STRUCTURAL ANALYSIS OF WATER TOWER ACCORDING TO SNIP II-7-81*

FOR

Project: “Technical Expertise and develop Detailed Technical Design for conservation/restoration works of Bender Fortress”

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1. INTRODUCTION

1.1. Objectives of structural analysis

The task consists of performing the structural analysis of the Bender Fortress – Water Tower. Construction element will be calculated individually. The process consists of calculation of characteristic and design loads and performing the static and dynamic analysis, including the determination of the dynamic proprieties of tower based on the Moldavian design standards.

1.2. Documentary basis of structural analysis

As reference documents for structural analysis were used the following:

[1] **"Studio Berlucchi" srl** – Technical expertise and develop detailed technical design for conservation and restoration works of Bender Fortress (Phase I)

[2] **Nicoara I.; Bogdevici O.** Report on geological data Tighina Fortress

[3] NCM E.02.02:2016. Fiabilitatea în construcții.

[4] NCM F.03.02-2005. Proiectarea construcțiilor cu pereți din zidărie.

[5] СНиП 2.01.07-85. Нагрузки и воздействия.

[6] СНиП II-7-81*. Строительство в сейсмических районах.

[7] СНиП 2.02.01-83. Основания зданий и сооружений.

Technical-scientific literature used:

- **Atanasiu M. Gabriela** "Structural Dynamics", *Vasilie Goldis University Press*, Arad 2000
- **Гордеев В.Н**. и др. "Нагрузки и воздействия на здания и сооружения", *Издательство Ассоциации Строителиных Вузов* – 2000
- **Birbrae r A.N.** "*Seismic Analysis of Structures.*" - St. Petersburg: Nauka, 1998. -255 p.
- СВОД ПРАВИЛ. *Трубы Промышленные Дымовые. Правила проектирования*, министерство строительстваи жилищно-коммунального хозяйствароссийской федерации - Москва 2016
- **Santwant Rihal, Edmiste John, Sinhui Chang** "*Seismic behavior of Masonry Cloister Valuts*", Academia XXI, 2018
- **Chiara Calderini, Sergio Lagomarsino** "*Seismic response of masonry Arches reinforced by Tie-Rods: Static test on a scale model*", American Society of Civil Engineers, 2014
- **SCAD Soft -** https://scadsoft.com/

1.3. Category of importance

Normative "NCM E.02.02:2016. Fiabilitatea în construcții." (Reliability in Construction) does not mention a clear category of importance for historical monuments or architectural heritage. But given the historical significance of the studied objective; structure could be classified as CC-3 level of importance (Hight level), group 2 (p.2.5, 2.12) with minimum value of reliability coefficient $\gamma_n = 1.1$.

2. ANALITICAL PART

2.1. Description of the analyzed object

Water tower, part of Bender Fortress complex represents a 7.43 meters height construction with regular form in plan with approximative dimensions 5.8 meters x 5.40 meters. The upper structure of tower represents a cloister vault.

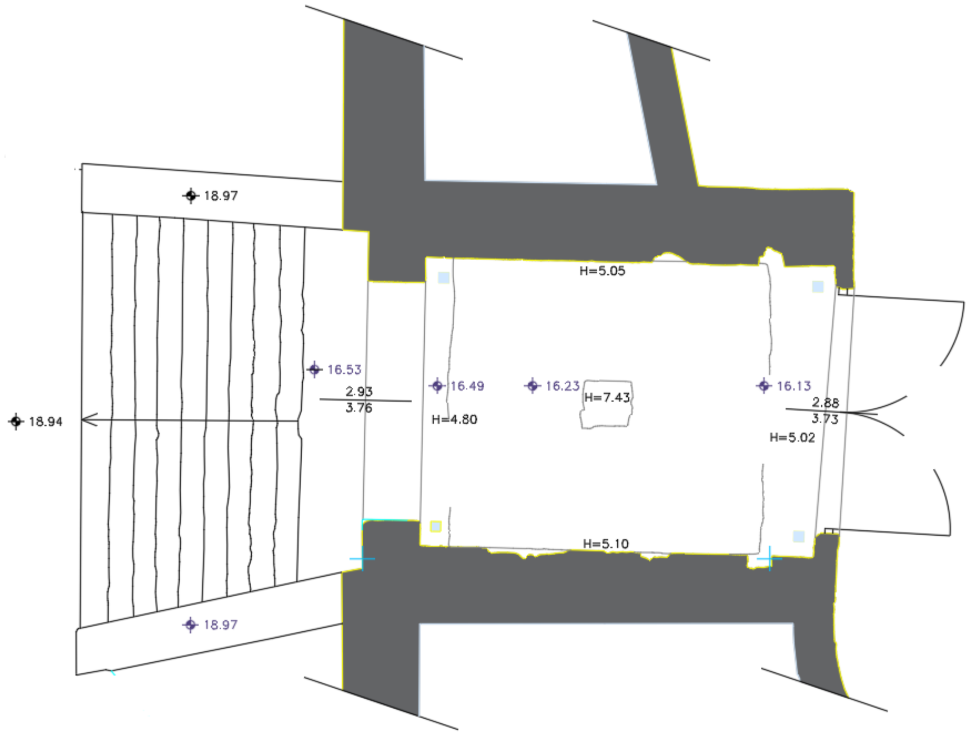

Figure 1 Plan view of Water Tower

One of the main problem regarding the consolidation of water tower is cloister vault. As can be noted for [1], the collapse mechanism can be triggered from bottom level of the vault. So it's critical to analyses the comportment of vault exposed to seismic actions.

Information about the construction region

- Air temperature:
  - minimum air temperature – (-) 41.4 °C;
  - maximum air temperature – (+) 31.2 °C;
- Area of the characteristic value of the snow load on the ground – I.
  The characteristic value of the snow load on the ground per 1 m^2– $s_0 = 0,5\ kPa.$
- Area of the characteristic value of the wind pressure on the ground – II.
  The characteristic value of the wind pressure – $w_0 = 0,3\ kPa.$
- Site seismicity – 7 grades according to MSK-64 scale.

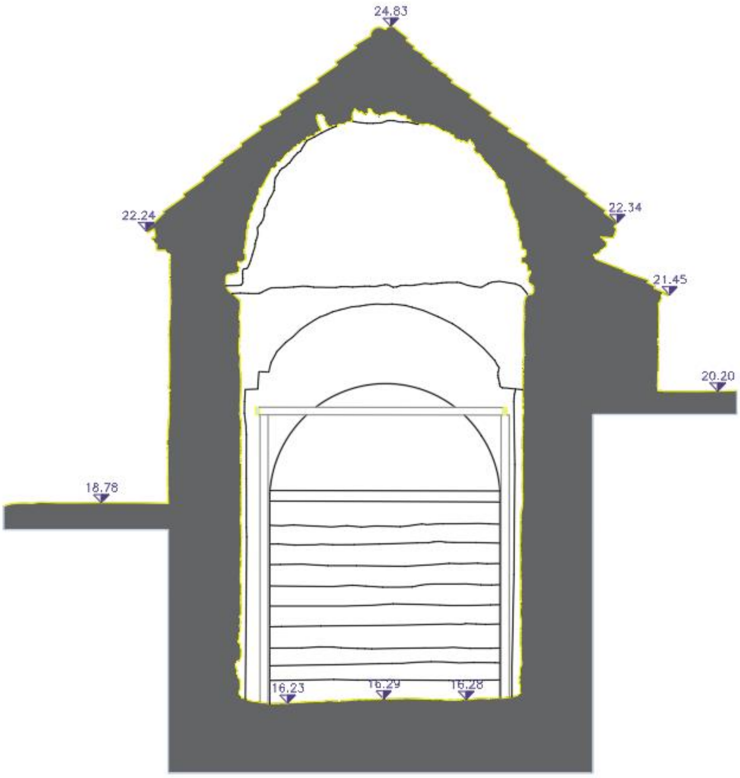

Figure 2 Section view of Water Tower

2.2. Structural characteristic of building

Vault will be analyzed as shell structure using Finite Element Model software.

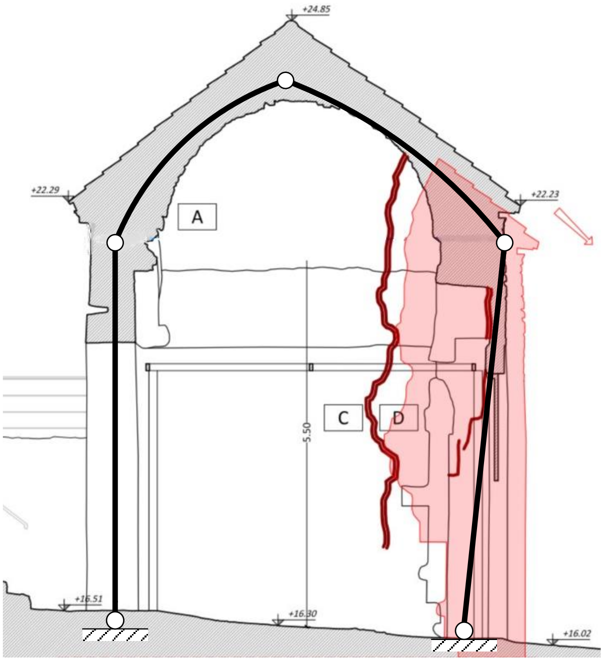

Figure 3 Theoretical collapse mechanism of vault.

2.2.1. Rigidity

The elastic modulus of masonry was computed by using expression (6) given in [4]:

$$E_0 = \alpha R_u$$

where α – the elastic characteristic of unreinforced masonry and R_u is assigned value of $2R$; R – design strength of masonry to compression taken from table 18 and 19 of NCM F.03.02-2005. Proiectarea construcțiilor cu pereți din zidărie.

$$E_0 = 350 \cdot 2 \cdot 1.3 = 910\ (MPa)$$

Deformational modulus is calculated by using following expression provided in [4]:

$$E = K_n E_0 = 0.8 \cdot 910 = 728\ (MPa)$$

2.2.2. Loads on structure

The self-weight of vault itself will be calculated automatically in software based on thickness of element (in this case thickness of vault it's considered $\delta = 0.25$). Weight of timber purlins and roofs tile are presented in table below.

Description	Unit	Normative value	Safety coefficient γ_f	Design value	Note
PERMANENT LOAD					
Timber purlins ($b\ x\ h\ =\ 50\ x\ 120\ cm$)	kN/m	0.03	1.3	0.038	NCM F.03.02-2005
Roofs tile	kN/m^2	0.5	1.3	0.637	СНиП 2.01.07-85, tab. 2
VARIABLE LOAD					
Snow Load	kN/m^2	0.5	1.4	0.5	СНиП 2.01.07-85

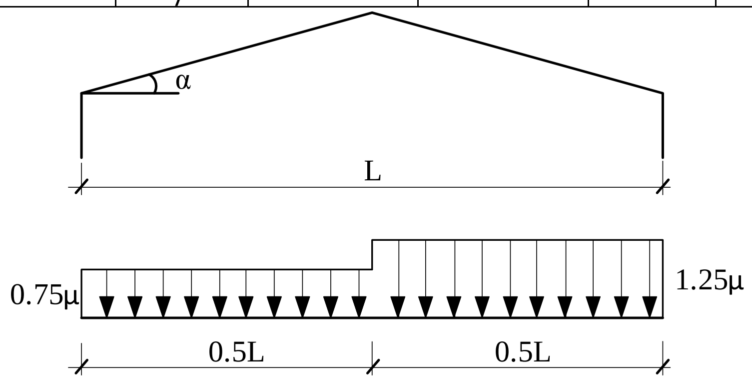

Figure 4 Snow load scheme according to Annex 3 from SNiP 2.01.07-85

$$S_1 = S_0 \cdot \mu = 0.7 \cdot 0.75 = 0.525\ (kN/m^2)$$
$$S_2 = S_0 \cdot \mu = 0.7 \cdot 1.25 = 0.875\ (kN/m^2)$$

2.3. Calculus

The design will be performed in FEM software - SCAD Soft. SCAD is an integrated system for finite element structural analysis and design. SCAD includes a highly developed library of finite elements for modeling bar, plate, solid and combined structures, modules of stability analysis, building design stress combinations, verifying stressed state of structural elements according to various failure theories, determining forces with which a fragment affects the whole structure, calculating forces and displacement caused by loading combinations.

3. RESULTS

In analysis was considered 2 load combinations:

- First load combination according to СНиП 2.01.07-85 “Нагрузки И Воздействия”, p. 1.12.
- Second load combination according to СНиП II-7-81* “Строительство В Сейсмических Районах”, p.2.1.

By comparing these two load combinations one can observe in what case the horizontal efforts at the bottom level of the vault will be higher.

Table 1

Load name	
Number	Name
1	Self-Weight
2	Roof Tiles
3	Snow load
4	Seism X
5	Seism Y

Table 2

Load combination	
Number	Equation
1	(L1)*1+(L2)*0.95+(L3)*0.8

Table 3

Loads			
Load number	Direction	List of elements	Value
1	Z	395-1144 1347-1456	Self-weight
2	Z	395-1144 1347-1456	0.637
3	Z	585-600 602-605 607-817 819-821 823-838 840-846 848-866 868-895 897-914 916-964 1357-1375 1377-1384 1387-1393 1397-1402 1407-1411 1417-1420 1427-1429 1437 1438 1447	0.525
3	Z	395-584 965-1144 1347-1356 1376 1385 1386 1394-1396 1403-1406 1412-1416 1421-1426 1430-1436 1439-1446 1448-1456	0.875
4	3	1 2 3	0.9; 0.9; 0.5
5	3	1 2 3	0.9; 0.9; 0.5

3.1. Modeling the strucutre

Structure was modeled using one type of shell finite element that is given in software. Type 44 of finite element that represents a quadrangular shell element.

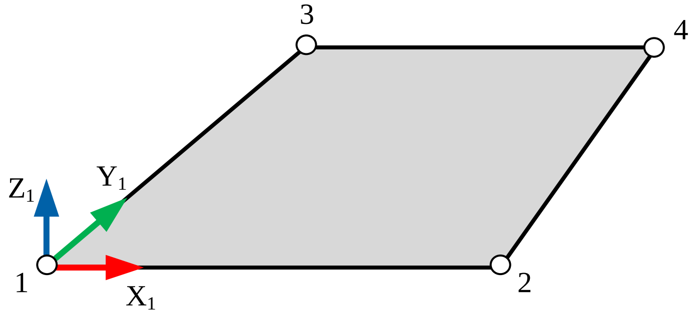

Figure 5 Finite element type 44

This finite element perceives the following type of efforts, stresses and reactions:

- N_x, N_Y – normal stress along axes X_1 and Y_1. The positive value corresponds to tension.
- τ_{xy} – shear stress parallel to the X_1 axis and lying in parallel plane to $X_1 0 Z_1$. The positive value determines the tension of the diagonal $1 - 4$
- M_x, M_y – bending moment acting on sections orthogonal to the axes X_1 and Y_1. The positive value corresponds to tension of the lower fiber (relative to the Z_1 axis)
- M_{xy} – torque. The positive value determines the curvature of the diagonal $1 - 4$, convexity directed downward.
- Q_x – shear force along the Z_1 axis in section orthogonal to the X_1 axis. A positive value determines the coincidence of the direction of the force with the direction of the Z_1 axis on the part of element in which there is no node 1.
- Q_y – shear force along the Z_1 axis in section orthogonal to the Y_1 axis. A positive value determines the coincidence of the direction of the force with the direction of the Z_1 axis on the part of element in which there is no node 1.

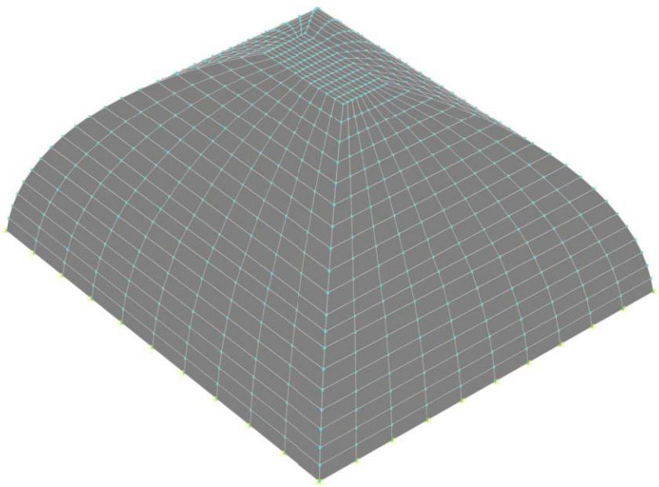

Figure 6 Cloister vault of Water Tower modeled in SCAD++

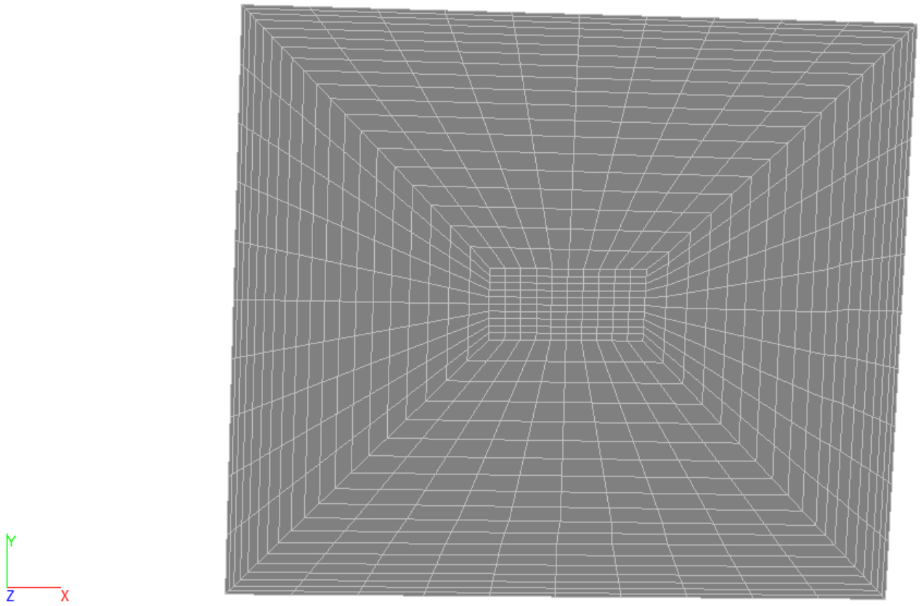

Figure 7 Plane view of vault with global axes

3.2. Dynamic proprieties of structure

Table 4

Load case nr.		Mode NR.	Frequencies		Period	Modal mass (%)		
			rad/sec	Hz	sec	X	Y	Z
4	Seismic action along X axis	1	146.211	23.27	0.043	0.173	67.285	0
		2	169.849	27.032	0.037	69.687	0.125	0
		Sum of modal mass				69.86	67.409	0
5	Seismic action along Y axis	1	0.007	146.211	23.27	0.043	0.173	67.285
		2	0.006	169.849	27.032	0.037	69.687	0.125
		Sum of modal mass				69.86	67.409	0

