Delft University of Technology
Faculty of Civil Engineering and Geosciences
Structural Mechanics Section

Exam CIEM5301 Shell Structures
Thursday 7 November 2024, 9:00 – 12:00 hours

Choose A, B, C or D.

1 Large deflection of a shell roof can be caused by …

A … the middle third rule.
B … edge disturbances.
C … inextensional deformation.
D … imperfection sensitivity.

2 $\frac{1}{2}+\frac{1}{4}+\frac{1}{6}+\frac{1}{8}+\frac{1}{10}+\frac{1}{12}+\ldots$ et cetera $=\ldots$

A … 2
B … e
C … π
D … ∞

3 The Jena planetarium dome is made by …

A … inflating a balloon, plastering fibre reinforced concrete.
B … assembling a steel grid, covering with mesh, spraying concrete.
C … building a timber formwork, placing rebars, casting concrete.
D … connecting prefab concrete panels, covering with copper plates.

4 Gaussian curvature k_G determines the ...

A ... natural frequency.
B ... point load stiffness.
C ... moment of inertia.
D ... edge disturbance.

5 Curvature is a tensor. How do we know?

A The teacher wrote this in the reader.
B There is a mathematical proof.
C Most engineers agree on this.
D Sanders and Koiter defined this independently.

6 How do we call the shape of Sillogue water tower?

A Paraboloid
B Hypar
C Conoid
D Hyperboloid

7 The dome of Saint Peter's basilica in Rome weighs 14 000 tons. Its inner diameter is 41 m and the outer diameter is 59 m. What is the largest stress?

A 0.1 N/mm^2
B 1 N/mm^2
C 10 N/mm^2
D 100 N/mm^2

8 n_{xx} = 1000, n_{yy} = -500, n_{xy} = -600 kN/m
k_{xx} = -1/10, k_{yy} = -1/20, k_{xy} = 1/(50 m)
What load is carried?

A 0.1 kN/m^2
B 1 kN/m^2
C 10 kN/m^2
D 100 kN/m^2

9 What can we do with an orthogonal parameterisation?

A Calculate membrane forces and deformation.
B Calculate knockdown factors.
C Calculate failure probabilities.
D Calculate imperfection sensitivity.

10 Consider the edge of a shell. The shell thickness is 70 mm. x Points in the direction of the edge and y points into the shell. m_{xy} = 10 kNm/m and v_x = 200 kN/m. What is the shear stress σ_{xz} in the edge?

A -5.7 N/mm^2
B 4.3 N/mm^2
C 9.7 N/mm^2
D 14.0 N/mm^2

11 The cassettes of Palazzetto dello sport have many shapes. How were these determined?

A Calculated by mathematical equations.
B Copied from a real size timber/plaster mock up.
C Measured from a scaled down wood model.
D Measured in a 3D AutoCAD drawing.

12 Consider a spherical cap. Span l = 50 m, sagitta s = 20 m, thickness t = 200 mm. What is the influence length? [1]

A 4.8 m
B 5.4 m
C 7.6 m
D 9.2 m

13 The influence length is used to ...

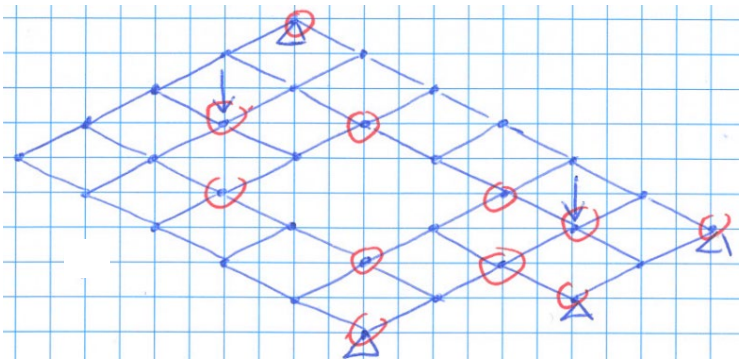
A ... determine the finite element size.
B ... perform parameter studies.
C ... prevent inextensional deformation.
D ... perform scale model tests.

14 A shell finite element analysis gives a stress of 342 N/mm^2. The element size is halved and the analysis repeated. This gives a stress of 354 N/mm^2 at the same location as before. If the element size were halved ten more times, what stress could be expected?

A 354 N/mm^2
B 366 N/mm^2
C 474 N/mm^2
D 486 N/mm^2

15 The red circles mark singularities in a finite element model of a flat plate. How many of these singularities cannot be resolved with solely smaller elements? [2]

A 5
B 6
C 10
D 11



16 Moments and shear forces computed by the finite element method may not agree with the shell boundary conditions. What is not the problem?

A The finite elements are too large.
B The boundary conditions are not properly selected in the software.
C The Mindlin-Reissner theory is applied.
D The Sanders-Koiter equations are not used in deriving the finite element.

