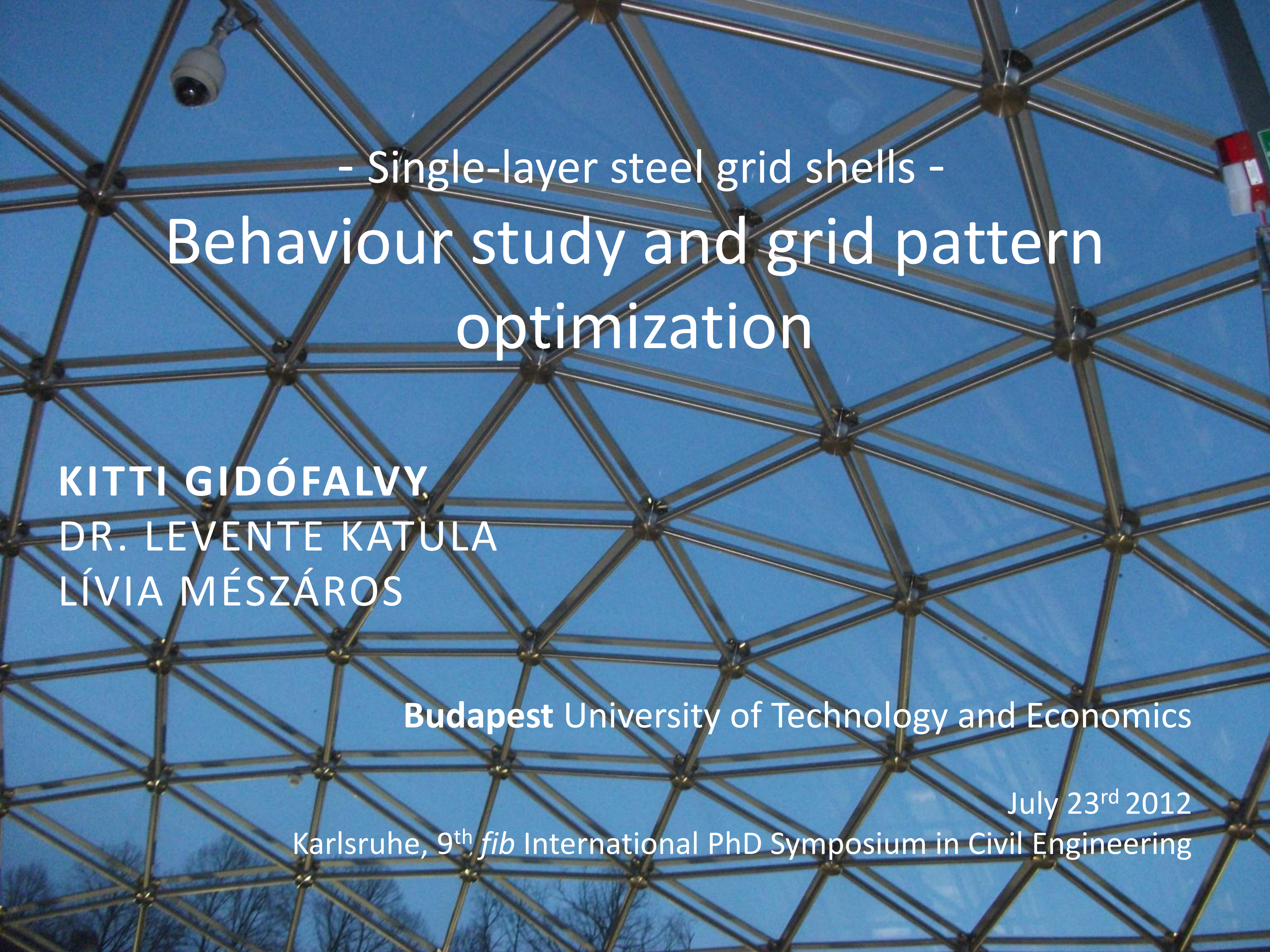

- Single-layer steel grid shells -

Behaviour study and grid pattern optimization

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Budapest University of Technology and Economics

July 23rd 2012
Karlsruhe, 9th *fib* International PhD Symposium in Civil Engineering

Single-layer steel grid shells

Free-form structures

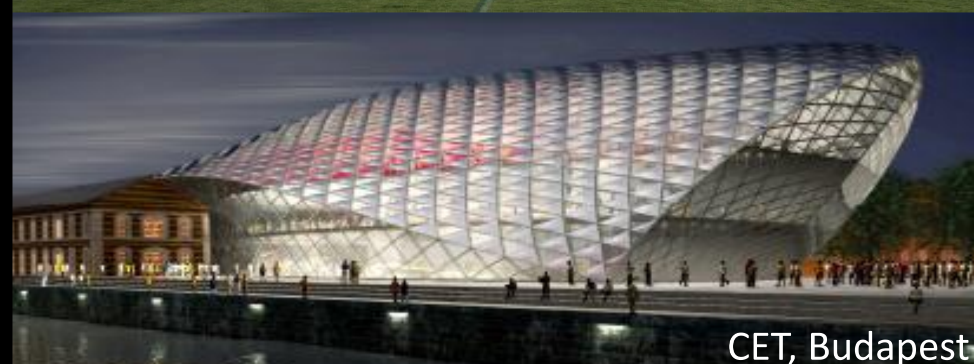
Roof structures, triangular network

Shell+beam-like behaviour

Shell buckling, snap-through

British Museum, Great Court Roof, London

Melbourne Stadium



CET, Budapest

Metro station roof, Budapest

Motivation

Can we improve the structural behaviour by changing the geometry?

Geometry: beam length, angles, mesh density, topology

↓

Improvement in structural behaviour: maximizing load-bearing capacity

Mesh, grid: network of beam centrelines

Load bearing capacity:

Nonlinear, numerical analysis

Moving the nodes along a predefined surface:

Fix - surface, topology, boundary nodes

Variables - inner nodes

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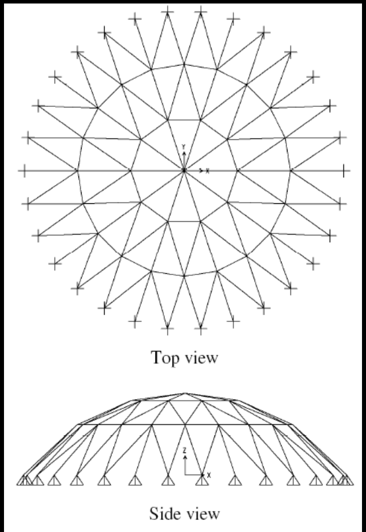
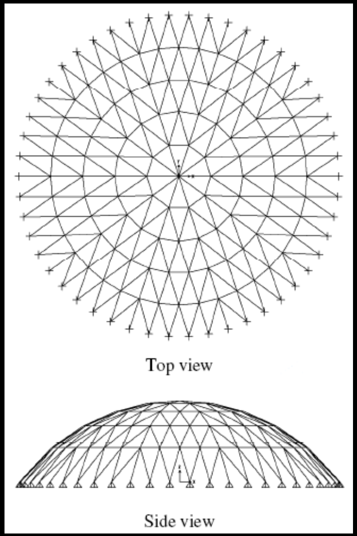


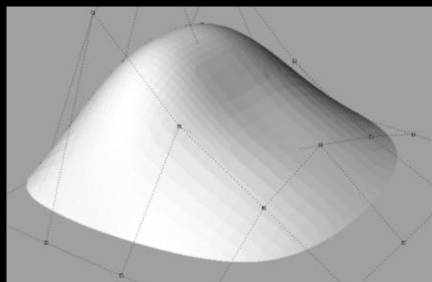


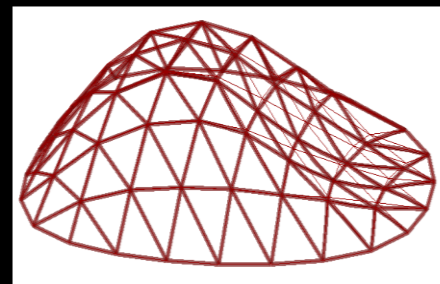
[Kaveh, 2011]

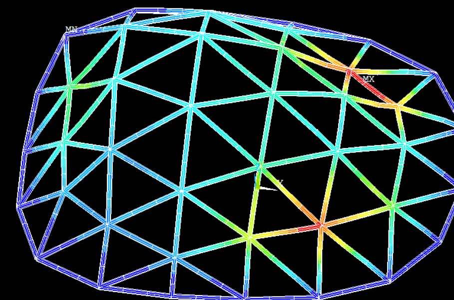
Topology and size optimization in literature: simple mesh types, simple surfaces → Mesh generating algorithm

