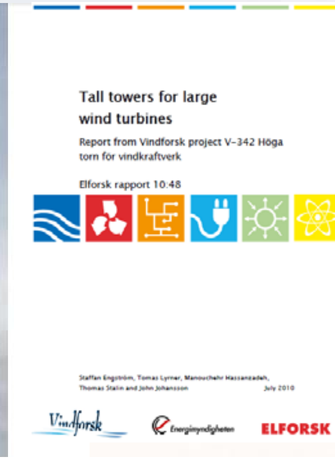


Table 6. Approximate cost of cranes, including transportation from Belgium to Swedish port[11]			
Type	Weight of unit + equipment	Mobilization cost, 1 000 NOK[12]	Long term hire, per week, 1 000 NOK
Liebherr LR 1400	450 t + 250 t	1 500	125
Demag CC 2800	500 t + 250 t	2 000	150
Liebherr LR 1800	700 t + 300 t	3 500	325
Demag CC8800	800 t + 400 t	4 500	450

Figure 1. Lifting of the 340 t hub section for Enercon E-126 7,5 MW wind turbine. The Terex Demag CC9800 crawler crane is formally rated 1600 t and in this configuration can lift 360 t.

4,5 mil NOK=0.56 mil€

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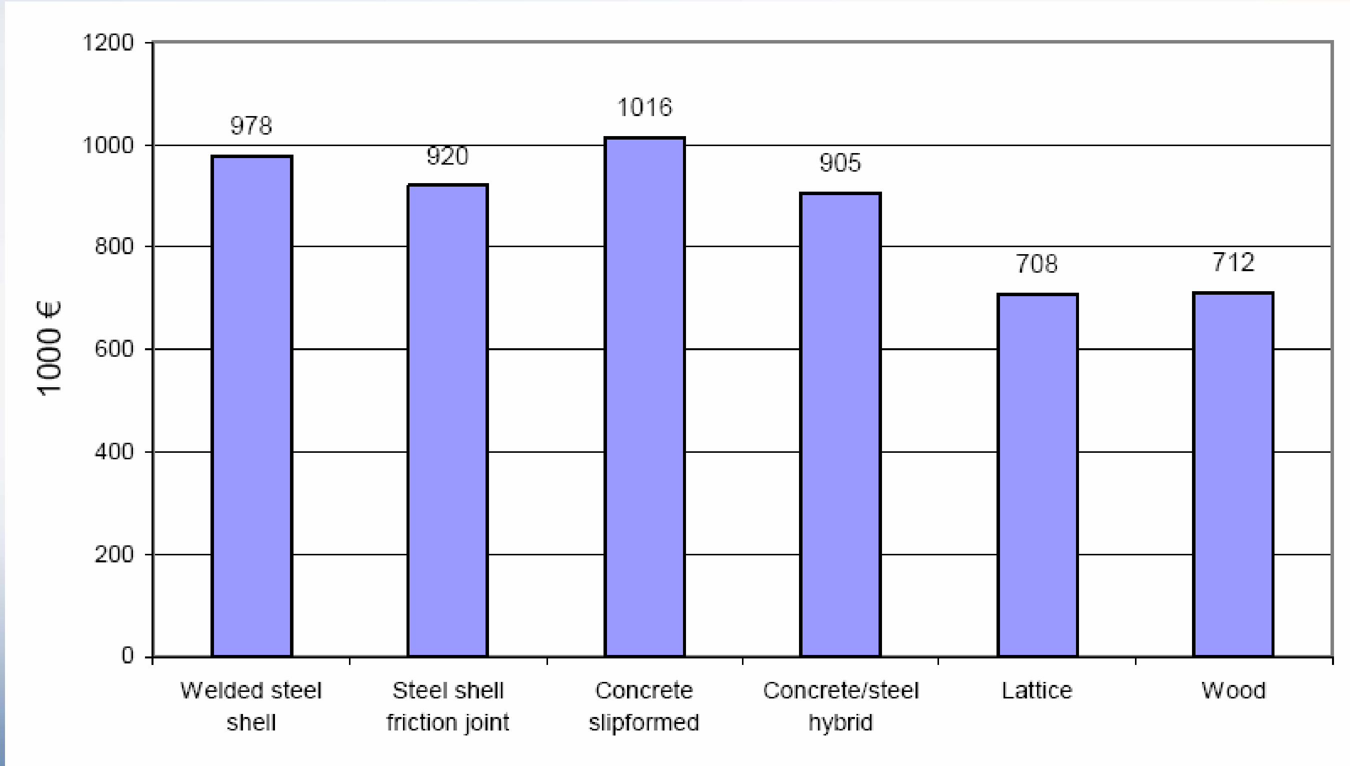
Steel towers vs concrete and hybride towers

Tower costs for the alternative designs.
Turbine power 3 MW, hub height 125 m

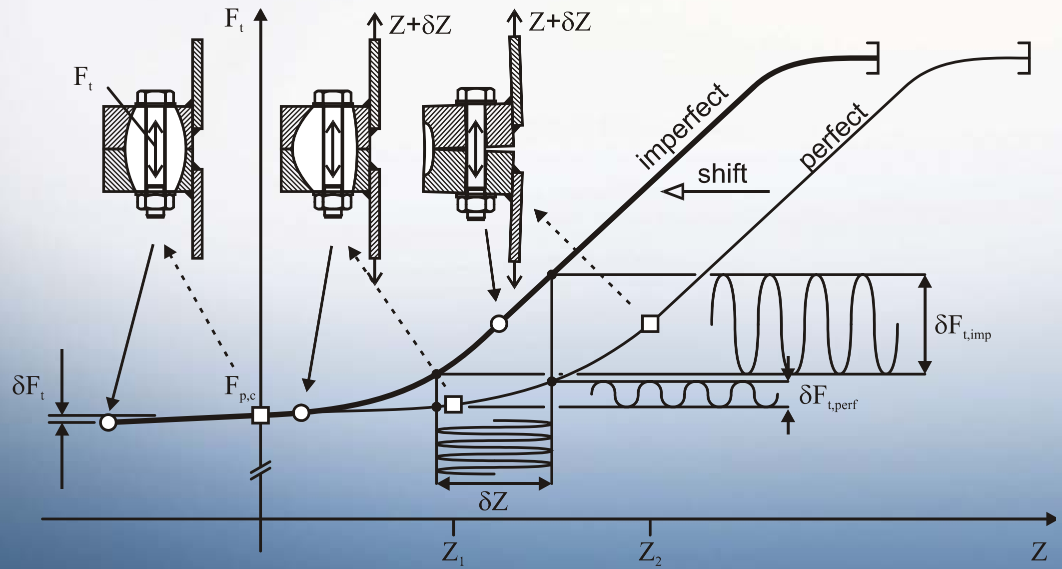


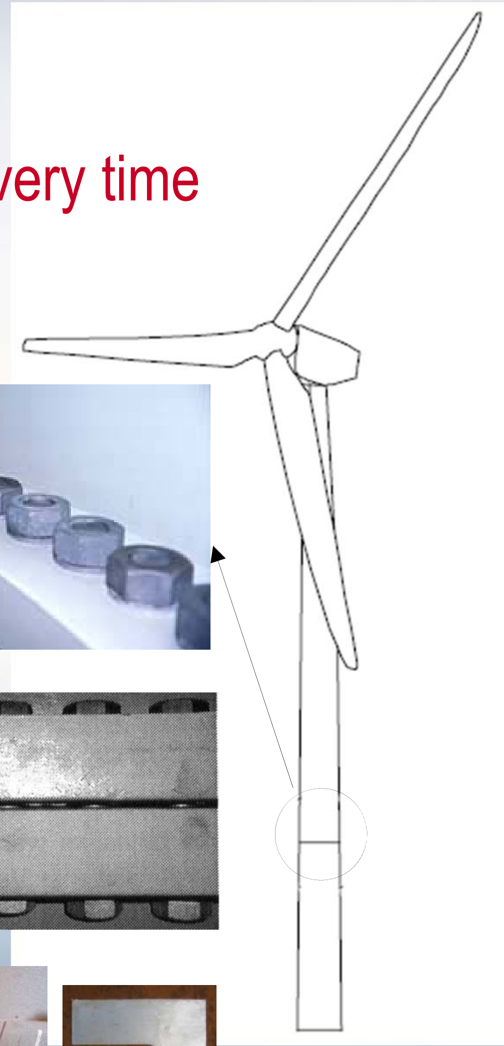
Tall towers for large wind turbines, Report from Vindforsk project V-342 Höga torn för vindkraftverk, **Elforsk rapport 10:48**

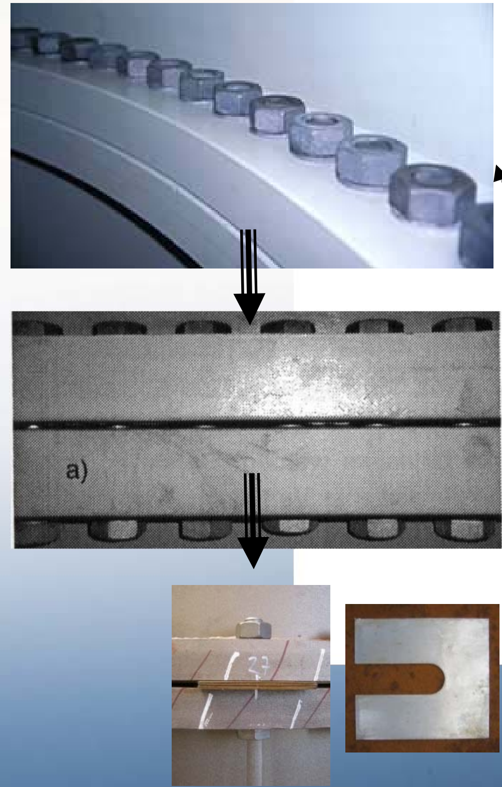
Common connections in towers for wind turbines

- High fabrication costs (app. 4-7k€/flange), long delivery time
- Relatively low fatigue resistance, approx. 50MPa
- Main limitations (design, transport)

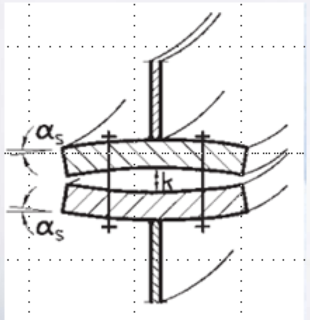
⇨**Impairs whole structure efficiency**



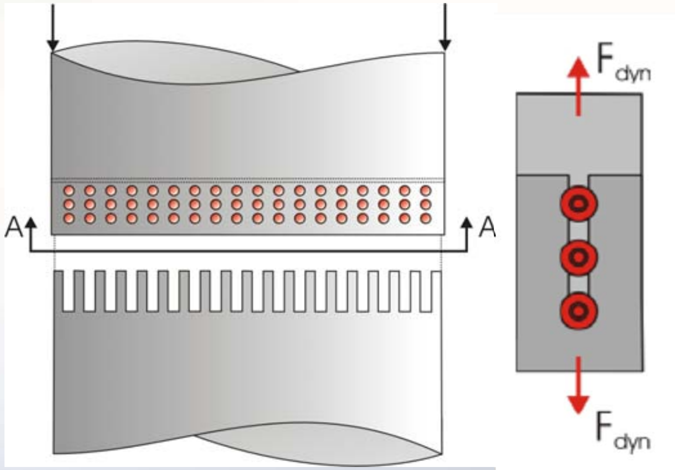




The main project idea of the HISTWIN project 2006-2009

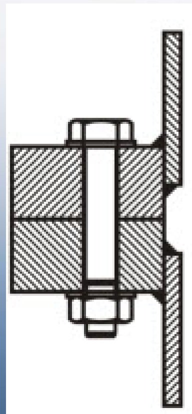


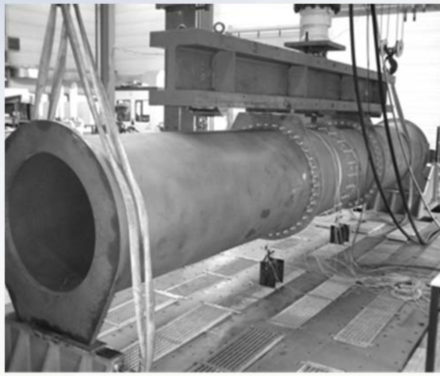
Repower 5MW assembled 2004, Germany

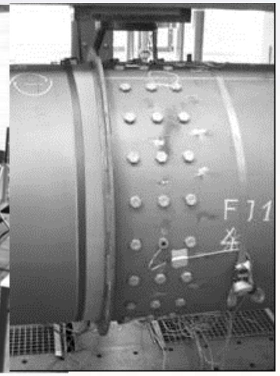


New proposal

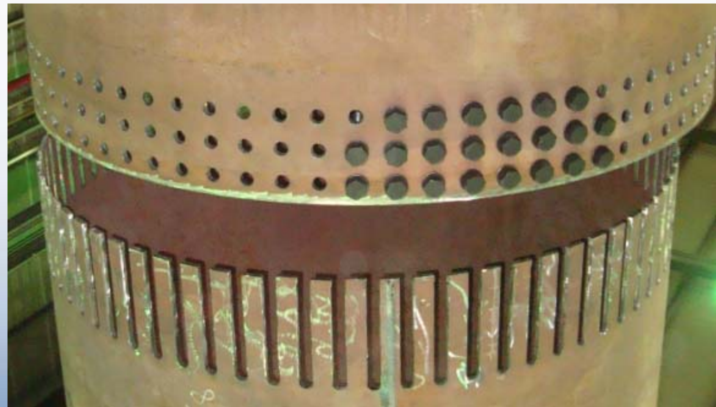
Evolution of Tubular Steel Assembly Joint



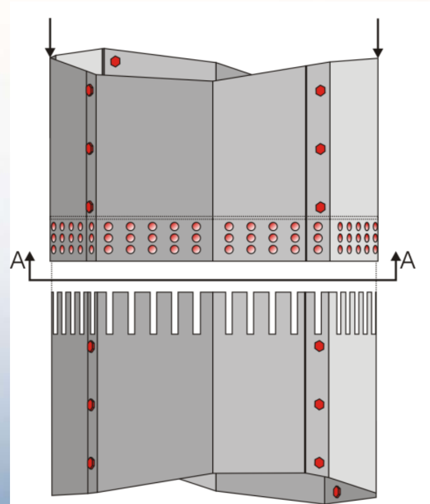




2006-2009

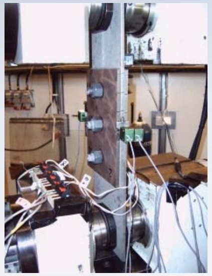


2010-2013

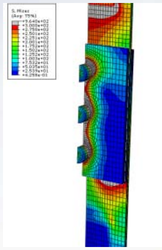


The research overview and partnership of the Histwin project

•Segment test on a new friction connection,



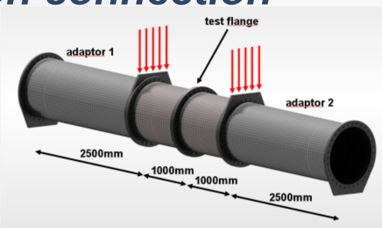
•Static
•Long time measurements

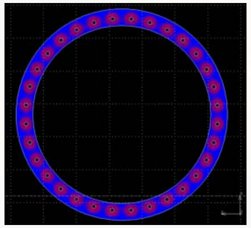


Simple connection

Design model

•Model test, flange and friction connection





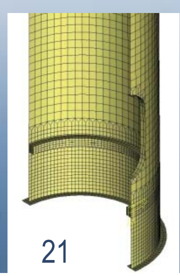
Flange and friction connection

Design model

Feasibility test

•In-situ measurements

• Fatigue tests on a friction connection

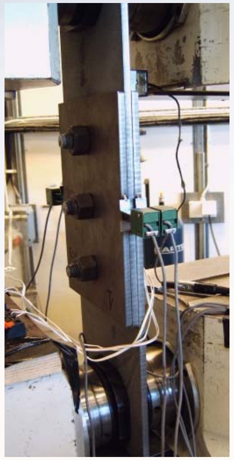


FEA

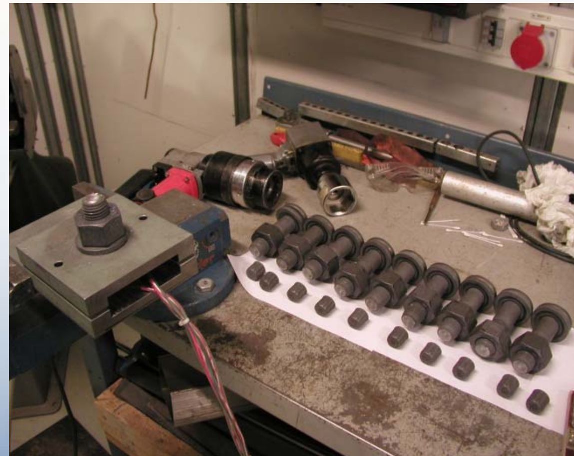
Design guideline

Overview of the experimental work

- Segment tests
  - Static resistance tests
  - Long term tests
  - Temperature cycles
- Standard friction tests
- Relaxation tests
- Pretension tests
- Short term monitoring (room)
- Fatigue

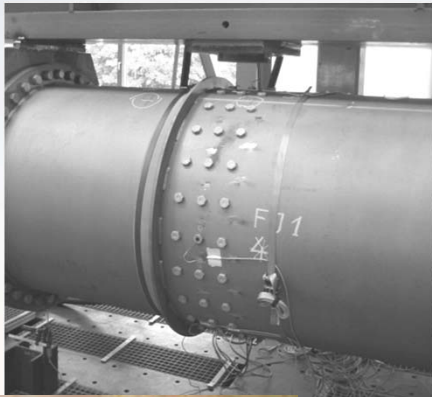


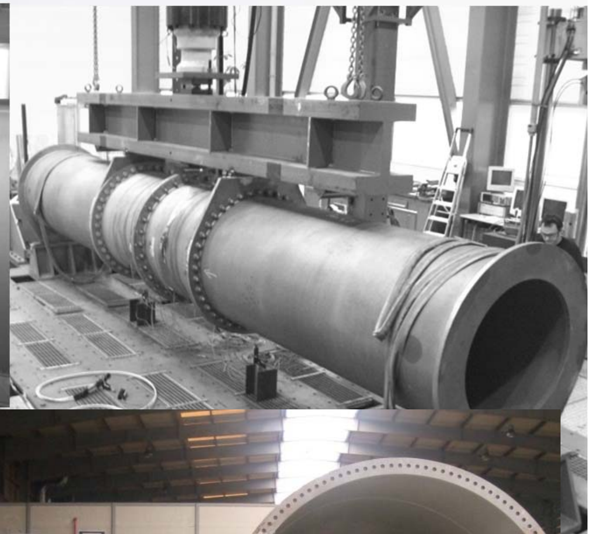




Overview of the experimental work (…cont.)

