

THE BASIC PRINCIPLES OF THE ALGORITHM RECALCULATING DATA ON EXPERIMENTAL AERODYNAMIC TESTS INTO WIND AFFECTED LOAD STRAINS

Michail Samofalov¹, Artur Kazakov², Roman M. Pavlovsky³

¹Faculty of Fundamental Sciences, Vilnius Gediminas Technical University,
Saulėtekio al. 11, LT-10223 Vilnius, Lithuania

²Vilnius Gediminas Technical University, Saulėtekio al. 11, LT-10223 Vilnius, Lithuania

³Ukrainian National Aviation University, Laboratory of Aerodynamic Investigations,
Cosmonaut Komarov ave 1, 03058 Kyiv, Ukraine

E-mails: ¹Michail.Samofalov@vgtu.lt (corresponding author);

²Artur.Kazakov@gmail.com; ³aerodyn@nau.edu.ua

Received 7 Jan. 2011; accepted 17 Mar. 2011

Abstract. The article examines an algorithm used for processing the results of laboratory tests when experimental data was obtained in the aerodynamic tunnel. The paper deals with information when data about pressure distribution on the surfaces of a designed building are recalculated into wind loads required for calculating a virtual model for the finite element method. Due to differences in methodology between experimental airflow testing in the aerodynamic tunnel and the simulation of wind loads for a complex facility referring to the finite element method, the proposed investigations are actual while taking into account the current design codes and climatology conditions for an individual site. A review of similar problems, design conditions, the principles of the conducted experiment, a concept of the algorithm, basic assumptions and some results are briefly described in the paper. The final conclusions and recommendations can help with choosing the right solution during such calculations.

Keywords: recalculation algorithm, wind engineering, complex facility, aerodynamic tests, finite element method.

1. Introduction

Sports entertainment facilities refer to original large span structures. A unique architectural form is especially emphasized in Europe or world level stadiums presented as modern design examples. In case of untypical shape properties of building volumes, the influence of wind effects on such kind of facilities is considerably increased.

Experimental investigations in the wind tunnel and a numerical simulation of aerodynamic problems fill the gap between wind engineering and structural design (Simiu and Scanlan 1986, 1996). For the last years, when huge complex facilities became popular, this solution has been described in many ways. First, there are extraordinary effects (as tornados or typhoons) for very tall buildings, stadiums, towers, etc. (Holmes 2007). Second, investigations into the aerodynamic properties of an original city site embracing many various industrial or civil buildings, when interferential and other properties of airflows form sub-climate conditions have been conducted (Кузнецов *et al.* 2010). Such results are different in comparison with typical schemes from valid design codes based on assumptions concerning an independent building and its aerodynamic characteristics. Certainly, individual detailed investigation is welcomed by design codes (STR 2.05.04 2003; СНиП 2.01.07–85 1987; LST

EN 1991 2005) but requirements for some control parameters or basic sequence are not commented. As a rule, engineering assumptions are chosen by the authors of investigations (Кузнецов 2009; Павловский, Кузнецов 2009).

A methodology of how to define the aim of an aerodynamic test and give the required experimental results is well known. The next question is how important is a hypothesis during data transforming, what kind of expressions should be chosen, how these algorithms and requirements can be unified? At the moment, similar problems are being solved by the engineers in an original manner (Лебедич *et al.* 2007) and cannot be qualitatively checked by a typical solution.

The given paper is based on the results of aerodynamic experimental research (Samofalov *et al.* 2008; Павловский *et al.* 2007). The subject of investigation is an original shape of an entertainment facility. The task of research is to describe a procedure when the experimental results received while investigating a wind tunnel have been recalculated to structural design loadings. Such kind of analysis has been important to provide safety when the strength and stability of structural members have been designed and when façade elements and the behaviour of the light tent have been checked. The main requirements and calculation sequence of design codes, a technique for experimental aerodynamic investigations and the trans-

formation of experimental data to finite element model loadings are briefly described above.