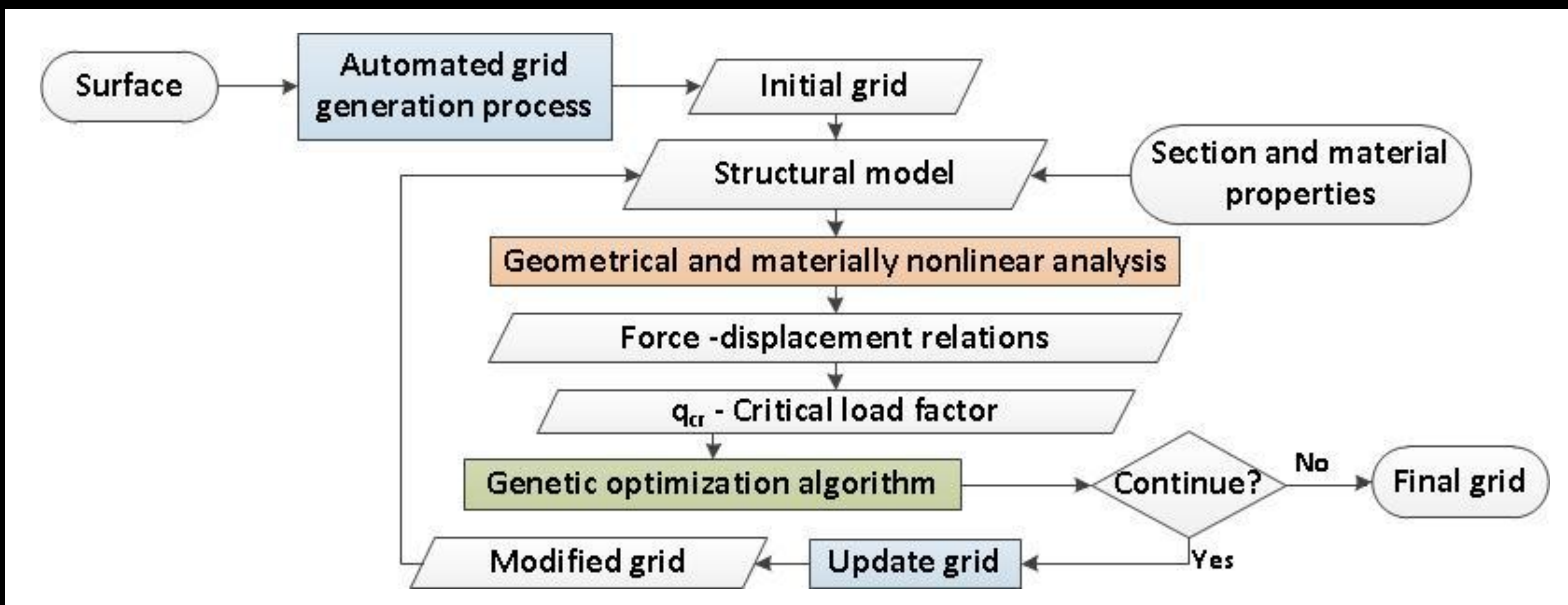
Method

Process and steps of grid pattern optimization







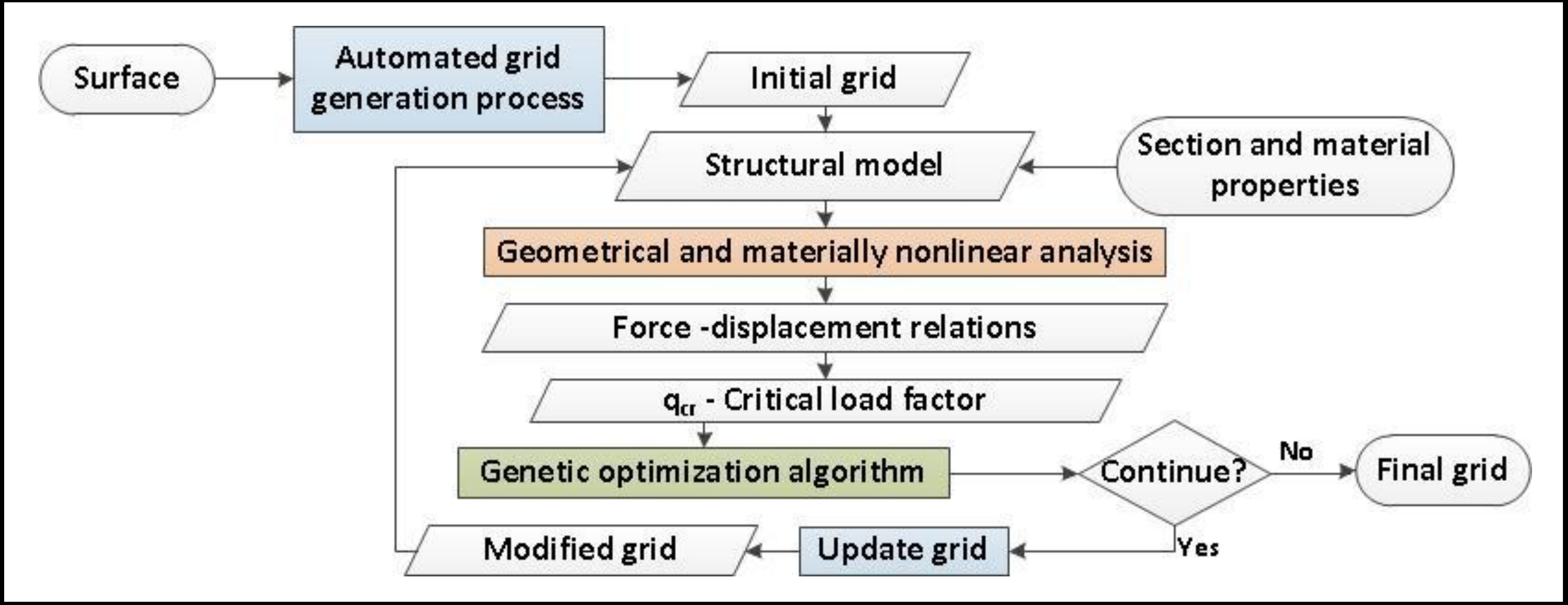


Method

Process and steps of grid pattern optimization

Contents of presentation:

- Analysis - Structural model
- Analysis - Solver
- q_{cr} : load bearing capacity
- Load, fitness function
- Automated grid generation process
- Results - domes, free-form surfaces



Analysis – Model

Finitel element model

Beam finite elements

Ridig nodes, fixed supports

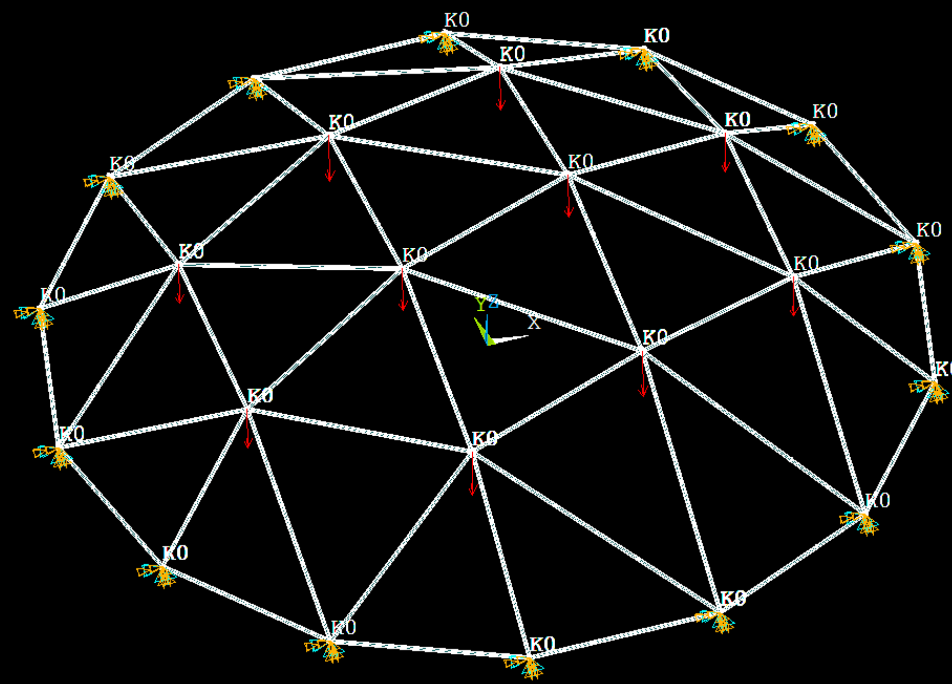
Perfectly elasto-plastic material model

Vertical nodal loads

Section: pipe: CHS 146*5 (r=73mm, t=5mm)

Steel grade: S235

Plasticity is not a typical failure mode
Beam length, λ_{rel}= 1÷1,8



Arc-length method

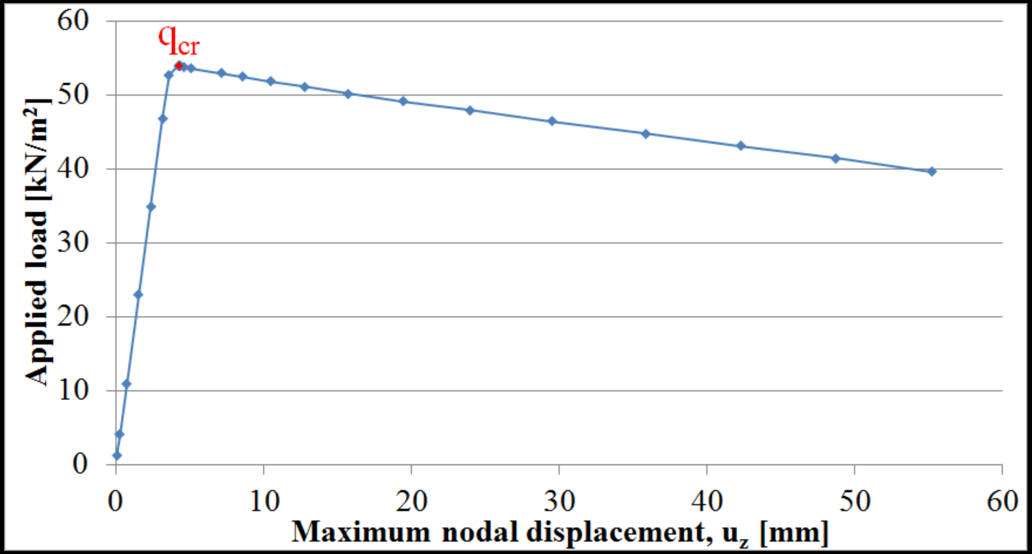
Geometrically nonlinear analysis,
no imperfections