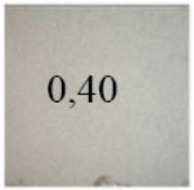
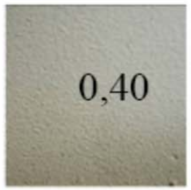
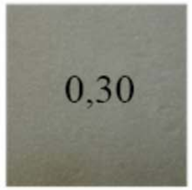
- 4 Point bending test
- Monitoring
- Feasibility study



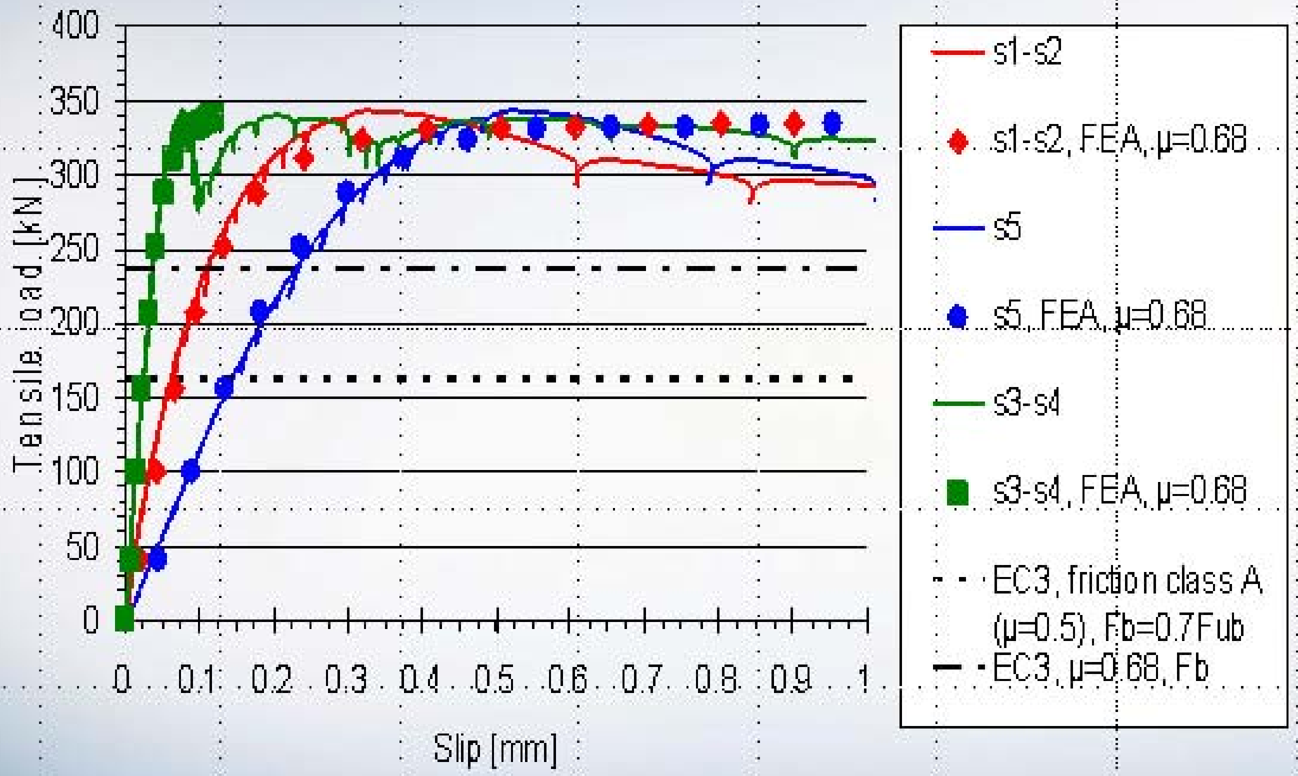


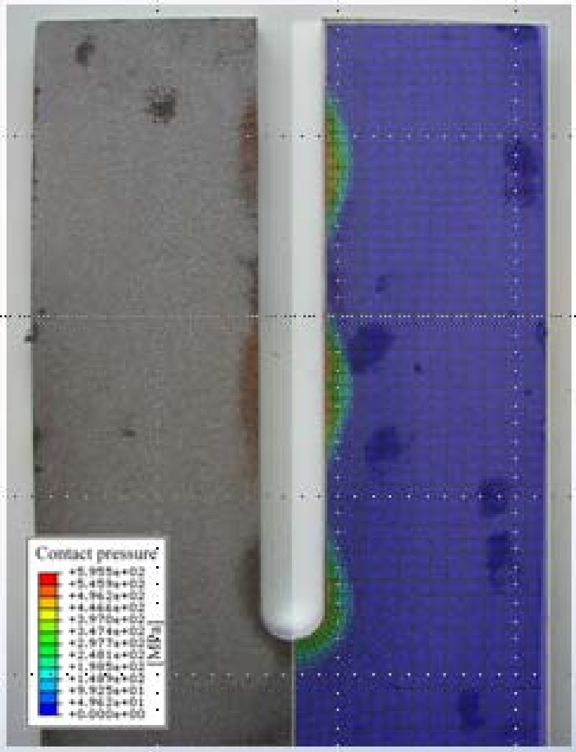
State of the art: Slip factor (FCTUC)

- Setup dependent:
  steel grade, surface finishing
- Testing acc. to EN1090-2

	Type A	Type B	Type C	Type D	Type E	Type F
Surface blasted	with shot grit, degree Sa 2½	with shot steel, degree Sa 2½	with shot steel, degree Sa 3	chemistry	with shot steel, degree Sa 2½	with shot steel, degree Sa 2½
Surface treatment	without treatment	without treatment	spray metalized with zinc 75 µm	galvanization by hot immersion with zinc 160 µm	painted with zinc ethyl-silicate (one layer) with 70µm	painted with zinc epoxy (one layer) with 70µm (current product in Portugal)
Surface appearance	 0,47	 0,50	 0,40	 0,40	 0,40	 0,30

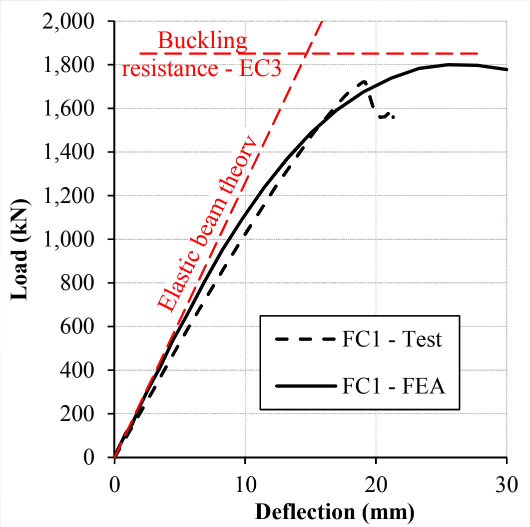
Experiment vs. FE modeling-friction connection



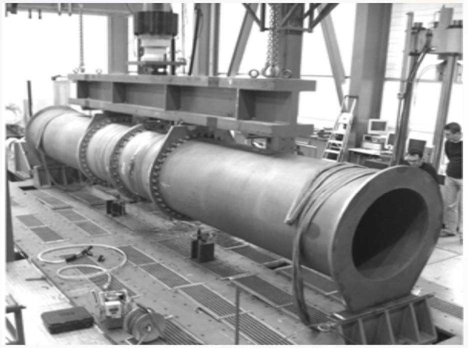


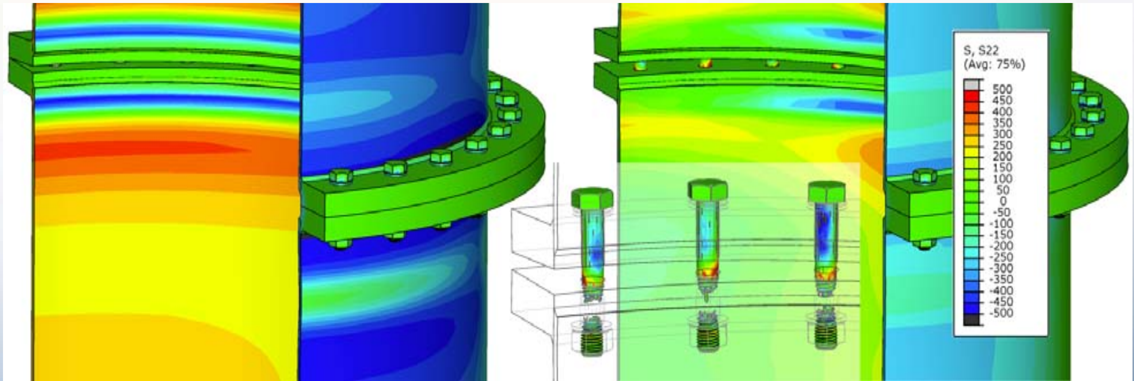
Validation of FE models

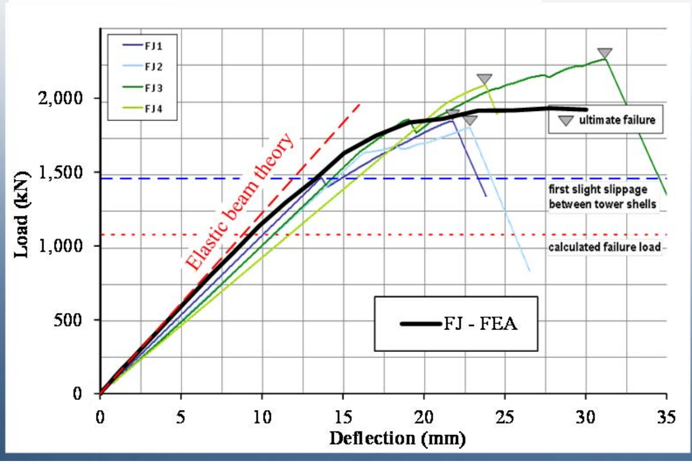
- Down-scaled four-point bending tests (RWTH)



- **Ring flange conneciton**



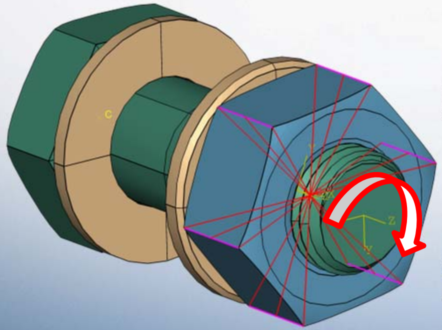


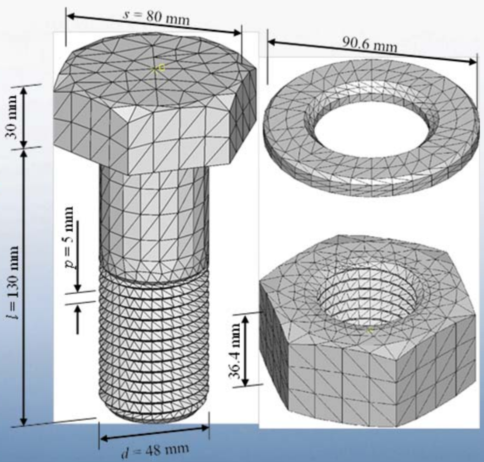


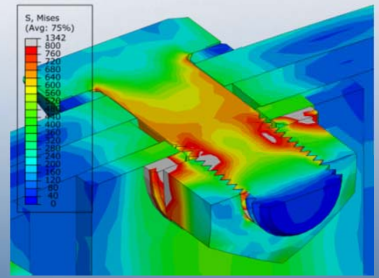
- **Friction connection**

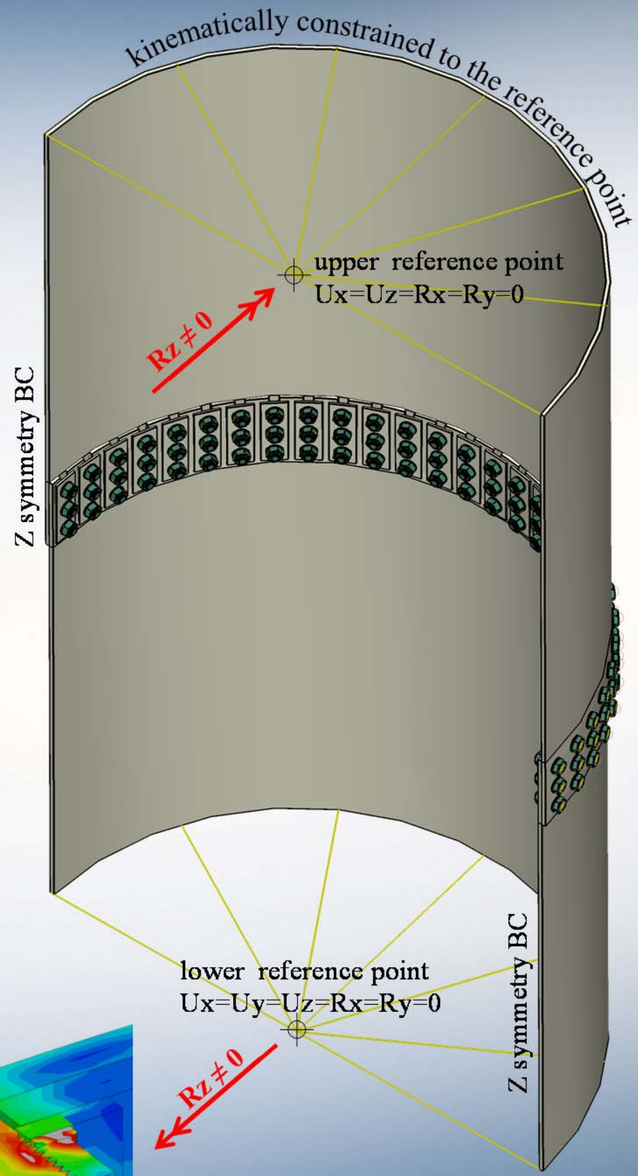
FE model

- Bending moments are applied as imposed rotations of the shell reference points.
- Vertical symmetry BC
- Realistic geometry of. bolts and nuts.
- Preloading of bolts by the „turn-of-nut-method“.