The obtained results are distinguished by their novelty due to the original shape of the facility and because of a complex and enough quick solution to this real problem. Such investigations widen knowledge about wind actions on public buildings with untypical aerodynamic properties.

2. Real design situation. Structural features. Principal design sequence

In 1985, one of the variants of the central stadium in Vilnius was supposed to mount an arch, but this variant was turned down. In 2007, the same architects prepared a new design of the arched stadium (Nasvytis *et al.* 2007).

The main constructions of the facility are divided into four basic groups (Fig. 1): stand roof structures over spectators, an arch, a temporary tent using cables and pedestrian overpass around the building. An optimum shape of the stands is stipulated by a desire to place spectators on the most comfortable seats near the centre of the oval arena. This results in the necessity to build the roof over the stands of an elliptic shape. Sports standards require the use of an exactly open arena. Stand roof bearing structures are presented by 56 transversal frames of different height and are joined by spatial braces. The diameter of the external contour of the main building is 220 m. Over the stadium along the arena, a steel arch of maximum 60 m height is located the supports of which are placed beyond the external contour. Over the sports arena, a temporary tent roof can be partially or completely rolled out. The cables are connecting the arch with the stand roof. A foot path is designed around the stadium.



Fig. 1. A general virtual view of the façade structures of the investigated facility

When affected by the wind, the surfaces of the facility are formally divided into three types (in engineering sense):

- continual areas of walls, roof and tent;
- trussed arch space structures;
- relative separate cables.

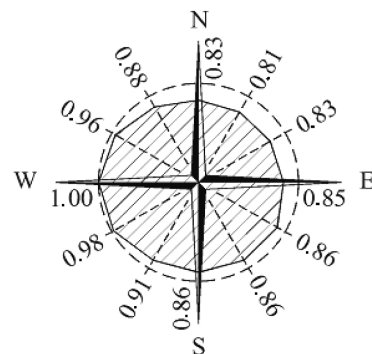
Analytical solutions to some simple geometric figures with continued surfaces are widely known and practically applied in engineering (Барштейн 1978; Simiu and Scanlan 1986, 1996). Therefore, such kind of analy-

sis cannot be used in our case of the first type surfaces. Conventional engineering methods for trussed systems are exactly described in design codes (LST EN 1991 2005; STR 2.05.04 2003; СНиП 2.01.07–85 1987) and successfully used for many years; thus, the problem of the second type dealing with arch loadings affected the wind is expressed. A situation looking at separate cables is of the same type while wind loadings are well calculated.

The complex facility has been mainly designed for 25 thousands of seats (and 5 thousands extra). During national festivals, the arena could be filled with 50 thousand of participants.

In this case, due to wind actions, loads are very important. First, the wind acts on the huge areas of the roof and tent. Load distribution depends on the shape of building geometry, i.e. aerodynamic properties. The distribution function $c_e(\beta)$ of wind pressure is expressed by wind direction angle β . Second, the wind acts directly on the structural members of the arch in two main directions: along and across the arch. All oblique directions are considered by the assumption as a linear combination of the main longitudinal and transversal ones. The wind action on the trussed arch construction has been calculated applying engineering methods and taking into account design codes STR 2.05.04 (2003). In general, 8 main directions of the wind have been studied: 2 along and 2 across the arch and 4 oblique (Samofalov *et al.* 2008; Samofalov and Cvirka 2010).

a)



b)

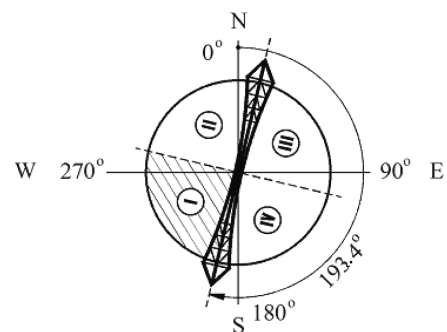


Fig. 2. Wind intensity directions according to building site climatology conditions (a) and orientation of the facility relative to azimuth (b) with the numbers of quarters

Wind velocity values relative to azimuth (STR 2.05.04 2003; RSN 156–94 1995) have been corrected by intensity direction coefficients from 0.80 to 1.00 (Fig. 2):

$$v_{ref}(\beta) = c_{dir}(\beta) \cdot c_{iem} \cdot c_{alt} \cdot v_{ref0}, \quad (1)$$

where v_{ref0} is a characteristic value of wind velocity, c_{alt} – the coefficient of a global altitude, c_{iem} – the coefficient of actual situations (value 1.000 for long life service, value 0.806 – for mounting).