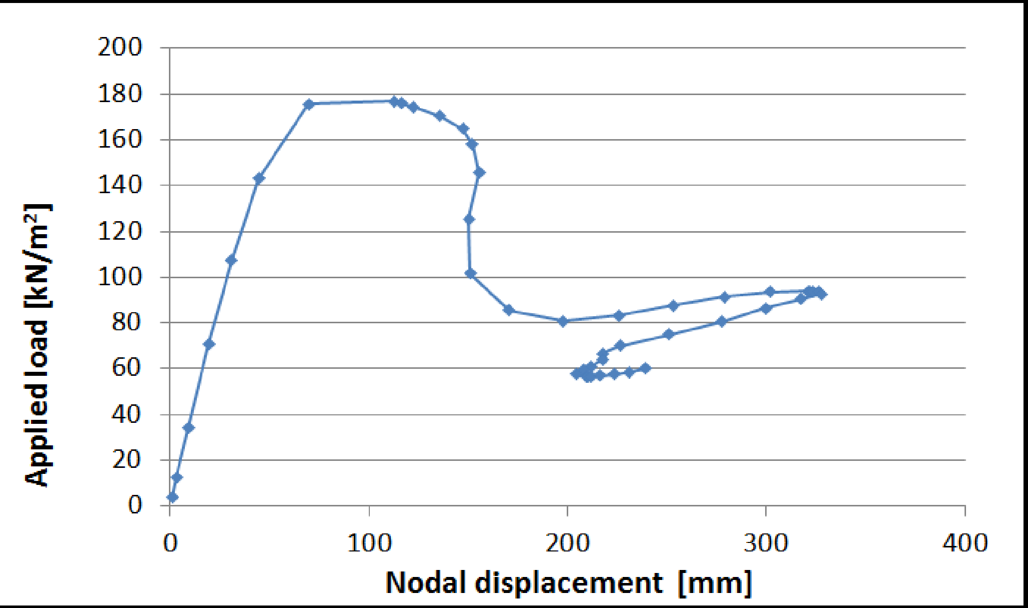
Instable behaviour

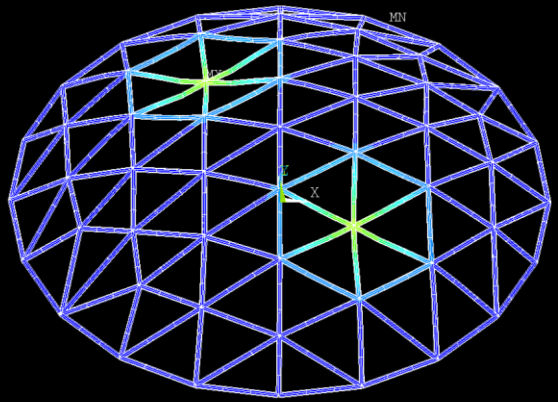
Load displacement curves → q_{cr}

ANSYS

Radius of arc-length:
- exact maximal load
- post-critical behaviour





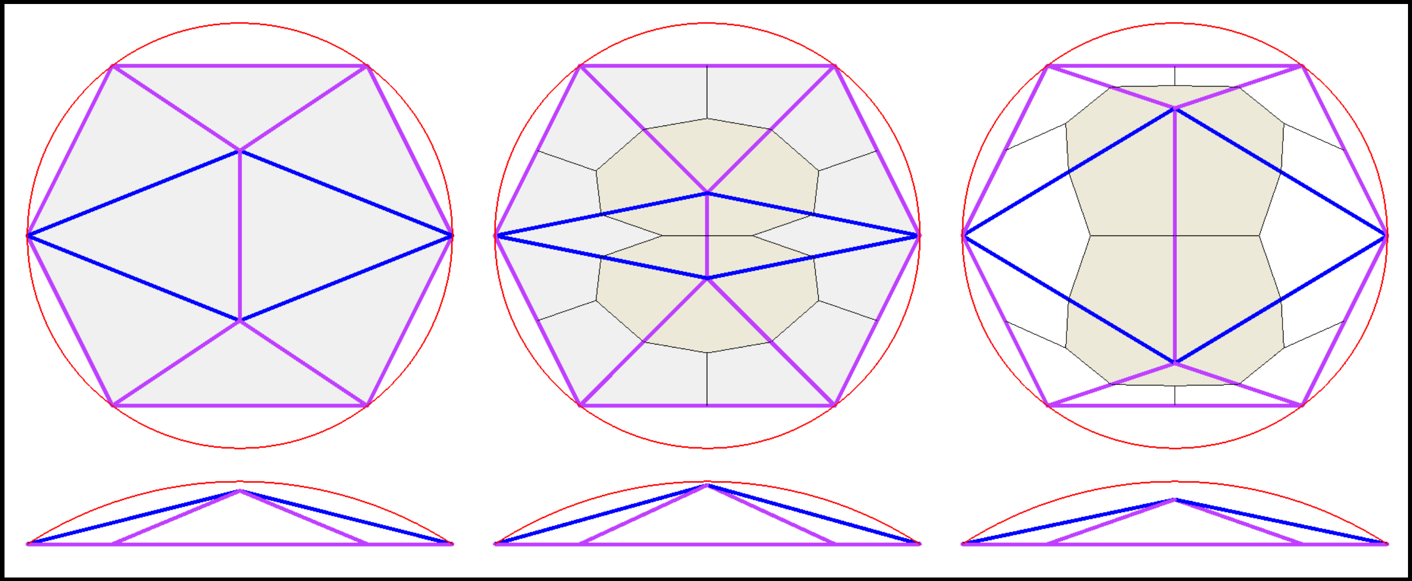


Analysis – Load

Vertical nodal loads

Uniform nodal loads

Uniform distributed load – transferred to nodes based on triangular areas



Fitness function:

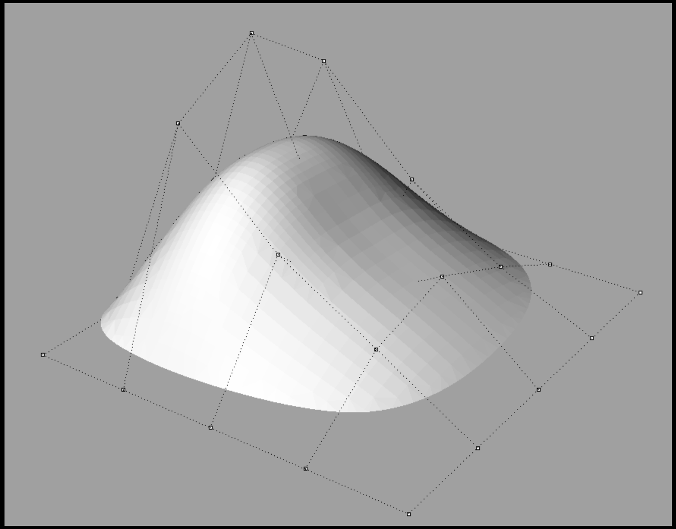
F_{cr} [kN] $\quad$ q_{cr} [kN/m^2] $\quad$ $q_{cr}*A_{inner}/A$ [kN/m^2]

Geometry

Automated mesh generation

Goal

- mesh – beam centrelines
- applicable for free form surfaces (NURBS)
- equidistant supports

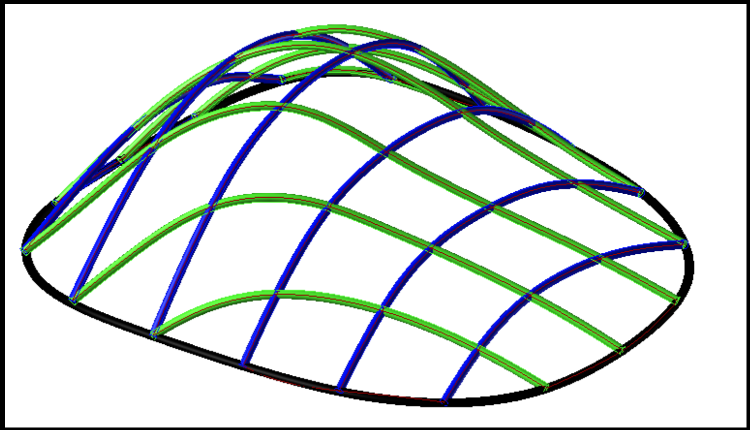


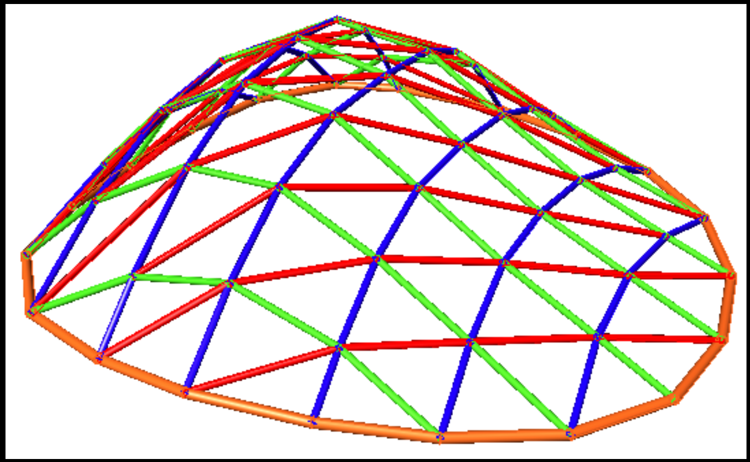
Geometry

Automated mesh generation

Goal
- mesh – beam centrelines
- applicable for free form surfaces (NURBS)
- equidistant supports

Method: slicing the surface with 2 sets of bent planes





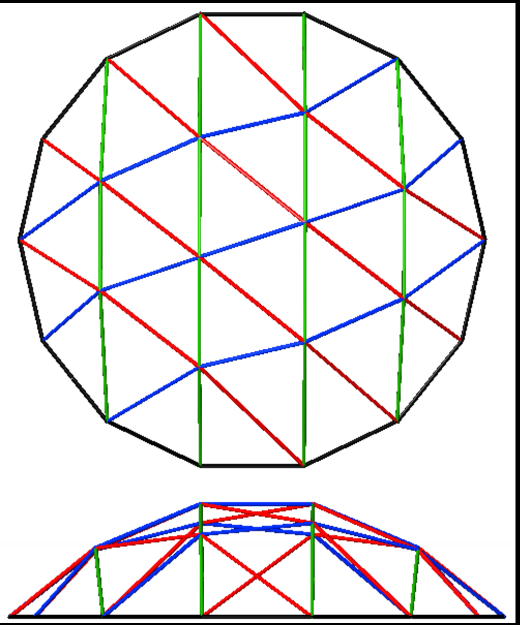
Geometry

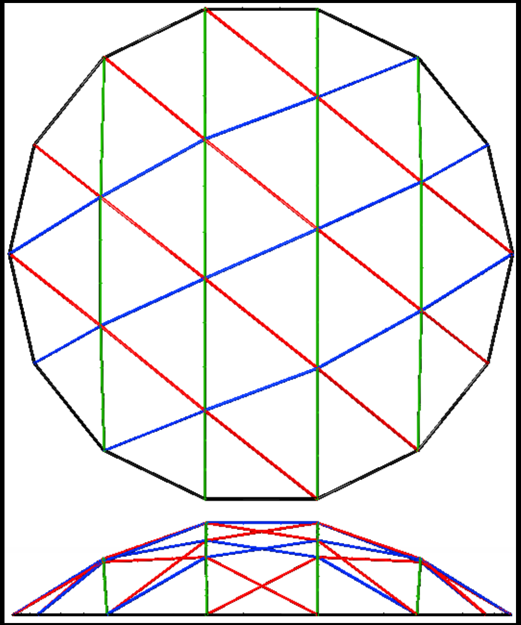
Automated mesh generation

Goal
- mesh – beam centrelines
- applicable for free form surfaces (NURBS)
- equidistant supports