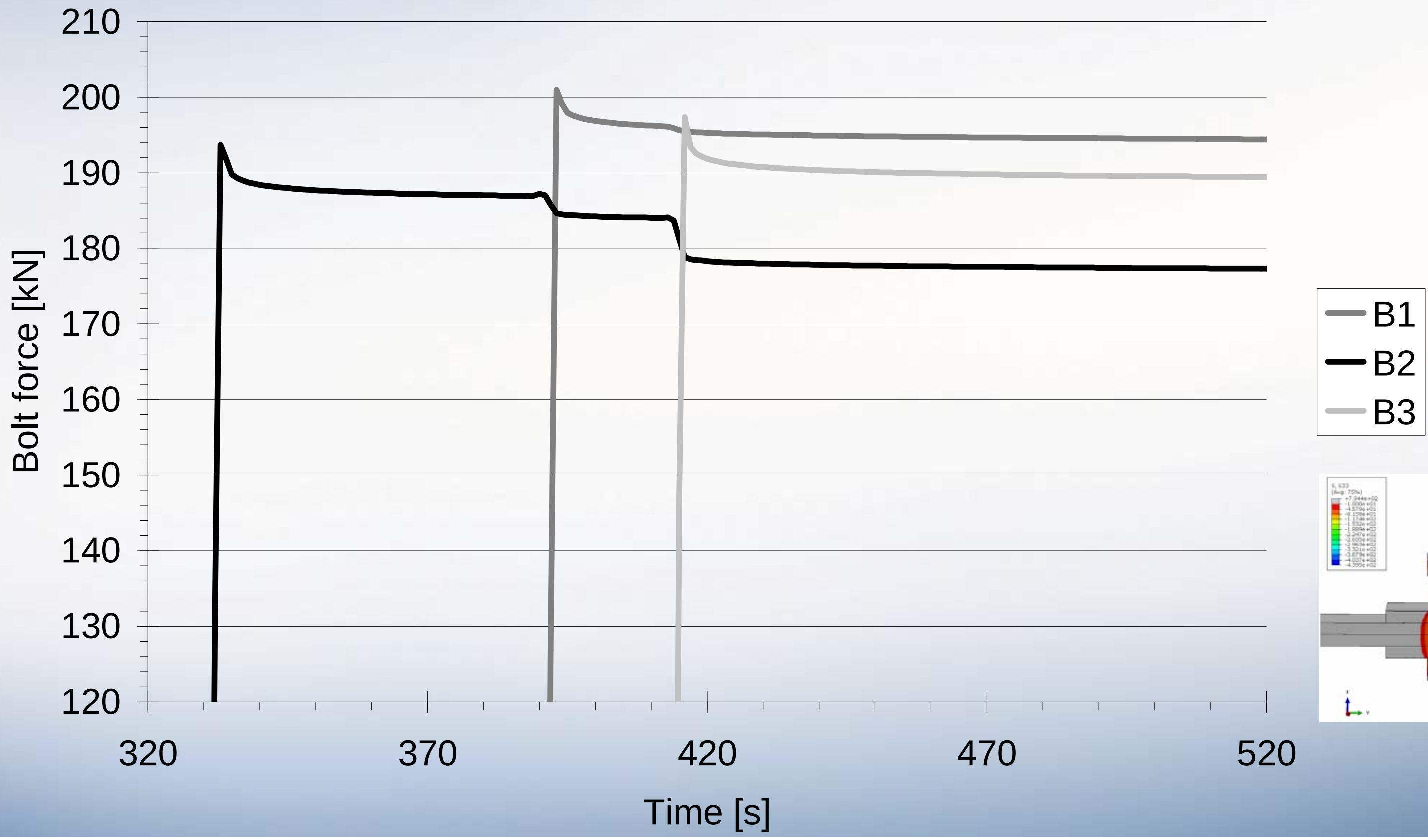


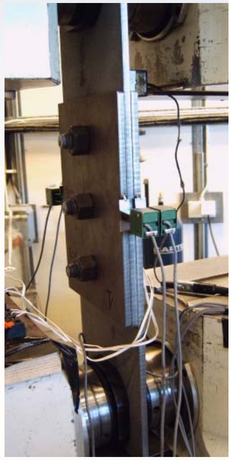




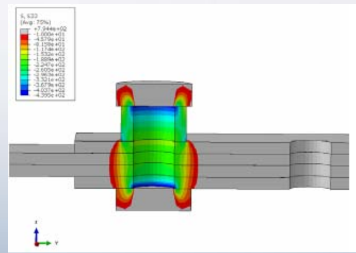


Loss of pre-tension force during the assembling

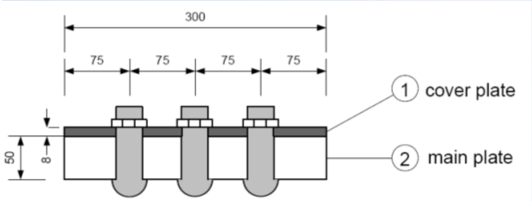




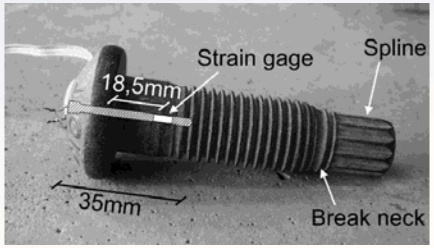
M20

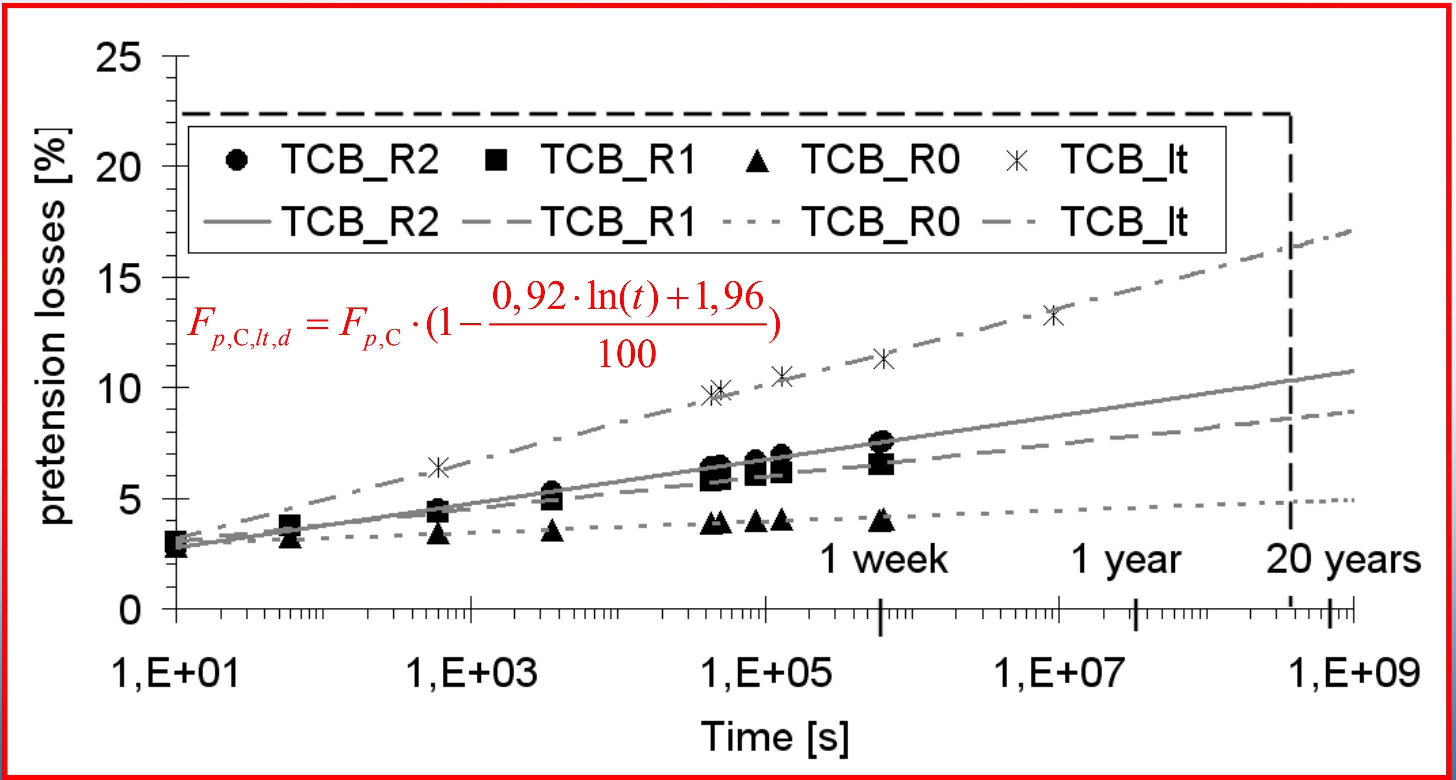


Results of TCB



Zinc rich primer,
t = 80 µm





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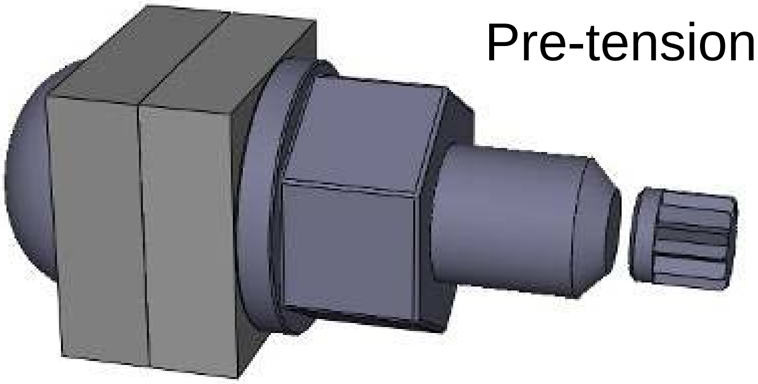
Special fasteners: Tension Control Bolts

- Quick and easy installation
- Properties equivalent to HS Bolts 10.9
- No torsion in the shank
- Corrosion protection

TCB S10T M20-55mm



Pre-tensioned !

Electric shear wrench

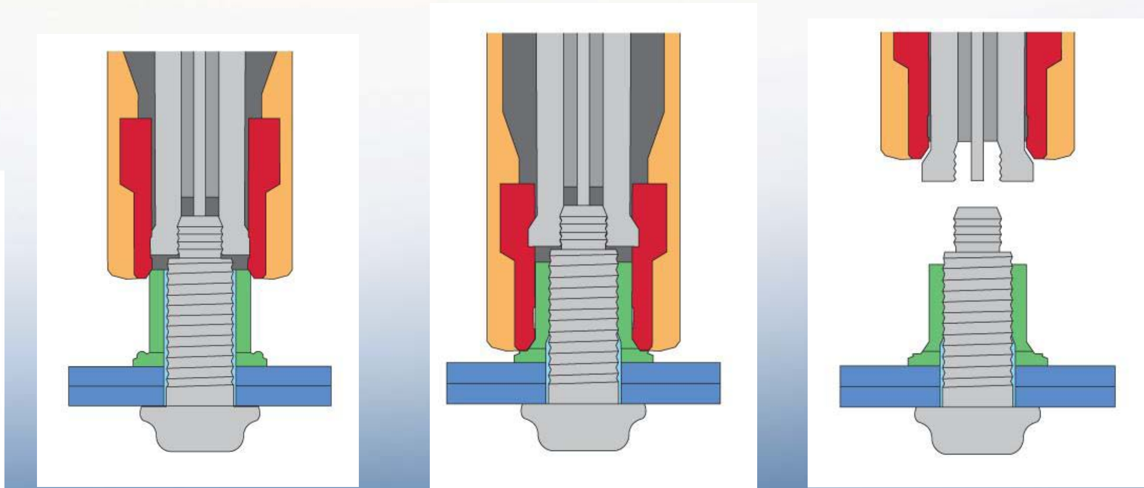
Special fasteners: Huck BobTail lockbolts

ALCOA

- Properties equivalent to HS Bolts 10.9
- No torsion in the shank, Junkers test
- Up to 25,4mm diameter, 1 inch
- Maintenance free bolts

Deutsches Institut für Bautechnik DIBt

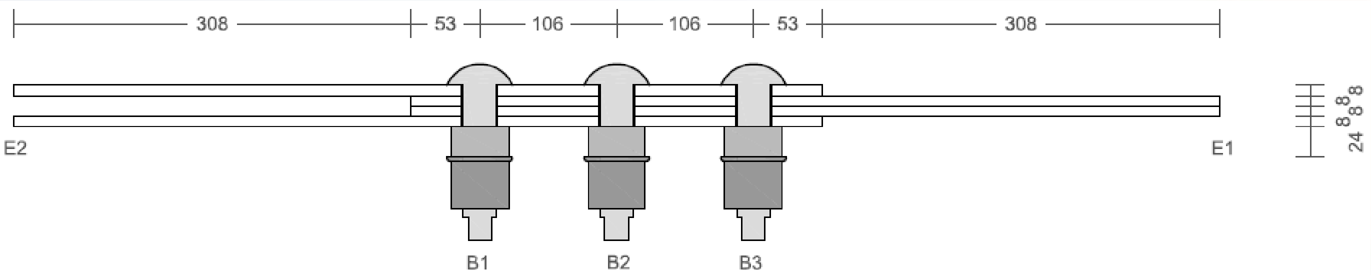
Zulassungsnummer:
Z-14.4-591
Geltungsdauer
vom: **4. November 2011**
bis: **4. November 2016**



Experimental investigation: Performed tests

- **Pure relaxation tests on double shear lap joint**

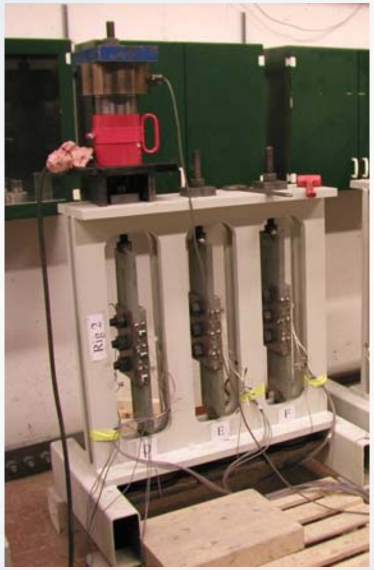
  Huck BobTail lockbolts



galvanization, t = 250 µm

Long term tests

- "Standard" configuration
- Load levels: 60 % and 80 % of
  static resistance
- Duration: 30 weeks