Characteristic values of wind pressure on the roof and tent surfaces have been calculated by the formula:

$$q_{ref}(\beta) = \frac{\rho}{2} \cdot v_{ref}^2(\beta), \quad (2)$$

where ρ is air density. The static component (constant stream) of wind pressure has been determined by:

$$w_{st}(\beta, h) = q_{ref}(\beta) \cdot c_h(h) \cdot c_e(\beta), \quad (3)$$

where c_h is a coefficient allowing for the distribution of wind pressure by height h above the ground surface.

The dynamic component (pulsation of the stream) of wind pressure in engineering solutions to design codes (LST EN 1991 2005; STR 2.05.04 2003; СНиП 2.01.07–85 1987; Барштейн 1978; Simiu and Scanlan 1986, 1996) has been defined by the formula:

$$w_{dyn}(\beta, h) = w_{st}(\beta, h) \cdot k_{dyn}(\beta, h), \quad (4)$$

where dynamic actions are expressed by the coefficient:

$$k_{dyn}(\beta, h) = k_{dyn}(m(h), \xi, \zeta(h), v(\beta), u(h)), \quad (5)$$

where m is a mass distribution factor, ξ – a dynamic factor of the whole building, ζ – a coefficient of pulsation, v – a space correlation coefficient of the whole building, u – displacements of mode shapes of natural frequencies.

In general, a dynamic action in calculations depends on natural structural frequencies and respective shape modes. The values of wind dynamic actions have been separately calculated using software based on the *finite element method* (FEM).

The temporal tent over the arena can be used only in the summer season.

Wind actions during the arch mounting process have been considered in a case of a short-term design situation while the roof is a building and there are no cables between the roof and the arch (Samofalov and Cvirka 2010).

3. Description of experimental research

For a detailed study of the peculiar features of airflow over the facility, a model of a scale of 1:150 has been tested in the aerodynamic tunnel (Fig. 3). The model on the turntable has been located at different angles (from 0 to 360 with respect to air stream direction) at every of 40 stops of which registrations of air pressure values at 253 drainage points and 2 points in the middle pressure on a pitot–static tube have been made. After averaging the

measured values, the calculation of the coefficients has been performed.

Taking into account the structural double symmetry of the facility, drainage points have been placed on the 1st quarter (frame numbers from 1 to 14 clockwise respectively) of the model. The flexible tent has been fabricated as a stiff shell corresponding to sagging the real flexible tent in windless weather. Drainage points have been mainly located along the middle lines between transversal frames at the roof and tent levels. For checking the received results, some drainage points have been doubled on another structural quarter.

With stretched above the playground tent, the wind inside is light, and thus the top of the tent is fitted mainly with single drainage points enabling to measure air pressure only on the outside surfaces of the tent. A circular chord with sealants has been made to provide blowing through the stadium model without air passage between the top of façade walls and the roof.