3.3. Vault reactions

Table 5 Maximum values in nodes from 1st load combination

Maximum reactions in nodes						
Reaction	Maximum value			Minimum value		
	Value (kN)	Node	Load case	Value (kN)	Node	Load combination
R_X	1.566	606	1	-1.56	250	1
R_Y	1.932	597	1	-2.057	790	1
R_Z	7.12	790	1	3.981	258	1

Table 6 Maximum values in nodes from 2nd load combination (along X and Y axis direction)

Maximum reactions in nodes						
Reaction	Maximum value			Minimum value		
	Value (kN)	Node	Load case	Value (kN)	Node	Load case
R_X	2.259	786	4	0.015	248	5
R_Y	1.786	608	5	0.013	597	4
R_Z	3.735	221	5	0.071	606	5

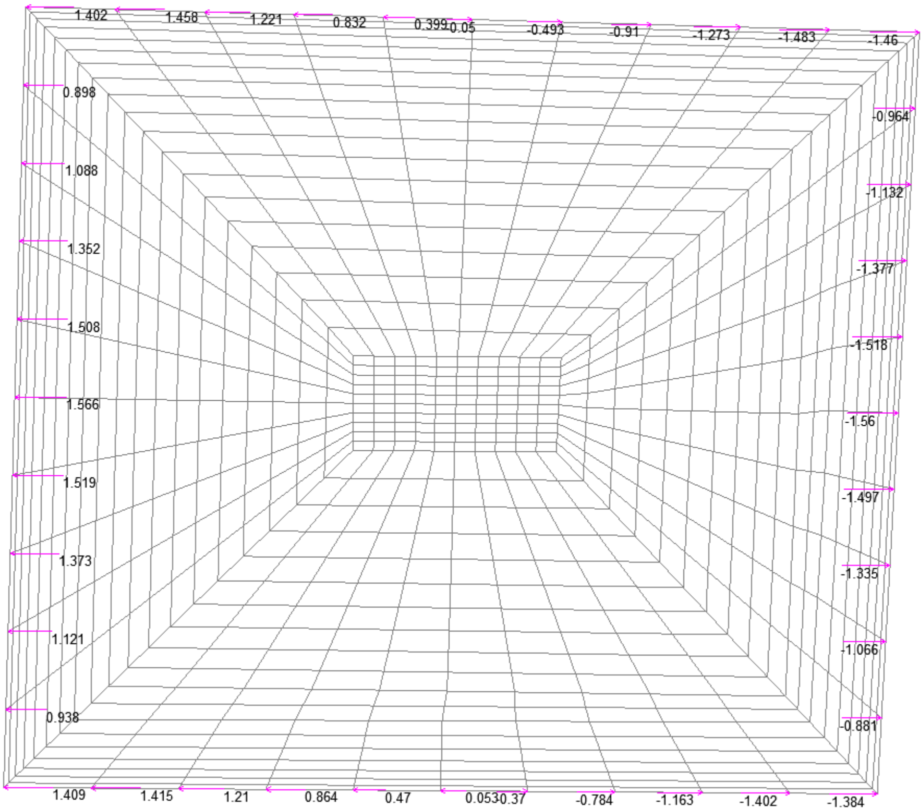

Figure 8 Rx from 1 load combination

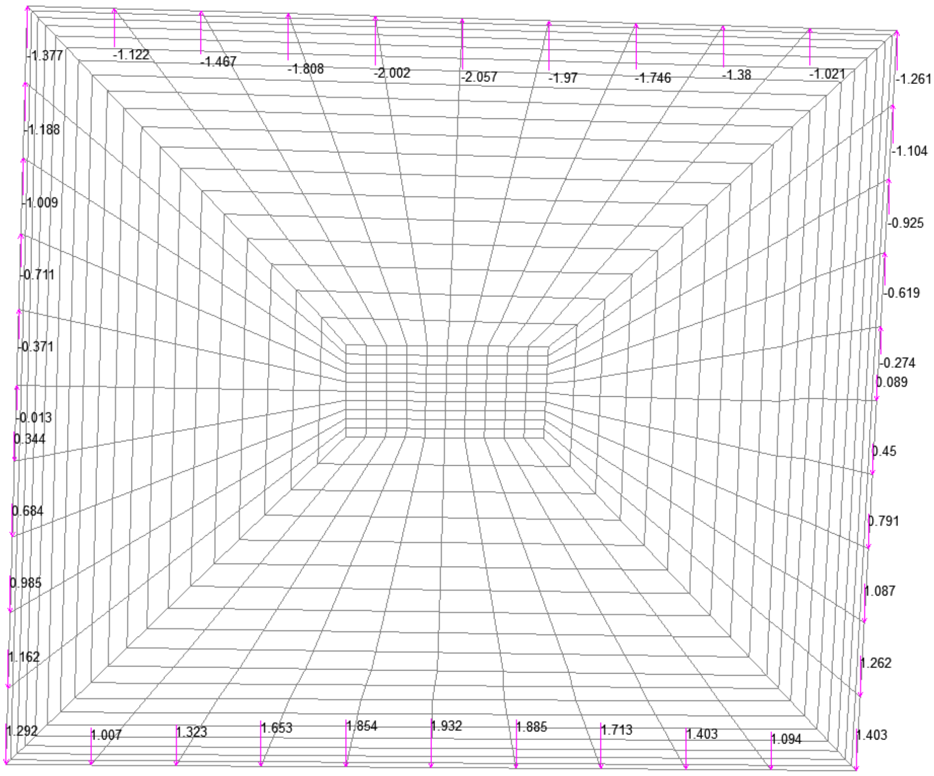

Figure 9 Ry from 1 load combination

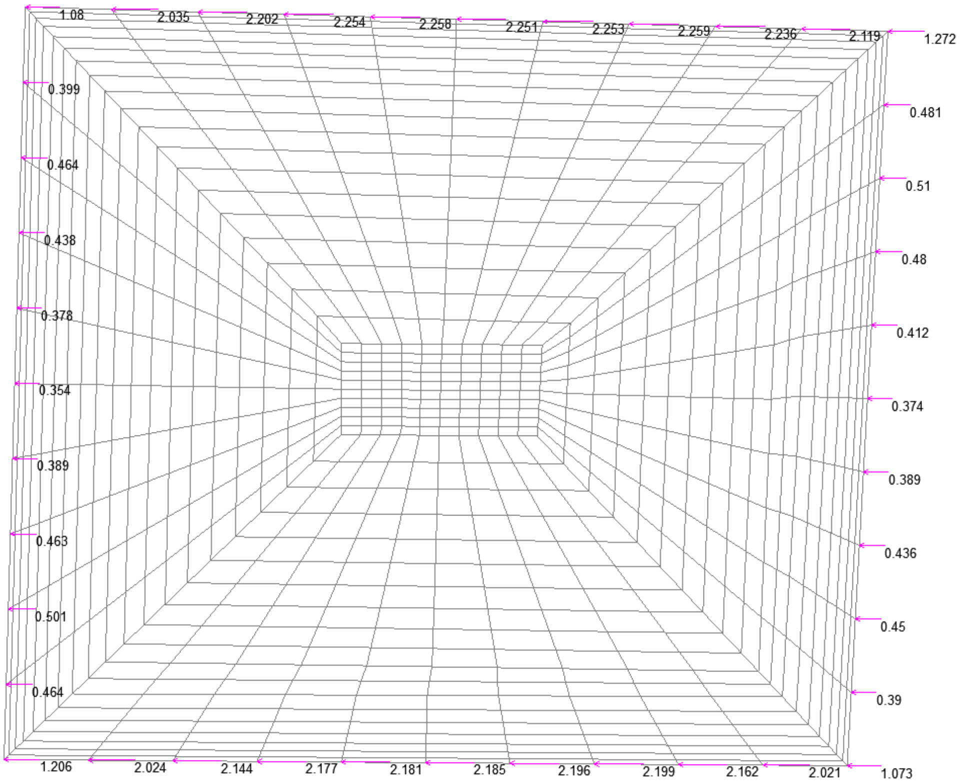

Figure 10 Rx from 2 load combination

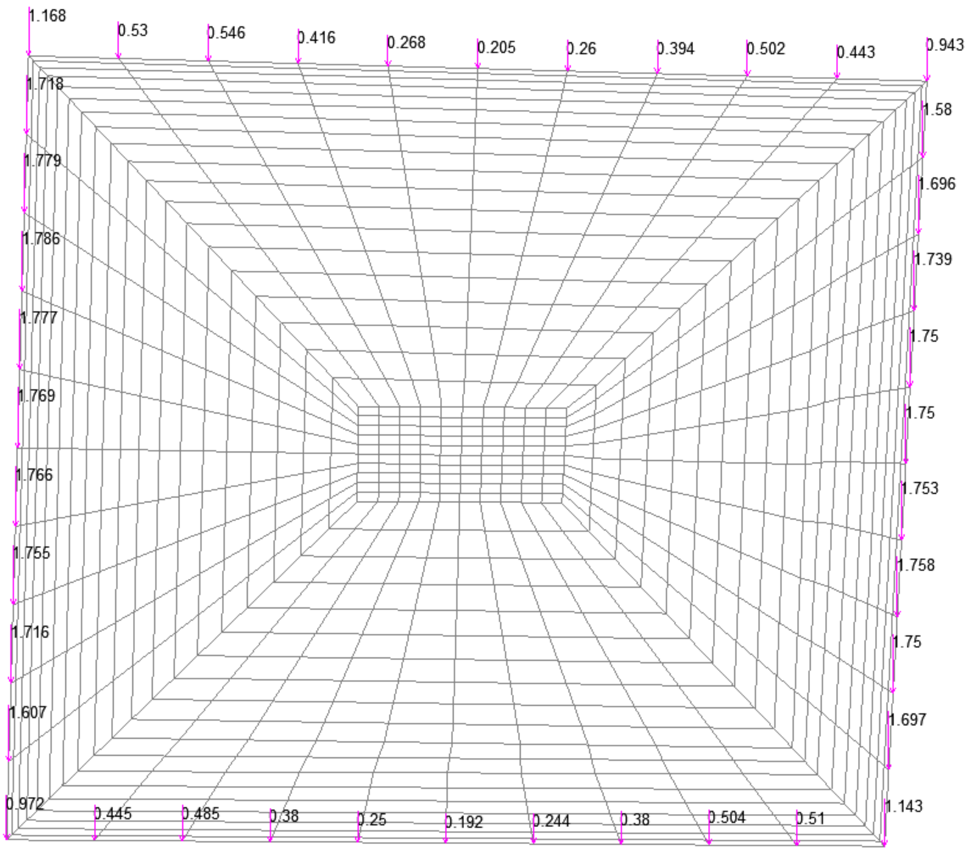

Figure 11 Ry from 2 load combination

4. CONCLUSION

The structural analysis of Water Tower according to SNiP-7-81* was made. As conclusion the following can be stated:

1. The cloister vault of Water Tower was modeled in FEM software, SCAD++. Vault was modeled as shell structure with finite element type 44. Reactions at the bottom level of cloister vault was obtained. Also, the stress map of vault was made.
2. From the analysis one could point out the highest values of vault reactions in X and Y direction of main axes from load combinations.
3. For the R_x maximum value is occurred with 2nd load combination according to SNiP II-7-81* ($R_{x,max} = 2.259\ kN$).
4. For R_y maximum value is occurred with 1st load combination according to SNiP 2.01.07-85 (main combination from permanent and variable load case) - $R_y = -2.057\ kN$
5. One can certainly affirm that water tower that is part of Bender Fortress represents an architectural landmark. This being said it should be noted that use of "behavior coefficient" $k_1 = 0.25$ is not justifiable. However, SNiP II-7-81* does not offer an alternative to use coefficient $k_1 \geq 0.25$.
6. From **"Studio Berlucchi" srl** – *Technical expertise and develop detailed technical design for conservation and restoration works of Bender Fortress (Phase I)* it is pointed that in water tower are presented cracks at vault level that could lead to pushing action.
7. **"Studio Berlucchi" srl** proposal for intervention consists installing two by two tie-rods at bottom level of vault. Also, due to ground subsidence at base of water tower it is proposed to reinforce the foundation with RC beams.
8. The intervention proposed above could lead to reduction of horizontal efforts in vault. Also installing RC beams at foundation level will prevent sliding of bottom part of tower wall.
9. Apart from this should be considered installing structural monitoring systems that will help to analyse the structural "health" and to monitor the building behavior, changing of dynamic proprieties during an earthquake and other parameters.

ANNEX 1 Vault reactions

Table 7 Reactions in vault from 1st load combination

Reactions in nodes			
Node	Value		
	R_X	R_Y	R_Z
162	1.409	1.292	4.562
193	-1.384	1.403	4.827
201	-1.46	-1.261	4.595
221	1.402	-1.377	4.712
242	-0.881	1.262	4.155
244	-1.066	1.087	4.722
246	-1.335	0.791	5.262
248	-1.497	0.45	5.577
250	-1.56	0.089	5.667
252	-1.518	-0.274	5.535
254	-1.377	-0.619	5.18
256	-1.132	-0.925	4.6
258	-0.964	-1.104	3.981
593	1.415	1.007	4.612
594	1.21	1.323	5.411
595	0.864	1.653	6.11
596	0.47	1.854	6.52
597	0.053	1.932	6.666
598	-0.37	1.885	6.561
599	-0.784	1.713	6.195
600	-1.163	1.403	5.545
601	-1.402	1.094	4.811
602	0.938	1.162	4.015
603	1.121	0.985	4.608
604	1.373	0.684	5.163
605	1.519	0.344	5.497
606	1.566	-0.013	5.614
607	1.508	-0.371	5.515
608	1.352	-0.711	5.194
609	1.088	-1.009	4.65
610	0.898	-1.188	4.068
782	-1.483	-1.021	4.832
784	-1.273	-1.38	5.741
786	-0.91	-1.746	6.516
788	-0.493	-1.97	6.966
790	-0.05	-2.057	7.12
792	0.399	-2.002	6.984
794	0.832	-1.808	6.548
796	1.221	-1.467	5.783
798	1.458	-1.122	4.885

Table 8 Reactions in vault from 2nd load combination (seismic load X direction)

Reactions in nodes			
Node	Value		
	R_X	R_Y	R_Z
162	1.206	0.926	3.571
193	1.073	0.795	3.211
201	1.272	0.914	3.632
221	1.08	0.823	3.144
242	0.39	0.257	1.663
244	0.45	0.112	0.522
246	0.436	0.156	0.374
248	0.389	0.173	0.974
250	0.374	0.146	1.146
252	0.412	0.128	0.848
254	0.48	0.149	0.157
256	0.51	0.267	0.786
258	0.481	0.477	1.95
593	2.024	0.357	1.895
594	2.144	0.237	1.118
595	2.177	0.184	0.707
596	2.181	0.102	0.331
597	2.185	0.013	0.101
598	2.196	0.088	0.405
599	2.199	0.16	0.705
600	2.162	0.204	1.01
601	2.021	0.32	1.664
602	0.464	0.484	1.926
603	0.501	0.275	0.73
604	0.463	0.16	0.23
605	0.389	0.141	0.922
606	0.354	0.168	1.201
607	0.378	0.2	0.996
608	0.438	0.179	0.362
609	0.464	0.112	0.554
610	0.399	0.255	1.679
782	2.119	0.314	1.955
784	2.236	0.205	1.136
786	2.259	0.151	0.682
788	2.253	0.066	0.261
790	2.251	0.04	0.191
792	2.258	0.132	0.527
794	2.254	0.203	0.805
796	2.202	0.245	1.06
798	2.035	0.366	1.652

Table 9 Reactions in vault from 2nd load combination (seismic load Y direction)

Reactions in nodes			
Node	Value		
	R_X	R_Y	R_Z
162	0.819	0.972	3.116
193	0.896	1.143	3.715
201	0.851	0.943	3.139
221	0.961	1.168	3.735
242	0.318	1.697	1.825
244	0.164	1.75	1.053
246	0.1	1.758	0.604
248	0.015	1.753	0.219
250	0.087	1.75	0.141
252	0.172	1.75	0.445
254	0.243	1.739	0.71
256	0.285	1.696	0.987
258	0.434	1.58	1.536
593	0.337	0.445	1.849
594	0.09	0.485	0.637
595	0.153	0.38	0.365
596	0.205	0.25	1.095
597	0.181	0.192	1.373
598	0.149	0.244	1.124
599	0.177	0.38	0.389
600	0.323	0.504	0.68
601	0.569	0.51	2.088
602	0.39	1.607	1.548
603	0.246	1.716	0.976
604	0.195	1.755	0.677
605	0.115	1.766	0.387
606	0.025	1.769	0.071
607	0.077	1.777	0.308
608	0.166	1.786	0.691
609	0.223	1.779	1.123
610	0.373	1.718	1.868
782	0.34	0.443	1.874
784	0.087	0.502	0.581
786	0.172	0.394	0.494
788	0.223	0.26	1.266
790	0.193	0.205	1.537
792	0.158	0.268	1.234
794	0.193	0.416	0.422
796	0.354	0.546	0.716
798	0.622	0.53	2.147

Table 10 Maximum values in nodes from 2nd load combination (along X axis direction)

Maximum reactions in nodes						
Reaction	Maximum value			Minimum value		
	Value (kN)	Node	Load case	Value (kN)	Node	Load case
R_X	2.259	786	4	0.354	606	5
R_Y	0.926	162	5	0.013	597	4
R_Z	3.632	201	5	0.101	597	5

Table 11 Maximum values in nodes from 2nd load combination (along Y axis direction)

Maximum reactions in nodes						
Reaction	Maximum value			Minimum value		
	Value (kN)	Node	Load case	Value (kN)	Node	Load case
R_X	0.961	221	5	0.015	248	5
R_Y	1.786	608	5	0.192	597	5
R_Z	3.735	221	5	0.071	606	5

