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INFLUENCE OF THE INITIAL IMPERFECTIONS ON THE STRENGTH AND STABILITY OF THE THIN-WALLED STRUCTURES

DOCTORAL DISSERTATION

(Annotation)

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Substance

Tab. 1: List of used physical quantities

Quantities	Description	Unit
A	cross sectional area of circumferential ring	mm^2
D	diameter of the edge	mm
E	Young's modulus of elasticity	MPa
E_{tan}	tangent modulus of hardening	MPa
l_g	reference length l_g (length of ruler to measure imperfections)	mm
R	radius of curvature of spherical cap	mm
p	external pressure	MPa
p_{Rcr}	elastic critical buckling pressure	MPa
p_{cr}^{GNIA}	critical outer pressure of imperfect spherical cap in elastic area	MPa
p_{cr}^{GNA}	critical outer pressure of ideal spherical cap in elastic area	MPa
$R_{p0,2}$	yield strenght	MPa
r	radius of the base circle	mm
t_c	wall thickness of the spherical cap	mm
t_r	wall thickness of the circumferential ring	mm
u_y	displacement of point in the center of the cap	mm
w	width of the circumferential ring	mm
Δw_k	characteristic amplitude imperfection	mm
Δw	depth of initial geometric imperfection	mm
α	elastic imperfection factor (reduction factor)	---
Γ	parameter influence of radial stiffness of the circumferential ring	---

δ	relative deviation	%
ε	strain	---
μ	Poisson´s number	---
ξ	parameter influence the depth of the initial imperfections	---
Φ	half angle	°
σ_{Rcr}	critical stress	MPa
χ	buckling reduction factor	---

1 Introduction

Thin-walled structures are often used in different branches of industry (chemical, energy, transportation, construction, food, etc.). The main advantage of the thin-walled structure is the high carrying capacity at low weight of structure. One of the possible limiting states of these types of structures is the loss of stability. Loss of stability can be significantly influenced by initial imperfections of the structure. The initial imperfection usually reduces carrying capacity of the structure. The initial imperfections sometimes influence the shape of loss of stability.

Initial imperfections can be considered as the imperfections of geometry, the attaching and loading of the structure, initial stress or irregularly distributed mechanical material properties, etc. The stability can be mainly influenced by initial geometric imperfections. Initial geometric imperfection is supposed in the form of a local buckle.

Doctoral dissertation deals with the influence of initial imperfections on the loss of stability of thin-walled spherical caps. The problem is reduced to the simply supported spherical caps subjected to an external pressure. The caps are stiffened by the circumferential ring at the lower edge.

The main aim of the doctoral dissertation is to determine a new reduction factor. This factor represents influence of the initial imperfections on the loss of stability of the spherical cap stiffened by circumferential ring at the lower edge.

2 Current situation in the studied problems

Loss of stability of thin-walled structures has been the subject of research of many authors. This chapter provides the summary of the most significant authors. Doctoral dissertation is founded mostly on research of authors W. Wunderlich and P. Paščenko.

D. Bushnell [8] marginally dealt with the numerical description of the behavior of spherical cap stiffened by circumferential ring. Bushnell in his book claims that spherical caps are less sensitive to the initial imperfections. This phenomenon is explained by nature of construction of a spherical cap, which it contains significant bending stress. The author presents that the influence of this bending effect on the loss of stability may be higher than the influence of bending effect of initial imperfections.

M. Esslinger and B. Geier [7] performed a series of experiments of loss of stability of the complete sphere. They found the complete sphere is very sensitive to initial imperfections. The authors likened the sensitivity of the complete sphere to the sensitivity of the axially loaded cylindrical shells. They confirmed that one of the critical load can correspond to multiple to eigen shapes of loss of stability.

P. Paščenko studied loss of stability of thin-walled spherical caps in his habilitation thesis [4]. He examined also spherical caps with final stiffness in the radial direction. He expressed the influence of initial imperfections on the loss of stability by reduction factor. This factor was derived for axially loaded cylinder. The author himself refers to this approach probably a conservative

W. Wunderlich [3] studied the loss of stability of spherical caps in terms of boundary conditions, the half angle of a spherical cap, non-linear material behavior (plasticity) and the influence of initial imperfections. Author reached the simple relations intended

to design a spherical cap for the uniform load. He compiled his findings in the European ECCS recommendations (stability of steel structures) [2]. Author did not, however, examine the influence of circumferential ring to the loss of stability of the spherical cap. Description of research (anchored in the ECCS) is shown in the following chapter 2.1.