17 $n_{xx} = 1000,\ n_{yy} = -500,\ n_{xy} = 0$ kN/m
$k_{xx} = -1/10,\ k_{yy} = -1/20,\ k_{xy} = 1/(50\ \text{m})$
$E = 30\ 000$ N/mm^2, $t = 100$ mm.
At what load factor will the shell buckle?

A 3
B 6
C 12
D 24

18 We design a wood grid shell with laths in the principal curvature directions. Why?

A In other directions there is torsion; the shear strength of wood is small.
B The curvature trajectory pattern is decorative.
C This provides optimum stiffness of the completed shell.
D The principal curvatures can be easily plotted and checked.

19 Is a bohemian dome a minimal surface?

A Yes, $k_{xy} = 0$
B Yes, for an appropriate parameterisation.
C No, $k_m \neq 0$
D No, $k_G < 0$

20 A flat square plate has a length and width of 1 m and a thickness of 15 mm. The plate is twisted by pushing one corner out of plane. At what radius of curvature will it buckle?

A 4 m
B 8 m
C 16 m
D 32 m

21 A linear buckling analysis gives us critical loads. How do we account for imperfection sensitivity?

A Select the highest consequence class.
B Specify appropriate partial load factors and partial material factors.
C Apply a knockdown factor.
D Add shape imperfections.

22 Consider two reinforced concrete shells roof designs. The shells have the same surface area. We made finite element models. Shell A has a buckling length of 2 m. Shell B has a buckling length of 3 m. We need to add shape imperfections to the models. How much larger is the imperfection amplitude of shell B?

A factor 1.5
B 18%
C 3.2 mm
D Undetermined: we do not know the imperfection lengths.

23 Consider a well-designed steel shell. a = 500 mm, t = 5 mm, f = 350 N/mm^2. The load is slowly increased. What will happen? [3]

A Fracture occurs before buckling.
B Buckling occurs before yielding.
C Plastic failure occurs before buckling.
D Plastic failure and buckling occur together.

24 Consider the calculation and test of your shell object. Which parameters (thickness, radius, yield strength, …) were difficult to determine and had a large influence on the ultimate load? Explain your answer.

25 Shell natural frequency must be …

A … higher than the frequency of the load.
B … lower than the frequency of the load.
C … as low as possible.
D … equal to the frequency of the load.

26 Which can be computed in a transient analysis?

A Largest stress in a storm
B Natural frequencies and eigen modes
C Damping of the materials and foundation
D Damage in an explosion

27 A strain gauge can be used to …

A … monitor yielding.
B … measure rolling stresses.
C … determine damping ratios.
D … detect crack growth.

28 A Monte Carlo analysis has been performed for a one year period. The number of trials is 1 000 000. Turkstra's rule is applied. There are 141 wind load failures, 6 snow load failures and 53 live load failures. What is the failure probability?

A 4 / 1 000 000
B 6 / 1 000 000
C 141 / 1 000 000
D 200 / 1 000 000

29 The British museum in London is very popular. Most of its staff works 8 hours a day 5 days a week. The museum has a shell roof that will be renovated to last for 30 more years. The governing load combination is gravity and storm. The renovation plan has been analysed for safety. The one year failure probability is 4/1 000 000. The 30 year failure probability is 479/1 000 000. Are these probabilities okay?

A yes, yes
B yes, no
C no, yes
D no, no

30 Write a good shell multiple choice question for next year's exam. The question needs to be not too easy and not too difficult. The question needs to be not just copied and not copied-and-modified-a-bit. (Unless the latter modification is substantial and original.)

Answers

1 C 85%
2 D 100%
3 B 92%
4 B 100%
5 B 100%
6 D 92%
7 A 62% ….

meridional stress =

$$-\frac{140000000\,\text{N}}{\frac{1}{4}\pi(59000\,\text{mm})^2-\frac{1}{4}\pi(41000\,\text{mm})^2}=-0{,}1\ \text{N/mm}^2$$

hoop stress = the same but tension

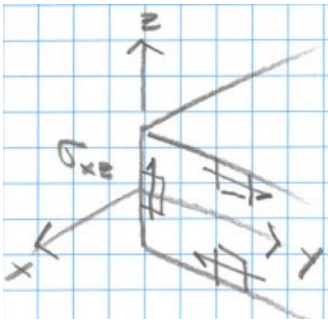
8 D 100% …..