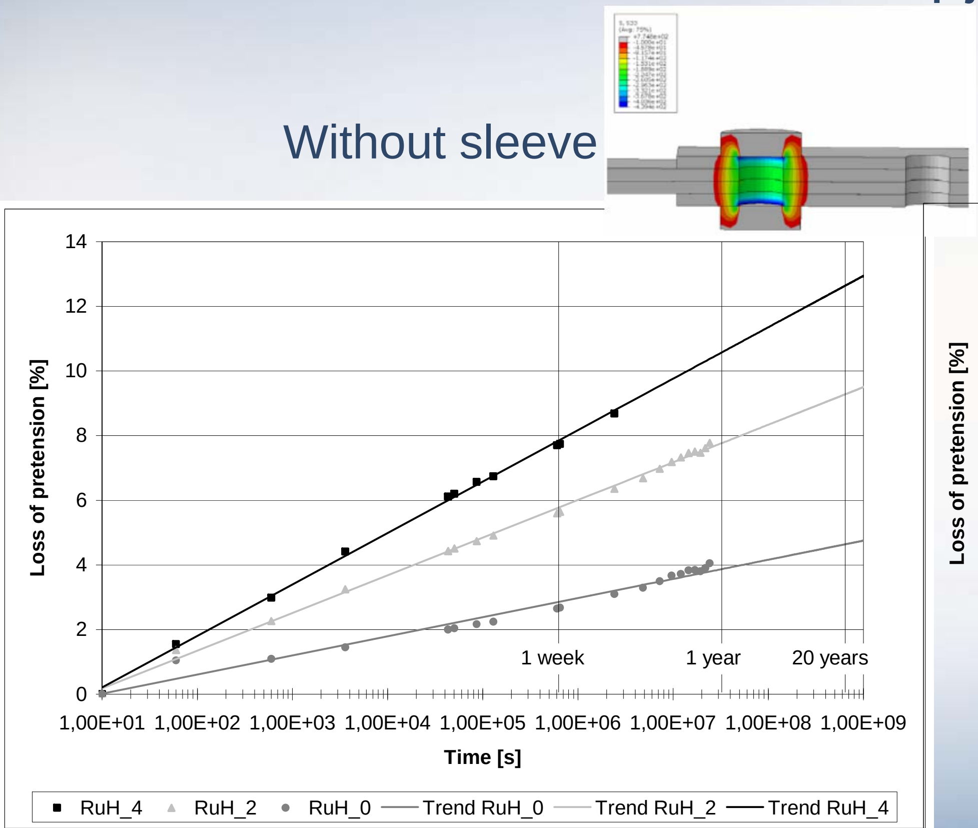
Long term test rigs

⇨ Creep
⇨ Relaxation
⇨ Remaining resistance

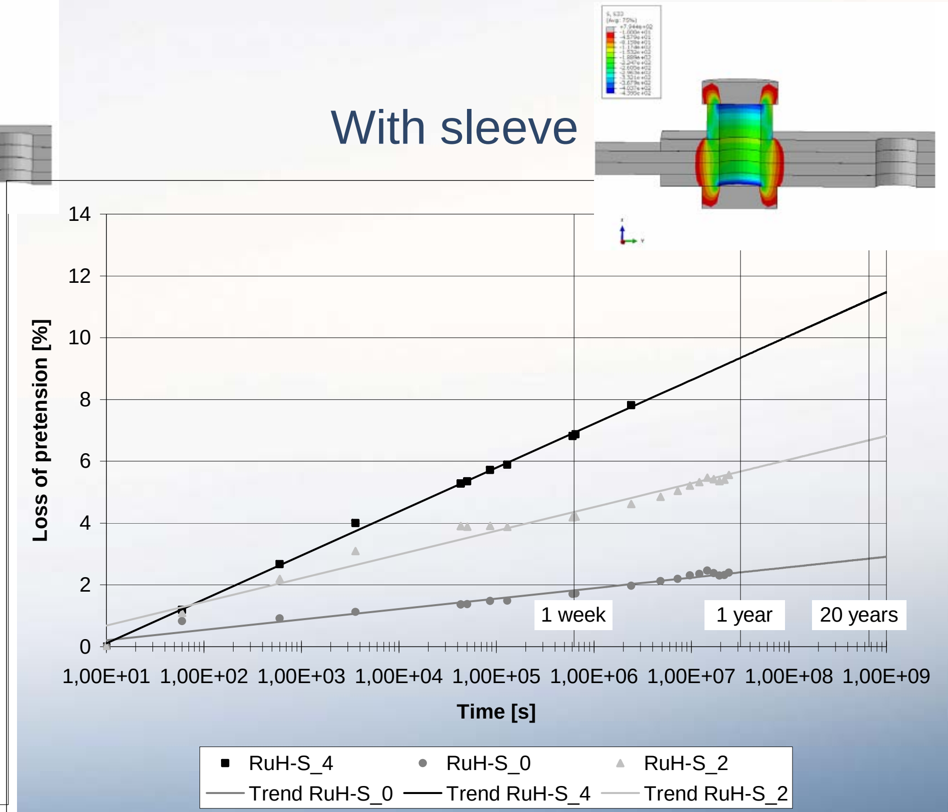
Test results

- **Pure relaxation tests on double shear lap joint**

Without sleeve



With sleeve



Feasibility test for flangeless modular tower

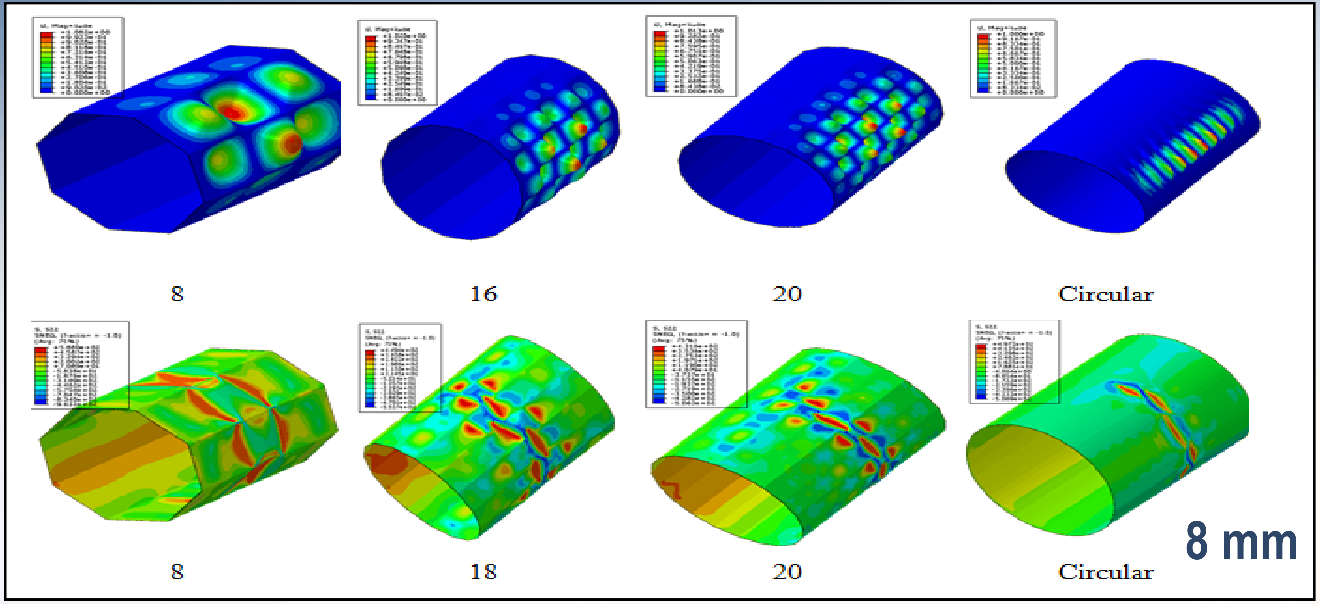
MARTIFER

t=15 mm

t=30 mm

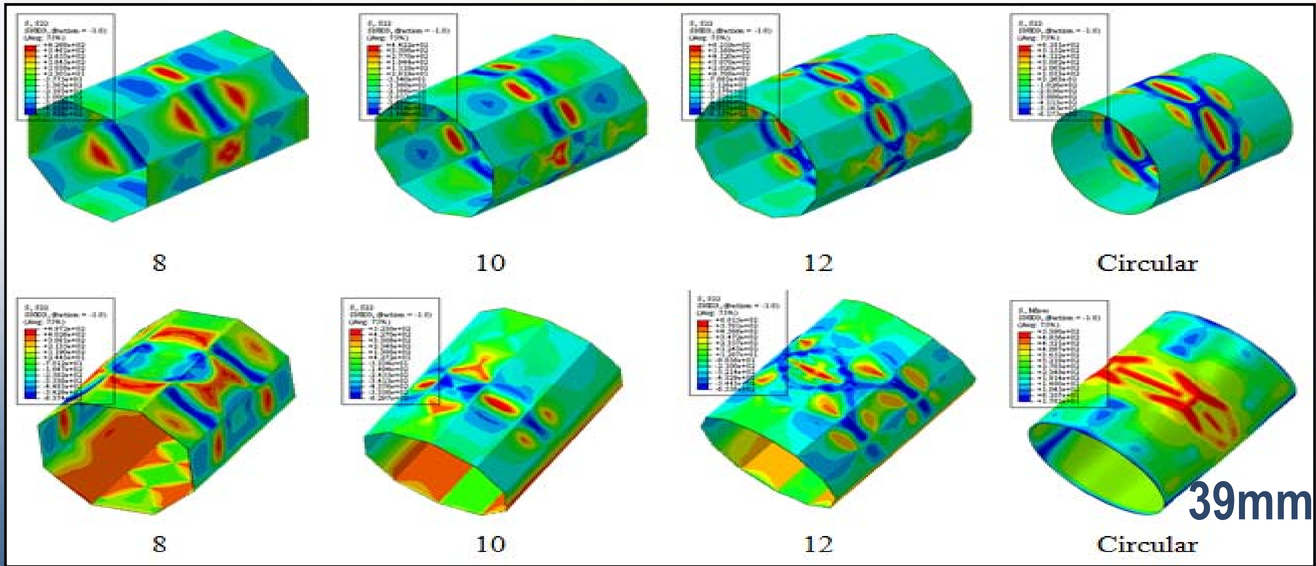
BobTail
M 1 inch

Circular vs. polygonal shell, modular tower



Bending Buckling analysis

Failure mode



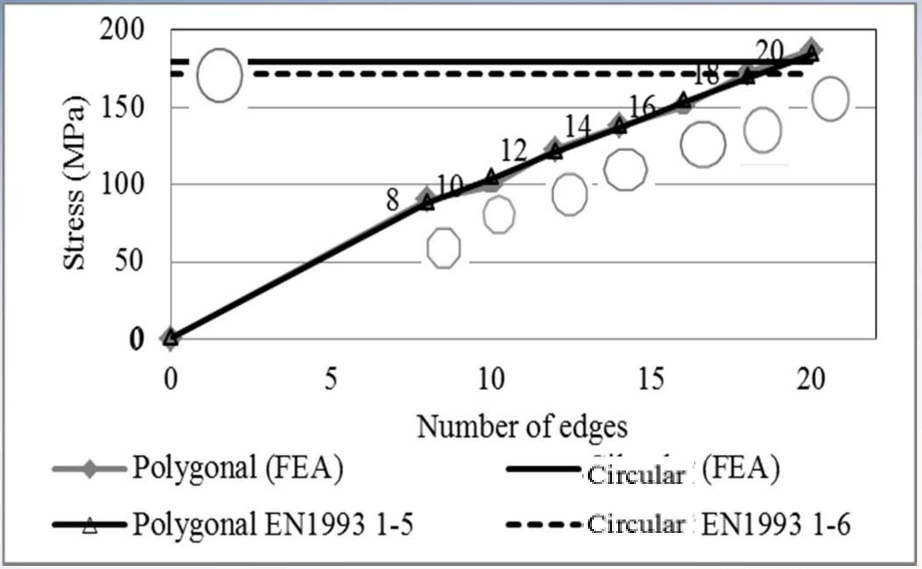
Compression Buckling Analysis

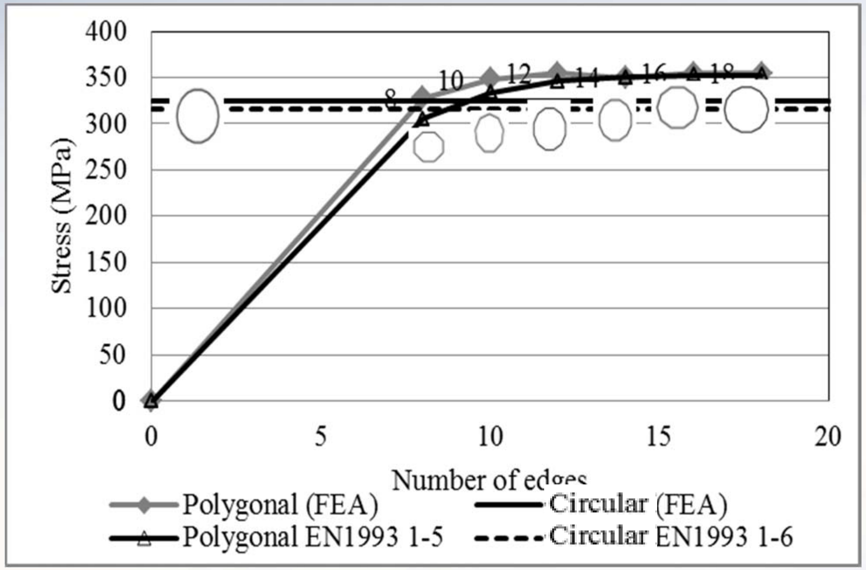
Failure mode

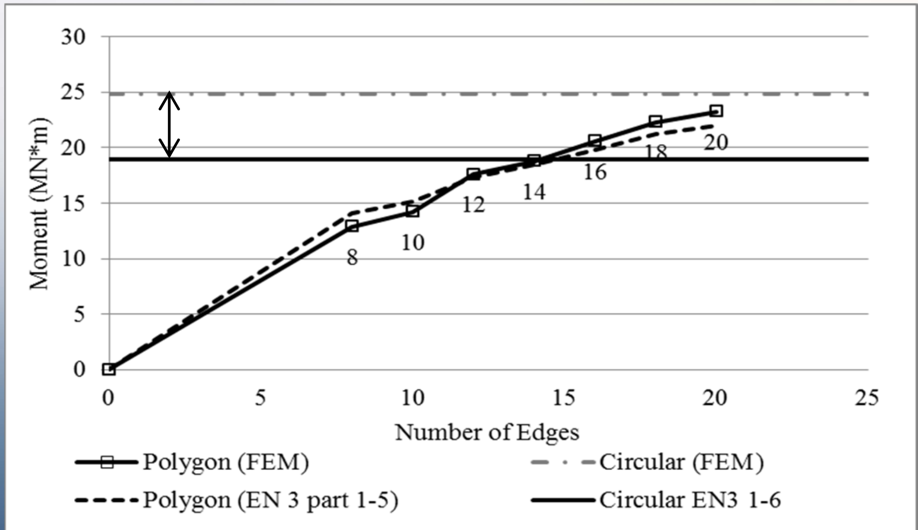
FEM and Eurocodes comparison

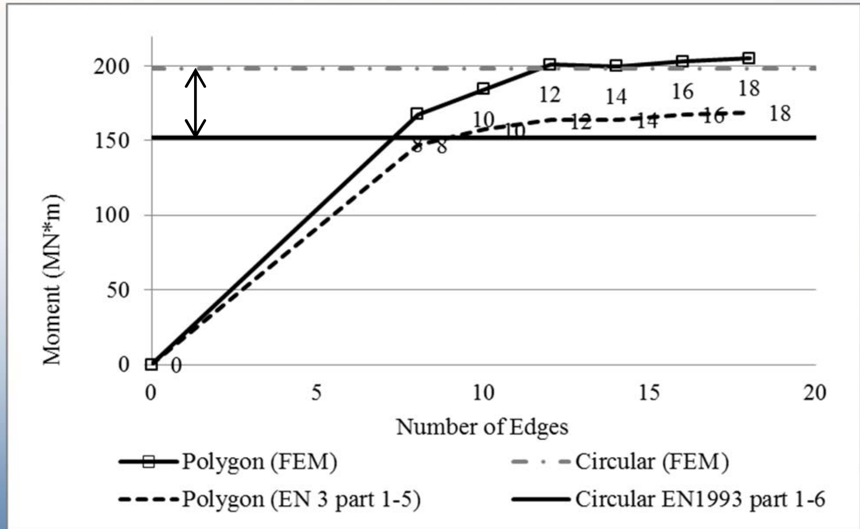
8 mm

39 mm

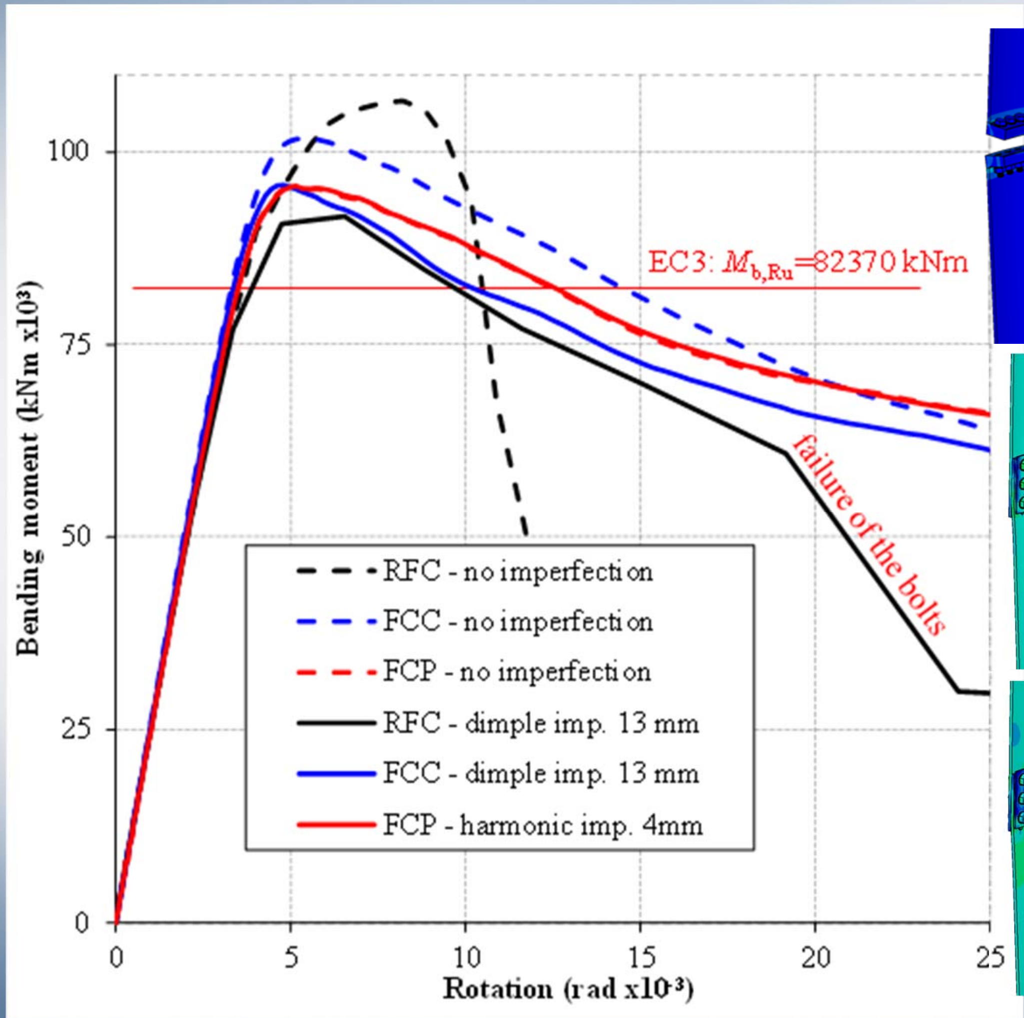


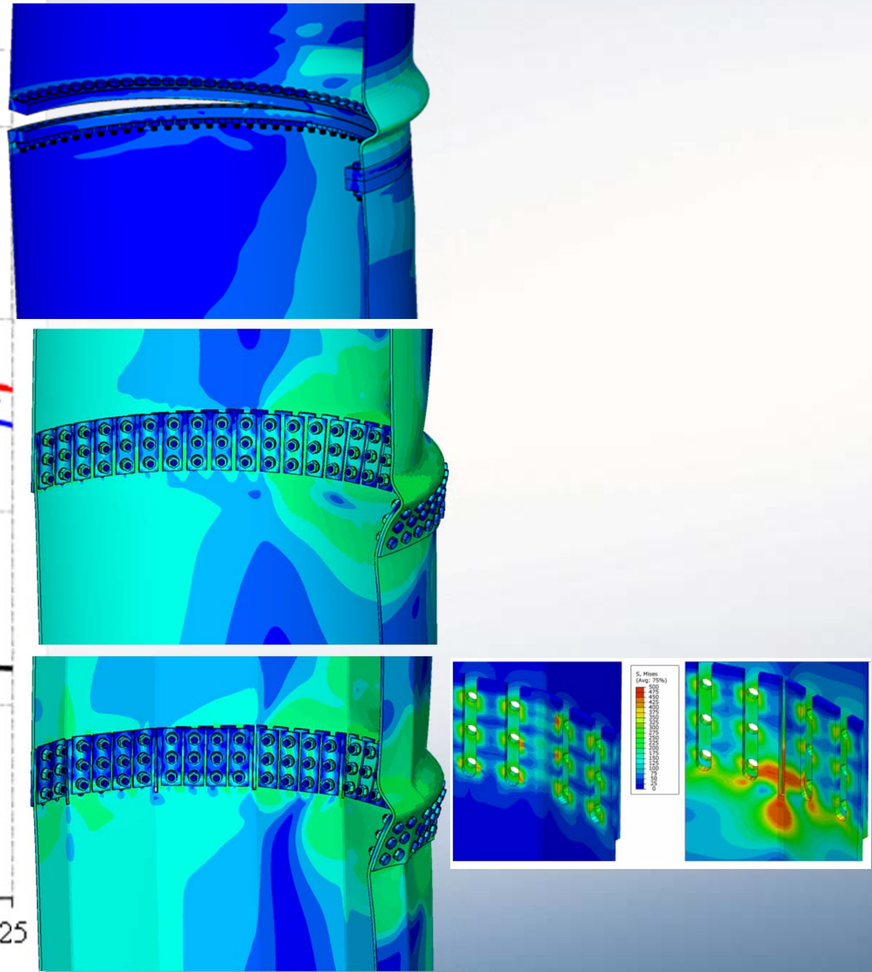




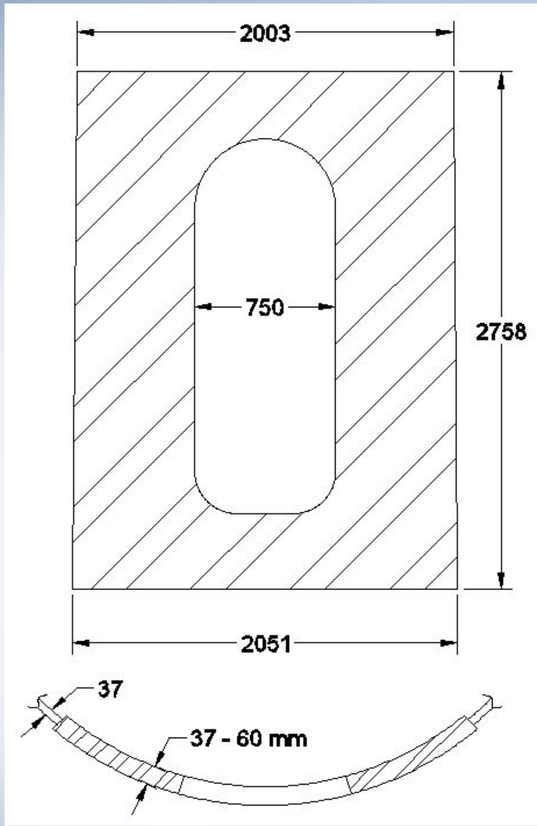


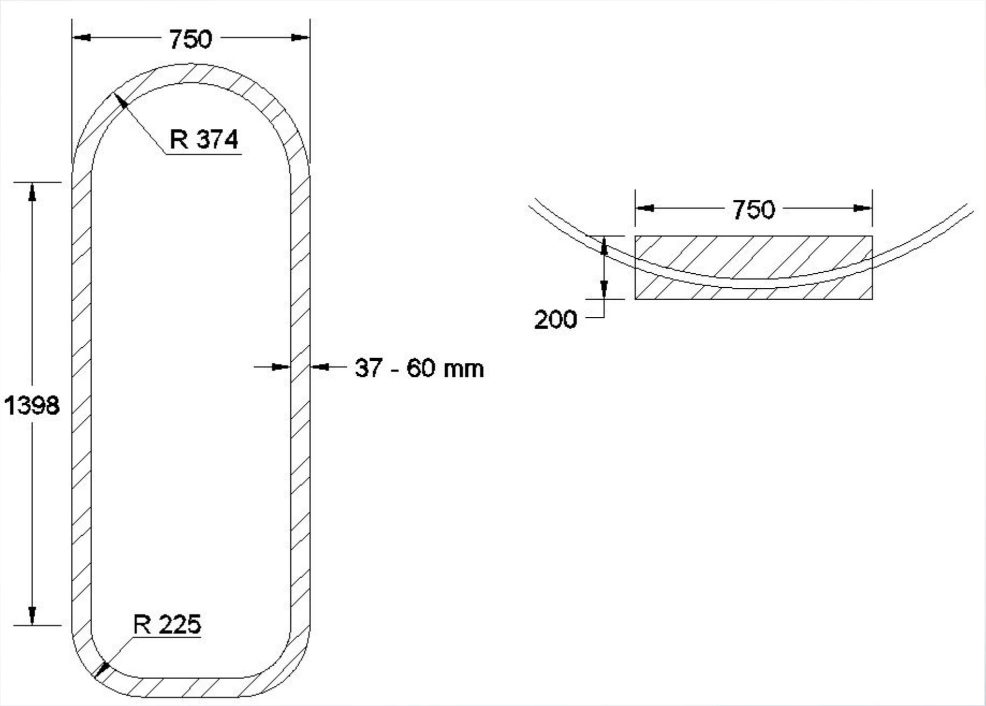
Main findings





Two Methods of Stiffening

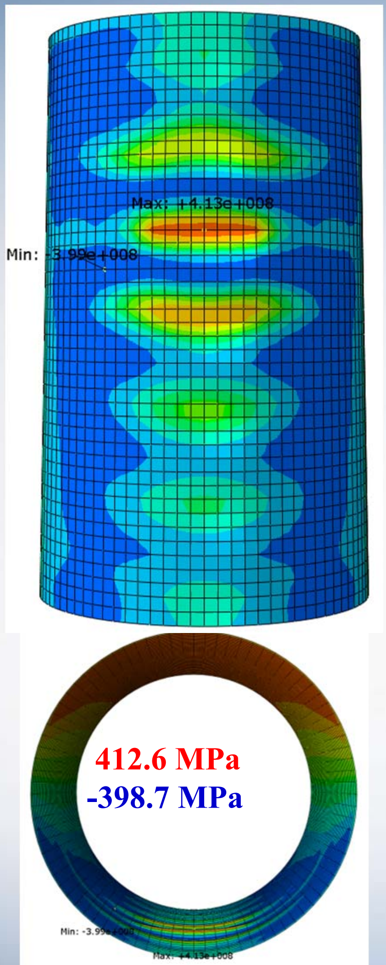




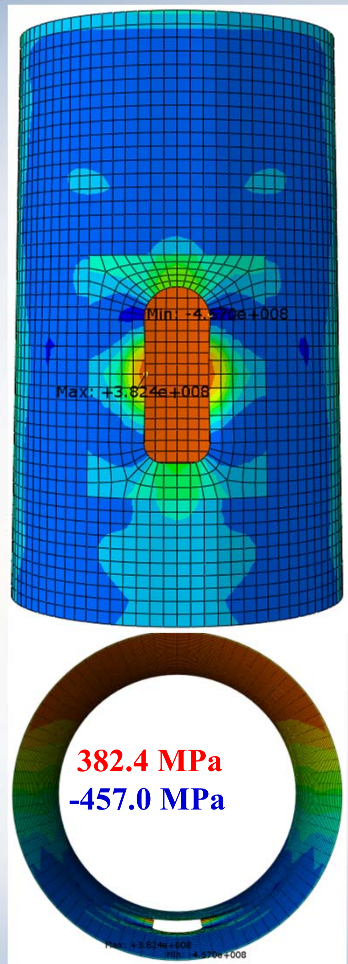