2.1 Influence of initial imperfections on the load carrying capacity spherical cap according to ECCS [2] (author W. Wunderlich)
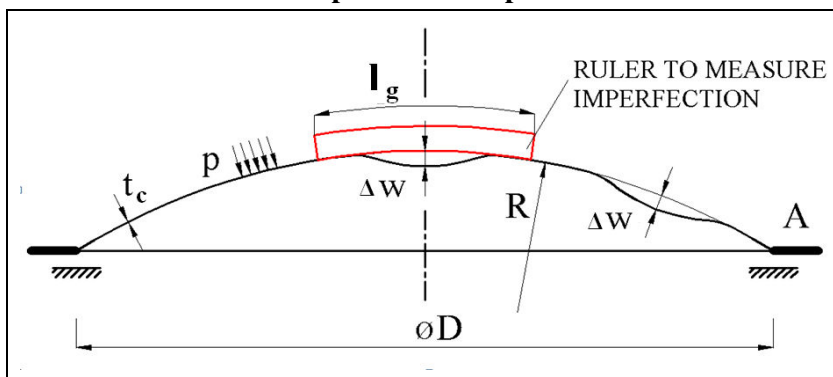
2.1.1 Characteristic imperfection amplitude

Fig. 1: *Simply supported spherical cap stiffened by circumferential ring.*

Characteristic imperfection amplitude Δw_k expresses the maximum depth of imperfections (local buckle). Its value depends on the accuracy class of production and on the geometrical dimensions of a spherical cap. The size of the characteristic imperfection amplitude is measured by using a ruler for measuring of initial geometric imperfections (Fig. 1).

Characteristic imperfection amplitude is determined by the equation:

$$\Delta w_k = \frac{1}{Q}\sqrt{R * t_c} \qquad (1)$$

where

Q – fabrication quality parameter from *Tab. 2*.

Tab. 2: *Value of quality parameter Q*

Accuracy class	Description	Q
Class 1	excellent	40
Class 2	hight	25
Class 3	normal	16

The dependence of the characteristic imperfection amplitude vs. thickness parameter R/t_c is shown in Fig. 2. It is obvious that the maximum allowable depth of local buckle increases with decreasing thickness parameter R/t_c.
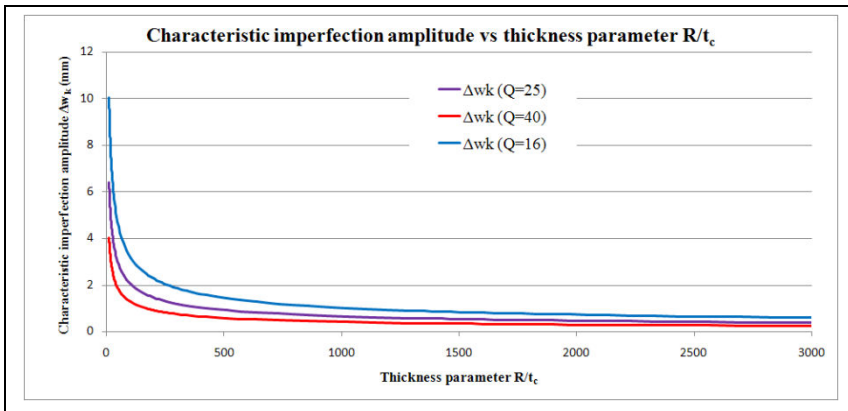

Fig. 2: *Dependence of the characteristic imperfection amplitude vs. thickness parameter R/t$_c$*

2.1.2   The elastic imperfection factor

The influence of the initial geometric imperfection on the carrying capacity of the spherical cap is expressed by elastic imperfection factor α. The elastic imperfection factor α is determined by formula

$$\alpha = \frac{0{,}70}{1 + 1{,}90 * \left(\frac{\Delta w_k}{t_c}\right)^{0{,}75}} \tag{2}$$

where

Δw_k – characteristic imperfection amplitude.

Example of elastic imperfection reduction factor α is shown in Fig. 3. The value of elastic imperfection factor α decrease with the increasing thickness parameter R/t_c. Reduction factor is conservatively set for hinged spherical cap in the ECCS. The bending effect caused by the boundary conditions simply supported cap is higher than that hinged cap. Elastic imperfection factor (specified in the ECCS) is excessively conservative to the design cap with the final stiffness in the radial direction.
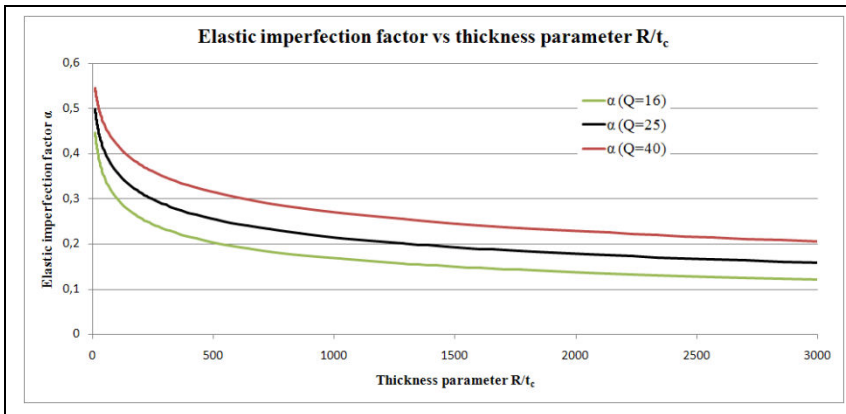