$$k_{xx}n_{xx}+2k_{xy}n_{xy}+k_{yy}n_{yy}+p_z=0$$

$$-\frac{1}{10}1000-2\frac{1}{50}600+\frac{1}{20}500+p_z=0$$

$$-100\quad -24\quad +25\quad +99=0$$

9 A 100%
10 D 54% …



$$\sigma_{xz}=\frac{3}{2}\frac{V_x}{t}+\frac{3}{2}\sqrt{10}\frac{V}{t^2}$$

$$=\frac{3}{2}\frac{200\ \text{N/mm}}{70\ \text{mm}}+\frac{3}{2}\sqrt{10}\frac{10000\,\text{N}}{(70\ \text{mm})^2}$$

$$=4{,}3\quad +9{,}7\quad =14{,}0\ \text{N/mm}^2$$

11 B 54%
12 B 92% …

$$a=\frac{1}{2}s+\frac{1}{8}\frac{l^2}{s}=\frac{1}{2}20+\frac{1}{8}\frac{50^2}{20}=10+15{,}5=25{,}5\,\text{m}$$

$$l_i=2{,}4\sqrt{at}=2{,}4\sqrt{25{,}5\times0{,}2}=5{,}4\ \text{m}$$

13 A 92%
14 B 92% ……

$$342\xrightarrow{+12}354\xrightarrow{+12}\cdots\rightarrow366$$

15 D 85%
16 D 38% … C 54% is wrong: Mindlin-Reissner has different boundary conditions.

17 B 46% ….

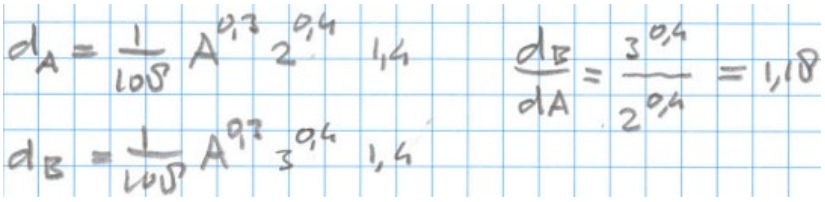
$$\lambda_{cr}=\frac{1}{n_{yy}}\frac{1}{6}\frac{-0{,}6Et^2}{a_x}=\frac{1}{-500}\frac{1}{6}\frac{-0{,}6\times30000\times100^2}{10000}=6$$

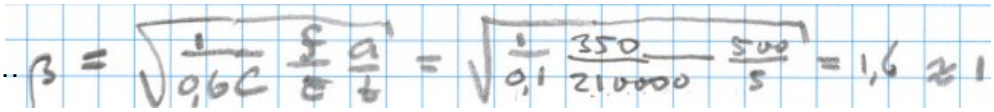
18 A 69%
19 C 100%
20 A 77% ….

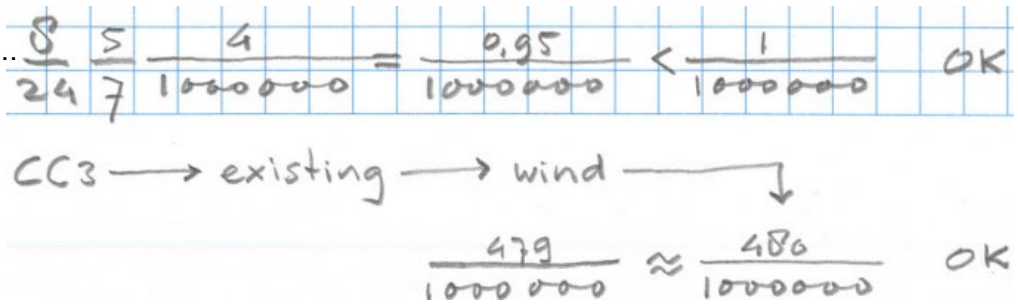
$$u=16{,}8t=16{,}8\times15=252\ \text{mm}$$

$$k_G=-\frac{u^2}{b^4}=\frac{-0{,}252^2}{1^4}=-\frac{1}{16\,\text{m}^2}$$

$$k_G=\frac{1}{a}\frac{-1}{a}=\frac{1}{4}\frac{-1}{4}\Rightarrow a=4\,\text{m}$$

21 C 100%
22 B 100% … 

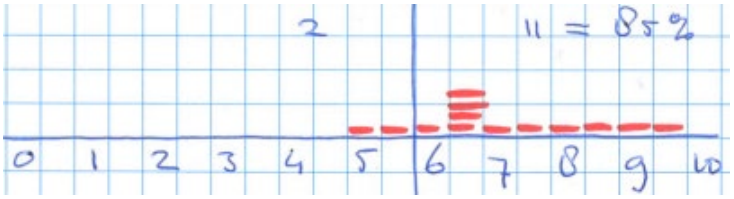
23 D 23% …… 
24 75%
25 A 100%
26 D 62%
27 C 8% … A 85% is wrong: the strain gauge would break.
Moreover, it is difficult to predict where exactly it will yield.

28 D 92%
29 A 46% …. 
30 81%

The grade is (10 *s* – 70) / 23 rounded to the closest halve, where *s* is the number of correct answers.

$g = a + b\,s$
$0 = a + b\ 28/4$
$10 = a + b\ 30$

$a = -70/23$
$b = 10/23$



[1] Question by Stijn Platzer, February 2024
[2] Question by Amco de Jong, February 2024
[3] Question by Kenneth Brouwer, February 2024