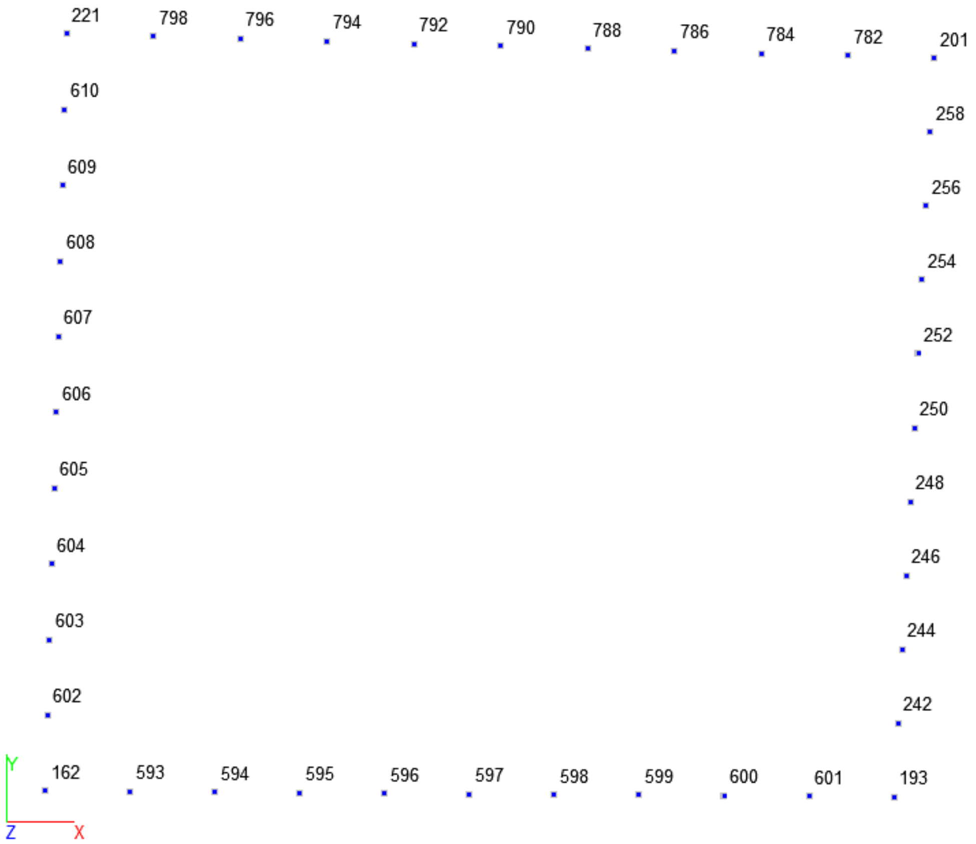

Figure 12 Nodes number at vaults bottom part

ANNEX 2 Stress maps in vault from 1st load combination

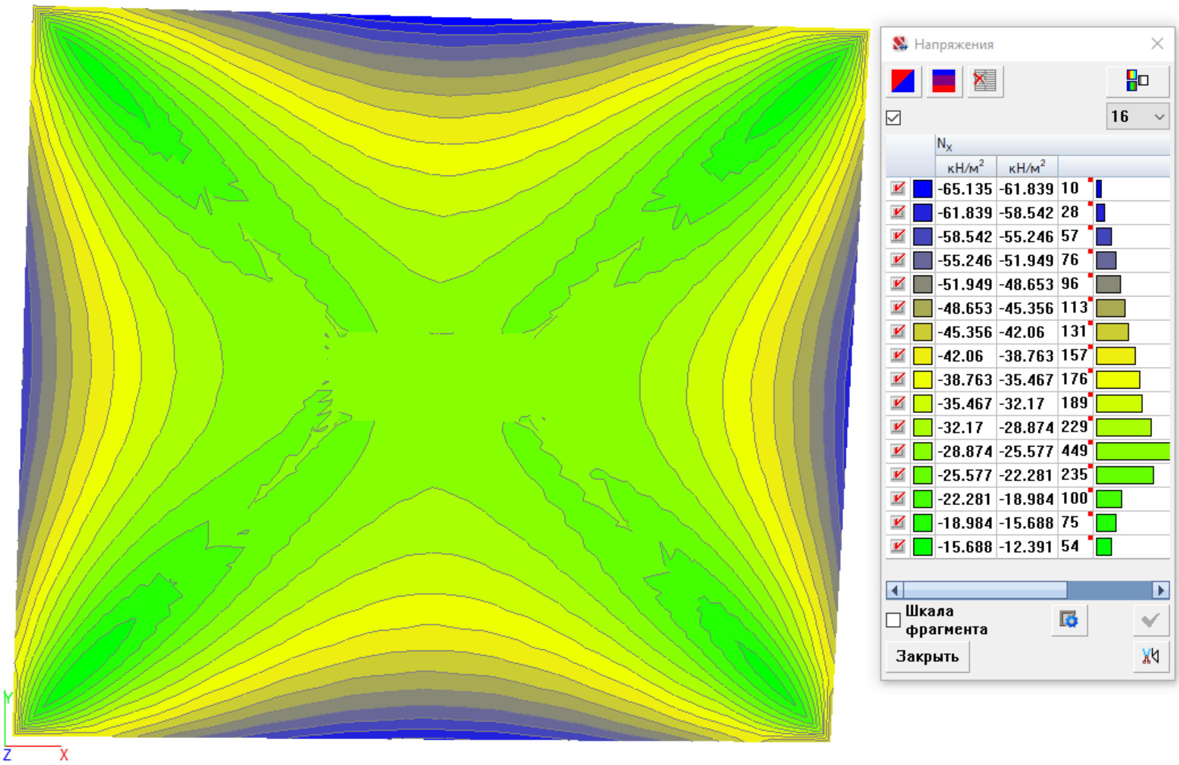

Figure 13 Normal stress N_x

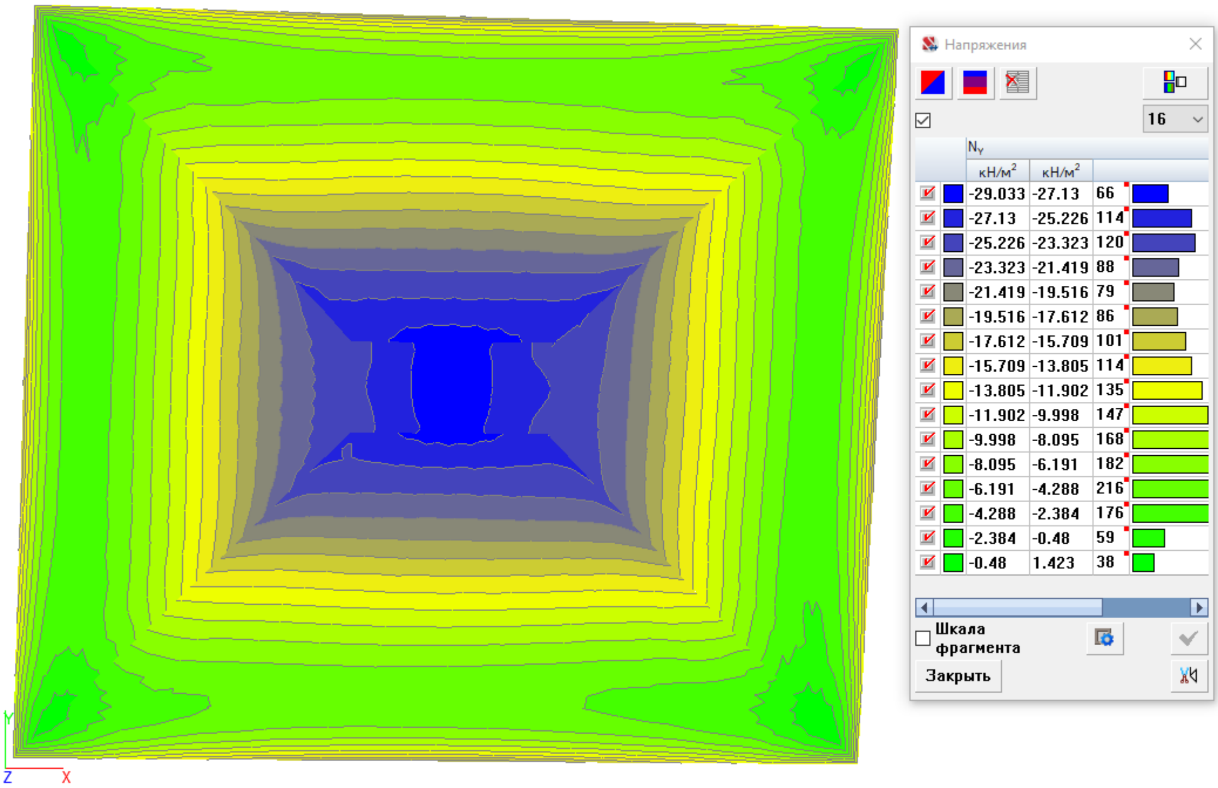

Figure 14 Normal stress N_y

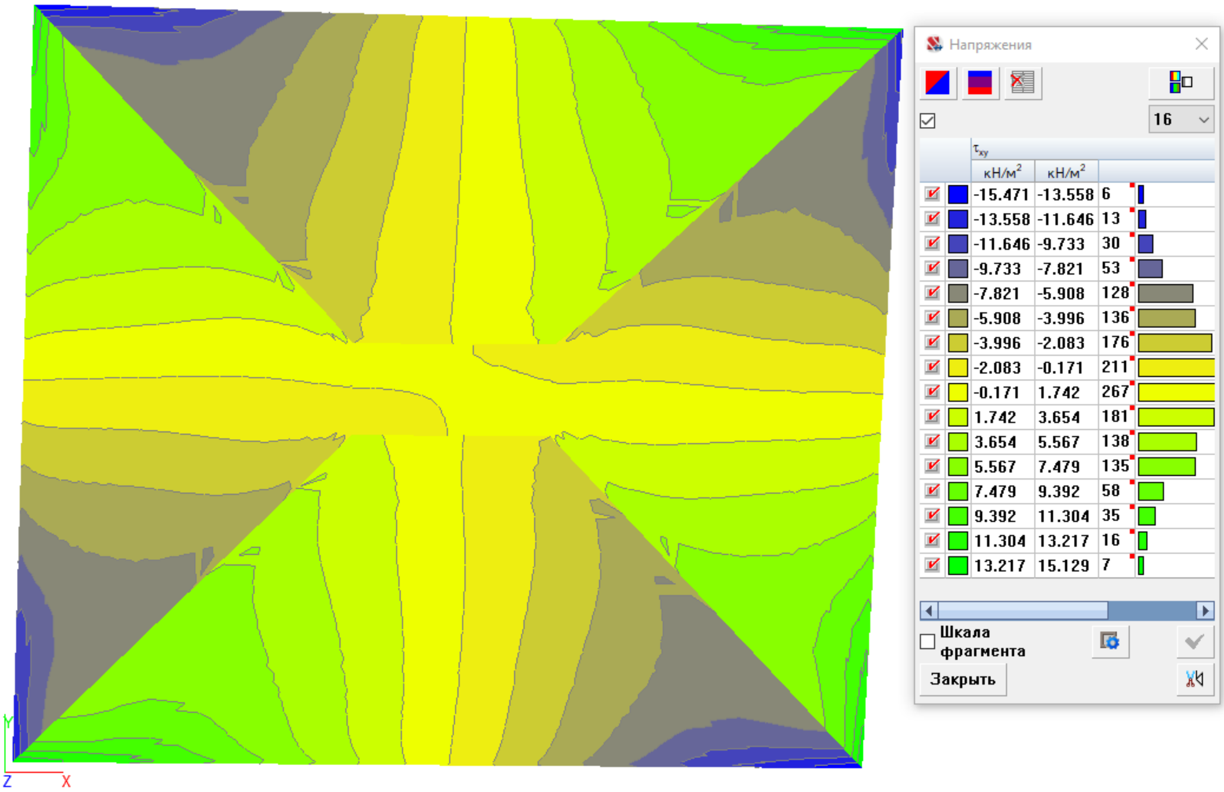

Figure 15 Shear stress

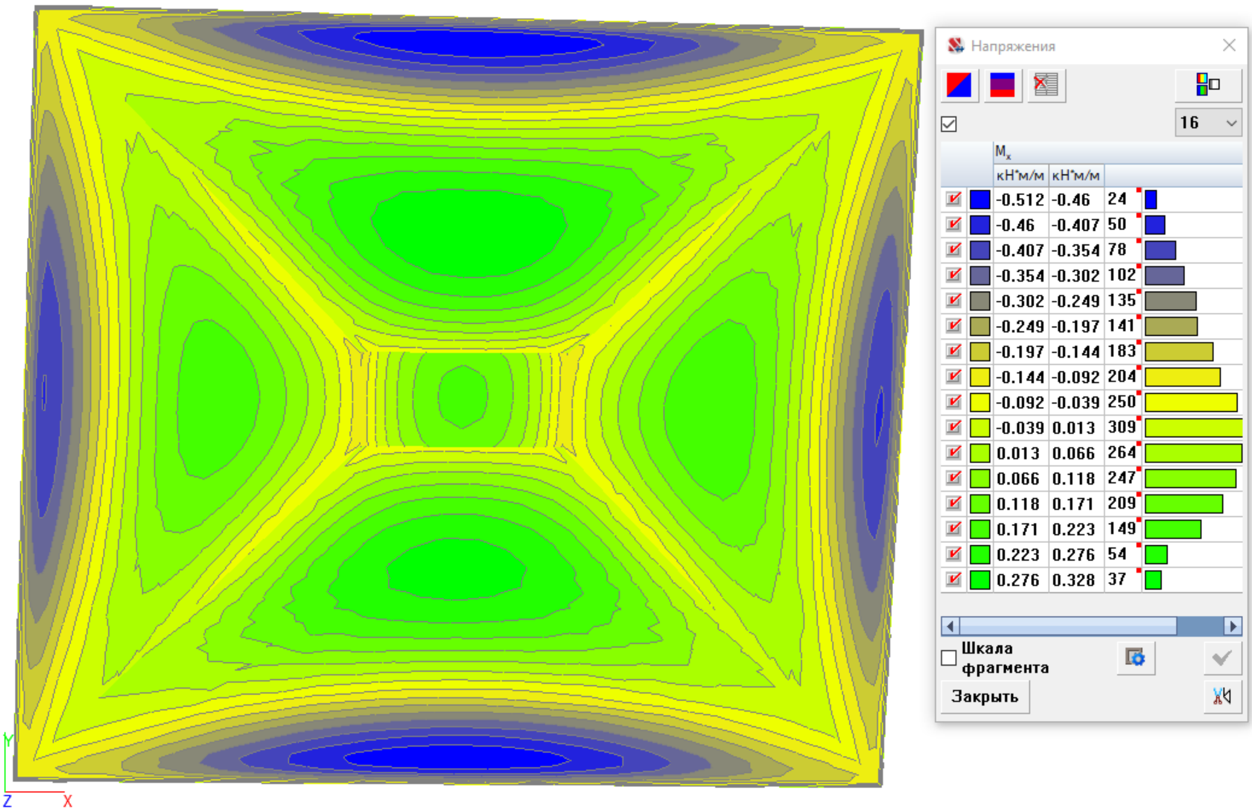