Method: slicing the surface with 2 sets of bent planes

Relaxation: refining the initial grid

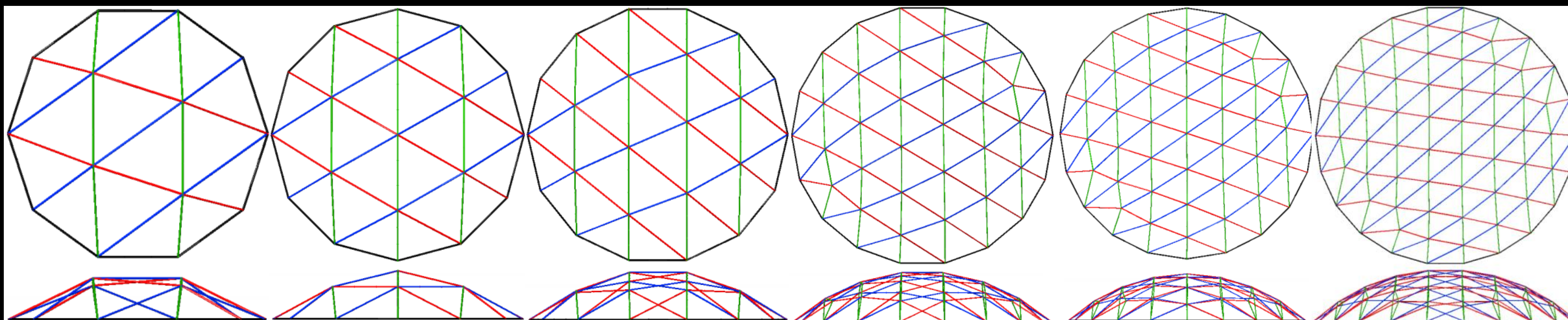




Automated mesh generation - generated meshes

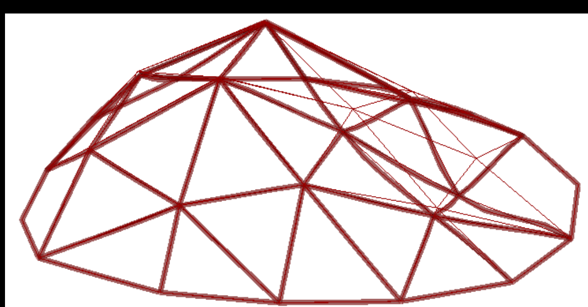
Basic parameter: division number: n → mesh density, coarseness

Dome:

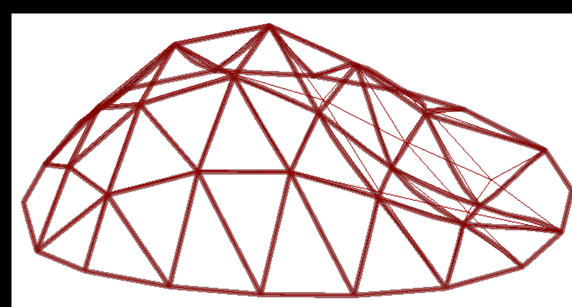


n = 3 n = 4 n = 5 n = 7 n = 8 n = 9

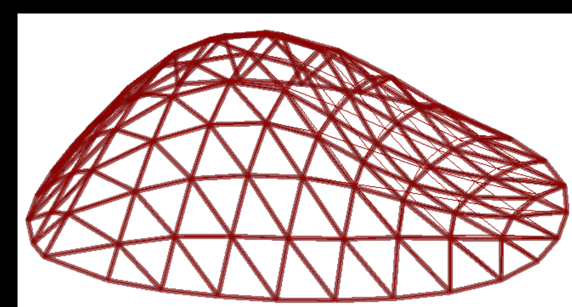
Free-form:



n = 5



n = 7



n = 10

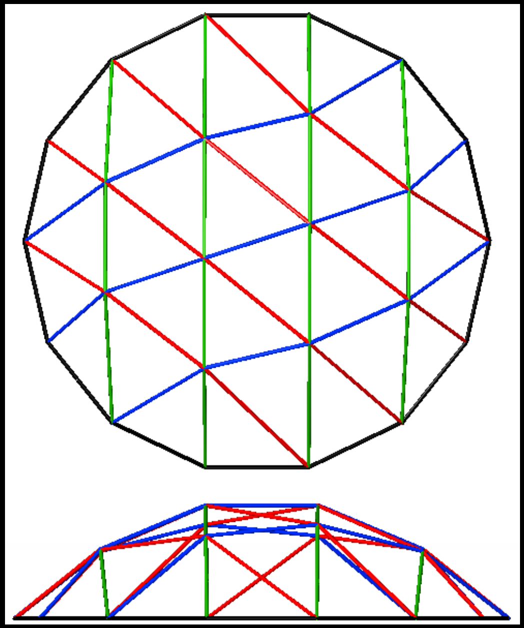
Results – Coarse mesh – Dome 10

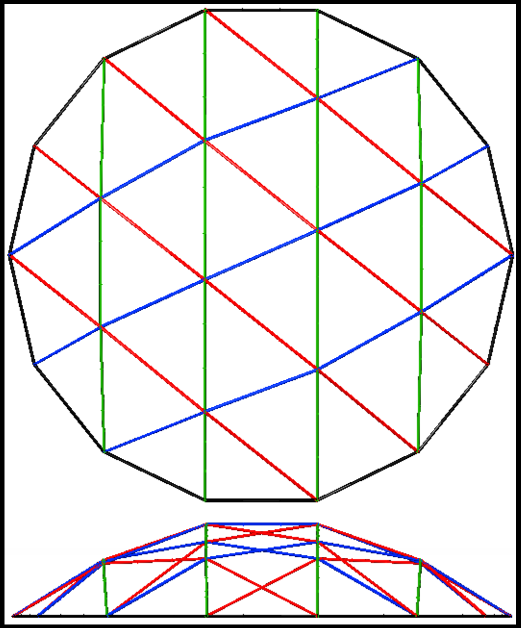
Coarse mesh

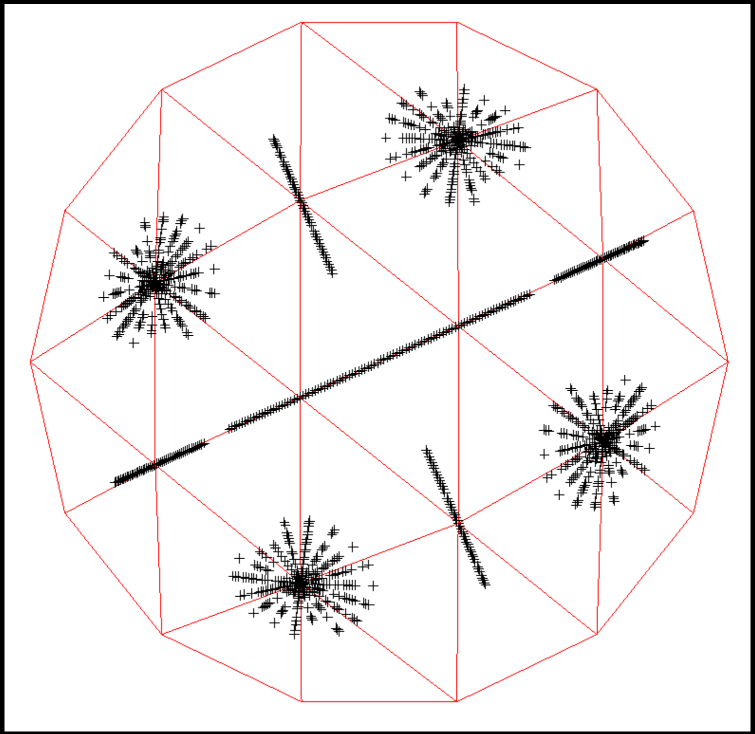
Generated mesh – relaxed mesh

No difference in qcr

Double symmetric layout – nodes are constrained







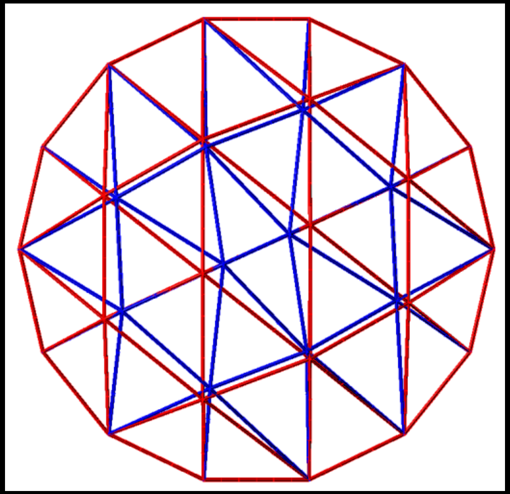
Results – Coarse mesh – Dome, n= 10

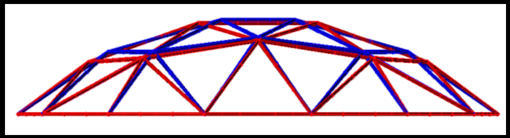
Coarse mesh

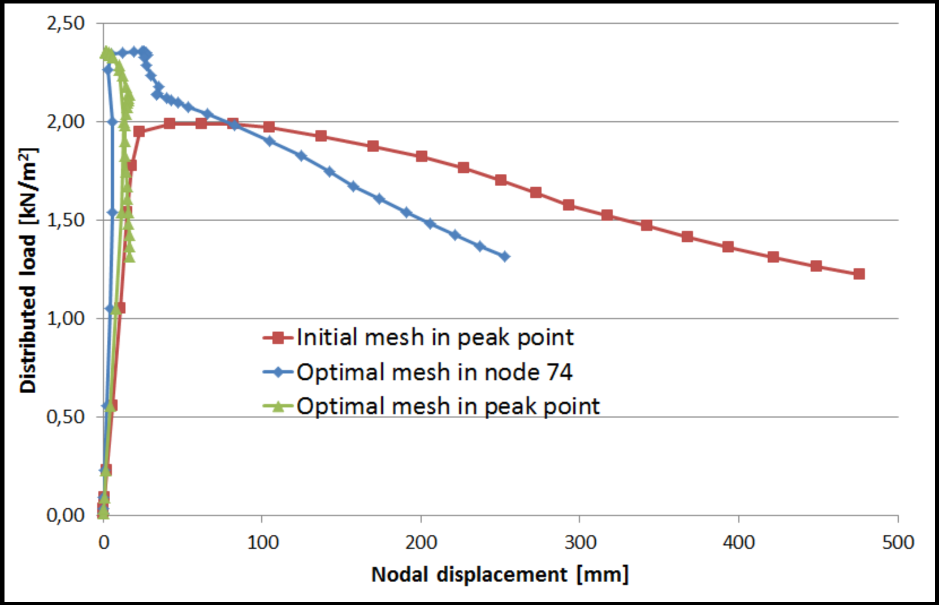
Improvement: 18 %

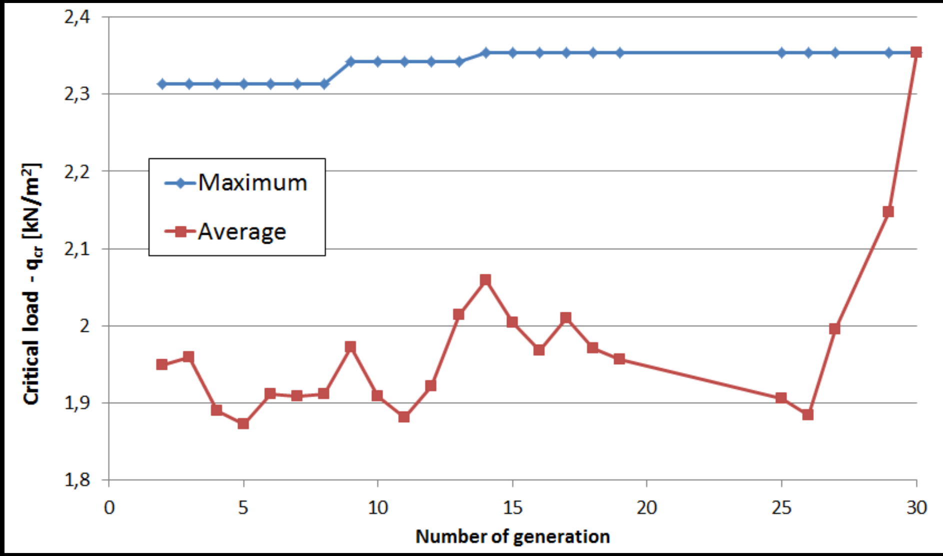
Initial mesh

Optimal mesh







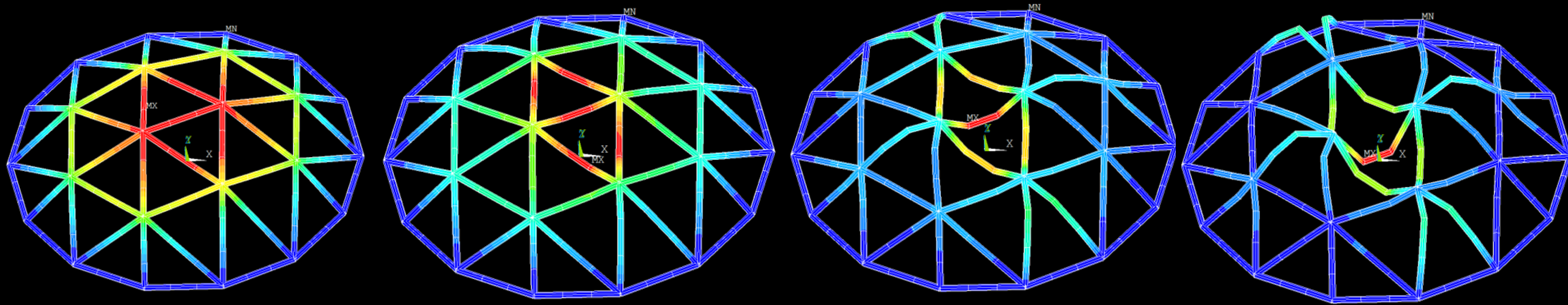


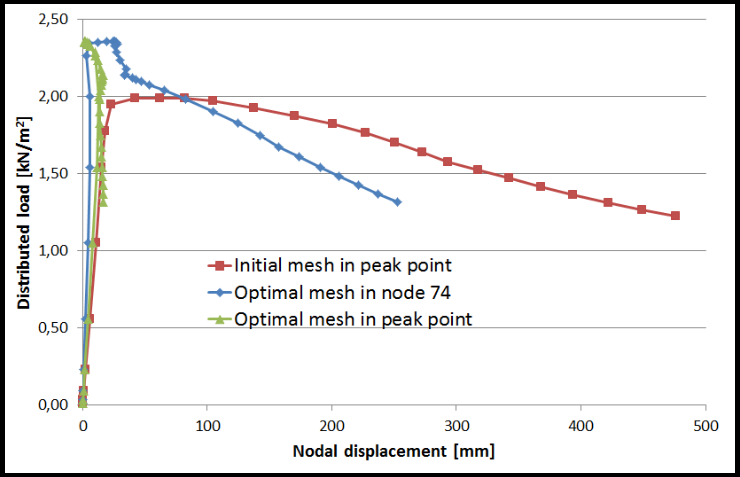
Results – Coarse mesh – Dome, n=10

Coarse mesh

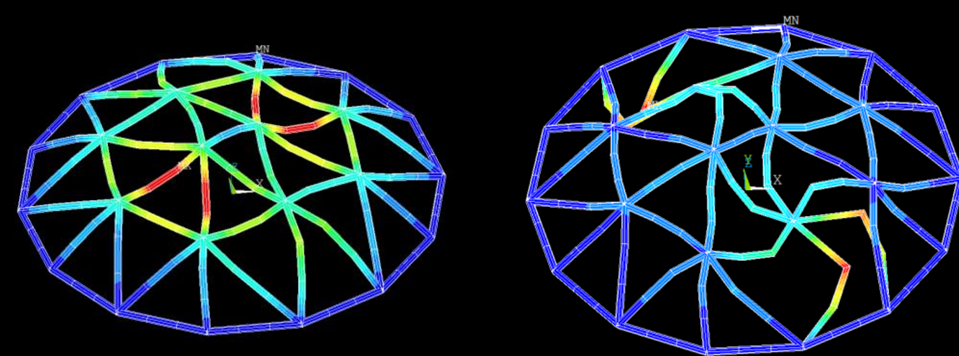
Different failure modes

Initial



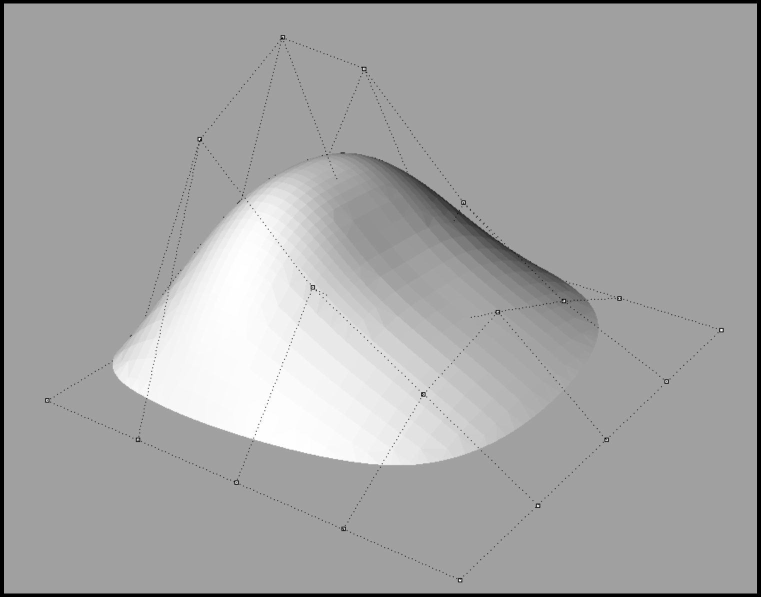


Optimal



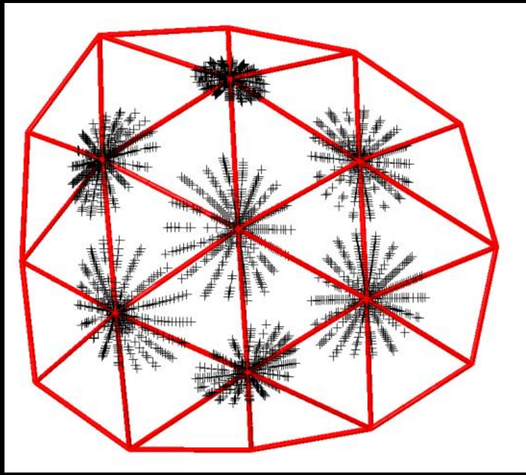
Results – Coarse mesh – Free-form #1, n=7