Fig. 3: Elastic imperfection factor vs. thickness parameter R/t_c

3   Aim of the doctoral dissertation

Doctoral dissertation builds on the current knowledge of science and technology in the design of steel spherical cap. These findings are anchored in standards, regulations and recommendations [1], [2], [18]. The calculation of spherical cap with a final stiffness in the radial direction is not included in the European the ECCS recommendations [2] or in the standard ČSN EN 1993-1-6 [1]. Using the relations to calculate simply supported cap can be regarded as too conservative.

P. Paščenko studied limit load of cap with final stiffness in the radial direction in his habilitation thesis [4]. The influence of initial geometric imperfections on the loss of stability of the spherical cap stiffened by circumferential ring is not sufficiently taken into consideration in his habilitation thesis [4]. Author used a reduction factor determined for axially loaded cylinder shell.

The aim of the doctoral dissertation is to determine new reduction factors and relationships. New reduction factors could be applied to common design of spherical cap in practice. Reduction factors will express the influence of initial imperfections on the loss of stability of a spherical cap with a finite stiffness in the radial direction.

Numerical analyses of the types GNA, GNIA, and GMNA GMNIA are the basis for solving the problem. Analyses are performed in software COSMOS/M [5] and CosmosWorks [6].

Another aim of the doctoral dissertation is to prepare an experiment of the loss of stability of the test specimens. Test specimens present a real spherical caps stiffened by circumferential ring. The aim of the performed experiments is to verify the results of numerical analyses.

4 Preparation of experiment – development of test equipment

The results of the numerical analyses will be verified by experiments. Geometric dimensions of the test specimen are determined in this chapter. In addition, the first stage of the development of test equipment for testing the loss of stability of thin-walled spherical caps is described here. The test equipment was developed in this doctoral dissertation and is available at the Department of Mechanics, Materials and Machine Parts.

First series of the tests of the loss of stability were performed during the development of test equipment. The main aim of the first series tests was to verify functionality of test equipment, the selected thickness of circumferential ring and production method of test specimens.
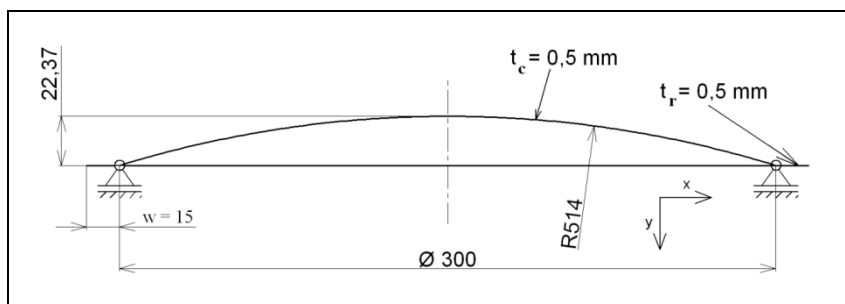

Fig. 4: *Dimensions of the spherical cap.*

Dimensions of the cap are given in Fig. 4. The thickness of wall of the spherical cap is $t_c=0,5$ mm, curvature radius $R=514$ mm, diameter of lower edge $D=300$ mm, thickness parameter $R/t_c=1028$ and cross sectional area of the circumferential ring $A=7,5$ mm^2. Width of the ring is $w=15$ mm and thickness is $t_r=0,5$ mm.

4.1　Test equipment

The test equipment is shown in Fig. 6. The test equipment is made of cylindrical shells (tubes) with a length of 300 mm, outer diameter Ø 273 mm and wall thickness 7.5 mm. The experimental model is simply located on the rubber sealing. The loading pressure is achieved by the suction pump. The dimensions of experimental model should be chosen so that the value of limit pressure is less then maximum attainable pressure $p_b=0,09$ *MPa* (determined by suction pump).

The loading pressure is continuously regulated by the choke. The value of loading external pressure (internal vacuum) is read on the analogue pressure gauge. In future test, the loading external pressure is supposed to the measured by electronic sensors.

Fig. 5: Test specimen　　　　　*Fig. 6: Test equipment*

4.2　Numerical model

Numerical analysis of the test specimen was performed before production test equipment. The numerical model of the spherical cap is shown in Fig. 7. The numerical analysis investigates only the influence of boundary conditions on loss of stability thus the initial imperfections are not considered. The nonlinear model of material is represented by von Mises´s bilinear model with Young´s modulus

$E=1,8E+5$ *MPa (N/mm^2)*, Poisson´s number $\eta = 0,3$, tangent modulus $E_{tan}=E/10^4=18$ *MPa (N/mm^2)* and yield strength $R_{p0,2}=180$ *MPa*.