Figure 16 Bending moment M_x

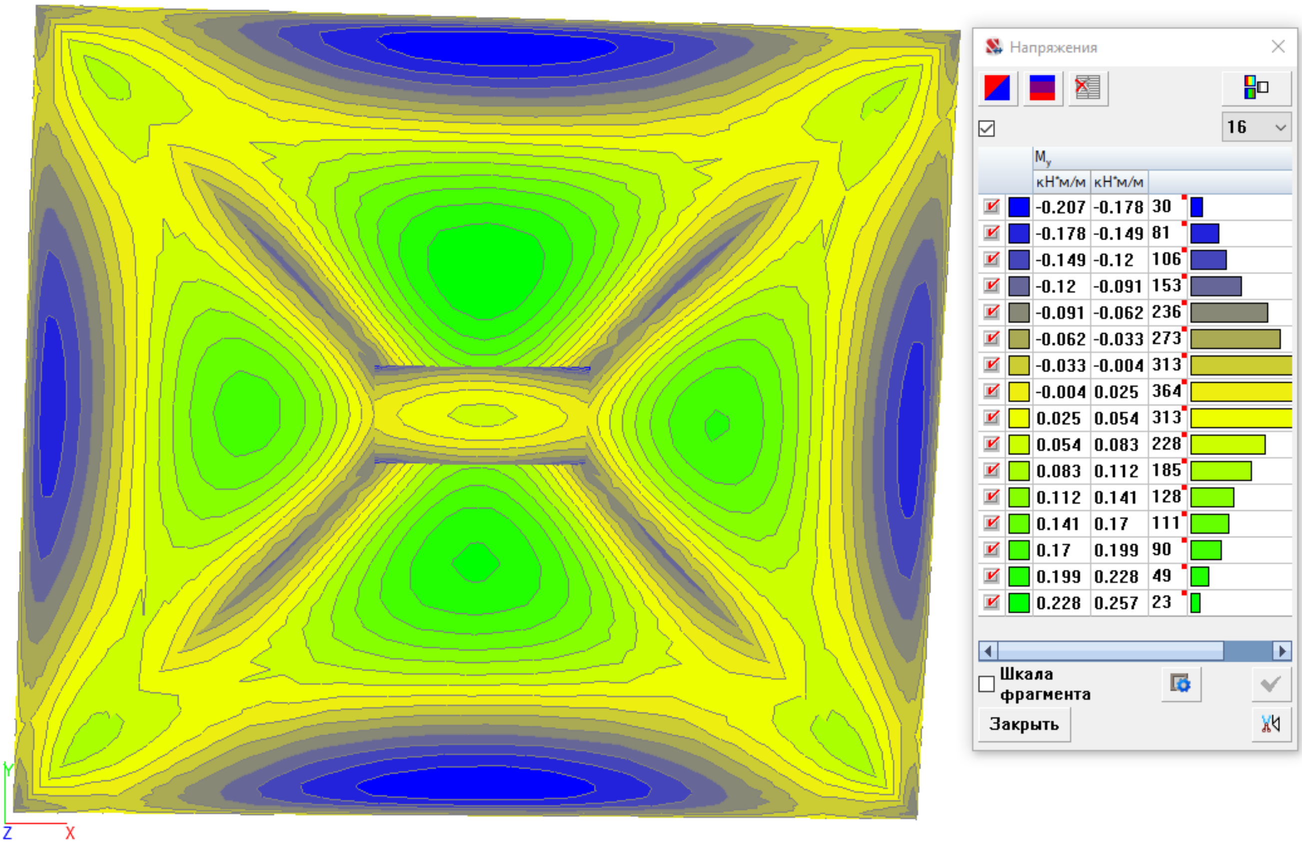

Figure 17 Bending moment M_y

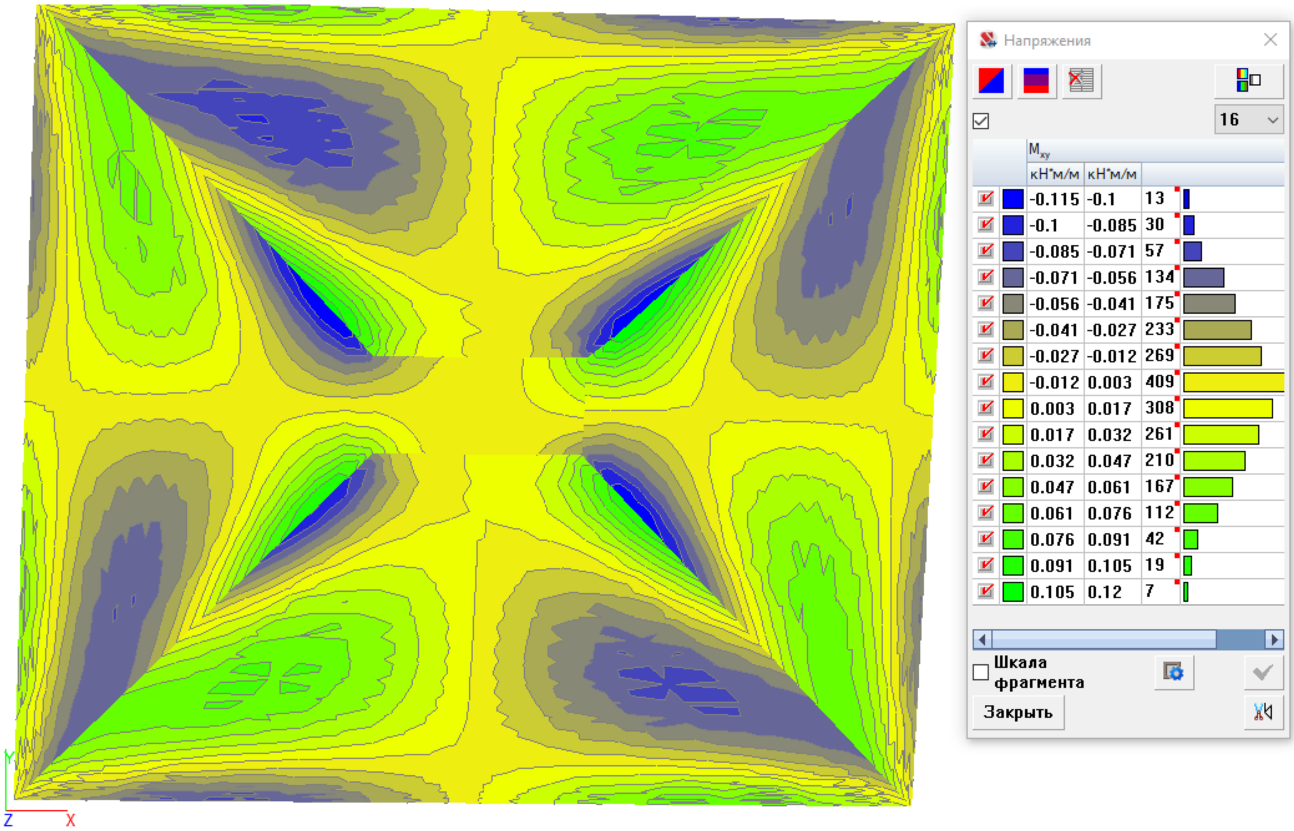

Figure 18 Torque M_{xy}

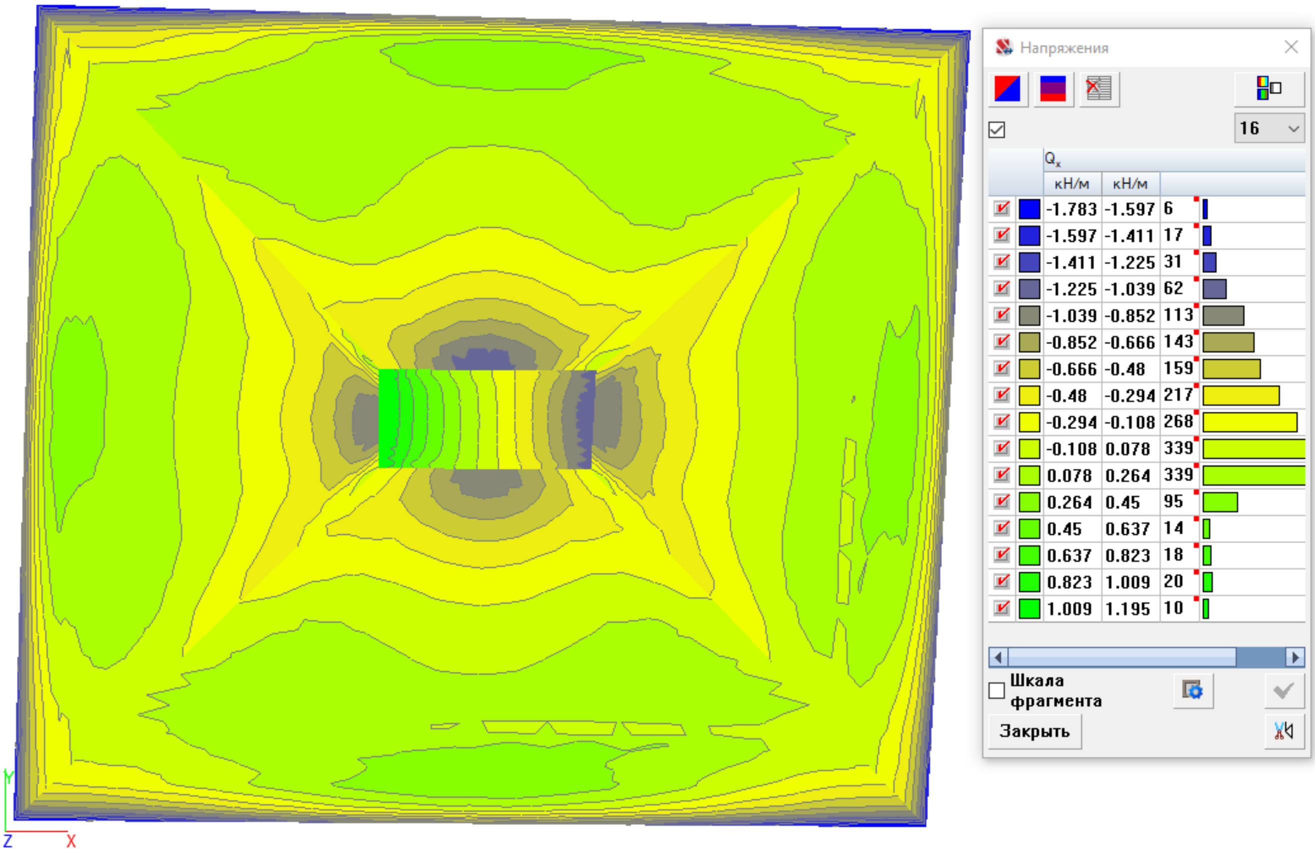

Figure 19 Shear force Q_x

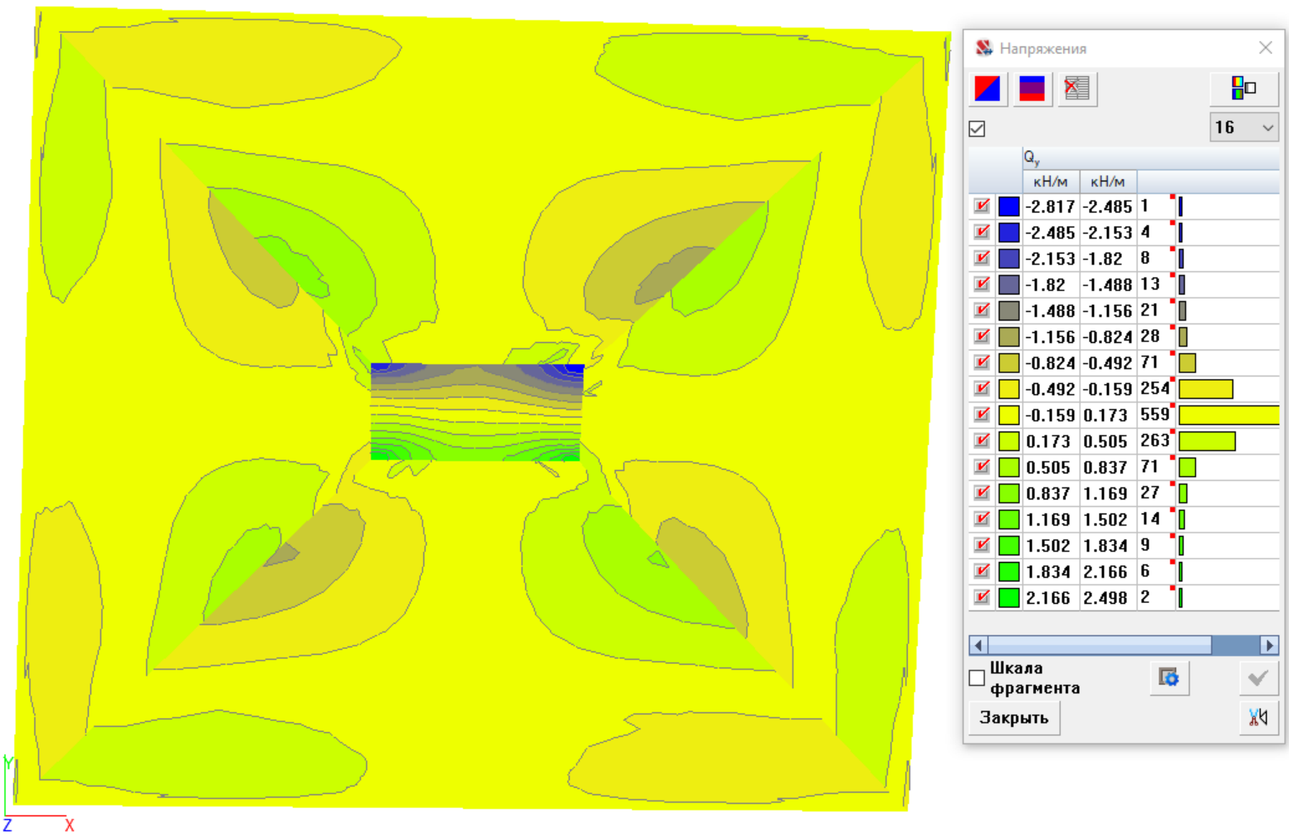

Figure 20 Shear force Q_y

ANNEX 3 Stress maps in vault from 2nd load combination (X direction)