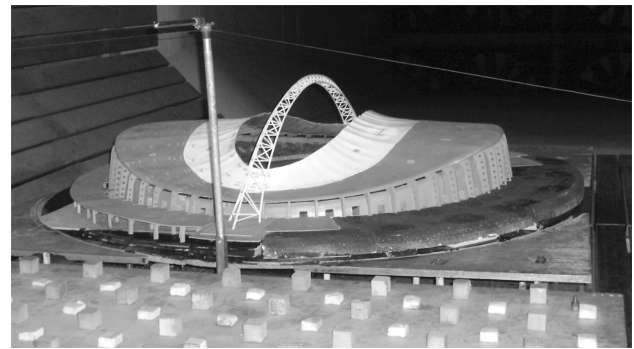


Fig. 3. The model within the aerodynamic tunnel: a view from the nozzle side, the angle of the turntable is 0° , the tent is stretched by a half of the cables length

In order to achieve sufficient levels of the initial signals of pressure transducers, stream velocity in the aerodynamic tunnel has been assumed to be 30 m/sec, Reynolds's value has been approximately $2 \cdot 10^6$. In this case, self-similarity has been provided by the presence of flow separations from the sharp edges of the model to be investigated and due to the availability of intensive turbulence within the area of its location. This indicates that conditions for geometric similarity between the tested model and real facility have been satisfied to a sufficient degree (Павловский, Кузнецов 2009).

The coefficients of air relative pressure on the model surface have been calculated by the following expression:

$$\eta = 1 - \frac{\Delta P}{\chi \cdot (P_0 - P_s)}, \quad (6)$$

where ΔP is excess pressure at the point to be investigated in Eifel chamber relative to atmospheric pressure, χ is a calibration factor of the pitot–static tube, P_0 – total pressure, P_s – static pressure. A value of the coefficient depends on the distribution of air velocity within flow getting on the model.

Due to the performed experiment, the results have been gained concerning the distribution of the average relative coefficients for the building façade and interior surfaces of the tent and roof at different directions of air flow and with different operational configurations (Samofalov *et al.* 2008): the tent has been rolled on the half or full length, exits to the arena have been opened or closed, holes between the roof edge and the top of the façade walls have been opened or shut (Table 1).

Table 1. A schedule of the experiment stages

No.	Tent bot-tom part	Top part of the tent	Holes under roof	Holes of the exits
1	taken away	taken away	opened	opened
2	existing	taken away	opened	opened
3	existing	existing	opened	opened
4	existing	existing	closed	opened
5	existing	taken away	closed	opened
6	taken away	taken away	closed	opened
7	taken away	taken away	closed	closed
8	taken away	taken away	opened	closed

According to the calibration results (Павловский *et al.* 2007; ГОСТ 8.207–76 1976), the reduced error of the measurement range of pressure transducers is less than 0.3% (accuracy class 0.3). The analysis of the experimental results has been mainly made for the following reasons:

- the test results demonstrated that the accuracy of measurement was sufficient (Павловский *et al.* 2007), the obtained model characteristics of the friction turbulent urban layer are satisfactorily consistent with scientific investigations (Барштейн 1978; Simiu and Scanlan 1986, 1996; Новицкий, Зорграф 1991; Горлин, Слезингер 1969; Египко *et al.* 1992) and technical requirements (LST EN 1991 2005; STR 2.05.04 2003; СНиП 2.01.07–85 1987);
- the distribution of aerodynamic coefficients of the wind is original and is not described in a typical manner considering the existing design codes LST EN 1991 (2005), STR 2.05.04 (2003) and СНиП 2.01.07–85 (1987);
- measurement accuracy analysis has recommended (Павловский *et al.* 2007) to define the tolerance ± 0.1 of the values of the aerodynamic coefficient;
- the number of drainage points on the tent internal surface has been relatively low because of invaluable pressure inside the arena under the stretched tent;
- shutting the holes between the roof and façade walls causes a non-essential reduction in differential pressure, maximum by ± 0.1 ;
- extreme values of relative pressure have been distinguished for angles 0.36 and 90°;
- the wind direction angle of 36° has been the most valuable when the roof above the stands is putting up;
- the influence of the arch trussed structures has been not valuable for the general distribution of

relative pressure and is the most important one in a tight zone of the tent top;

- the influence of the asymmetric arrangement of VIP loggias on coefficient distribution has not been observed.

Finally, the distribution of relative pressure coefficients in all drainage points during 40 different wind directions has been analyzed. Various 8 configurations of the building model have been experimentally set and expressed by numerical values. Such data are adequate for creating wind loadings on a virtual FEM model.