The nonlinear GMNA analysis (geometrically and materially nonlinear analysis) is performed in the FEM computer program COSMOS/M [5]. Both material and geometric nonlinearity are considered. The Rick´s arc length nonlinear computational procedure is used. The FEM mesh of the numerical model is created by SHELL4T elements. The spherical cap located on the rubber sealing is simulated by simply supported spherical cap.
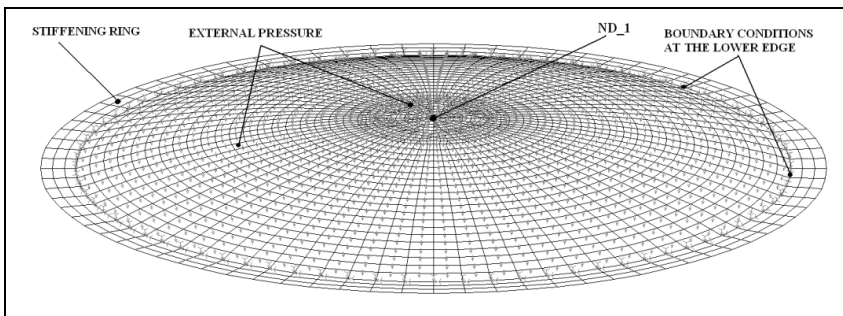

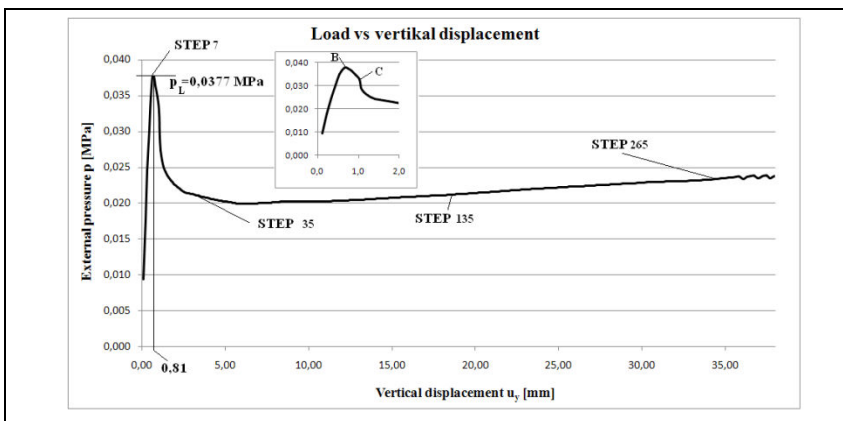***Fig. 7:*** *Numerical model of the spherical cap*

Fig. 8: *Equilibrium curve*

The equilibrium curve is shown in Fig. 8. The curve represents a relation of external pressure and vertical displacement of node *ND_1* (see Fig. 7). The numerical model of the spherical cap performs a linear behavior until value of external pressure $p_L=0,0377\ MPa\ (0,377\ bar)$. Then the carrying capacity is falling down.

The loss of stability occurs close to $u_y=0,81\ mm$. Deformed shapes in the selected steps are shown in Fig. 9 on the next page. The limit state occurs in the nonsymmetrical shape of deformation called nonlinear axially nonsymmetrical collapse (see Fig. 9). This type of loss stability is followed by the creating visible circumferential waves of the edge ring. This effect should be verified by experiment.
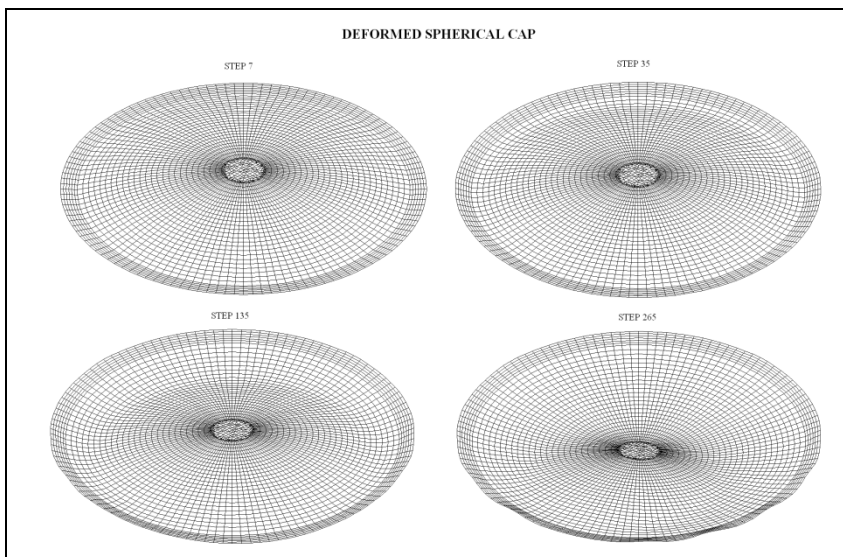

DEFORMED SPHERICAL CAP

STEP 7   STEP 35

STEP 135   STEP 265

Fig. 9: Process of deformation of the numerical model.