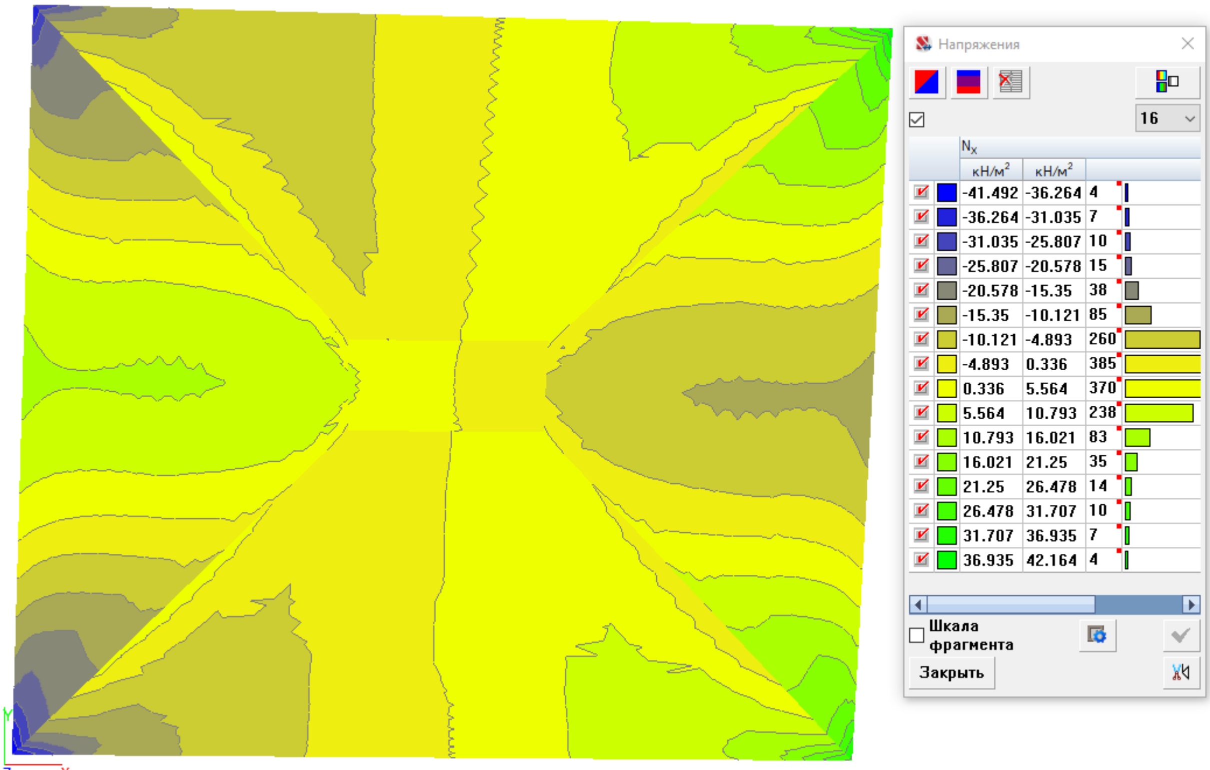

Figure 21 Normal stress N_x

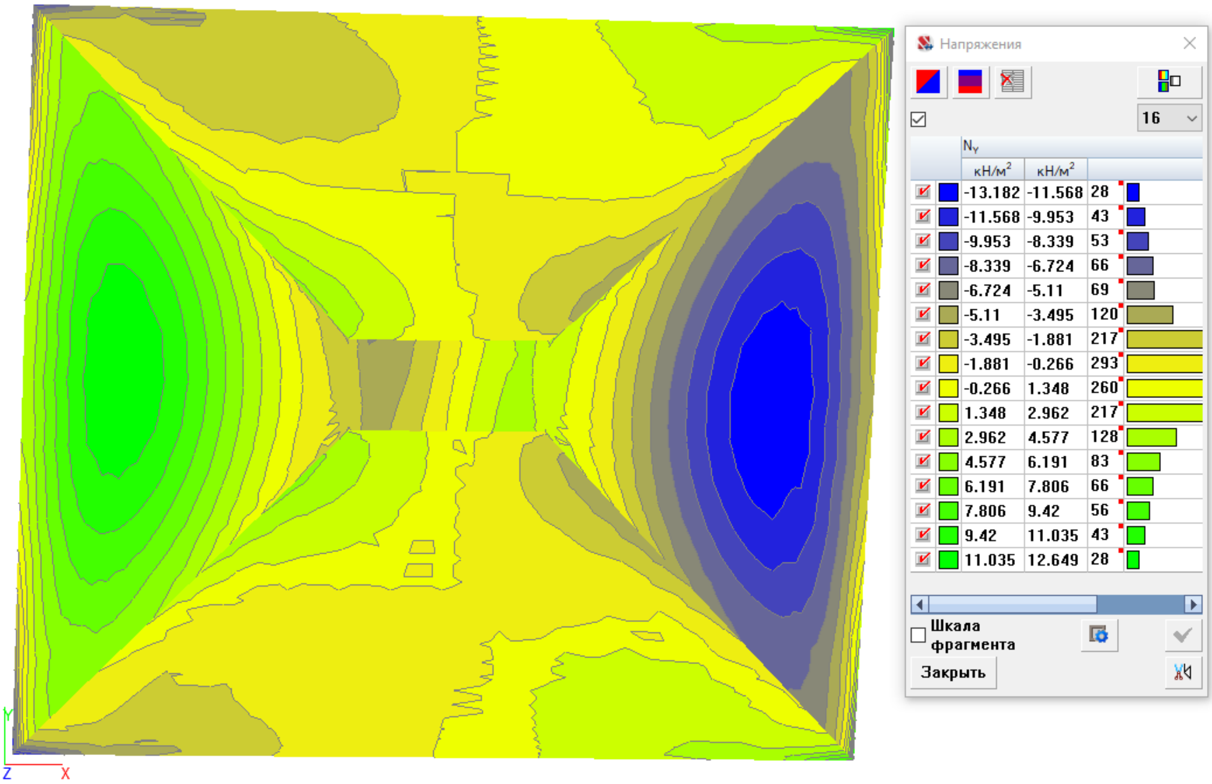

Figure 22 Normal stress N_y

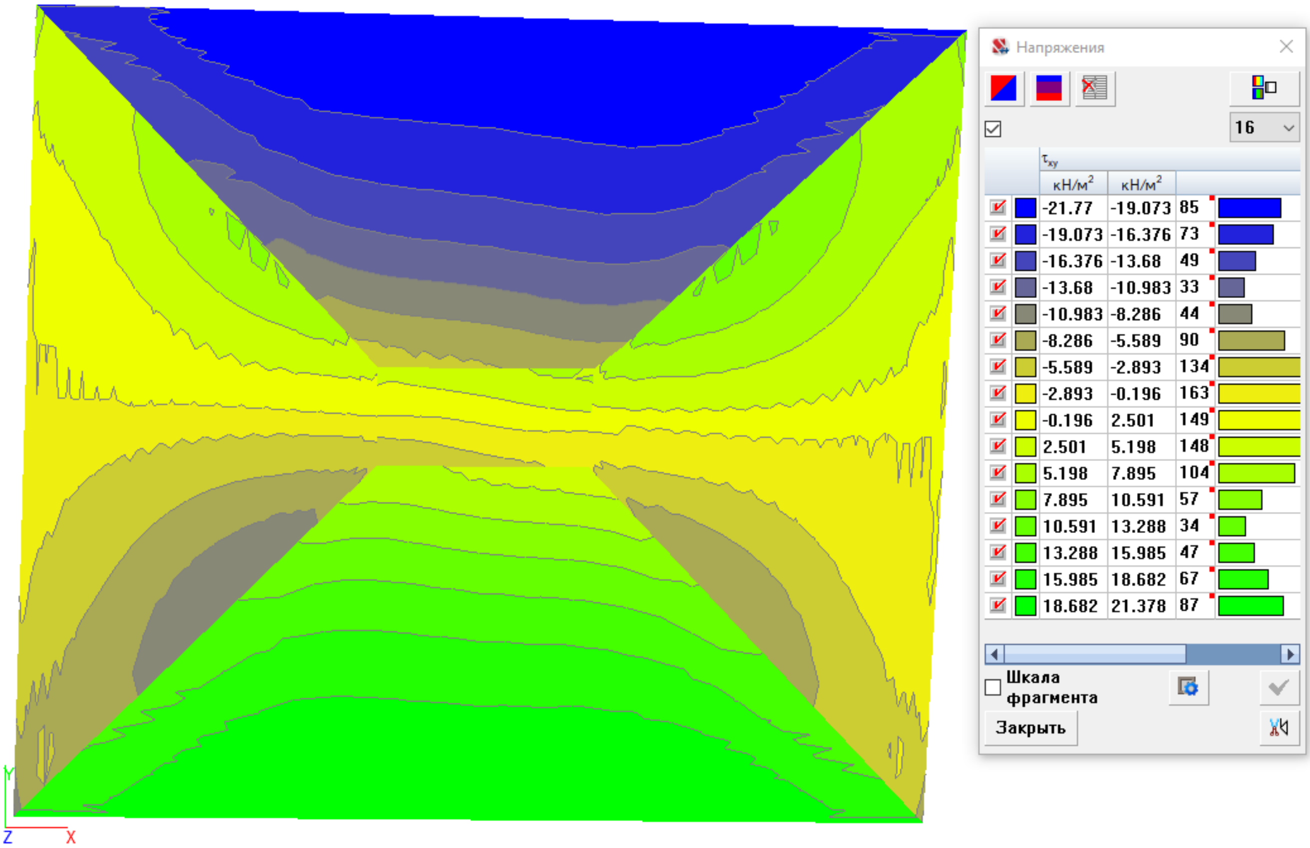

Figure 23 Shear stress

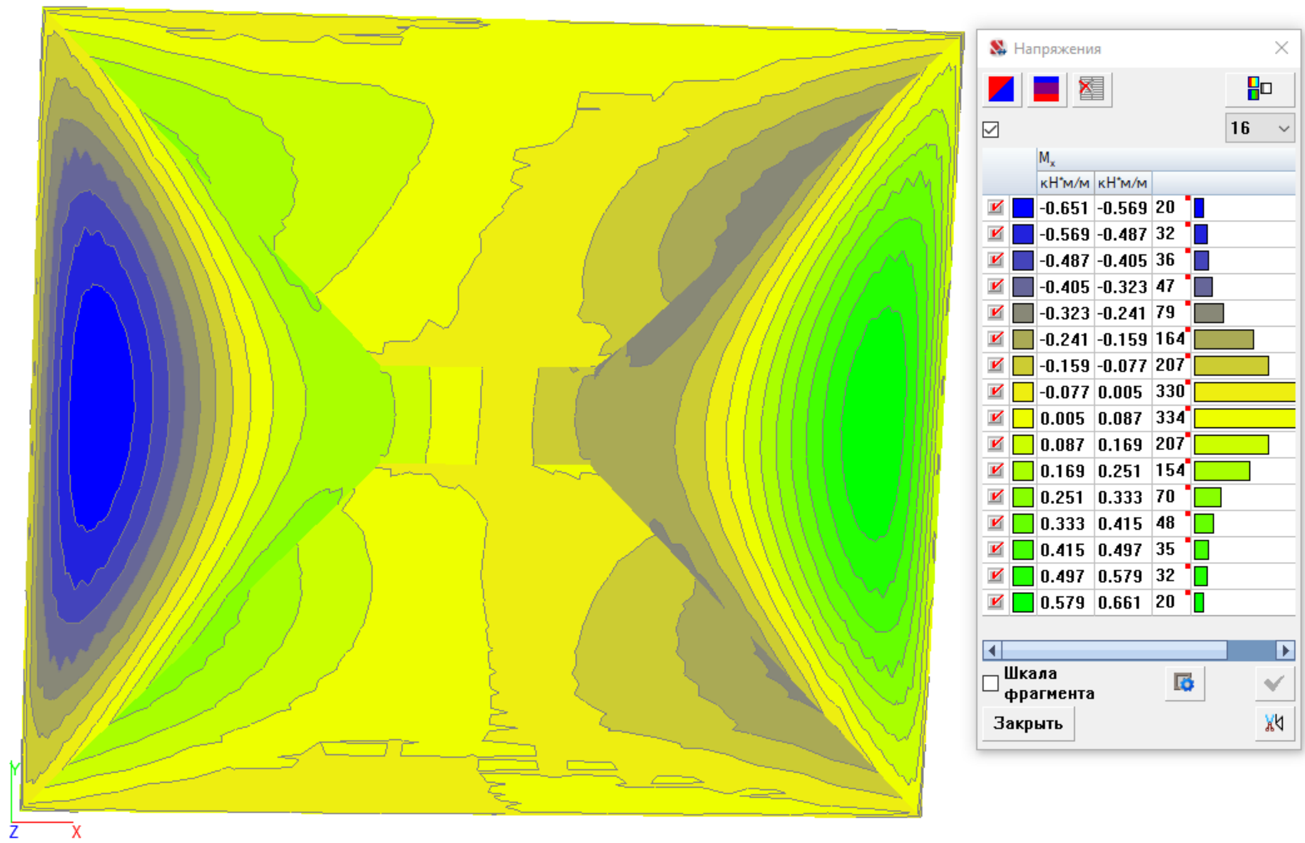

Figure 24 Bending moment M_x

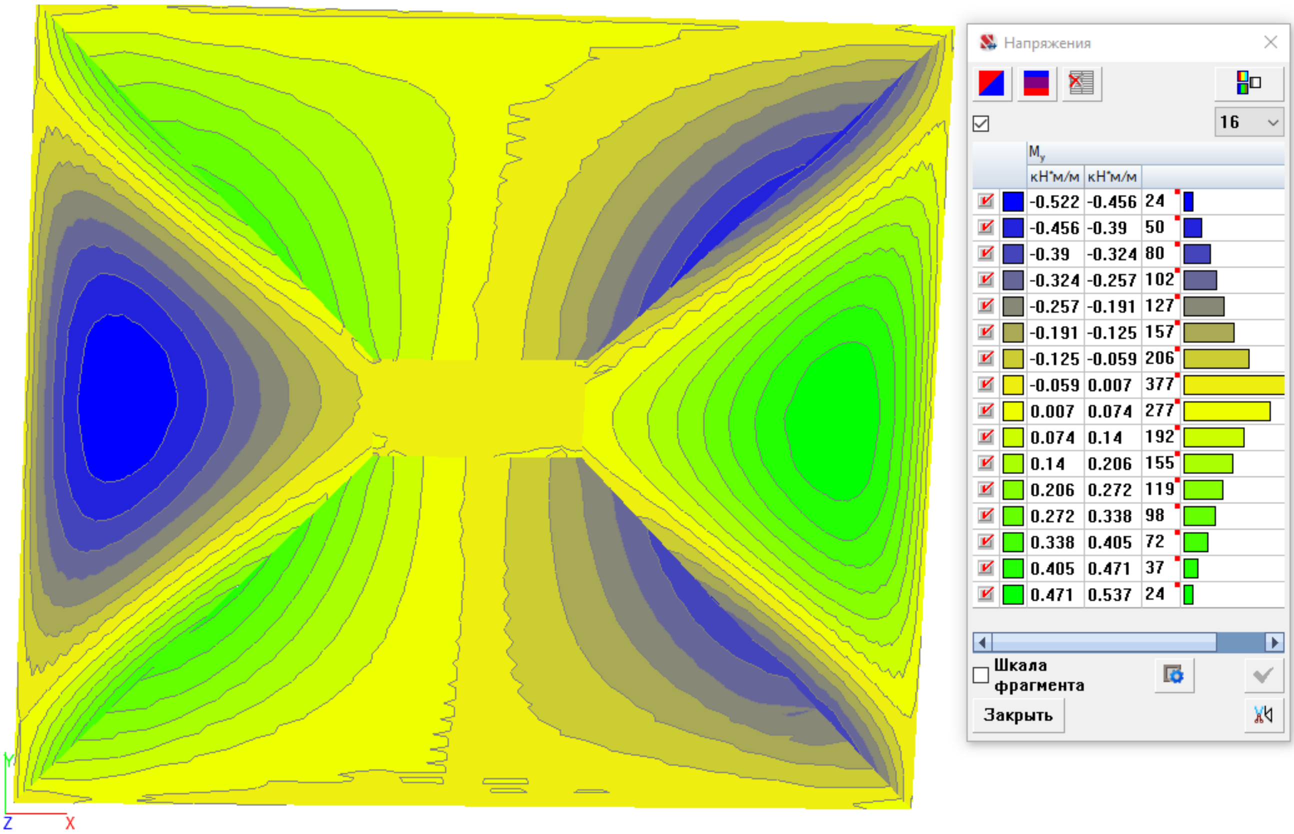

Figure 25 Bending moment M_y

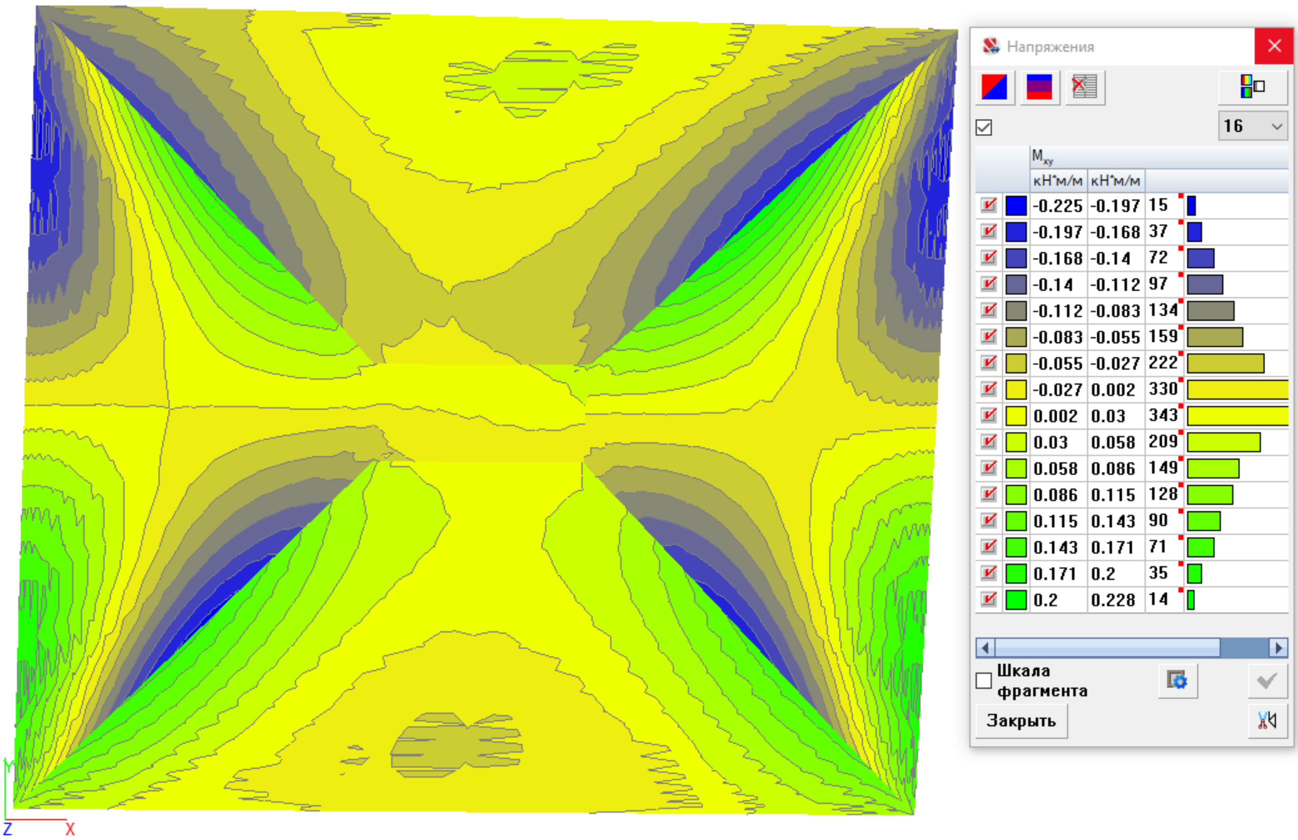

Figure 26 Torque M_{xy}

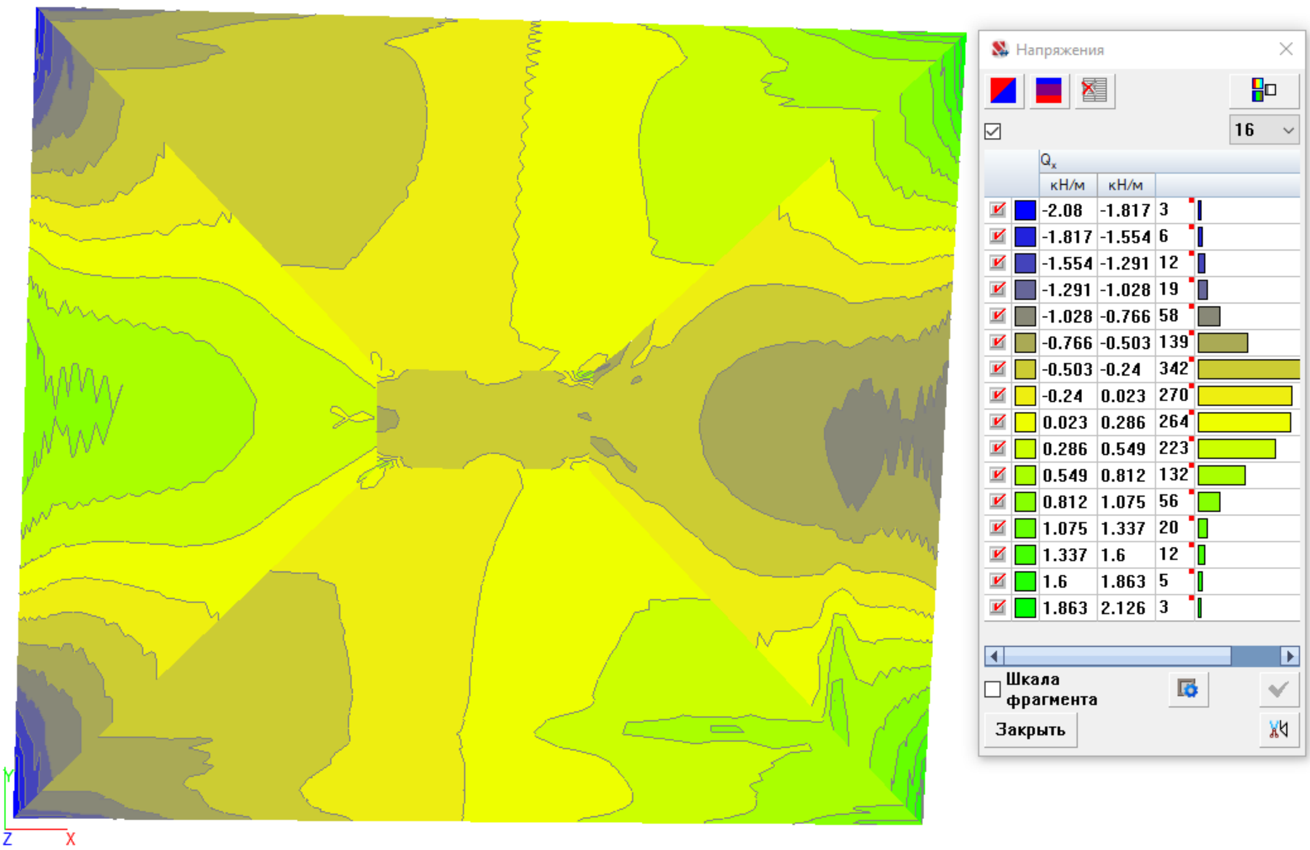

Figure 27 Shear force Q_x

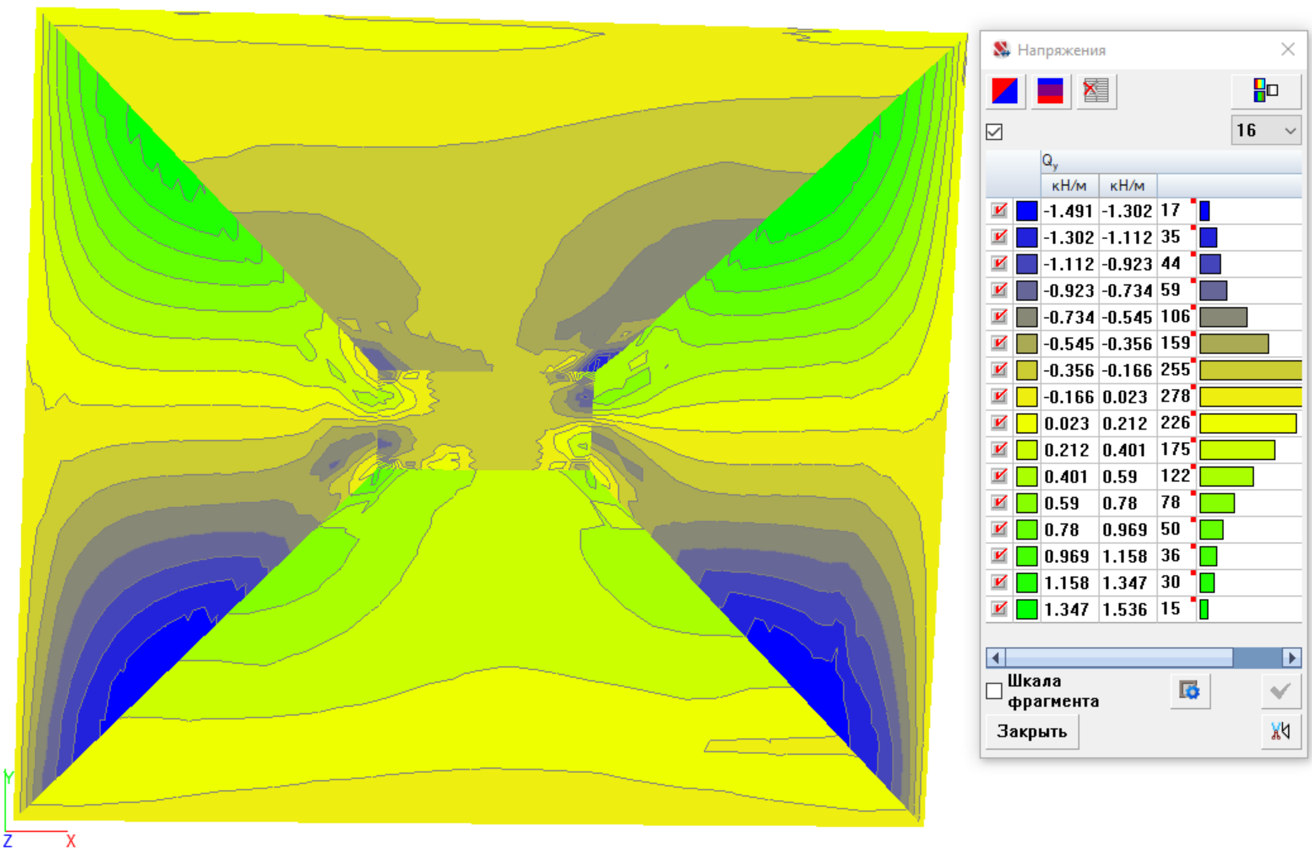

Figure 28 Shear force Q_y

ANNEX 4 Stress maps in vault from 2nd load combination (Y direction)