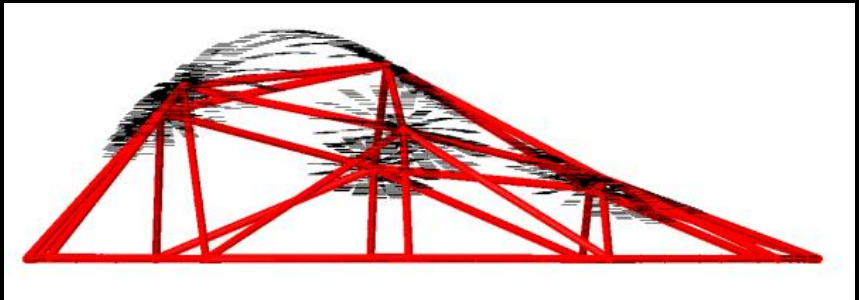
Coarse mesh



Results – Coarse mesh – Free-form #1, n=7

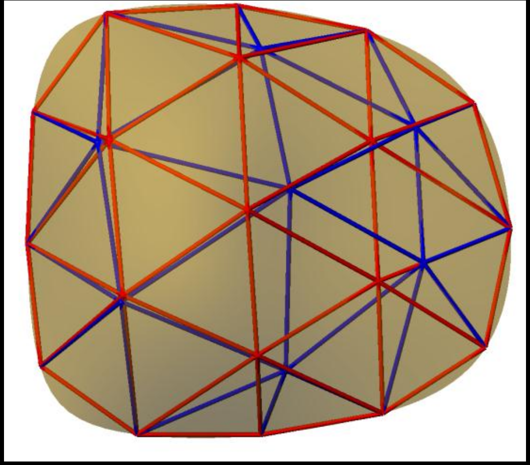
Coarse mesh

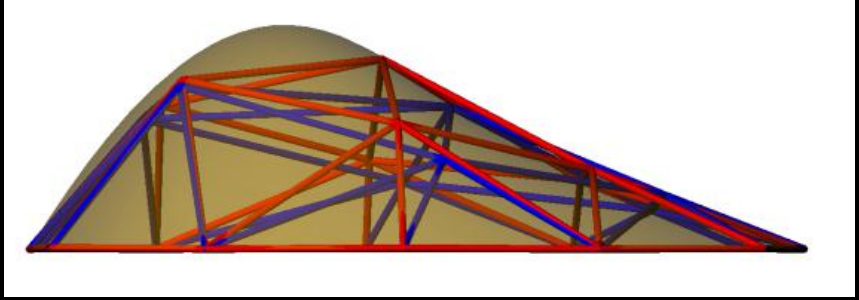




Initial mesh
Optimal mesh

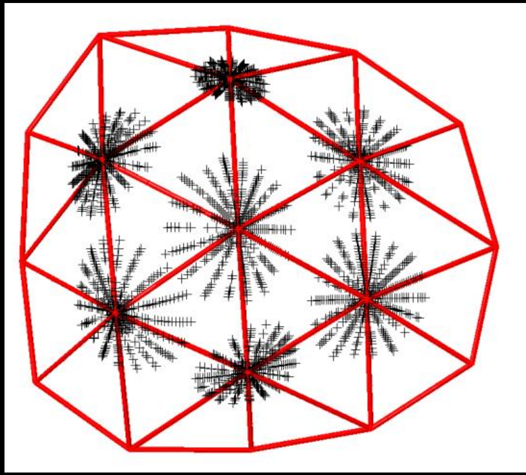
28 %

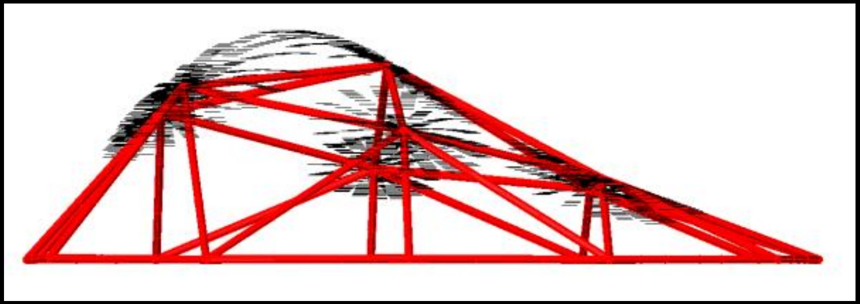




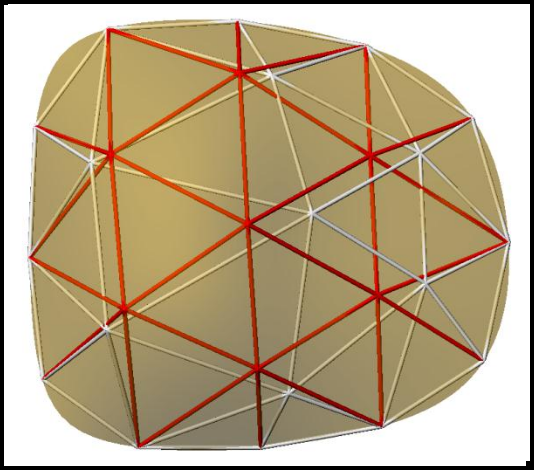
Results – Coarse mesh – Free-form #1, n=7

Coarse mesh

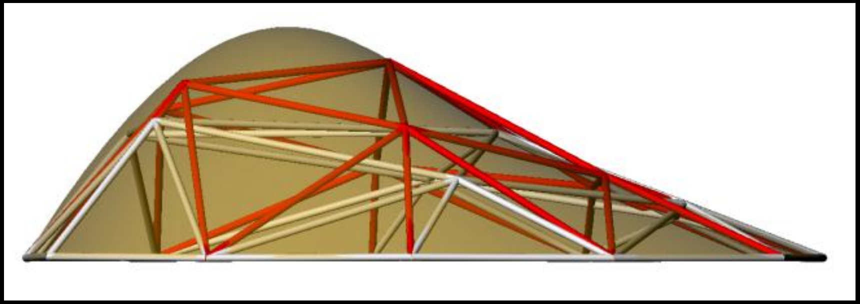




Initial mesh
Optimal mesh



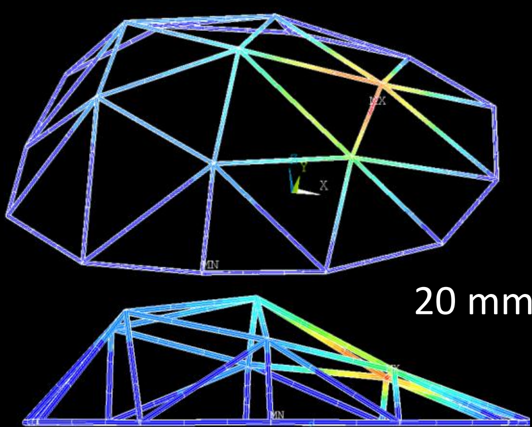
35 %



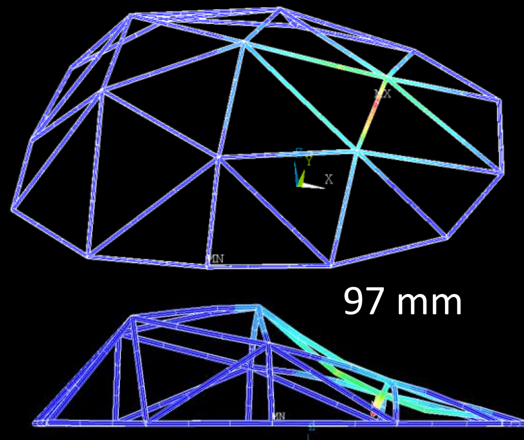
Results – Coarse mesh – Free-form #1, n=7

Different failure modes

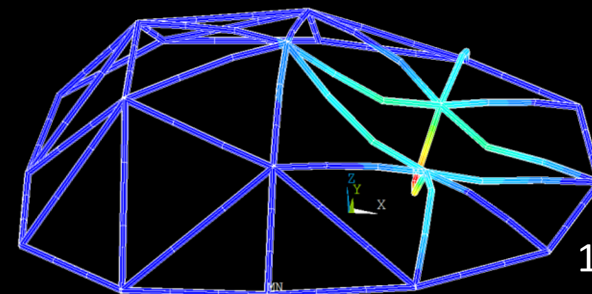
Initial mesh – element buckling



20 mm

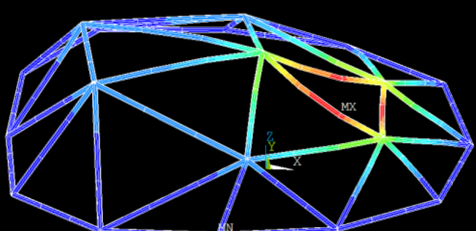


97 mm

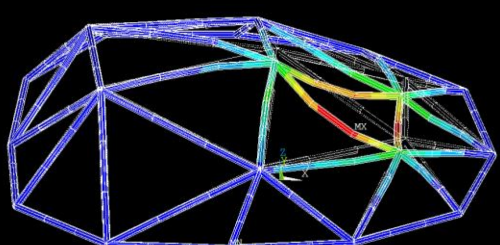


197 mm

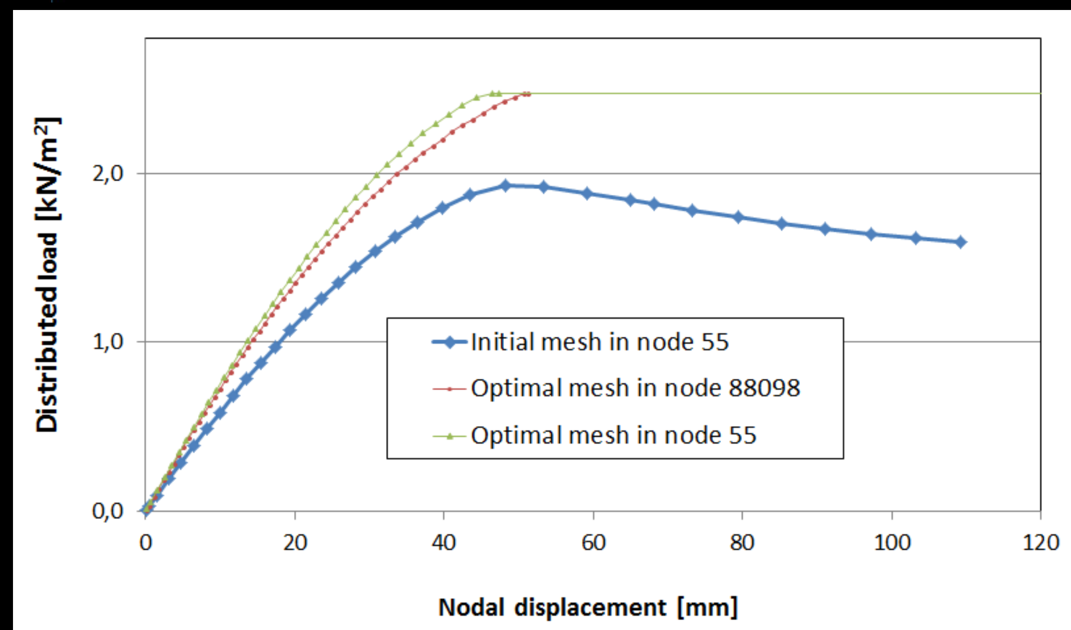
Optimal mesh – snap through of 3 nodes
+ plasicity