4. A concept of the engineering algorithm

The distributions of relative pressure coefficients (6) on the external (facade) and internal (inside) surfaces of the facility are different. There is an actual problem for the cantilever roof of 43 m (maximum) and a light tent over the arena. In case of the same directions (Fig. 4) on both surfaces, the extreme effects of the wind on the construction appeared.

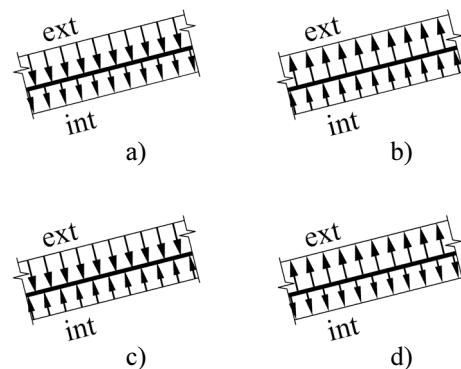


Fig. 4. The directions of wind actions on the roof and tent surfaces: downward (a), upward (b), mixed (c, d)

A value of the aerodynamic coefficient for wind pressure calculations (3) has been defined by an expression:

$$c_e = \pm | \eta_{ext} - \eta_{int} | \pm \Delta \eta, \quad (7)$$

when η is the experimentally given coefficient (6) with algebraic direction signs on external or internal surfaces, $\Delta \eta$ is the accuracy of experimental results.

All 40 wind directions (in general 360°, each turn-step is of 9°) in combination with other loadings of the facility should lead to the FEM model in a huge number of possible design situations. On the other hand, wind pressure distribution via wind direction angle is described by enough smooth functions (Павловский *et al.* 2007); thus, a large number of design situations and such kind of exact analysis are not needed for civil engineering. The main three directions have been practically selected:

- “transversal” across the arch while the structural members of the roof, tent and arch are extremely subjected to the wind; this case has been classified as the most dangerous one and extreme values from 7 nearest directions have been chosen;

- “diagonal” in oblique directions when the roof without the tent (really the most frequent case) is extremely acted by inside putting up load – 5 nearest directions have been reviewed;
- “longitudinal” along the arch (this case is not important for the whole facility but is the extreme one for some structural members of the trussed constructions) – 3 nearest directions.

Generally, for every configuration of the facility (Table 1), 8 basic wind directions have been applied (Table 2).

Table 2. Selection of the main wind directions

Direction No.	Main angle	Group angles
1	0	351, 0, 9
2	36	18, 27, 36, 45, 54
3	90	63, 72, 81, 90, 99, 108, 117
4	114	126, 135, 144, 153, 162
5	180	171, 180, 189
6	216	198, 207, 216, 225, 234
7	270	243, 252, 261, 270, 279, 288, 297
8	324	306, 315, 324, 333, 342

In the aerodynamic tunnel, only the 1st quarter of a double symmetric facility has been precisely investigated. For a real building site, wind pressure should be corrected employing various coefficients from expressions (1)–(3) via wind direction angle: azimuth coefficient, aerodynamic coefficient, building shape coefficient in dynamic solutions. The 1st quarter measurement data have been transformed for all 56 frames in a linear manner to the 3rd one and using the oblique symmetry rule to the 2nd and 4th quarters (Table 3).

Table 3. Transformation of experimental data to loadings

Direction No.	Experiment angle	2 nd quarter	3 rd quarter	4 th quarter
1	0	180	180	360
2	36	144	216	324
3	90	90	270	270
4	114	36	324	216
5	180	0	0	180
6	216	324	36	114
7	270	270	90	90
8	324	216	144	36

The axes of azimuth and plane axes of the facility are different, and an angle between them is 193.4° (Fig. 2). Wind velocity values (1) from design codes (STR 2.05.04 2003) have been recalculated to basic wind directions with respect to constructions (Table 4).