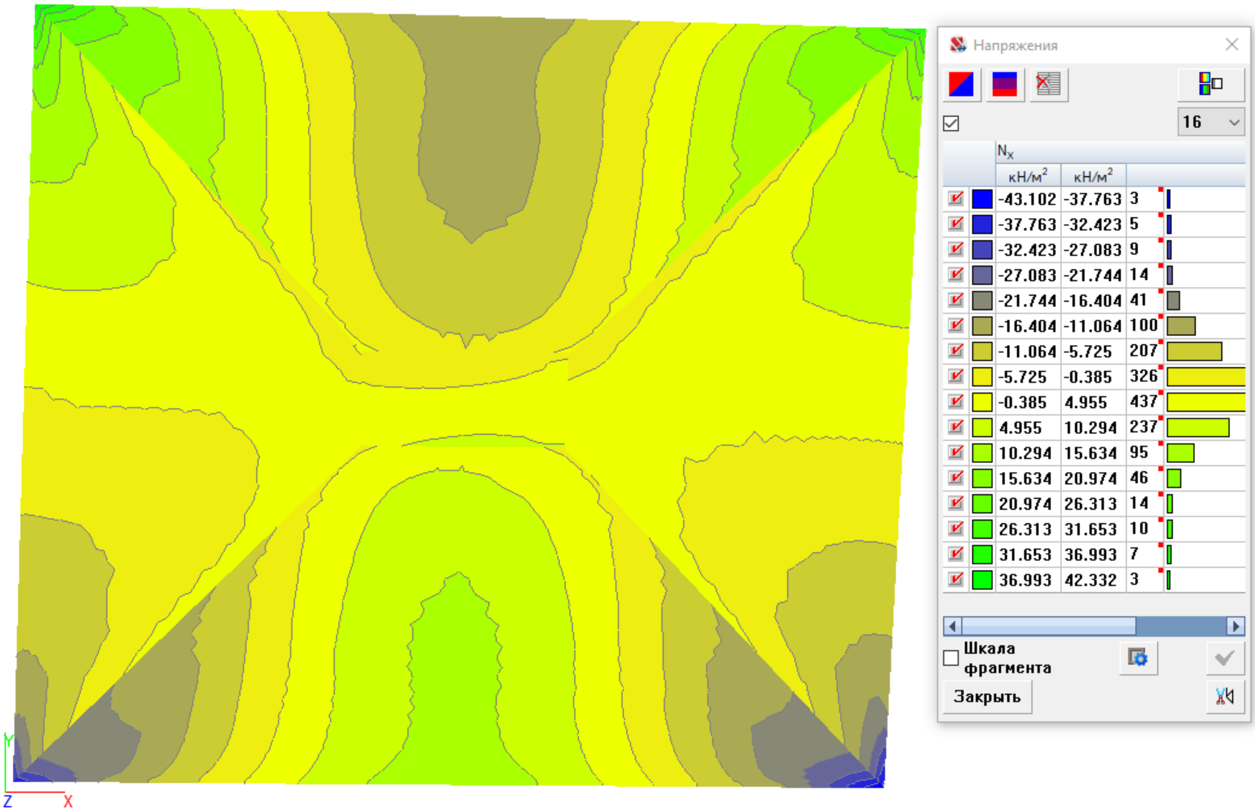

Figure 29 Normal stress N_x

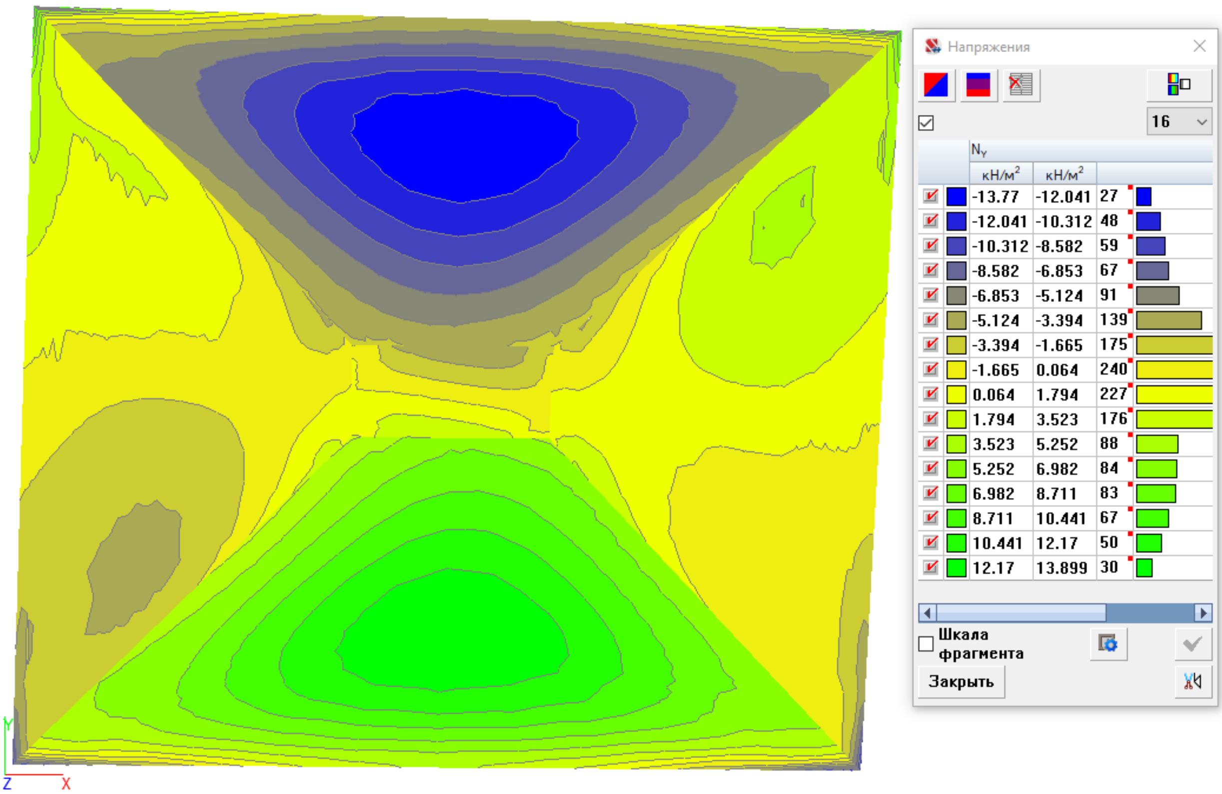

Figure 30 Normal stress N_x

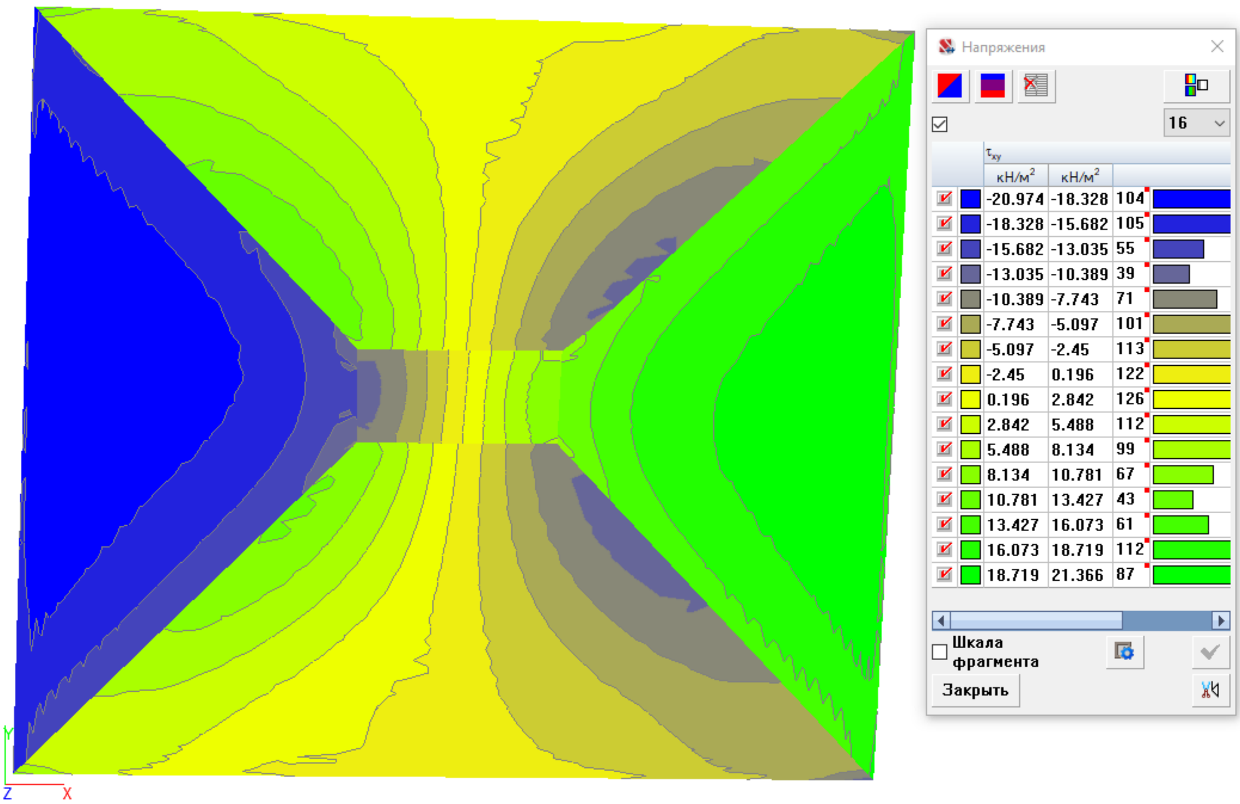

Figure 31 Shear stress

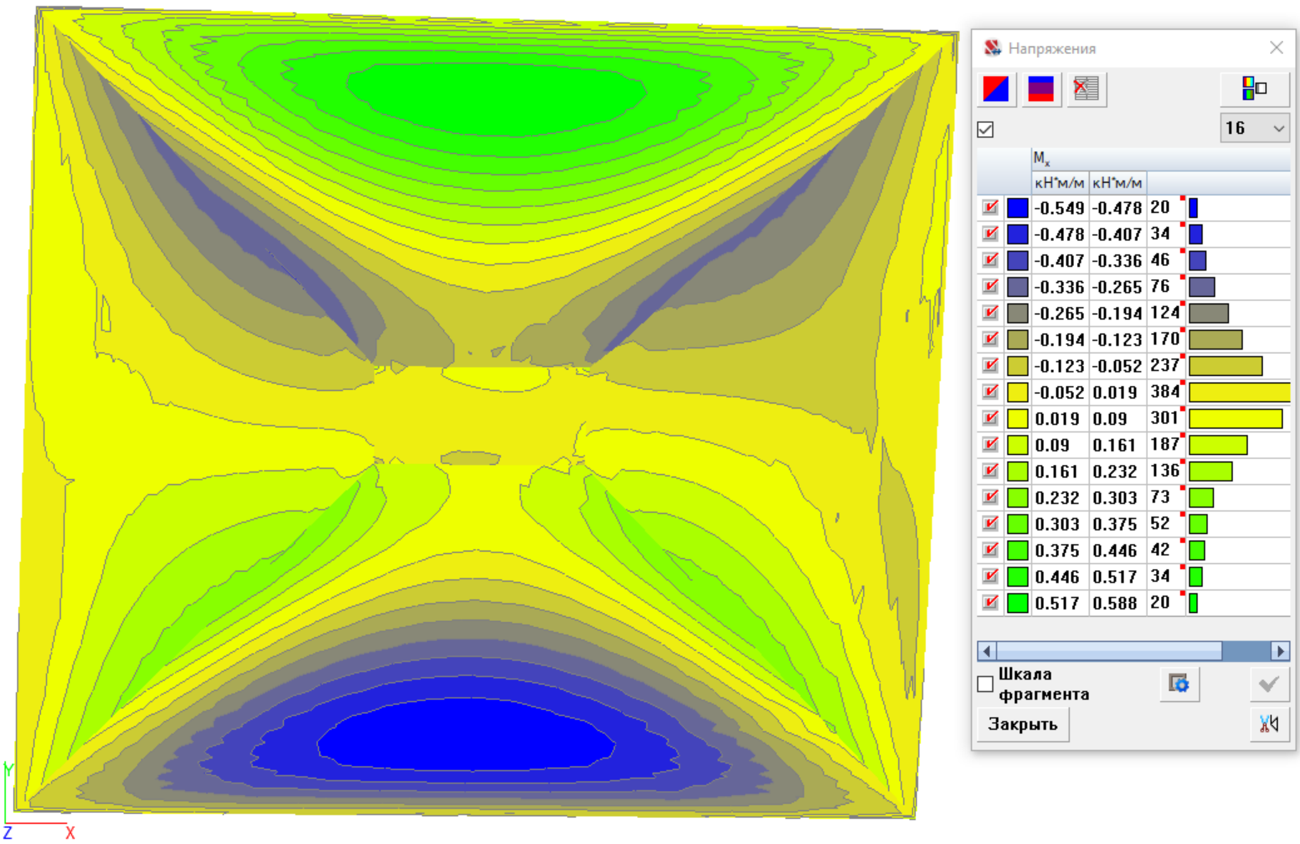

Figure 32 Bending moment M_x

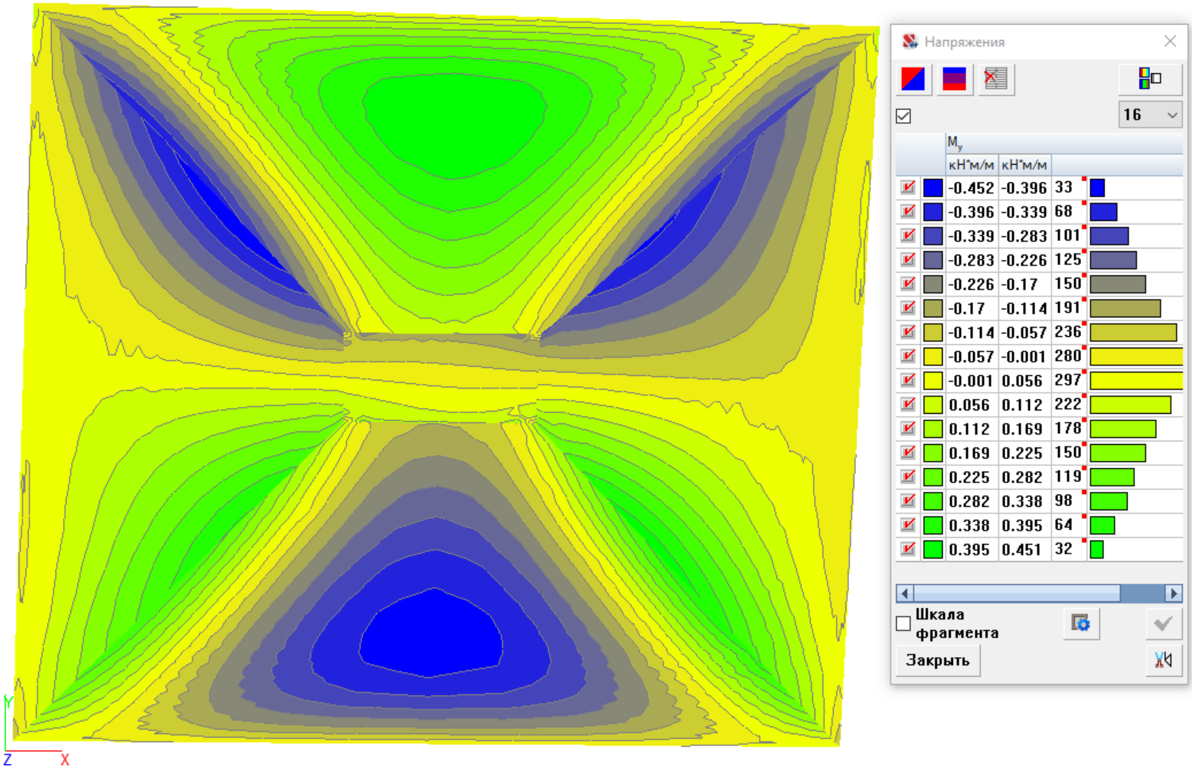

Figure 33 Bending moment M_y

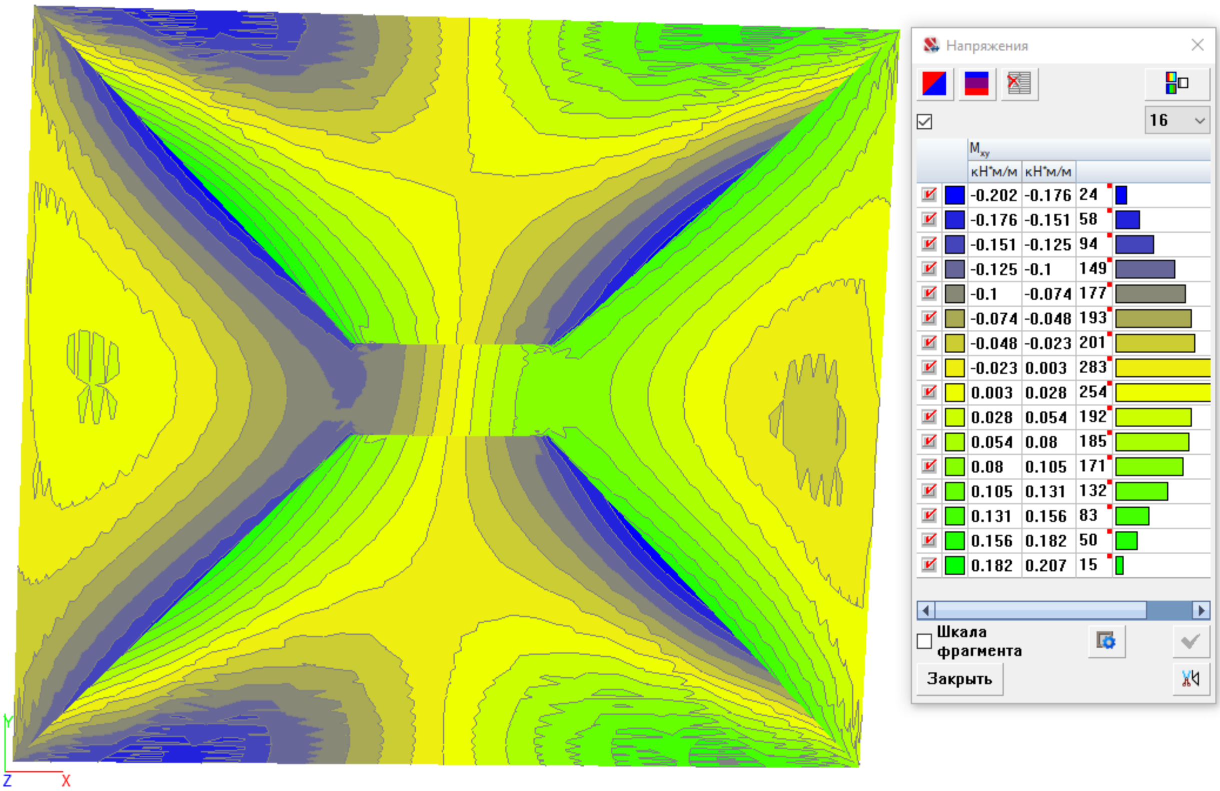

Figure 34 Torque M_{xy}

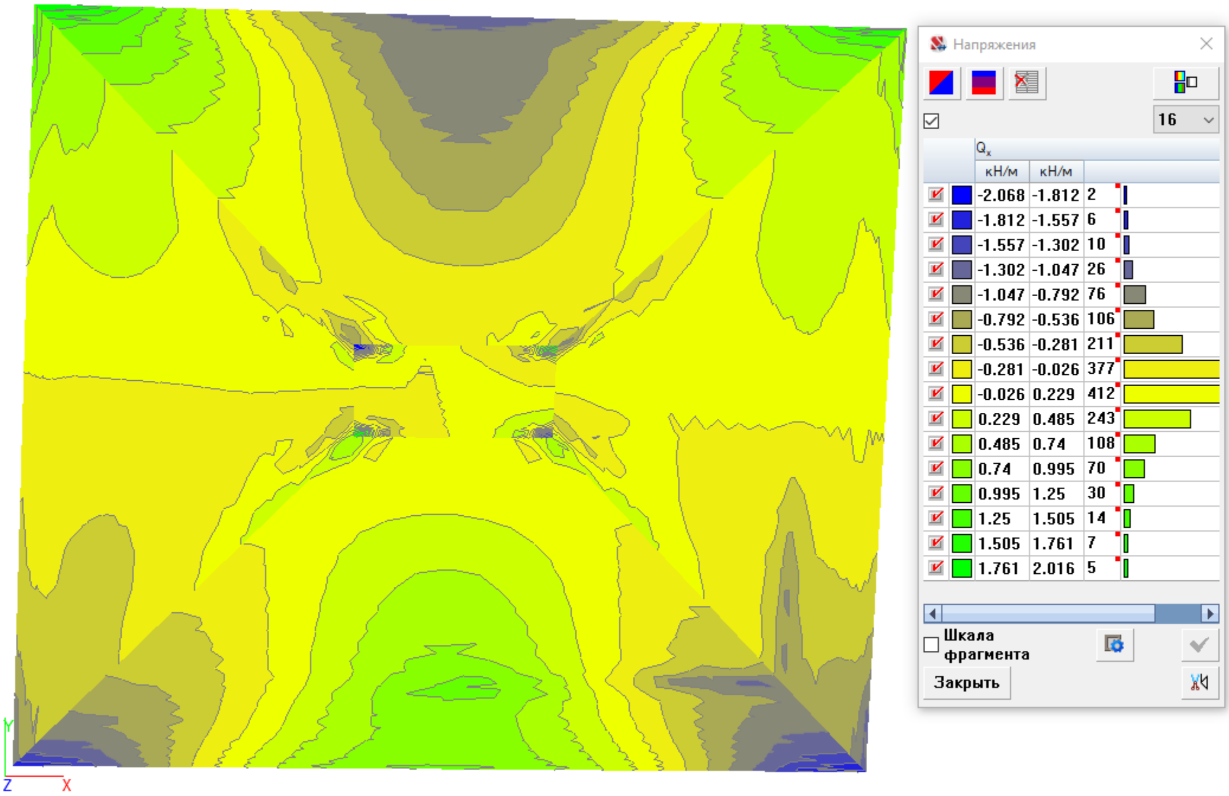