28 mm

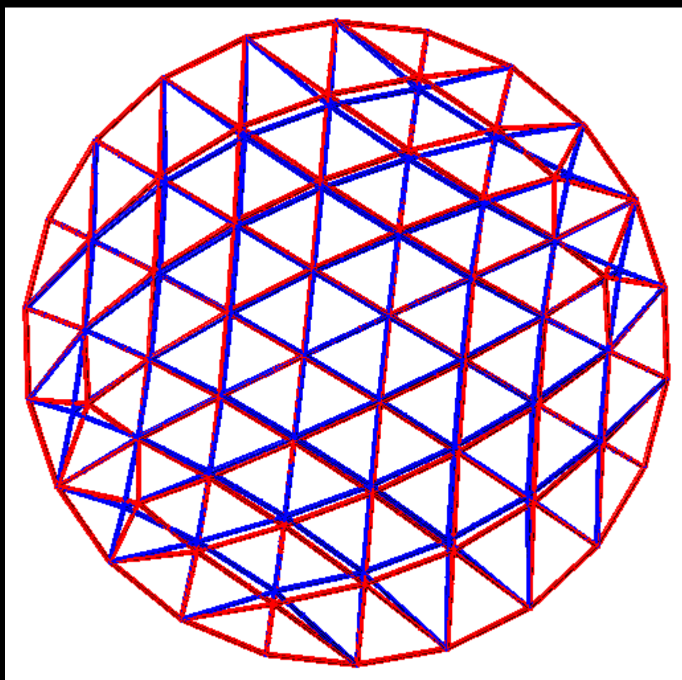


51 mm



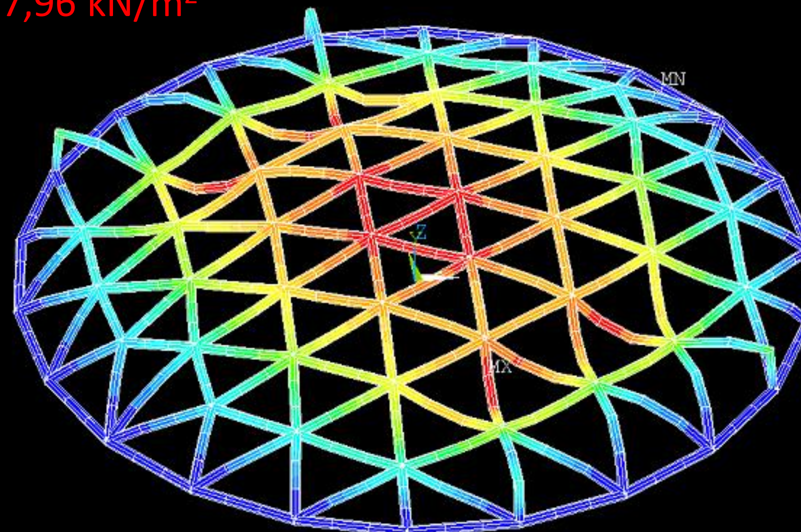
Results – Dome, n=42

Failure mode: plasticity

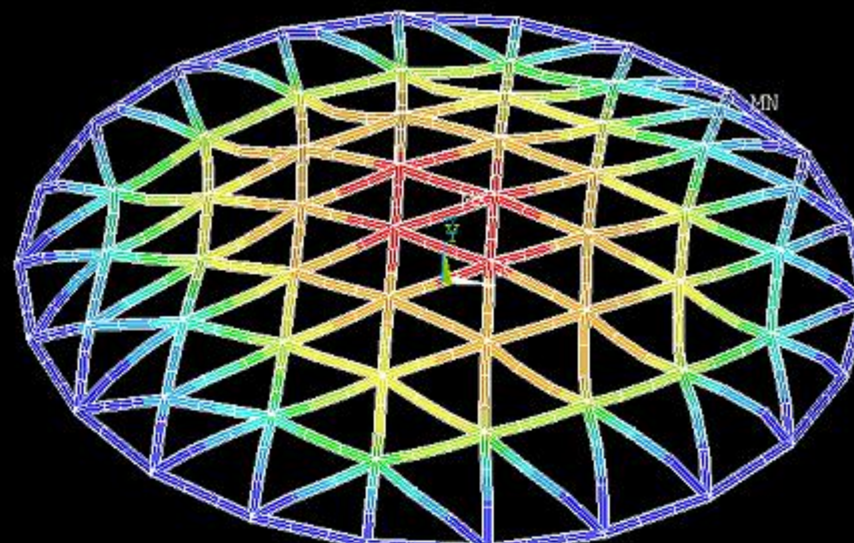


4 %

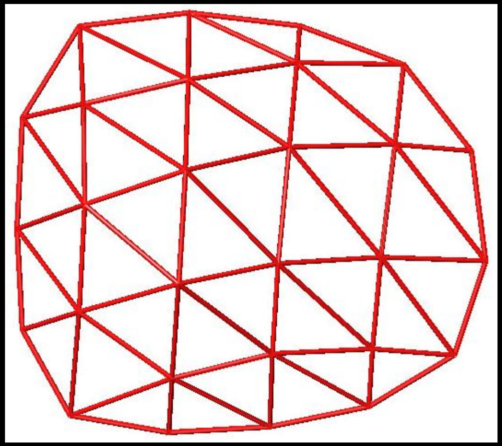
Initial - 7,96 kN/m^2



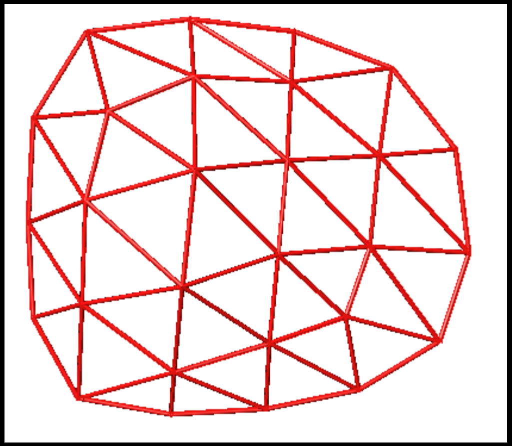
Relaxed = Optimal - 8,21 kN/m^2



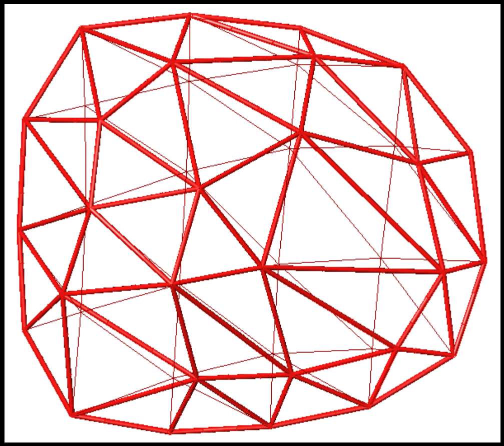
Results – Free-form #1, n=14



Initial (generated) 2,06 kN/m²



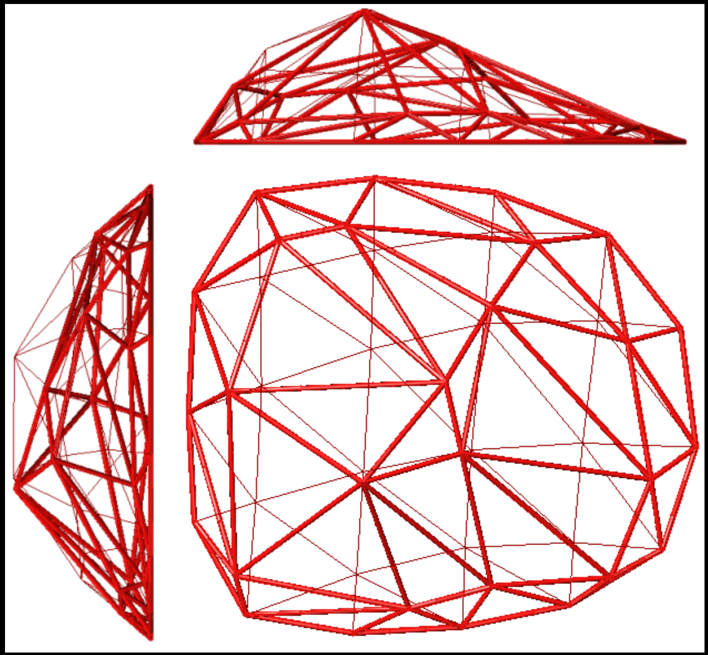
Relaxed 2,14 kN/m²



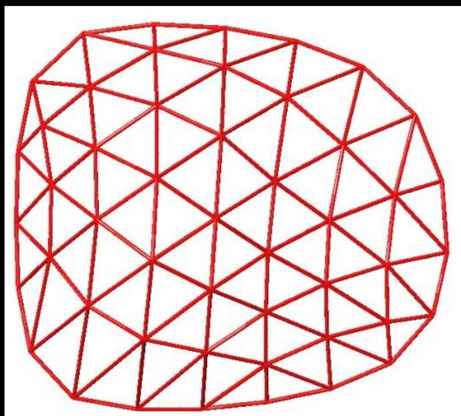
Modified 3,20 kN/m²

Optimal 4,11 kN/m²

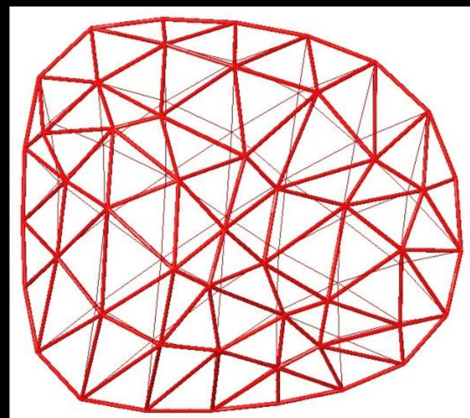
100 %



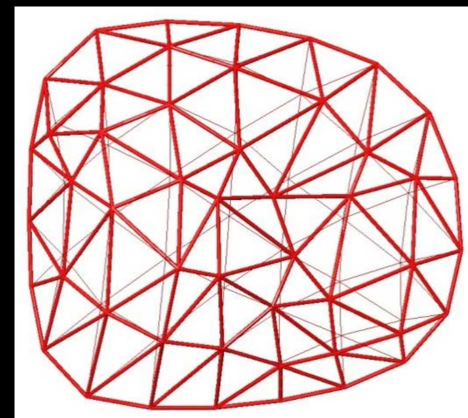
Results – Free-form #1, n=29



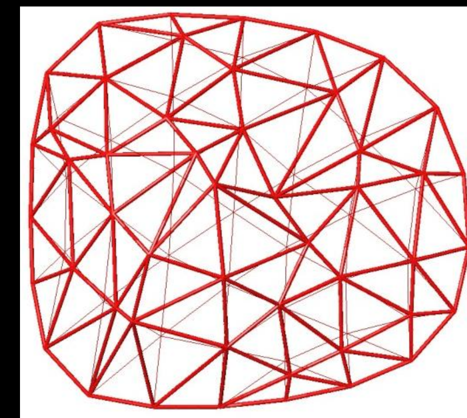
Initial mesh (unrelaxed)
3,56 kN/m^2



3,96 kN/m^2



4,10 kN/m^2



Optimal
4,23 kN/m^2

19 %

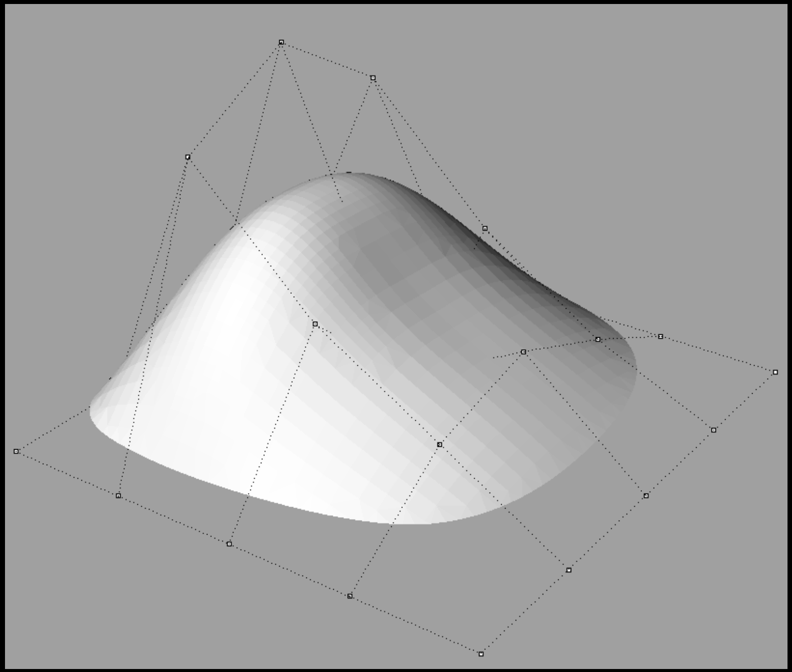
Failure mode:
Shell buckling (many nodes involved) due to very shallow surface
Nodes can not move away from here