During the transformation procedure for experimental data from the aerodynamic tunnel to wind loadings on the FEM model, some assumptions in mathematical, physical and engineering meaning have been considered:

- city development conditions around the building site would be the same during the whole maintenance period of the facility (B-type building intensity has been provided according to STR 2.05.04 (2003));

Table 4. Wind direction angles and direction coefficients

Direction No.	Facility angle	Azimuth angle	Direction coefficient
1	0	193	0.86
2	36	229	0.89
3	90	283	0.99
4	114	307	0.92
5	180	13	0.85
6	216	49	0.82
7	270	103	0.84
8	324	157	0.86

- the influence of asymmetrical pedestrian overpass around the whole arena building is insignificant;
- the trussed arch does not affect the general distribution of wind loads on the walls, roof and tent;
- the arch structures can be calculated independently as separate ones while the internal forces of the cables have been replaced by internal forces;
- during the winter season, the iced surfaces in calculations of wind pressure on the facility have not been considered;
- the main configurations of the facility in calculations are the same for winter and summer seasons (according to climatology RSN 156–94 (1995); stronger wind was registered in winter while the tent cannot be used due to operation conditions of the arena);
- wind direction coefficients in calculations have been set the same for both seasons winter and summer;
- along each of the frames, a shape of the relative pressure function has been considered as “smooth” without “jumps” – not significant local distortions of such main rules have been observed on the edge of the roof or tent;
- the distribution of wind pressure between the nearest drainage points in the circular direction has been described by linear rules without jumps or gaps;
- the distance between the nearest drainage points in comparison with the dimensions of an experimental model is small, thus the value of an intermediate point can be calculated using a linear interpolation;
- a recommended experimental accuracy value of ± 0.1 is sufficiently high in comparison with the average aerodynamic coefficient (approximately ± 0.5) of all surfaces;
- pulsation is mainly actual for roof internal edge (cantilever frames) and arch trussed structures;
- in the FEM model, the cables have been numerically calculated by strength lines (without a sag) of the constant shape;
- during wind actions, the shape of the tent has been considered as constant;
- along each of the frames in the FEM model, wind loads have been presented by (a middle value between two values of the edge nodes of the finite element) uniformly distributed loads for every of the finite elements.

During the recalculation of experimental relative pressure values (6), some practical problems have been defined. First, all data that have been practically expressed by a series of values along the frames, should be visually reviewed by an engineer with the aim to answer why extremely high or low values have appeared in some individual points. This practical analysis required high qualification and experience in civil engineering design because similar procedures cannot be automatically unified. The second problem is small experimental values near zero as in this case, an engineer should solve “by hand” what kind of signs to set in (7) while an action on a frame to be considered could create serious danger. The third problem is that there are some serial results (Table 2) of different signs and an engineer should manually select only one case, which could be the most extreme for an individual load zone. These operations have been subjected to the clearly analytical analysis of some real distortions; however, their influence cannot be valuable.

Drainage points on the experimental model (Fig. 2) have been placed between the frames at logically fixed distances. During the simulation of the finite element grid for the trussed frames, other principles have been applied. Because of clearly different working methods dealing with experimental and numerical models, drainage points and FEM grid nodes have not coincided. These differences were observed considering two directions: along the frame axis and across it. The transversal direction has been recalculated by using the simplest linear interpolation, whereas longitudinal – by applying polynomial interpolation functions. A degree of polynomials has been chosen such that standard deviation should be with a tolerance of 5%. The highest degree of polynomials has been set at 6. In such a manner, all wind load values for every finite element nodes have been calculated.