Figure 35 Shear force Q_x

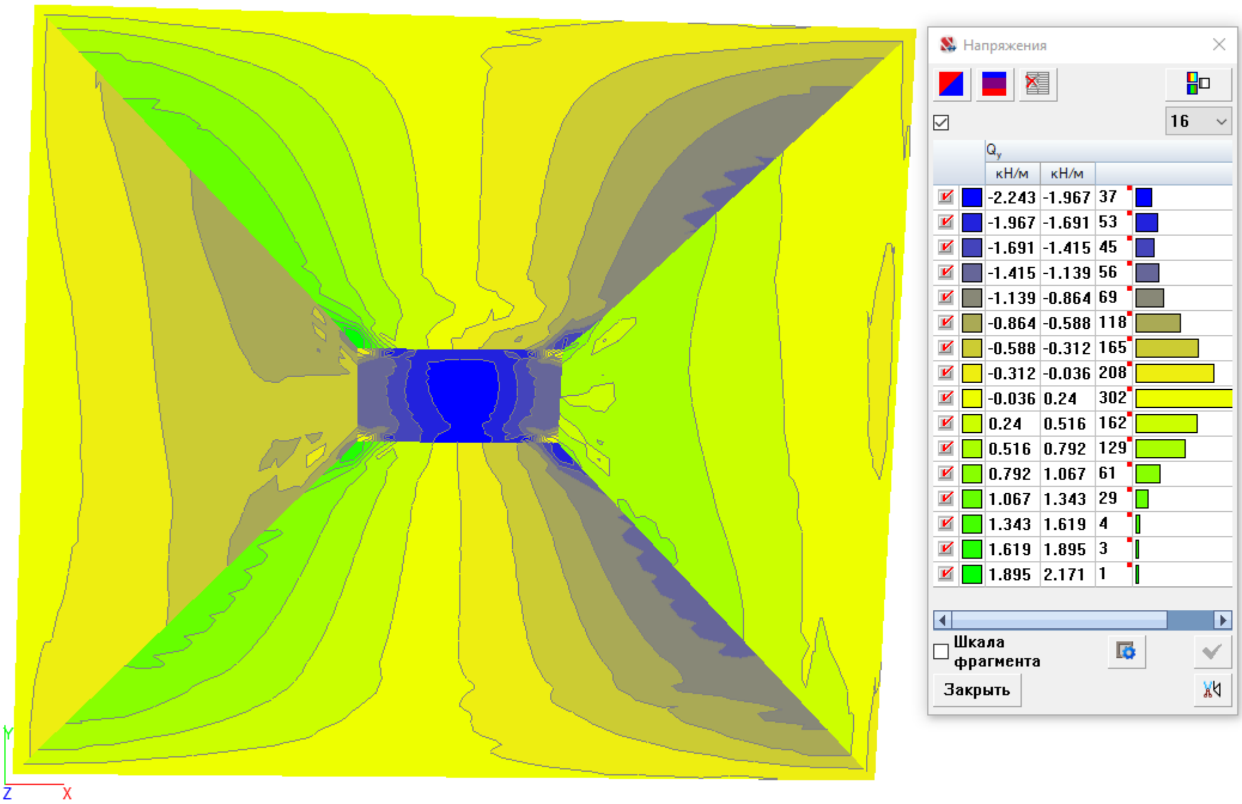

Figure 36 Shear force Q_y

ANNEX 4 Displacements from 1st load combination

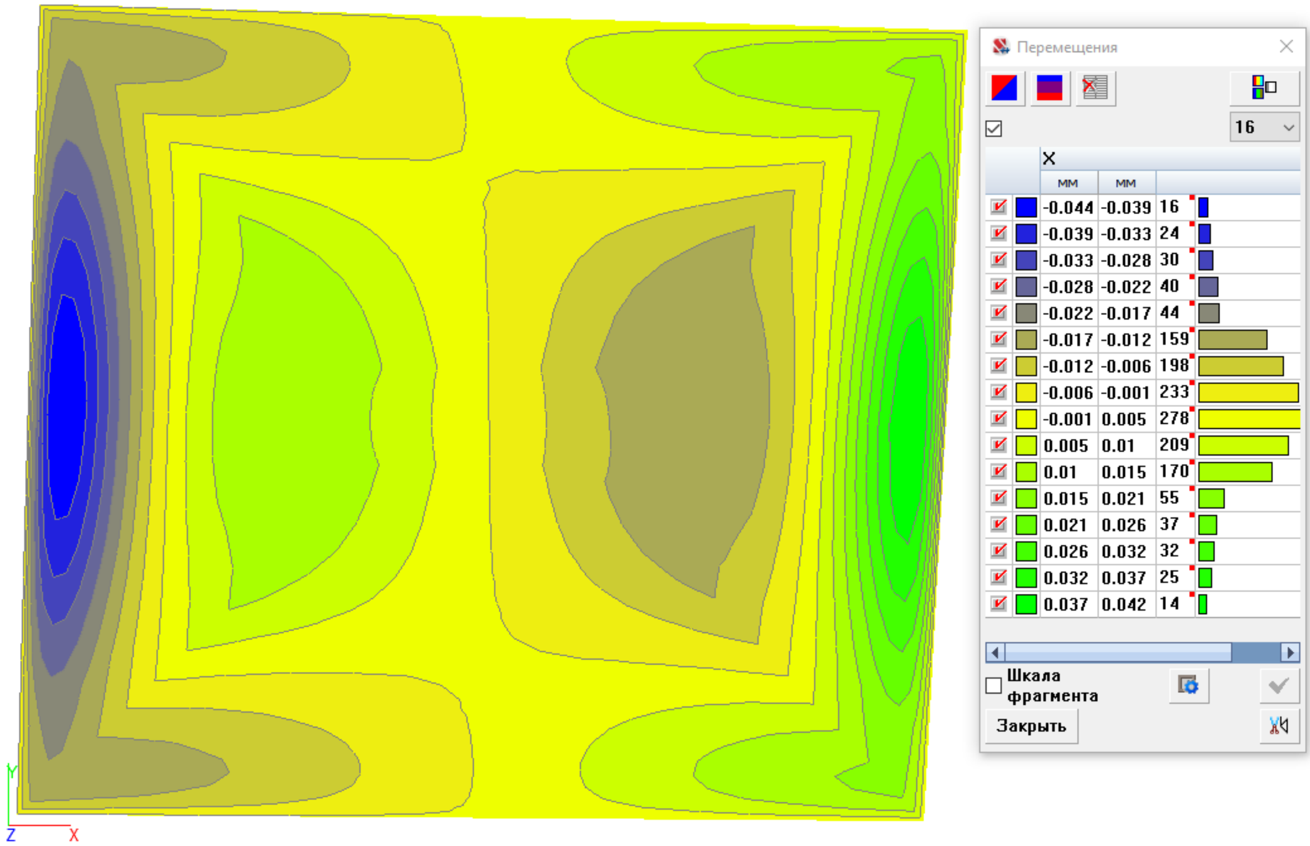

Figure 37 Displacement along X axis

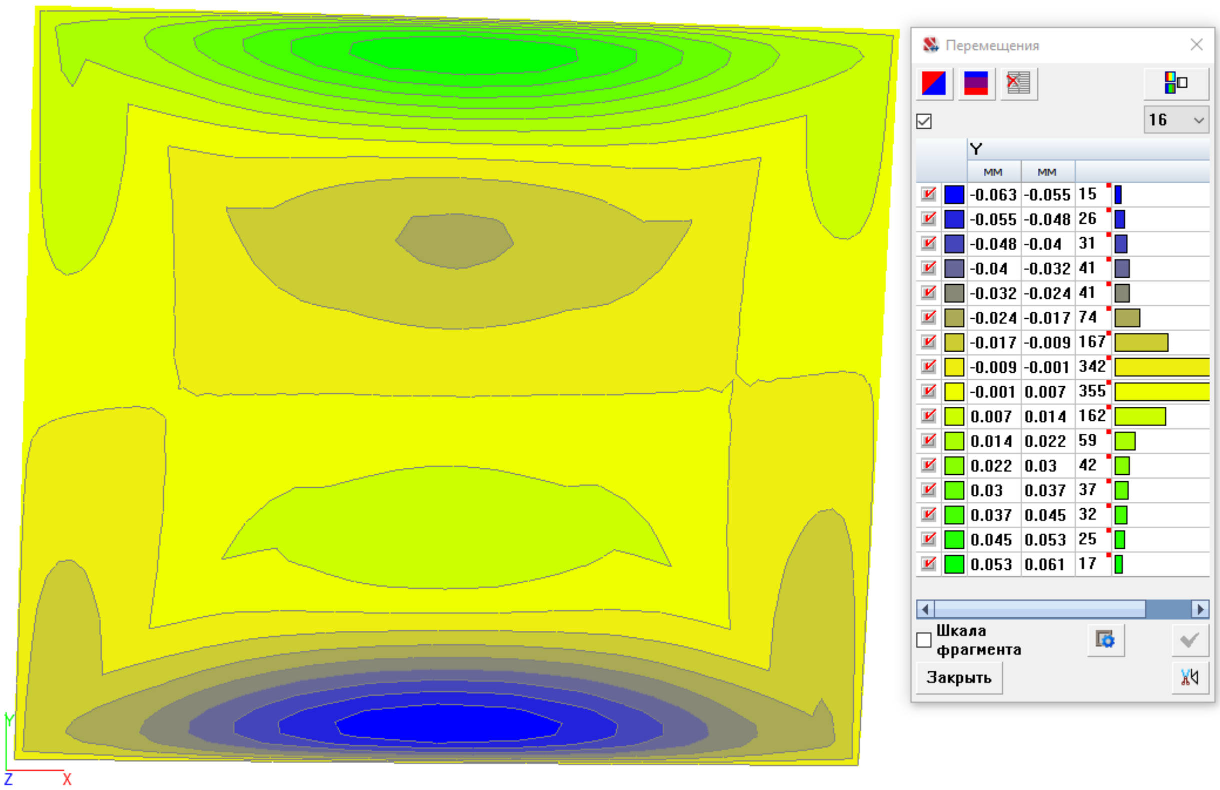

Figure 38 Displacement along Y axis

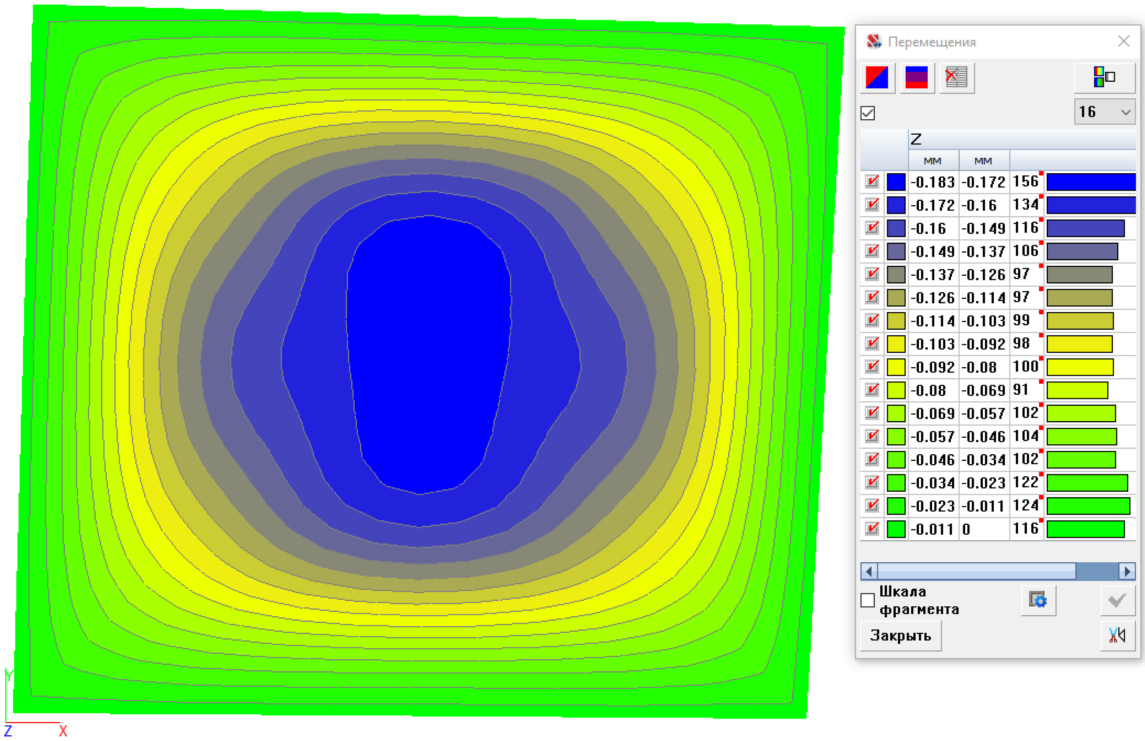

Figure 39 Displacement along Z axis

ANNEX 4 Displacements from 2nd load combination (X direction)