4.3   Experimental model

The experimental model of spherical cap is shown in Fig. 5. The dimensions of both numerical model and test specimen are equal (see Fig. 4). The experimental specimen is made of carbon steel. Young´s modulus $E=1,8E+5$ MPa (N/mm^2), Poisson´s number $\eta=0,3$, and yield strength $R_{p0,2}=180$ MPa are taken from the tensile test performed at the laboratory.

The test specimen is not yet equipped with purposely inserted the initial imperfections in the form local buckle. Limit external pressure was recorded during the experiment. Limit external pressure, in which the loss of stability occurred, are given in Tab. 3 on the end of this chapter. The deformed shape of the test specimen before and after the experiment is shown in Fig. 10.

Fig. 10: Original and deformed test specimen.

Fig. 11: Test specimen located on the test equipment.

The deformed shape is shown in Fig. 9. It is evident that the nonsymmetrical collapse occurred. The deformation of circumferential ring (creating circumferential waves and rotation of the ring) are obvious.

Tab. 3: *Limit outer pressure.*

Number of test specimen:	1	2
Limit outer pressure p_L [MPa]	0,024	0,022
The relative deviation δ (%) Num. model vs specimen	57 %	71 %

4.4   Conclusion

The deformation of the ring caused the loss of tightness of the vacuum space. Hence, the experiment was stopped before total collapse of the spherical cap. The deformations of the experimental model are a bit different from the deformations of the numerical model. It is probably caused by initial imperfections.

The findings are used for verification of the numerical model and for adjusting the thickness of the circumferential ring. The test equipment will be modified so as to prevent rotation of the ring. A thicker ring should be used for the next experimental test specimens.

The relative deviation is relatively high (see Tab. 3). This effect can be explained by the elastic imperfection factor (eg Fig. 14, Chap. 5). Elastic imperfection factor decreases very quickly even for small depth of imperfections. It is difficult to prevent such small initial imperfections in the production of test specimens. Neglected initial imperfections obviously caused a decrease in load carrying capacity of the test specimens.

5 Determination of the reduction factor α for spherical cap stiffened by circumferential ring.
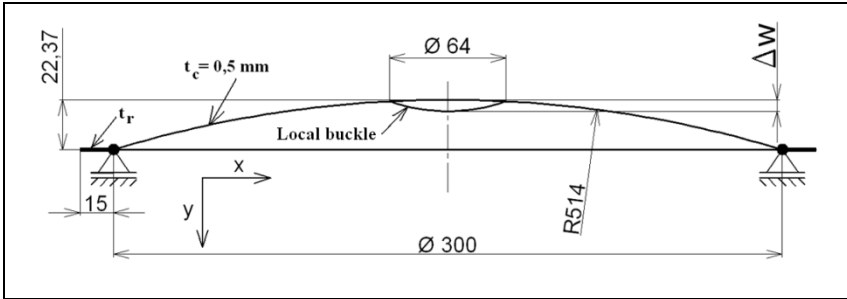

Fig. 12: Dimensions of the model of roof

Influence of geometrical imperfections on the loss of stability a spherical cap is expressed by reduction factor α. Reduction factor is the ratio of critical load of imperfect cap to critical load of ideal cap (equation (3)). Nonlinear numerical analysis was performed for determination of reduction factor. Numerical analyses were type of GNA and GNIA.

$$\alpha = \frac{p_{cr}^{GNIA}}{p_{cr}^{GNA}} \qquad (3)$$

where

p_{cr}^{GNIA} – critical outer pressure of imperfect cap,
p_{cr}^{GNA} – critical outer pressure of ideal cap..

The loss of stability a real roof corresponds to numerical model of simply supported spherical cap with prevents tangential rotation of the lower edge (see Chap. 6 doctoral dissertation). The results of numerical analysis for simply supported caps with prevent tangential rotation of the lower edge will be verified experimentally.