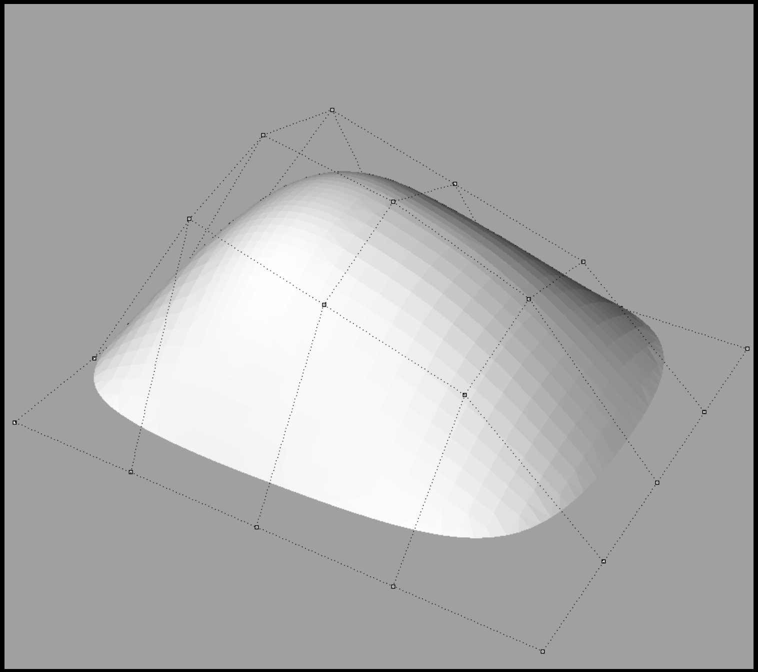
Different initial surface suggested

Results – Free-form #2

Modifying the surface

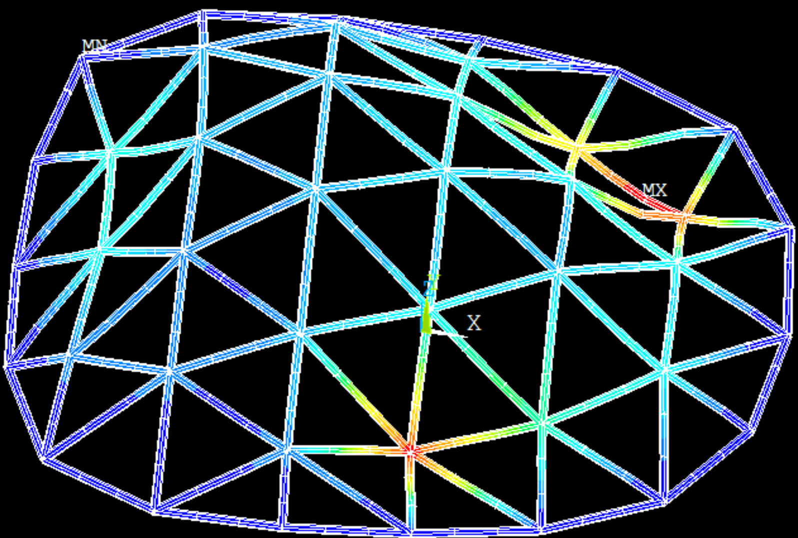
NURBS control points



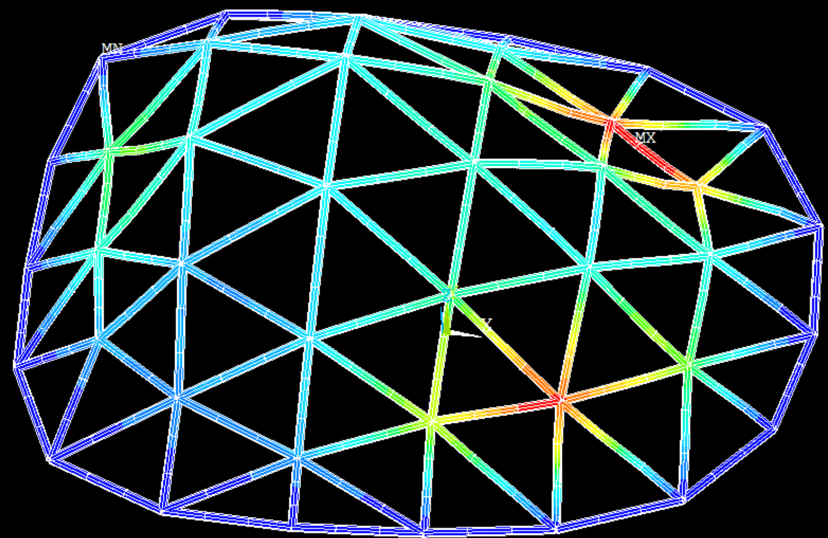


Results – Free-form #2, n=24

Plastic failure



Initial mesh - 5,45 kN/m^2



Relaxed mesh - 7,06 kN/m^2
Optimal mesh - 7,16 kN/m^2

31 %

Conclusions

Developed a method for grid pattern optimization

The significant effect of member grid pattern on load bearing capacity of single-layer steel grid shells has been demonstrated

Conclusions

Surface	Number of inner nodes	Load bearing capacity [kN/m²]			
		Initial	Relaxed	Optimal	Improvement [%]
Dome, H/L=0,2	10	1,99	2,08	2,37	14
	10 sym.	1,99	2,08	2,35	14
	42	7,96	8,21	8,25	4
Free-form #1, L=25m	7	1,92	1,88	2,46	28
	14	2,06	2,14	4,11	100
	29	3,56	-	4,23	19
Free-form #2, L=26m	24	5,45	7,06	7,16	31

Domes + freeform surfaces; coarse + dense meshes; various beam lengths

Beam length and failure modes are different!

Conclusions

Surface	Number of inner nodes	Load bearing capacity [kN/m²]			
		Initial	Relaxed	Optimal	Improvement [%]
Dome, H/L=0,2	10	1,99	2,08	2,37	14
	10 sym.	1,99	2,08	2,35	14
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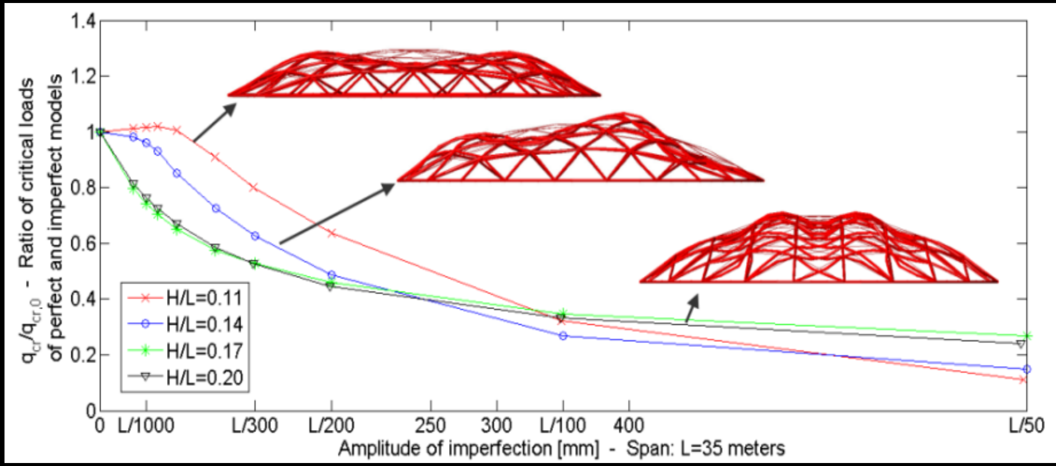
Free-form #2, L=26m	24	5,45	7,06	7,16	31

1. Improvement achieved by optimization is highly dependant on failure modes,
2. Understanding the failure modes is important – generally failure is different for initial and optimal grid pattern → local to global
3. More efficient for coarse meshes with less node number, surface is not approximated well enough
4. Dome: symmetry → aesthetic results
5. Higher node numbers for freeform structures: the mesh is distored for practical use Optimality criteria should be more complex (e.g. incuding maximal beam length)
6. Dense meshes: in certain cases (probably depending on failurethe mode) relaxation results in the same mesh as the optimization – fast process

Further investigations

Optimization

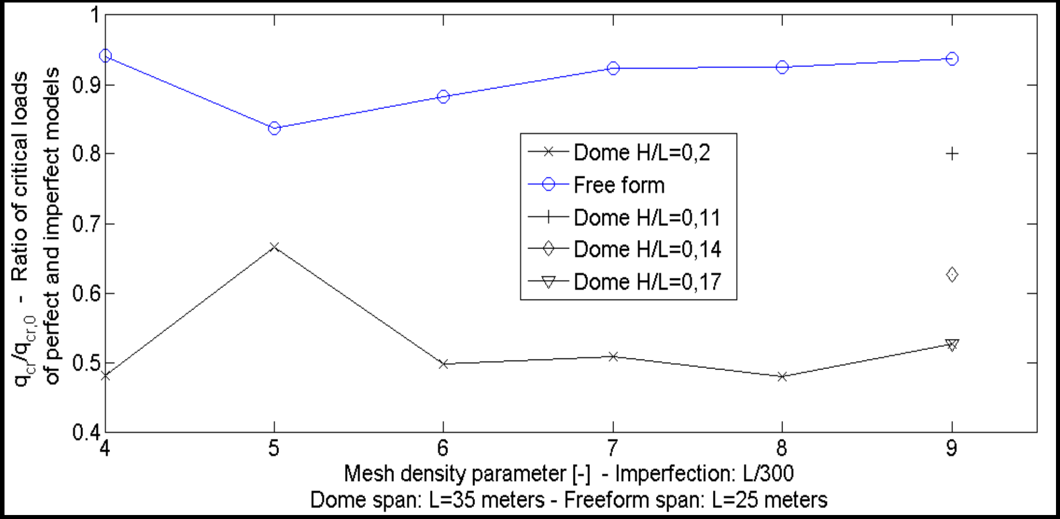
- Fitness function
- Very slow
- More realistic load cases – multidisciplinary optimization



Settings of arc-length method

Imperfection

- Exact nonlinear analysis
- First eigenmode
- High effect on q_{cr} : 20÷90 %
- Depends on:
  - Surface
  - Mesh density, beam length
  - Scale



Imperfection sensitivity analysis before each optimization process

Literature

Fan, F., Cao, Z., Shen, S.: Elasto-plastic stability of single-layer reticulated shells. In: Thin-Walled Structures (2010) Vol. 48, pp. 827-836

Kato, S., Fujimoto, M., Ogawa, T.: Buckling Load of Steel Single-Layer Reticulated Domes of Circular Plan. In: Journal of the IASS (2005) Vol. 46, pp. 41-63

Dimcic, M.: Structural Optimization of Grid Shells based on Genetic Algorithms, Ph.D. dissertation. (2011)

Kollár, L., Hegedűs, L.: Analysis and Design of Space Frames by the Continuum Method. Akadémiai Kiadó, Budapest, Hungary (1985)

Toğan V., Daloğlu AT.: Optimization of 3d trusses with adaptive approach in genetic algorithms. In: Engineering Structures (2006) Vol. 28, pp. 1019–1027

Divatcsarnok, Budapest, 2009

Thank you for your attention!

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