Stiffening by varying the plate thickness

Stiffening by the stiffener

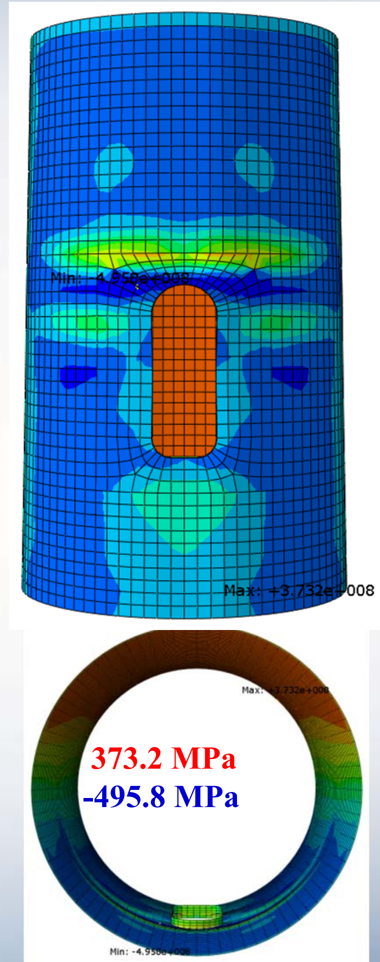
Stresses at the maximum load



Model without door opening



Model of the door opening with varying the plate thickness



Model of the door opening with the stiffener

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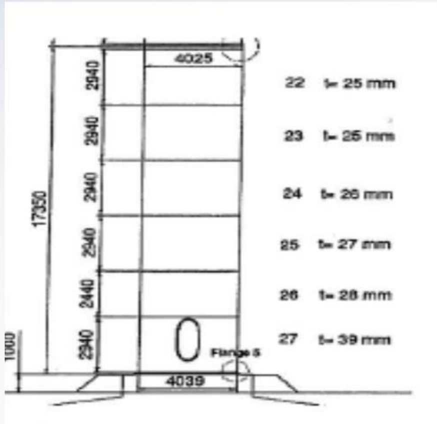
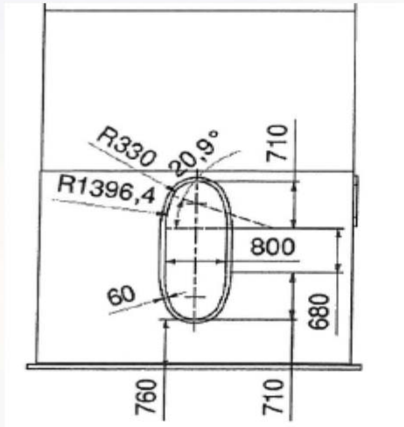
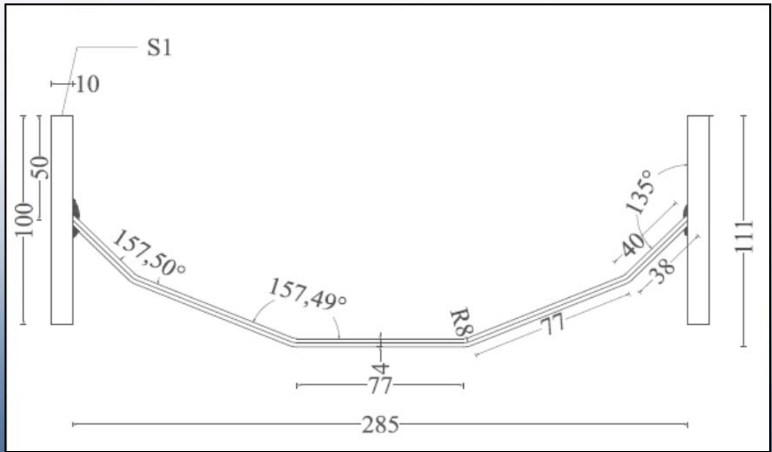
Laboratory tests preparation

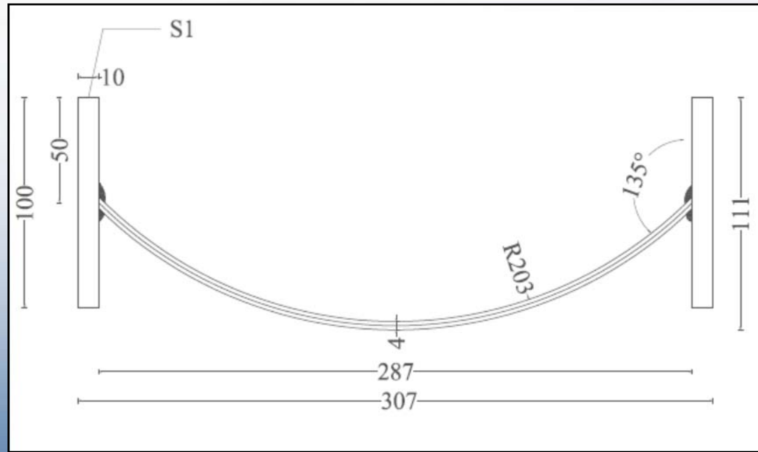
$$\sigma_{crit} = \frac{E}{6\cdot\left(1-\upsilon^2\right)}\cdot\left[\sqrt{12\cdot\left(1-\upsilon^2\right)\cdot\left(\frac{t}{r}\right)^2+\left(\frac{\pi\cdot t}{b}\right)^4}+\left(\frac{\pi\cdot t}{b}\right)^2\right]$$

Critical stress for simply supported curved plates C.W. YOUNG









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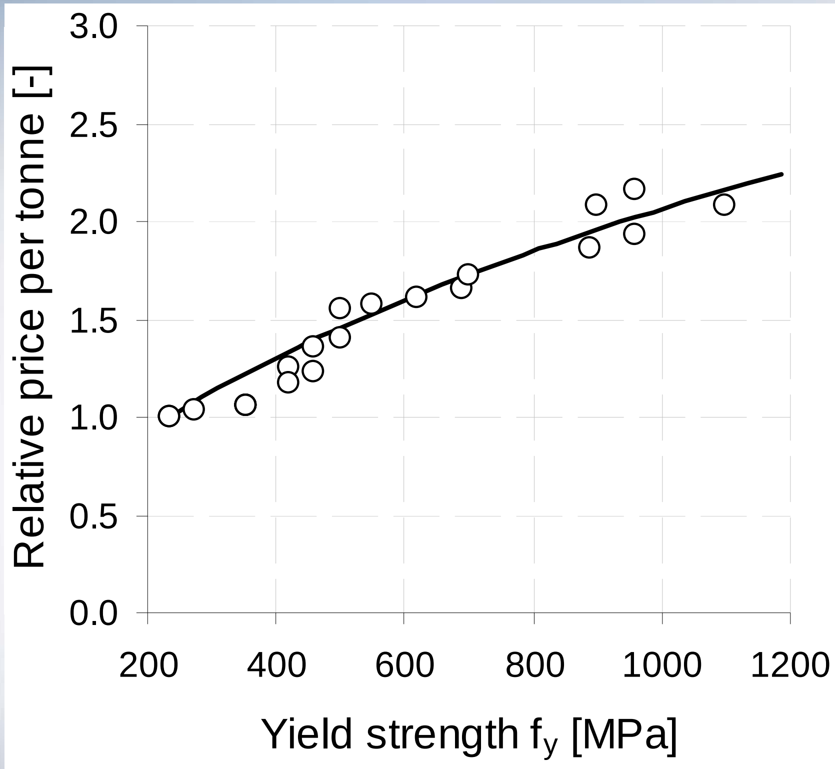
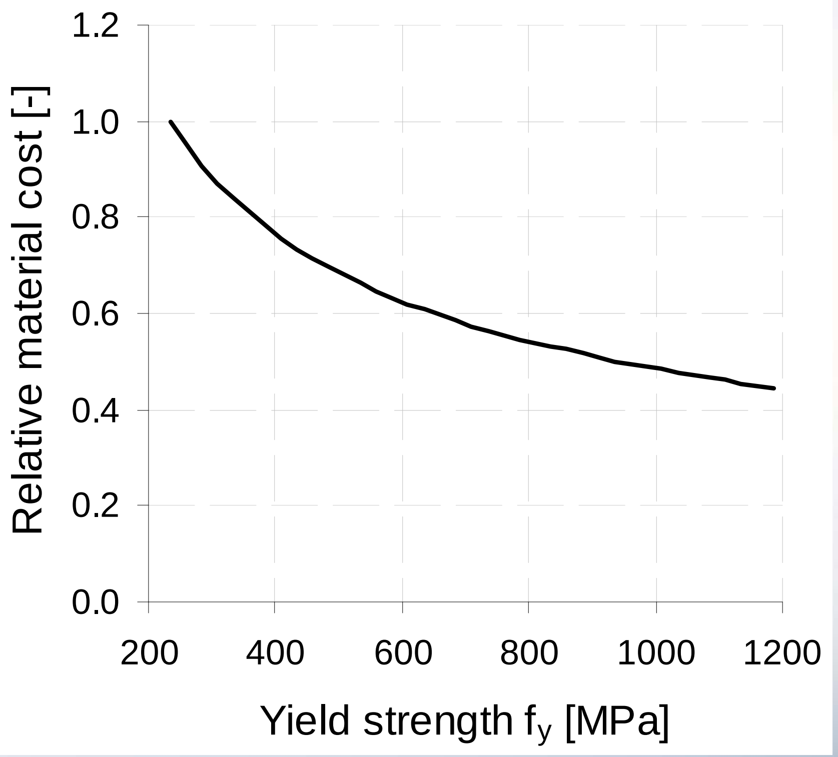
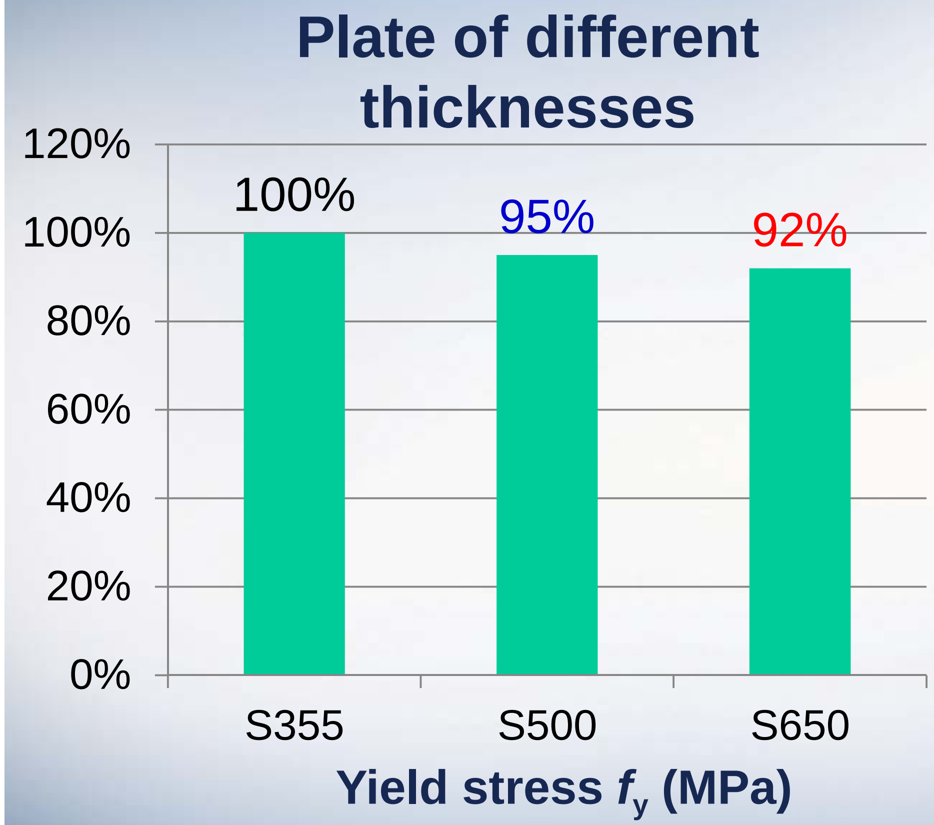
Costs vs. strength, LTU- price model*