Spherical caps are stiffened by a circumferential ring of width w=15 mm. Computations are performed for four types of circumferential rings of different sizes of cross sectional areas (A_1=7,5 mm^2; A_2=15 mm^2; A_3=30 mm^2; A_4=60 mm^2).
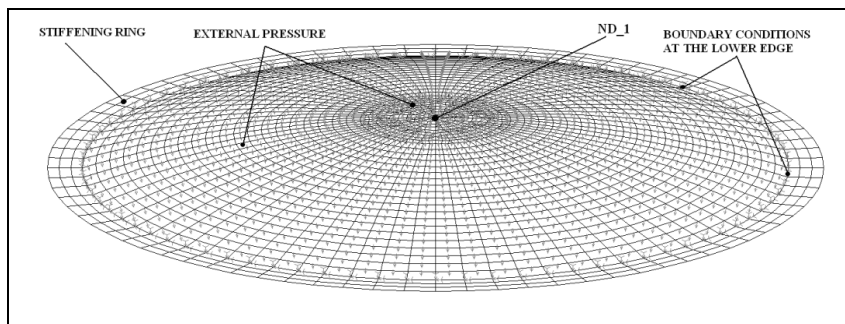

Fig. 13: Numerical model

The reduction factor α is determined on the basis of the numerical analysis. Geometric initial imperfection (local buckle) is considered in the middle of the spherical cap.

Depth of imperfection is gradually increased until it reaches the boundary validity of the recommendations ECCS [2]. Four non-linear analyses (type GNIA) are performed for chosen depth imperfection.

The influence material nonlinearity (plasticity) is not considered in the calculation of the reduction factor α. The influence of plasticity on the loss of stability of a spherical cap can be expressed as in addition factor of buckling reduction factor χ (see Chap. 2.3.6 of the doctoral dissertation).

Dimensionless parameters $\Delta w/t_c$ and $\Gamma=A/(r*t_c)$ are determined in Chapter 9 of the doctoral dissertation. Dimensionless parameters are based on the similarity theory. Reduction factor α determined to model the roof can be on the basis dimensionless parameters used for the structural design of a real roof.
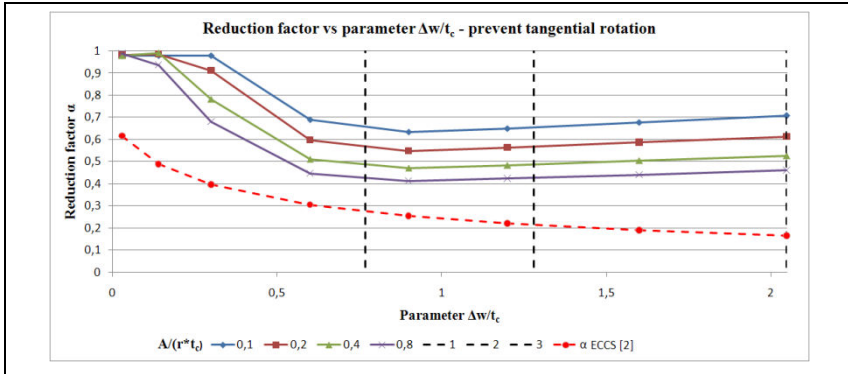
Fig. 14: *The diagram of reduction factor*

The diagram of the reduction factor α versus parameter $\Delta w/t_c$ of the cap with the ring of cross-sectional area A_1, A_2, A_3, A_4 is shown in Fig. 14. The diagram is for a better summary supplemented by curve valid for elastic imperfection factor α from ECCS (see equation (2)). The elastic imperfection factor for the calculation simply supported cap stiffened by circumferential ring is too conservative.

Vertical boundaries 1, 2, and 3 represent the maximum allowable depth of imperfection for the accuracy classes (1, 2, 3) according to the ECCS [2]. Graph on Figure 14 is shown for better illustration in 3D format on Fig. 15.

The central imperfection of depth greater than $\Delta w = 0.4$ mm is not affine to the shape of the collapse of the cap and it starts perform as a stiffener. This has the effect that the curve of reduction factor α has in fact no decreasing character after crossing depth of imperfection $\Delta w = 0,4$ mm.
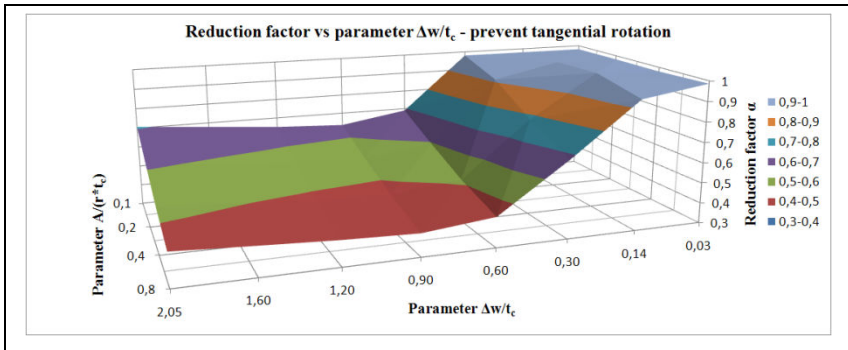
Fig. 15: *Reduction factors α vs parameter Δw/t_c and* $\Gamma = \dfrac{A}{r * t_c}$.