Each of 56 transversal frames is presented in the *finite element analysis* (FEA) model by a trussed cantilever beam on a trussed column, both of a triangle cross section (Fig. 5). All transversal frames of the stadium are joined by braces on the roof and by beams at visitor stand levels. One-dimensional beam finite elements have been applied for the simulation of such space system (Fig. 6). The arch has been modelled in the same manner. All temporary roof cables have been presented by one-dimensional non-linear finite elements. The structural stiffness of roof profiled sheeting, a light tent and walls have been eliminated from the FEA model. The wind actions have been expressed by distributed loads (along the frames and cables). Load values of every finite element on the contact zone between the frames and roof sheeting or outside the The next step of the practical calculation of wind loads is that distributed pressure should be presented as the longitudinal one. There are two important features of structural engineers: distances between the nearest frames for every node of the FEM model are different (Table 5) and the load problem accepts other accents; lengths of finite elements along the frame have been different. This factor is important because of “jumps” during the final load distribution. Around the whole facility, on the free edge of the cantilever roof, the distance between finite

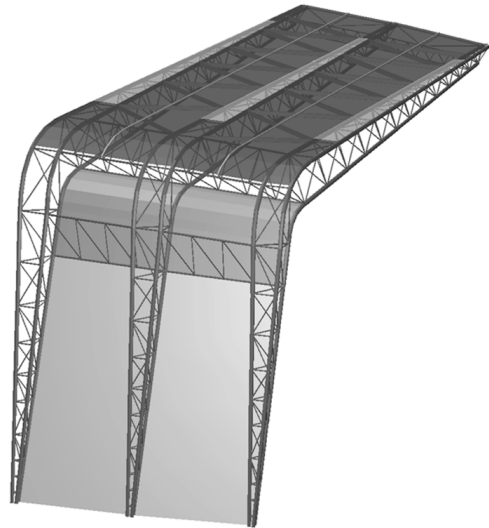


Fig. 5. A fragment of three nearest frames with the wall façade and roof cover

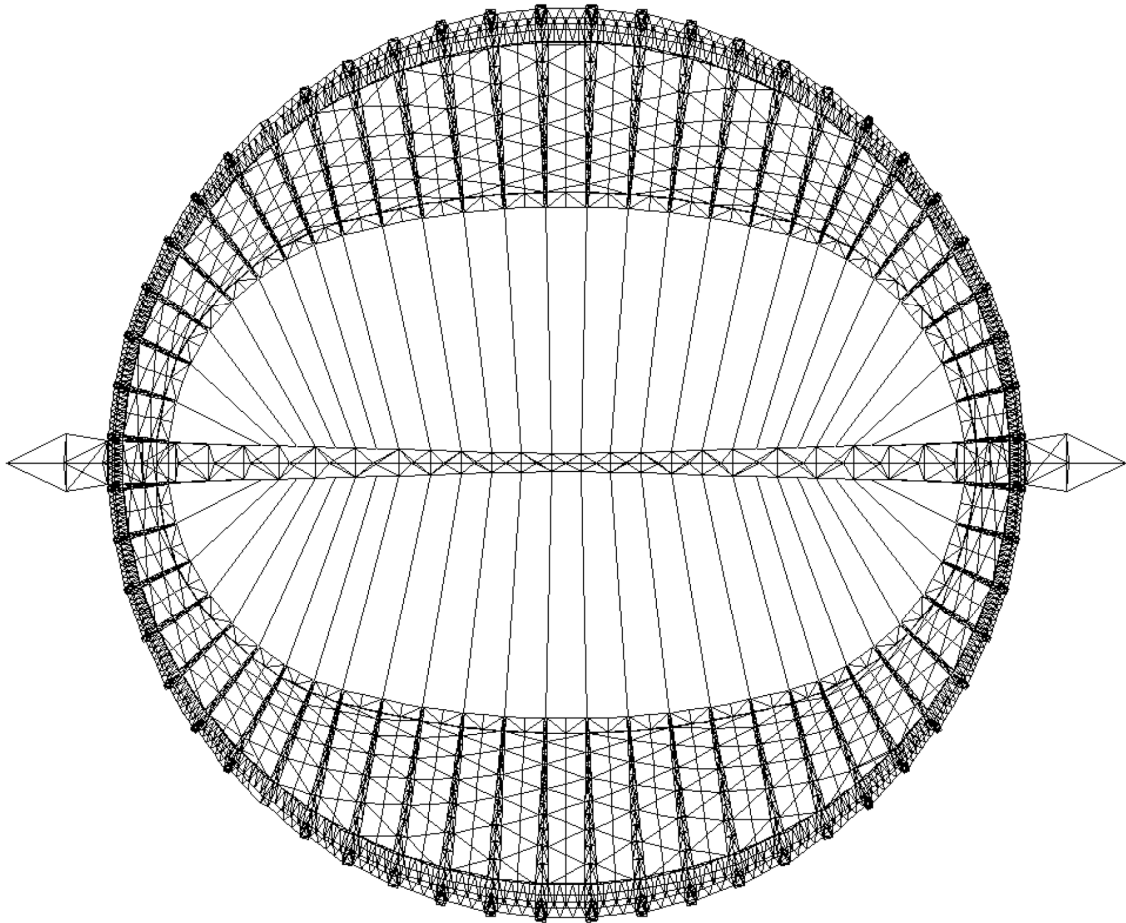
element nodes is less; the load approach on this part of the frame has been accurately kept. walls have been calculated.