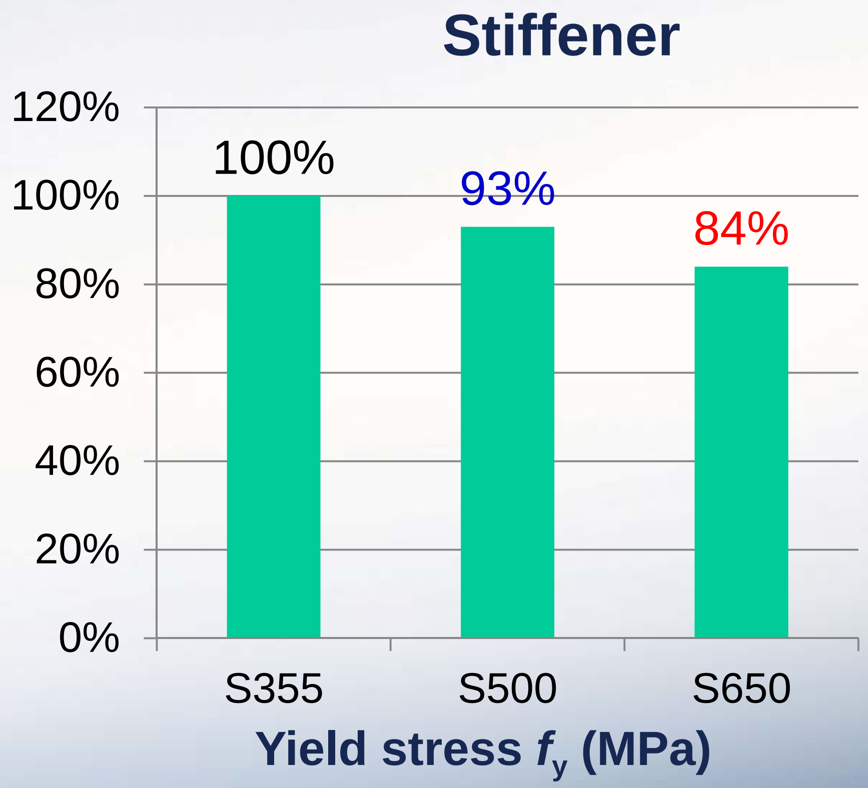




*** Prof. Johansson, Ch. 5.3. Buckling Resistance of Structures of High Strength Steel, in Structural Engineering Document 8, Use and Application of High-Performance Steels for Steel Structures, IABSE 2005**

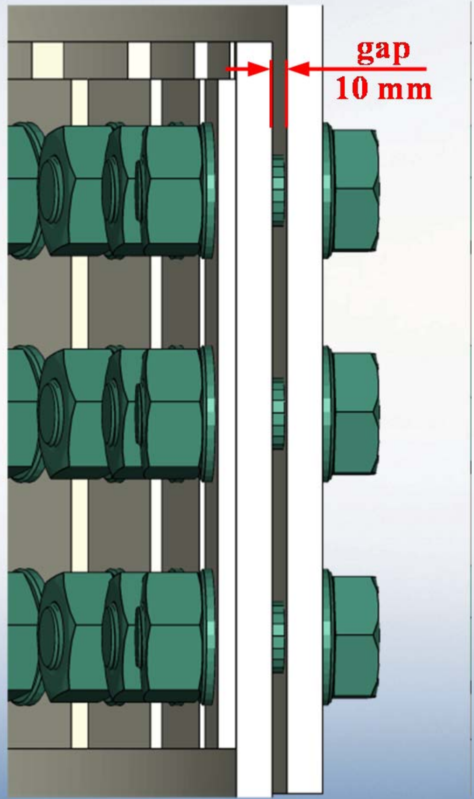
Material Cost Reduction for Stiffening of Door Opening

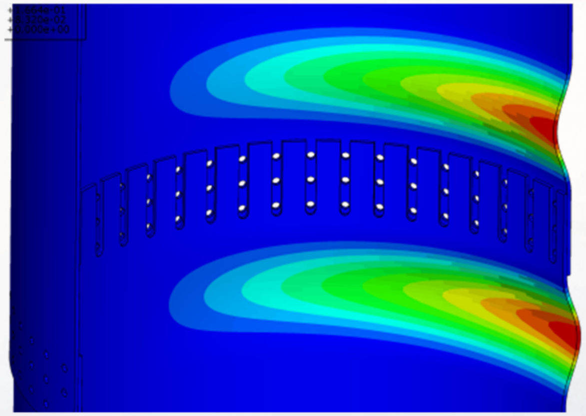




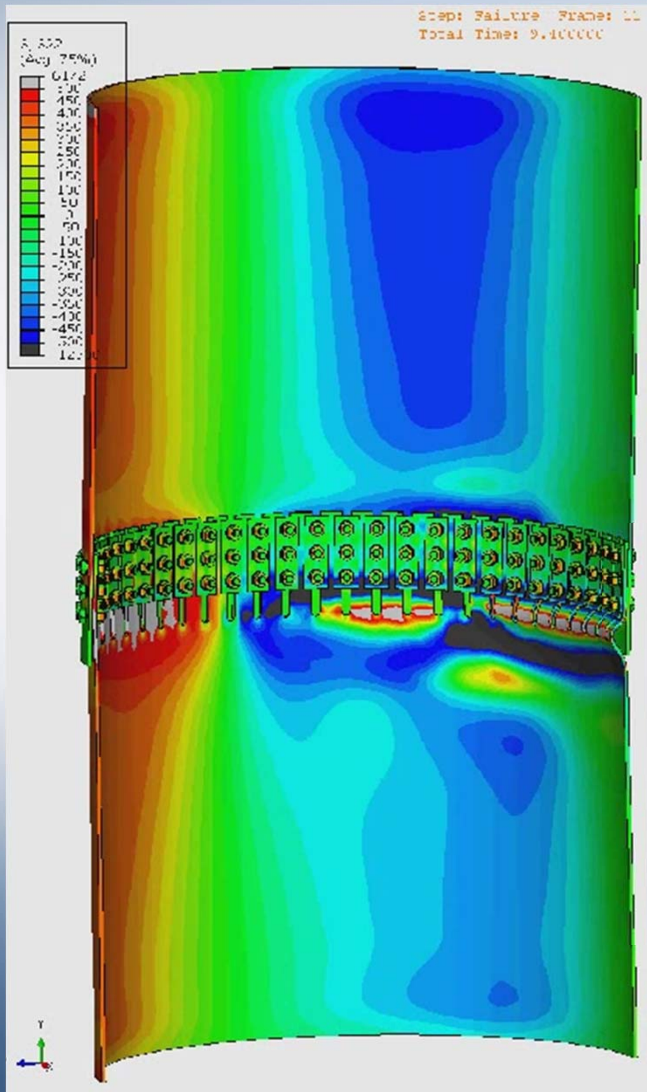
Initial imperfections

- Assembling tolerances for CFC
- Dimple imperfections EN 1993-1-6

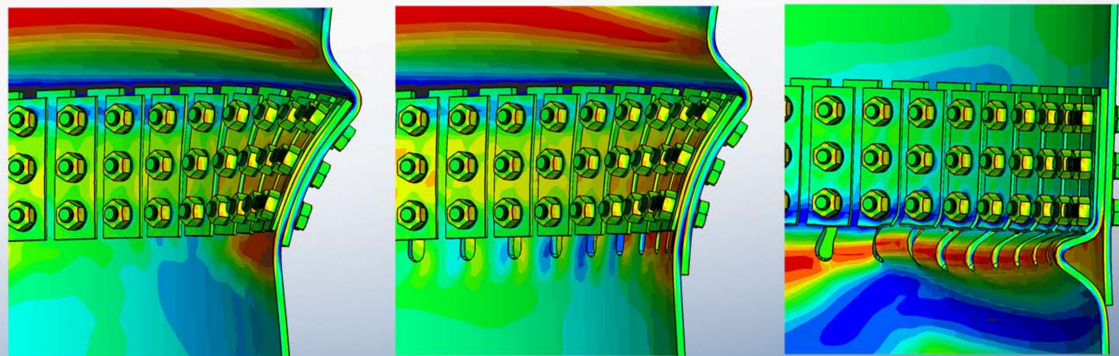




FEA: Nonlinear analysis
-failure modes, influence of the finger length



- Failure mode for the friction:
  - Local buckling, adjacent to the connection
  - ”Global buckling” of the fingers.



a) L_F = 450 mm (C1B450)   b) L_F = 550 mm (C1B550)   c) L_F = 650 mm (C1B650)

Flange connection- RINGMAN project

Offshore Wind Turbine Towers
- A Quicker, Cheaper Flange Supply Route

(http://ringmanproject.com)

Objectives:

Develop of high quality, low distortion, thick section electron beam welded flanges.

Understanding of the flange property requirements.

Procedures for inspection.

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TWI
Technology Engineering

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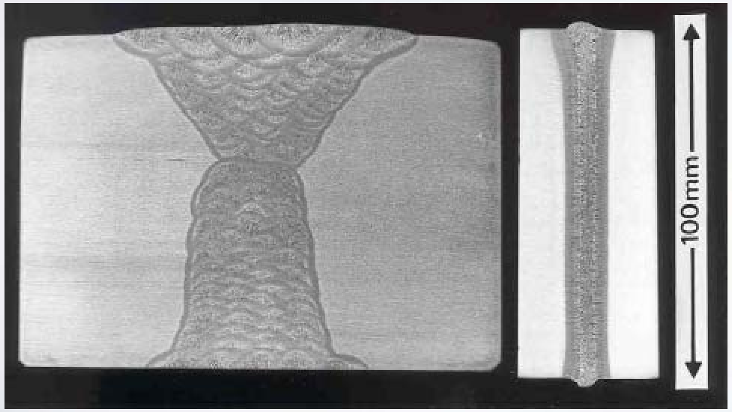
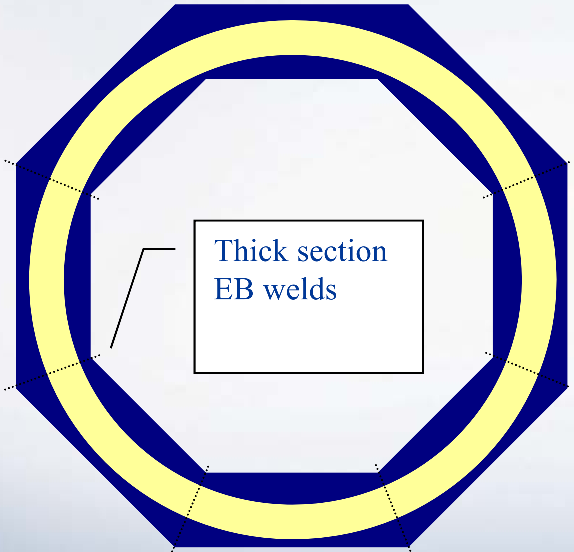
RINGMAN (http://ringmanproject.com)



Flanges are very thick section – i.e. greater than 150mm, conventional welding fabrication would be time consuming and distortion of the flange would require expensive compensation.

Electron beam thick section welding has been used in the power industry to make deep section, low distortion welds at a fast rate.

RINGMAN (http://ringmanproject.com)

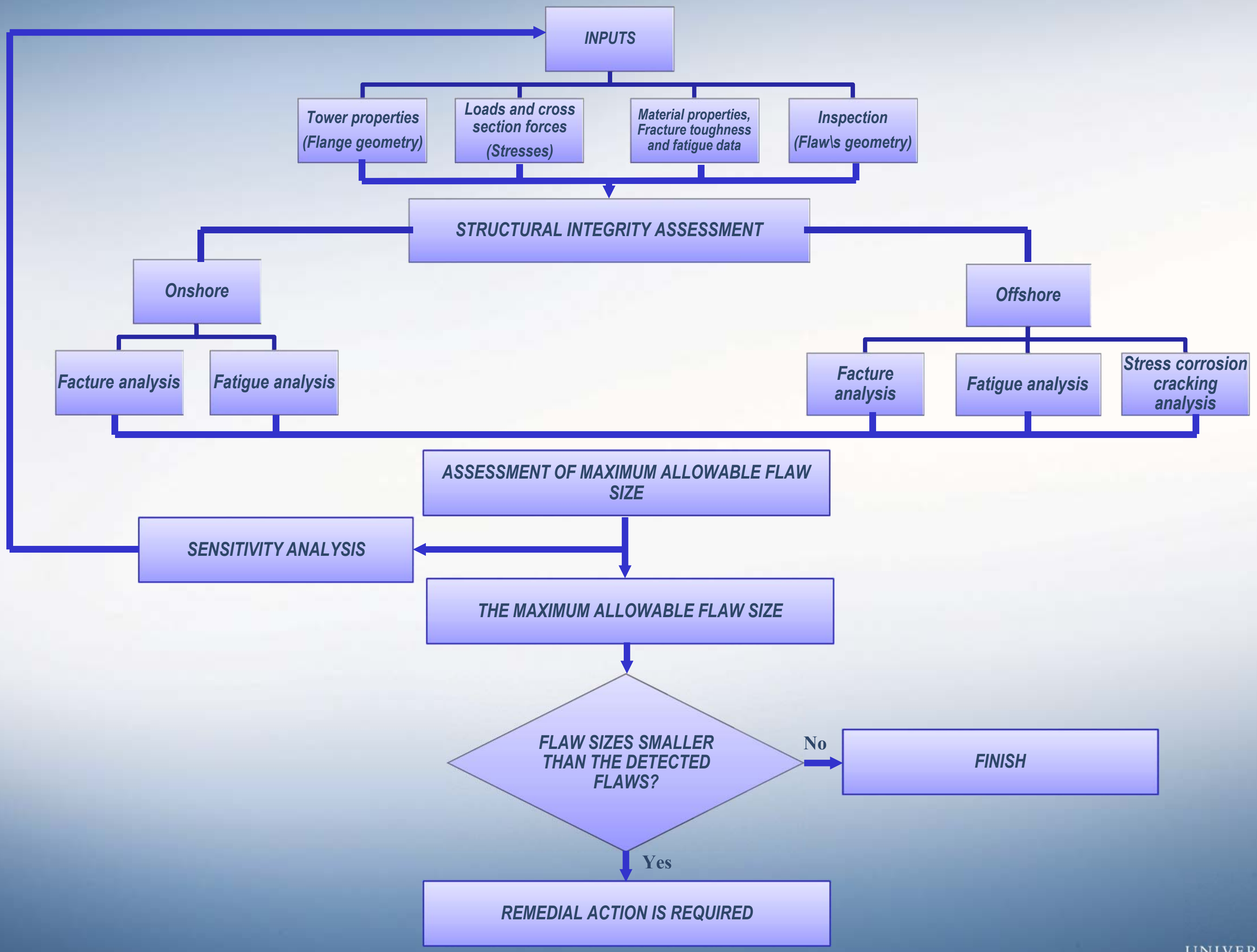


- The EB process (and heat treatment and accurate machining) produces flanges with high integrity welds, of high strength comparable to the parent material.

Structural Integerity Assessment of Wind Turbin Tower Flanges

(Assessment of the maximum allowable flaw size)

Methodology



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Material properties, fracture and fatigue data

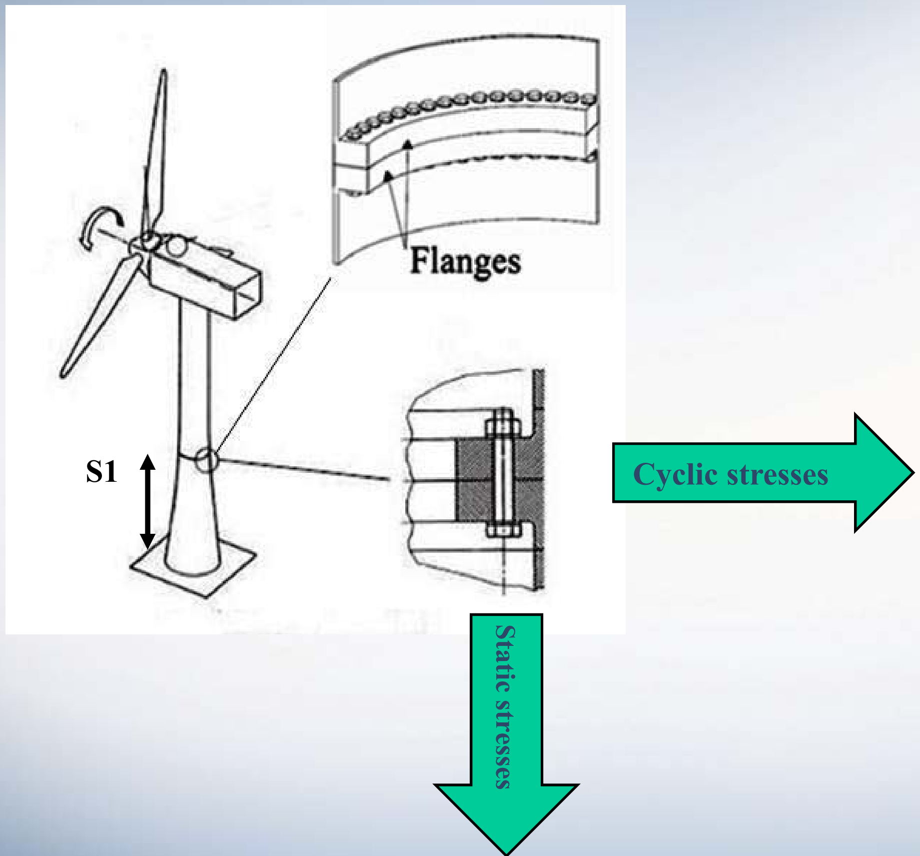
Material Properties			
Material	Yield stress (σ_y, MPa)	Ultimate tensile stress (σ_u, MPa)	Modulus of elasticity (E, MPa)
S 355	355	510	207000