Tab. 4: *Reduction factors α determined for model of roof - prevent tangential rotation lower edges.*

$\Delta w/t_c$ $\qquad$ $\Gamma = \dfrac{A}{r * t_c}$	0,1	0,2	0,4	0,8
0,03	0,98	0,98	0,98	0,99
0,14	0,98	0,98	0,99	0,94
0,30	0,98	0,91	0,78	0,68
0,60	0,69	0,60	0,51	0,45
0,90	0,63	0,55	0,47	0,41
1,20	0,65	0,56	0,48	0,42
1,60	0,68	0,59	0,50	0,44
2,04	0,71	0,61	0,53	0,46

The so-called the enveloping curve can be created for each curve of reduction factor α. The result of the application envelope curve can be useful in practise. Reduction factor α never falls below the value specified by the enveloping curve. Using the enveloping curve is conservative and on the safe side.

Graph from Fig. 14 supplemented with enveloping curves is shown in Fig. 16. Straight line parallel to the axis of depth imperfections (x-axis) were used as enveloping curve. Each enveloping curve represents a constant reduction factor α. Values of reduction factor α for the individual enveloping curve are given in Tab. 5.
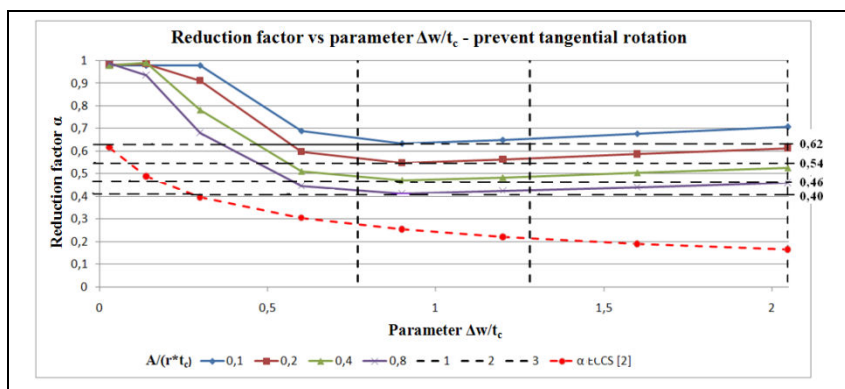

Fig. 16: Determination of the reduction factors for use in engineering practice

Tab. 5: Determination of the reduction factors for use in engineering practice - dimensionless parameter Γ

$\Gamma = \dfrac{A}{r * t_c}$	Γ=0,1	Γ=0,2	Γ=0,4	Γ=0,8
Reduction factor α	0,62	0,54	0,46	0,40

6 Conclusion

6.1 Short summary of the doctoral dissertation

Doctoral dissertation focuses on the influence of initial geometric imperfections on the loss of stability spherical caps stiffened by circumferential ring. Investigated area is limited to simply supported spherical caps with the final stiffness in the radial direction. The described problem is mostly solved by numerical analyses in the environment of program COSMOS/M [5] and CosmosWorks [6].

Current state of resolution the problem of stability loss of a spherical cap was fully described in the introductory part of the doctoral dissertation. The aim of glossary topic was to show the area of solutions that have not yet been explored. The influence of initial geometric imperfections on the loss of stability of cap with the final stiffness in the radial direction has not yet been fully described.

The influence of location of the geometric imperfection (local buckle) on the loss of stability of the spherical cap is part of the doctoral dissertation. Construction of type roof of cylindrical shell or partition of cistern trucks is examined in the doctoral dissertation. Boundary conditions (see Chap. 6 of the doctoral dissertation) of numerical models are determined so that the results of numerical calculation the most correspond with researched types of structures (roofs of cylindrical shell and partitions cistern trucks).

Calculations of the reduction factor α was performed by numerical analysis of computational model of simply supported spherical cap stiffened by circumferential ring and with prevented tangential rotation of the lower edges of the cap.

The new reduction factor α (see Fig. 16 and Tab. 5) established in the doctoral dissertation could find use in designing a similar spherical cap in practice. The value of the reduction factor

for the real roof can be determined from Tab. 5. Results in Tab. 5 are conservative and therefore on the safe side.

Verification of the results of numerical analysis performing the experiment is currently still ongoing. Preparation of experiments and the development of the test equipment are described in the doctoral dissertation. First tests of the loss of stability test specimens were performed on the test equipment. Results of the experiments were used to modify test equipment and method of production of test specimens.

6.2 The scientific - technical contribution doctoral dissertation

The influence of initial geometric imperfections on the loss of stability of spherical cap with the final stiffness in the radial direction has not yet been fully described. Reduction factor α referred in the European recommendations ECCS [2], expresses the influence of initial imperfections on the loss of stability of a spherical cap.