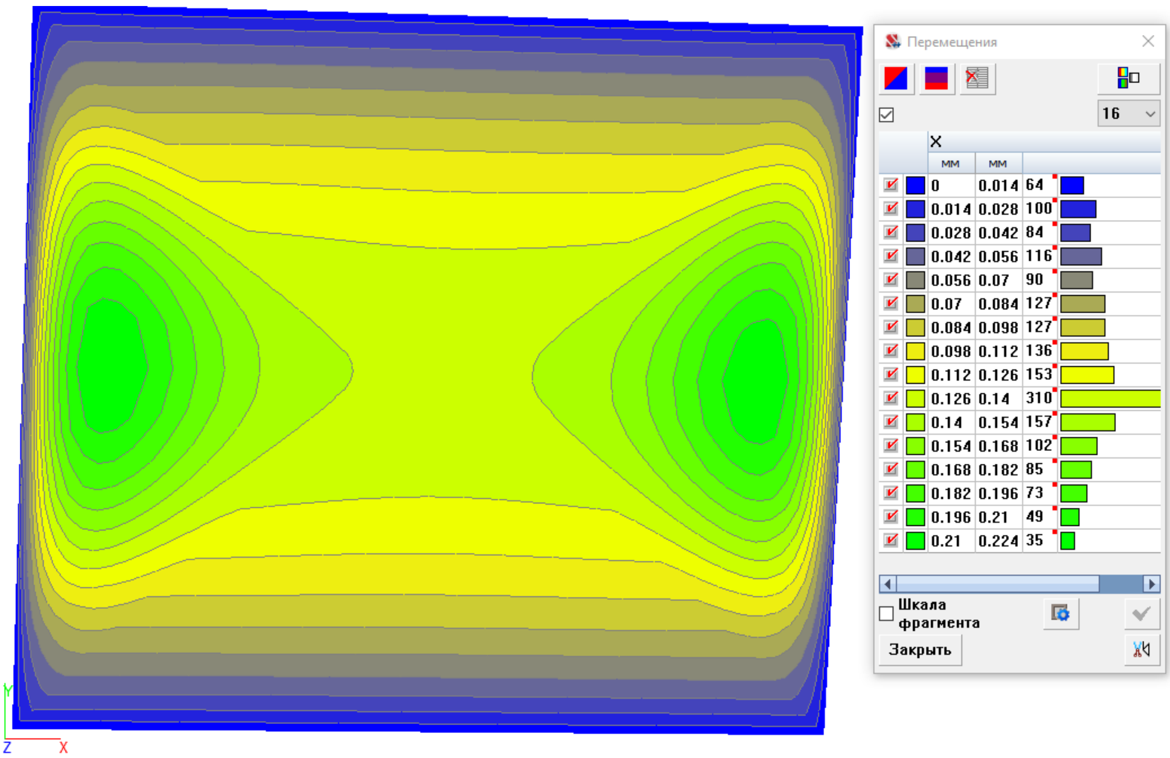

Figure 40 Displacement along X axis

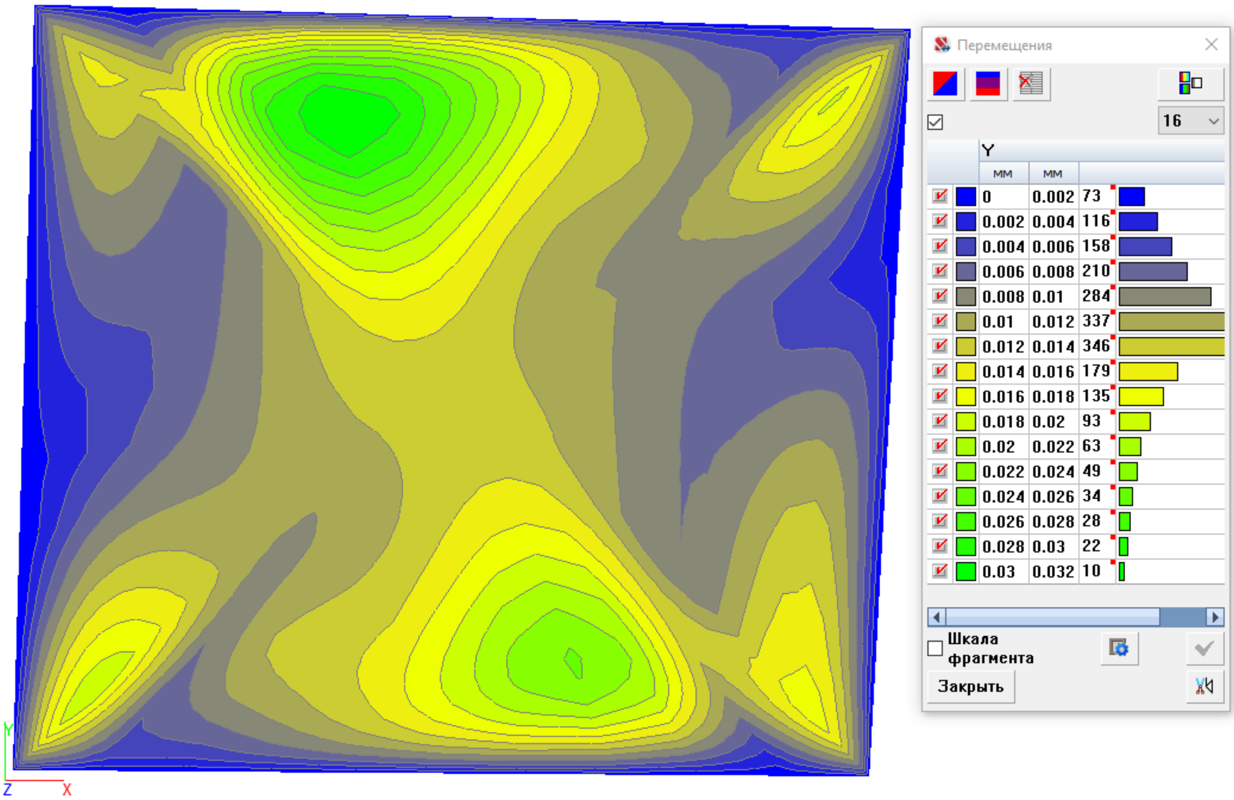

Figure 41 Displacement along Y axis

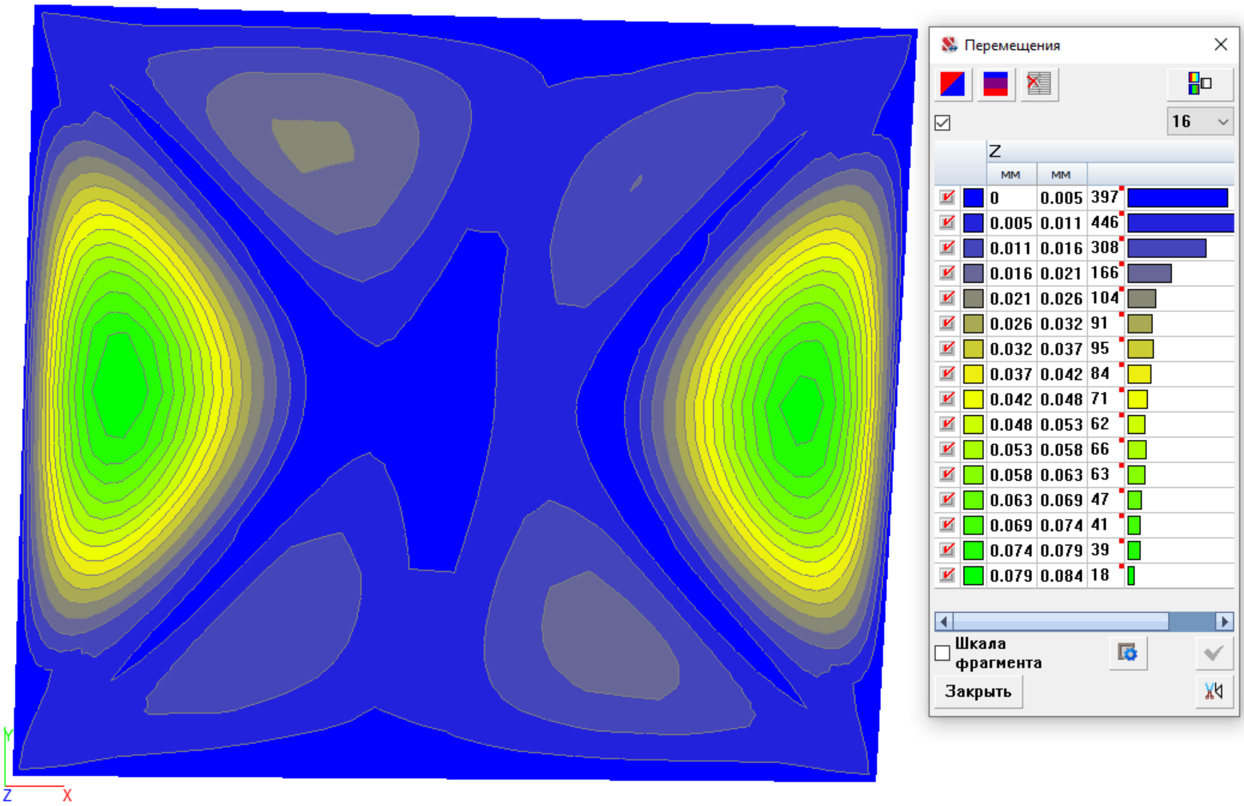

Figure 42 Displacement along Z axis

ANNEX 5 Displacements from 2nd load combination (Y direction)

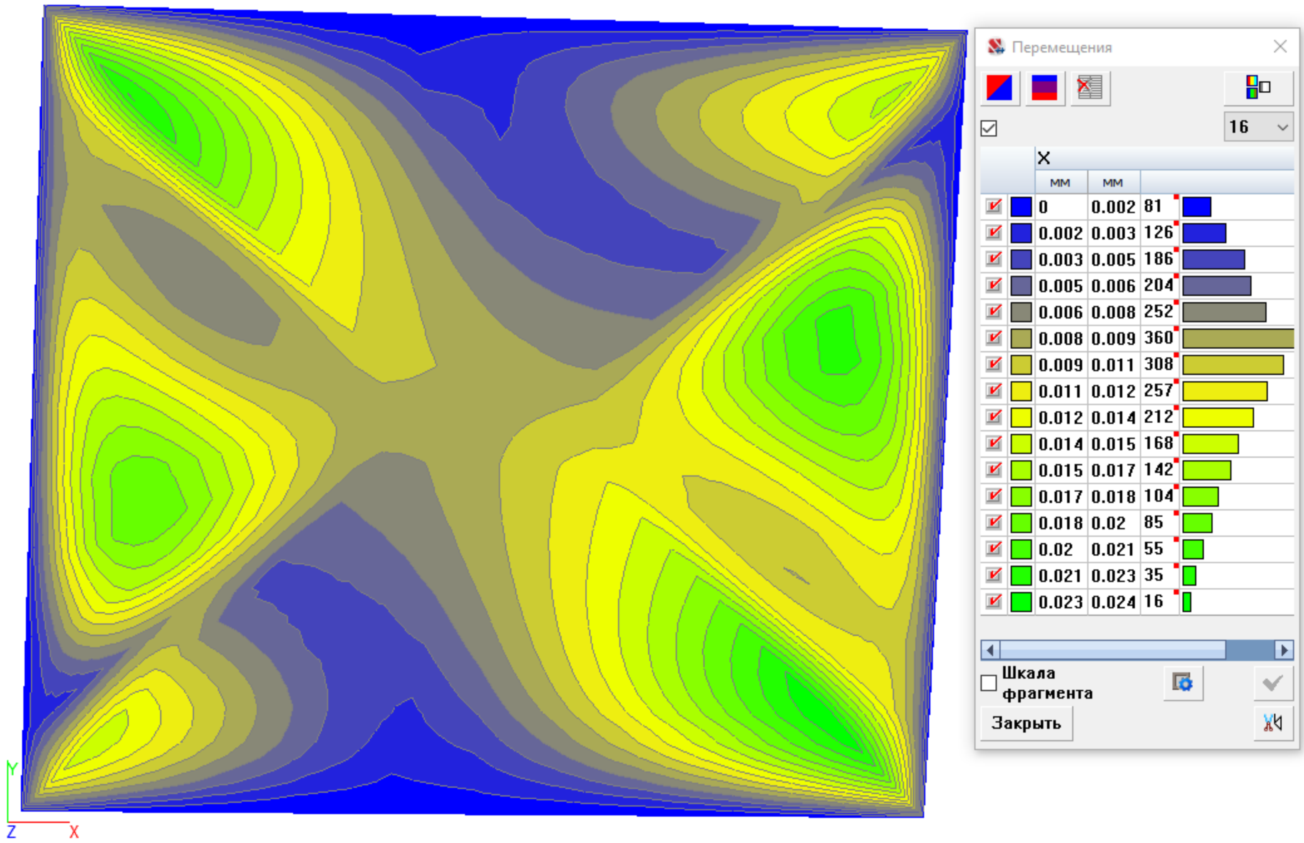

Figure 43 Displacement along X axis

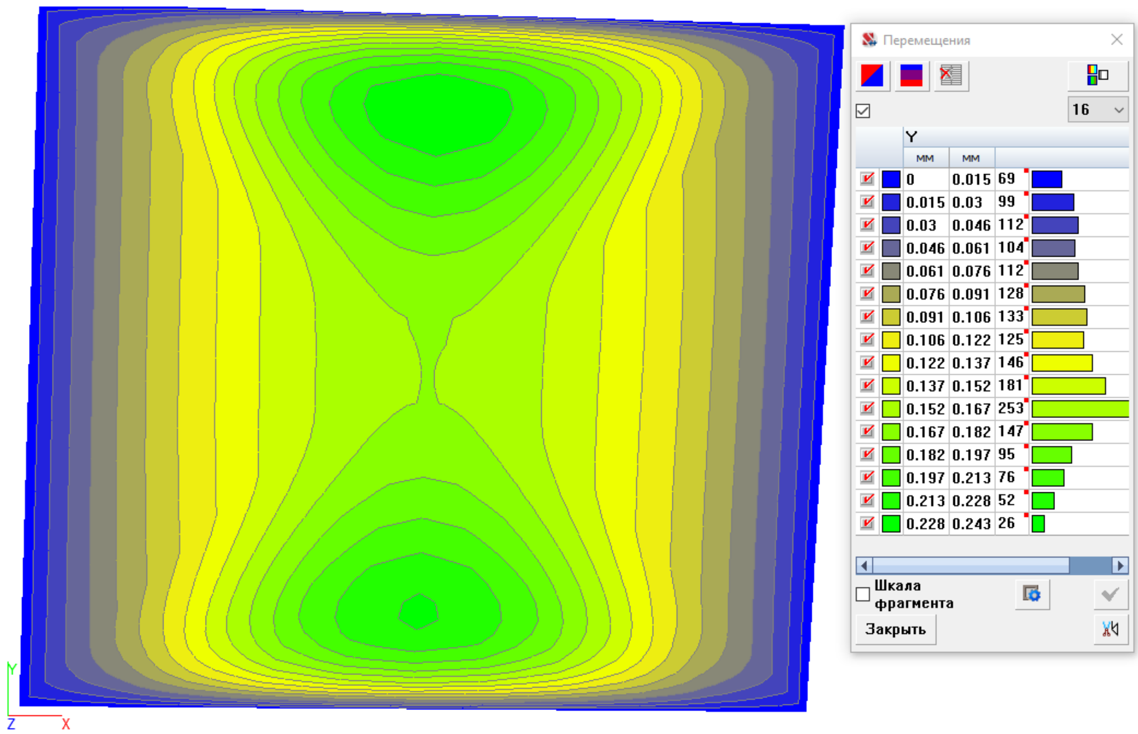

Figure 44 Displacement along Y axis

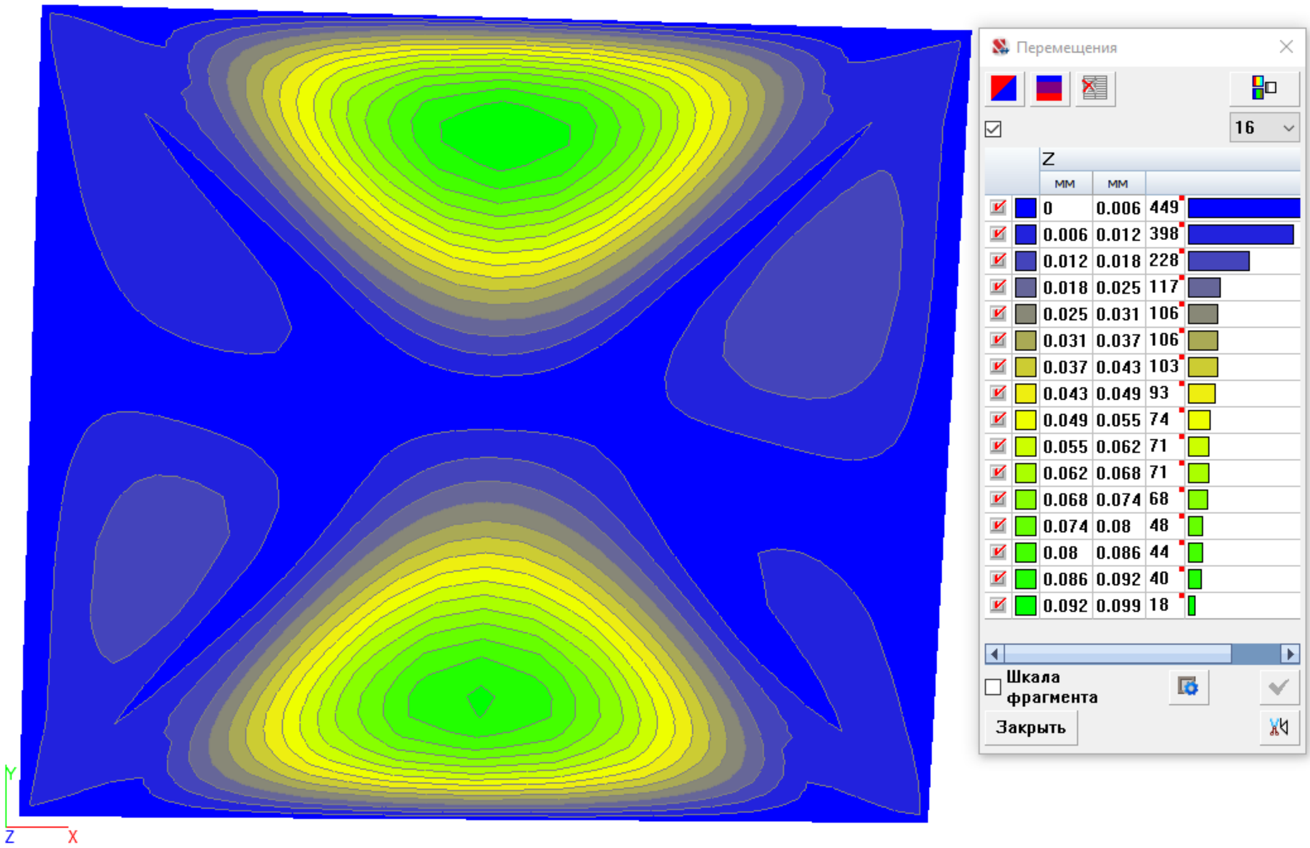

Figure 45 Displacement along Z axis