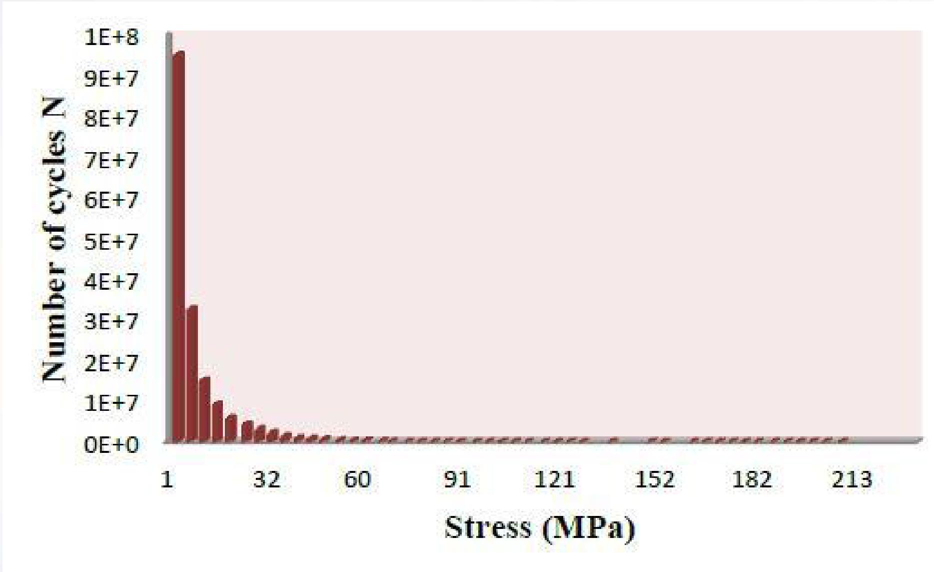
Fracture toughness data (BS 7910:2005 Annex J)		
Test temprature	T_{test}(°C)	-50
Charpy V impact energy	C_V(J)	6
Transition temprature	T_{27J}(°C)	-22
T_0	$T_{27J} - 18$°C	-40
Design Temprature	T(°C)	-30
Temprature term	T_K(°C)	25
Material thickness	B(mm)	24
Probability of failure	P_f	0.05
Fracture toughness (J.4)	$K_{mat}(MPa\sqrt{m})$	53.12

$$K_{mat} = 20 + \left[11 + 77e^{\{0.019(T-T_0-T_K)\}}\right]\left(\frac{25}{B}\right)^{1/4}\left\{\ln\left(\frac{1}{1-P_f}\right)\right\}^{1/4}$$

Recommanded fatigue crack growth parameters for steel in air (BS 7910:2005, Pages 56 and 58)			
Stress ratio (R)	$\Delta K_{th}(MPa\sqrt{m})$	C(da/dN in m/cycle)	m
-1	5.37	6.77E-13	2.88

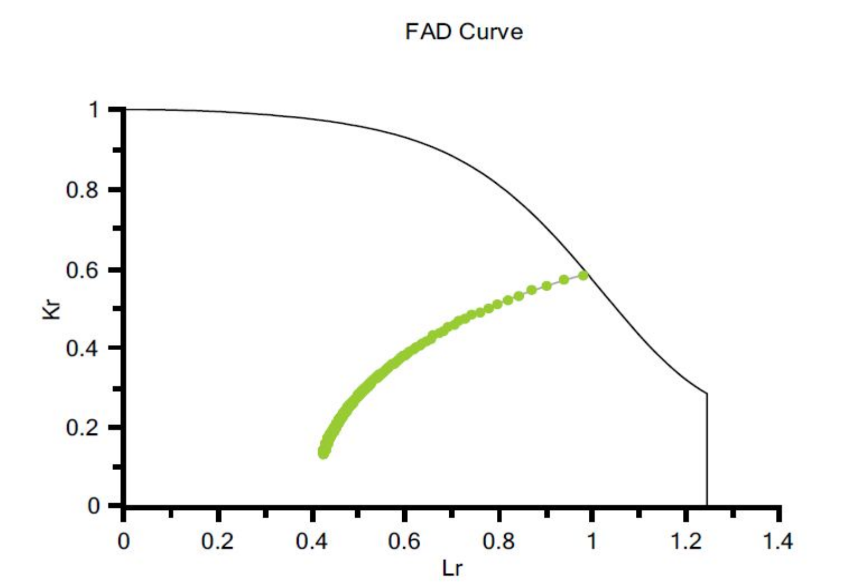
Loads and stresses (a virtual example)





Extreme load at S1	
ΔM [kNm]	Δσ (Mpa)
4.58E+04	218.1

Maximum allowable flaw size

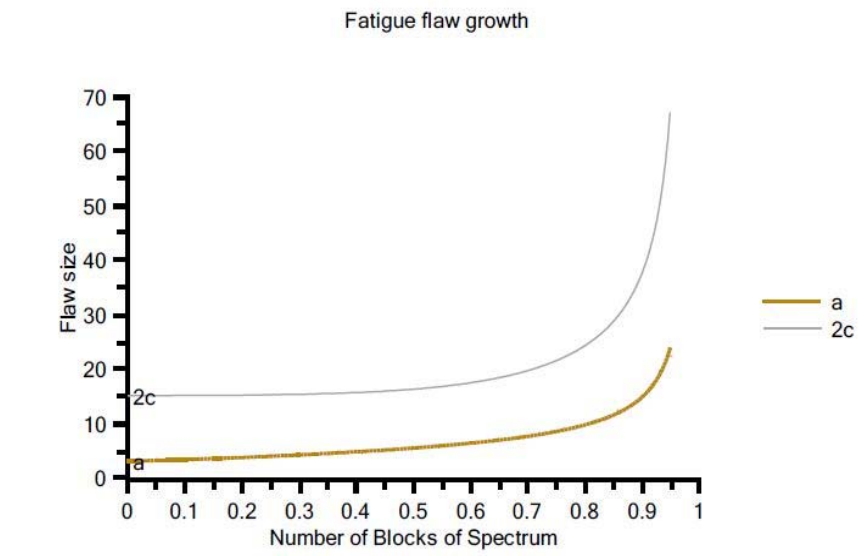


$$K_r = \frac{K_I}{K_C} \qquad L_r = \frac{\sigma_n}{\sigma_y}$$

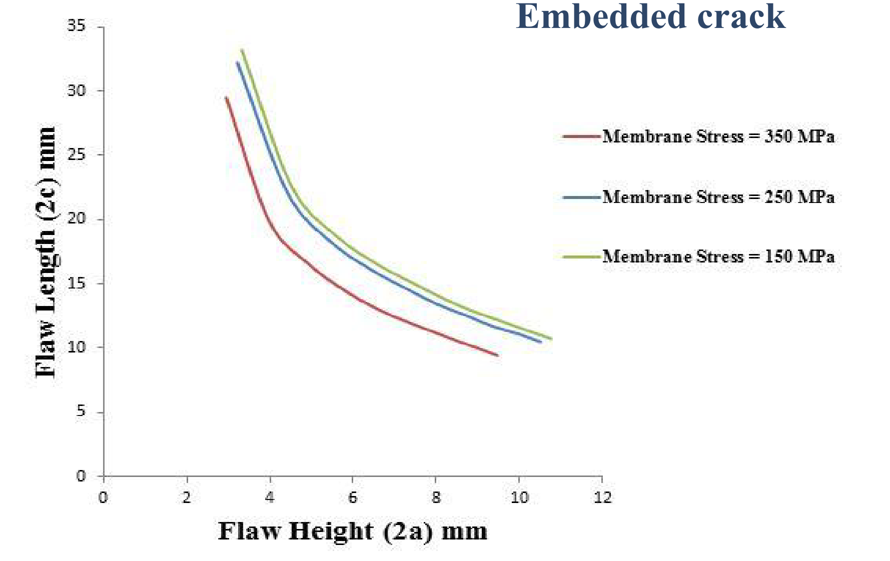
Where

K_I	**Stress intensity factor**
K_C	**Fracture toughness**
σ_n	**Applied stress**
σ_y	**Yield strength**

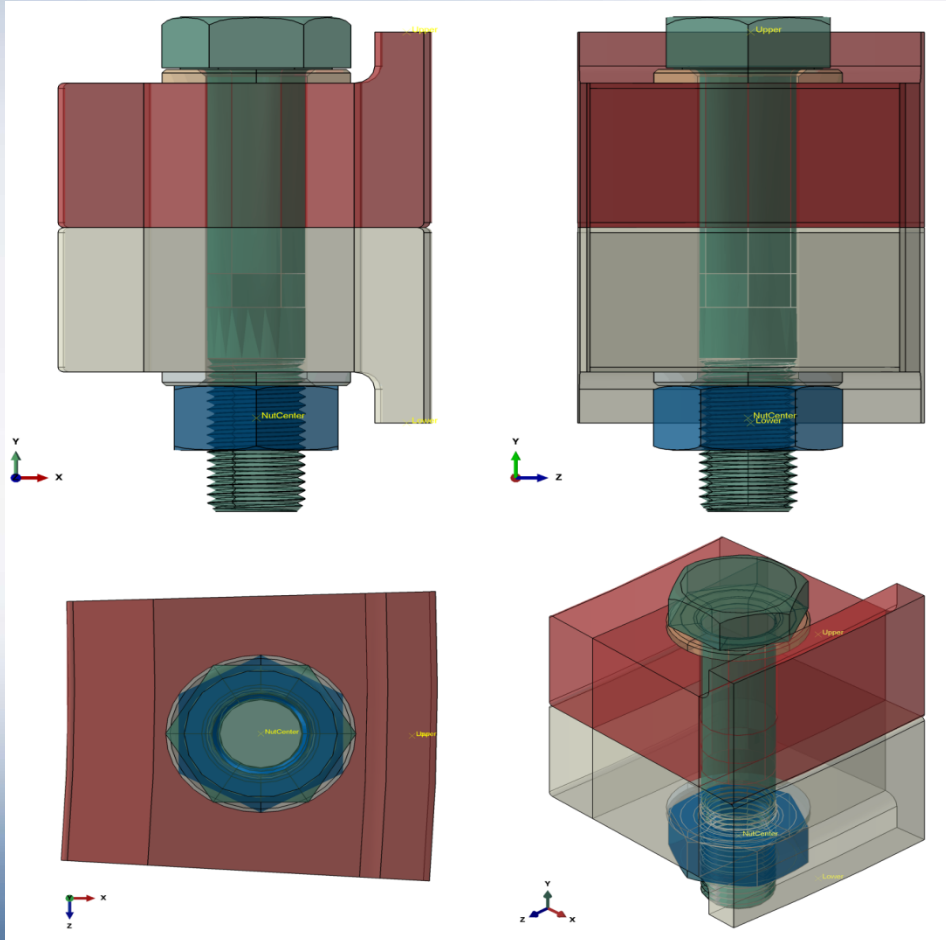
Surface crack



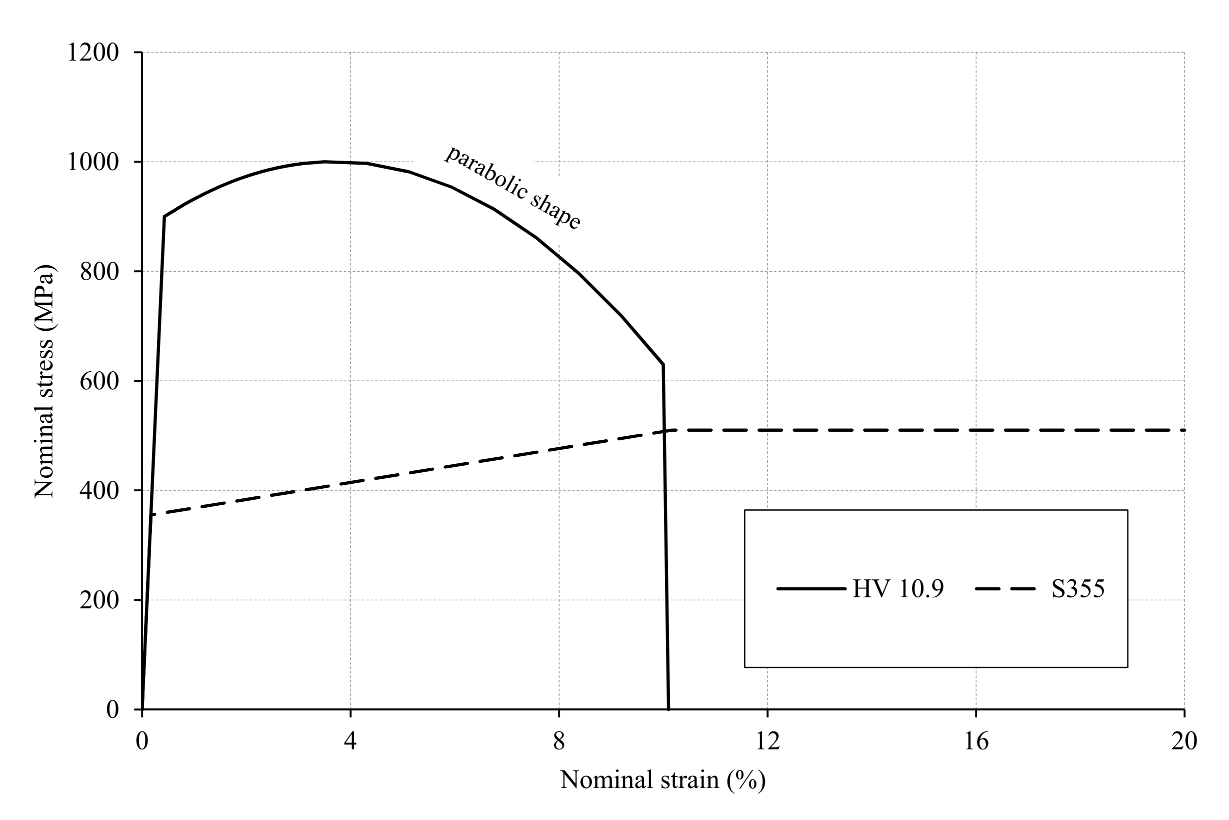
Embedded crack



The most detailed FE model for global analysis of the flange



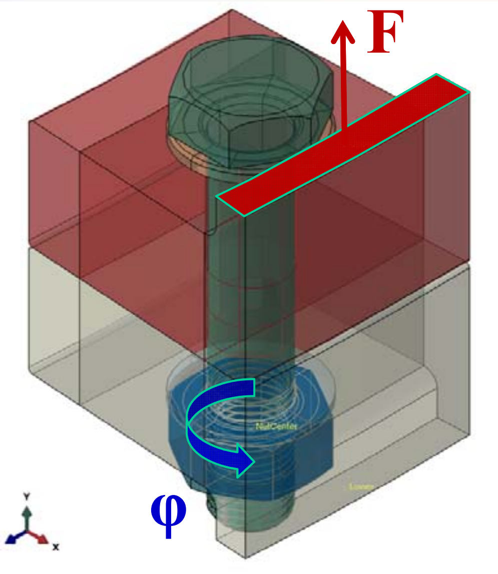
Material models



- Nominal values
- Plasticity
- Ductile damage for bolt material

Loads

- Bolt preloading by Turn-of-nut method (980 kN)
- Force controlled loading up to failure
- Smoothed amplitude functions

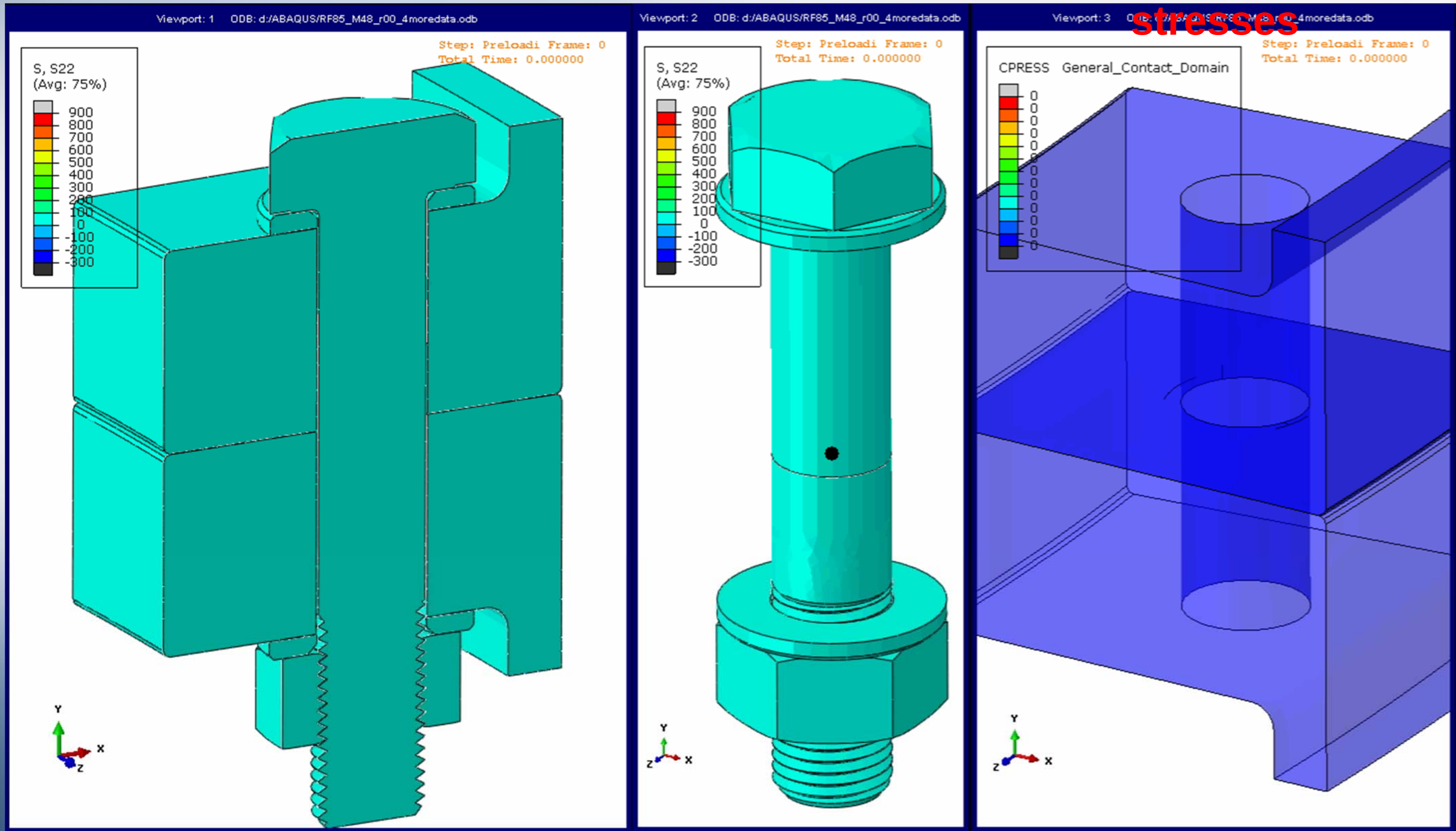


Results – bolt preloading (980 kN)