Reduction factor specified in the ECCS [2] is determined for a hinged spherical cap. Using this factor to calculate the loss of stability of a spherical cap with the final stiffness in the radial direction may be too conservative.

The results presented in the doctoral dissertation suitably complement the current state of knowledge of science and technology. Reduction factor α (Fig. 16) provided in the doctoral dissertation expresses the influence of geometrical imperfection on the initial loss of stability of a spherical cap with the final stiffness in the radial direction. The problem of determining the reduction factor has not yet been fully resolved. It is necessary to finish the verification of the results of numerical analysis performing experiment.

The results presented in the doctoral dissertation are necessary to submit to analysis of professionals. After fulfilling all the criteria, it is possible to seek of anchoring the reduction factor α specified in Tab. 5 into the recommendations the ECCS and normative regulations.

6.3   Application of results in practice

The structures types of spherical caps are used in various branches of industry for example chemical, energy, food, automobile, etc. The doctoral dissertation deals with structures types of roof of cylindrical shell, etc. Materials used for production of equipment in the chemical, energy and food industry can be very expensive. Reduction factors α determined for spherical cap stiffened by circumferential ring provides safe reduction of thickness of spherical cap. Thinner shells reduce weight of structure and, therefore, reduce manufacturing costs.

Reduction factor α (Fig. 16 and Tab. 5.) can be safely used in the design of real roofs of tanks only after complying with additional points.

- Verification results of numerical analysis performing the experiment.
- Verify the correctness dimensionless parameters for caps with different half angle Φ.
- Determine the extent validity calculations reduction factor (half angle Φ; thickness parameter R/t_c).

These additional points will be subjected to further research. The results presented in this doctoral dissertation are the next step for putting the reduction factor α (Fig. 16 and Tab. 5.) for the design of spherical caps with the final stiffness in the radial direction to the engineering practice.

6.4 Objectives for future research

The main objectives of future research are indicated in the previous text. Performed experiments will be associated with contactless scanning of changes in the geometry test specimen during loss of stability.

Contactless measurement of changes in geometry is ensured by ARAMIS, which it works on the principle of optical scanning of irregular pattern of points. The exact model of a spherical cap with initial geometric imperfections will be compiled on the basis of the measurement system ARAMIS (see Fig. 17).

It is necessary to solve the question of how to influence the connection of circumferential ring and spherical cap in future research. Circumferential ring for the first experiments were welded to the shell test specimen. Welding influenced the results of the experiment. Now circumferential rings are glued to the shell test specimen cap
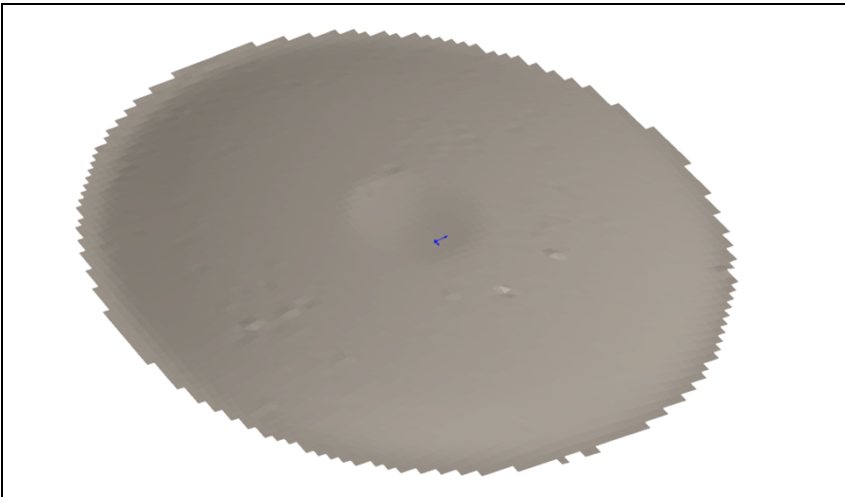

Fig. 17: *The exact model of a spherical cap created by the measurement system ARAMIS.*

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ANOTACE

Tato práce se zabývá vlivem počátečních imperfekcí na ztrátu stability tenkostěnných skořepinových konstrukcí. Zkoumaný případ je omezen na prostě podepřený kulový vrchlík zatížený rovnoměrným vnějším přetlakem. Kulový vrchlík je vyztužen obvodovým prstencem.

KLÍČOVÁ SLOVA

kulový vrchlík, ztráta stability, imperfekce, numerická analýza, MKP

ANNOTATION

This work deals with influence of the initial imperfections on the loss of stability of thin - walled structures. The problem is limited on the simply supported spherical cap subjected to external pressure. The spherical cap is stiffened by a circumferential ring.

KEYWORDS

Spherical cap, loss of stability, imperfections, numerical analysis, FEM

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