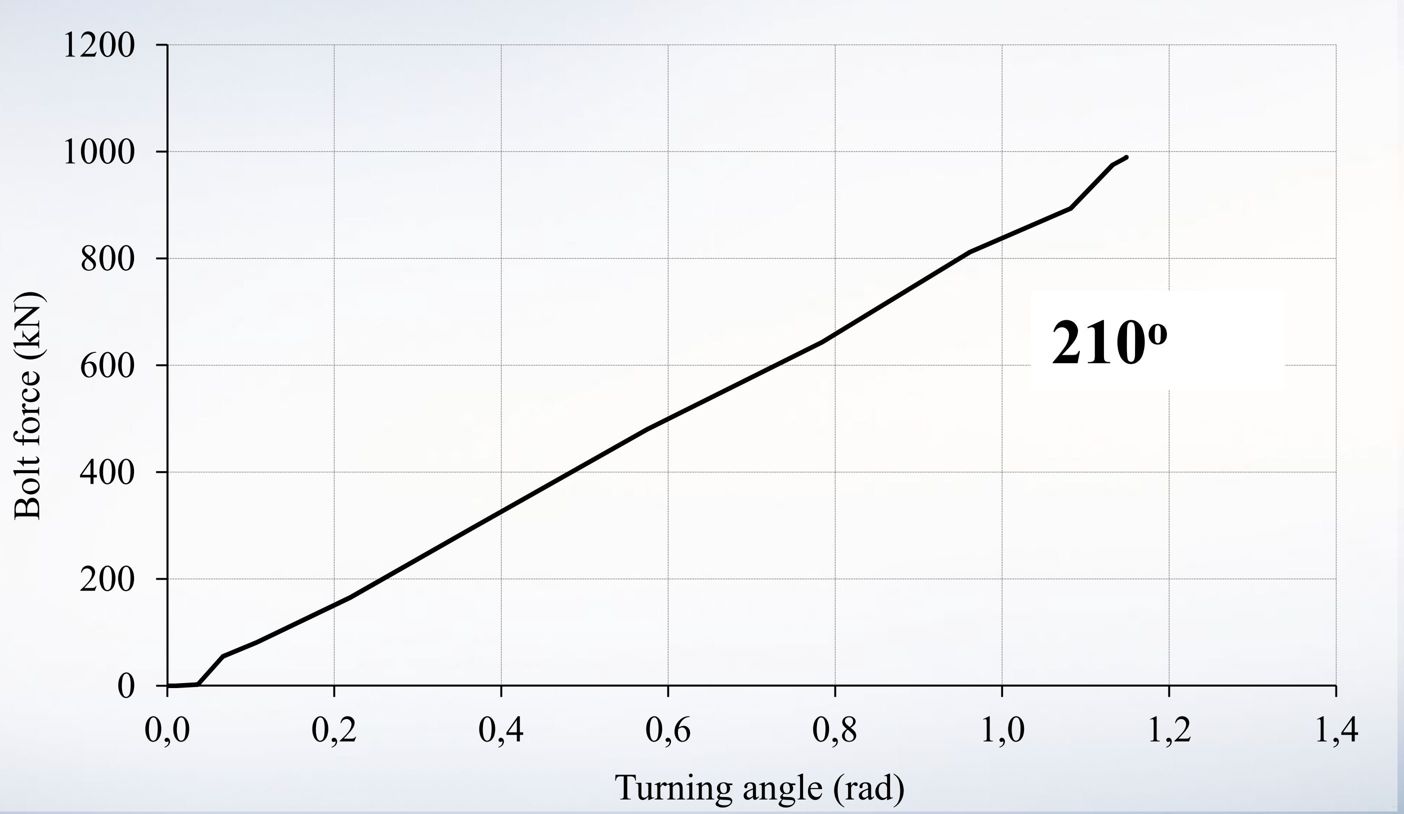
Vertical stresses

Bolt force

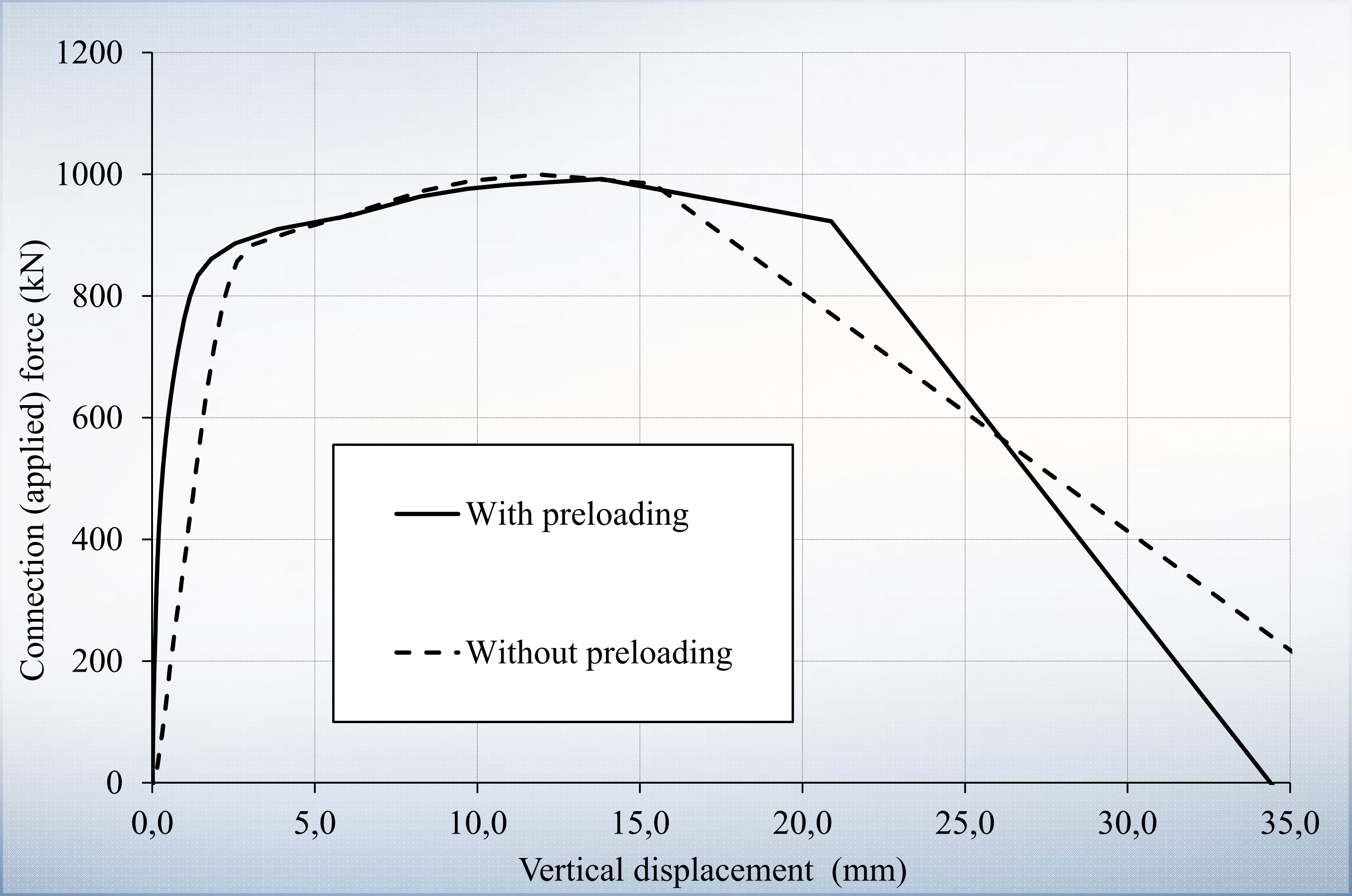
Contact stresses



Results – bolt preloading

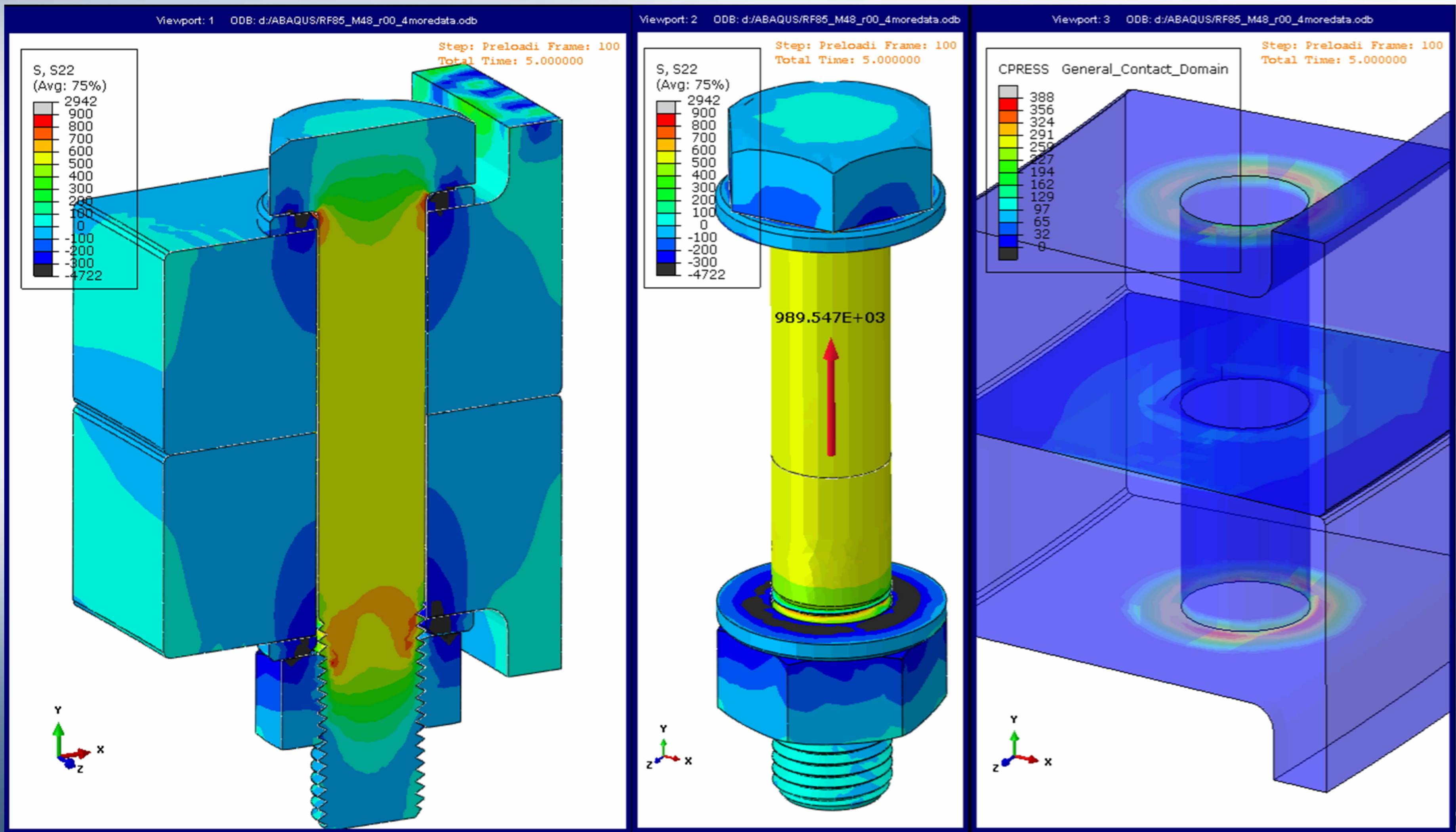


Results – loading up to failure



Loading up to failure – with bolt preloading

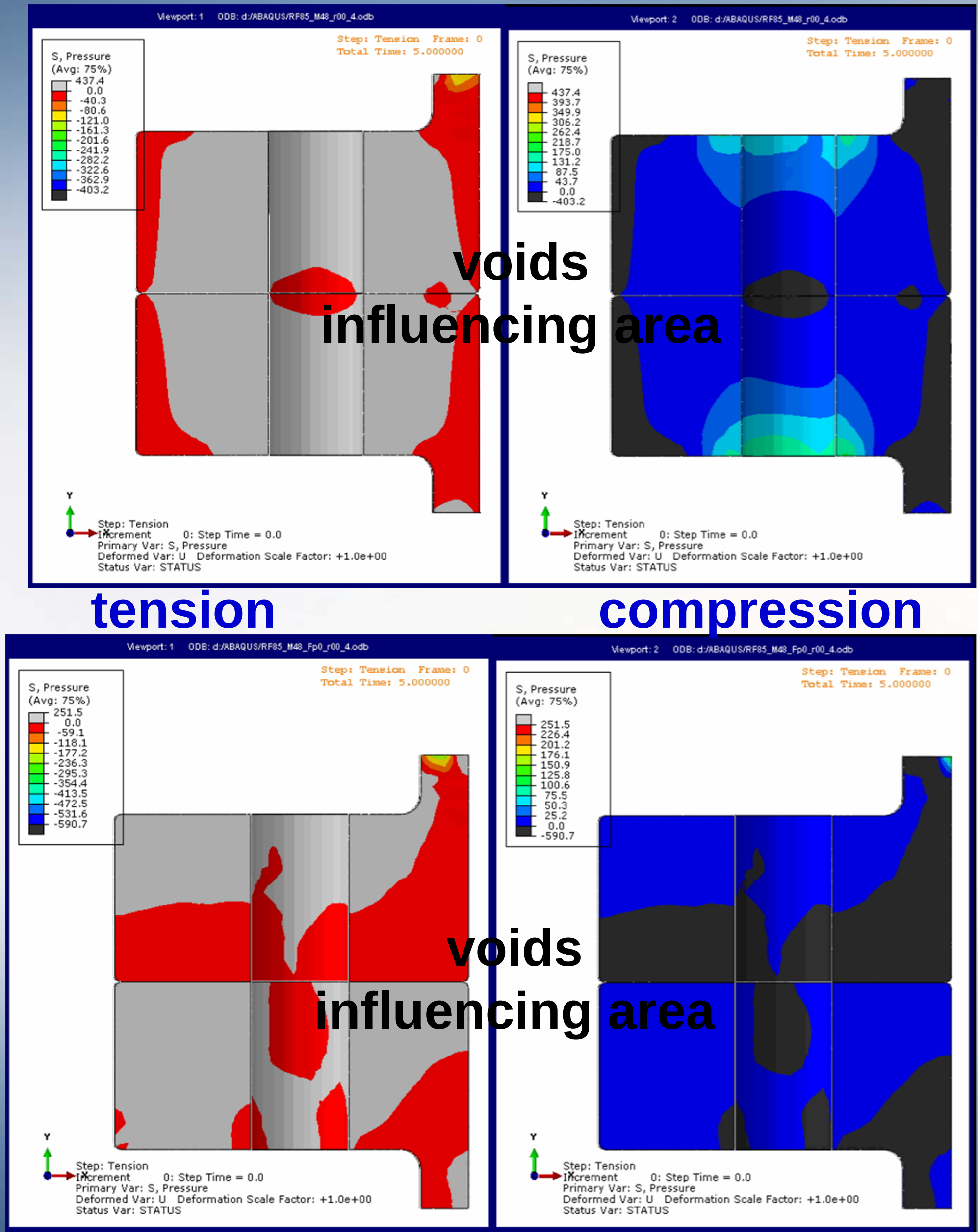
Vertical stresses **Bolt force** **Contact stresses**



Loading up to failure

Pressure

$(\sigma_1 + \sigma_2 + \sigma_3)/3$



With bolt preloading

Without bolt preloading

Conclusions

Research achievements (HISTWIN projects):

- **Large** market opportunities.
- Component tests used to provide **new design values.**
- Down-scale tests demonstrated **quality/safety** of the connection.
- Feasibility tests demonstrated **usefulness** of the innovation.
- Proved that use of **Higher-strength steel** grades are advantageous.
- **"Maintenance free"** connection for tubular and lattice towers.
- Advantages off **"semi-closed cross-section"** for bolted connection in lattice towers.
- **Bolted connections** may be a competitive alternative to welded connections.

Conclusions

Research achievements (RINGMAN project):

- A new welding technology (EB welding) may be competitive alternative to flange forging.
- State of art methodology for structural integrity.
- Detailed FE model which allows the most realistic stress assessment in the bolts and flanges.
- FE flange model requires advance evaluation of material data but allows economical evaluation of material imperfection (flaws) and geometrical imperfections (flange out of flatness, loss of pretension).
- Fracture assessment based n material data.
- Fatigue endurance assessment based on an arbitrary assumed crack in the flange for realistic stress conditions.
- Clearly defined flange regions for the flow control.

Acknowledgments

- Part of the work presented here, page 18-45 was supported by funding from the European Community's Research Fund for Coal and Steel (RFCS) under grant agreement n° RFSR-CT-2006-00031, and partially from Center for High-Performance Steel at Luleå University of Technology.

Acknowledgments

- Part of the work presented here, page 46-69, has been carried out within RINGMAN, a project financed by the European Union's Seventh Framework Programme managed by REA-Research Executive Agency under grant agreement n° 286603."

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Dissemination - Publications

•	2011: 7 conference papers	
•	2012: 4 conference papers	3 journal papers
•	2013: 8 conference papers	1 journal paper
•	2014: 3 conference papers	6 journal papers (2 published)
•	22 conferences	10 journal papers

- List of publications

https://pure.ltu.se/portal/sv/publications/search.html?search=veljkovic&uri=

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Exploitation

- TRL 1 – basic principles observed
- TRL 2 – technology concept formulated
- TRL 3 – experimental proof of concept
- TRL 4 – technology validated in lab
- TRL 5 – technology validated in relevant environment (industrially relevant environment in the case of key enabling technologies)
- TRL 6 – technology demonstrated in relevant environment (industrially relevant environment in the case of key enabling technologies)

MRL 5

Capability to produce prototype components in a production relevant environment.

MRL 6

Capability to produce a prototype system or subsystem in a production relevant environment.

Thanks to:

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- Vestas
  - Peter Sigfred Mortensen