During the next step, characteristic wind values have been multiplied by the coefficients of load safety (STR 2.05.04 2003; LST EN 1991 2005) and facility responsibility (STR 2.05.03 2003; LST EN 1990 2004). It should be noted that calculations at a stage of mounting (while the facility is calculating without cables for a short-term operation period) and during the service period of the facility are very important because of principally different boundary conditions and various values of loads. Expressions (1) and (2) clearly show that wind squared velocity has been provided with a decrease in one third during the mounting process if compared with the period of service.

Table 5. Relative breadths of load zones and relative lengths of load sectors along the highest frame

Sector No.	Relative breadths of load zones			Relative lengths
	Left	Centre	Right	
1	0.656	0.589	0.653	0.390
2	0.689	0.529	0.686	0.296
3	0.716	0.479	0.714	0.267
4	0.741	0.434	0.739	0.241
5	0.763	0.394	0.762	0.218
6	0.783	0.357	0.782	0.197
7	0.801	0.324	0.800	0.178
8	0.818	0.294	0.817	0.160
9	0.835	0.263	0.835	0.202
10	0.853	0.229	0.853	0.174
11	0.869	0.201	0.869	0.151
12	0.883	0.176	0.883	0.130
13	0.894	0.154	0.895	0.113
14	0.905	0.135	0.905	0.104
15	1.000	0.000	0.999	1.000
16	0.928	0.000	0.926	1.000
17	0.856	0.000	0.853	1.000
18	0.783	0.000	0.780	1.000

a)



b)

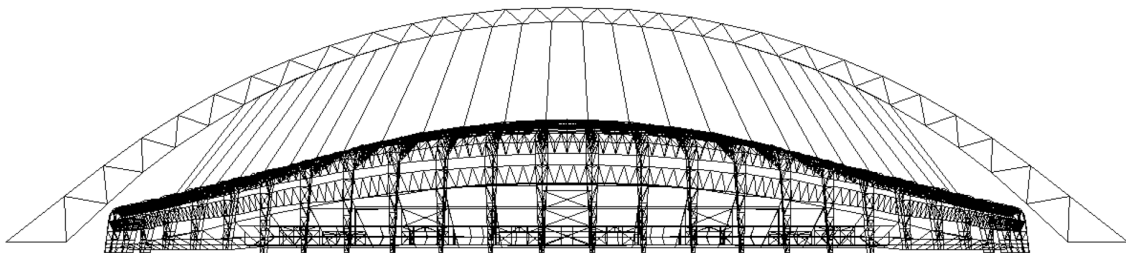


Fig. 6. General views of the model for finite element analysis: plane (a); side view (b)

The visual analysis of polynomial functions (Fig. 7) and a review of the obtained results point to some interesting features of the algorithm. First, the enveloped selection results of aerodynamic coefficients are different in all cases but most in a case of the completely stretched tent. Second, the biggest differences between individual experimental measurements and generalized data appear on the top part of the tent. Third, the selection procedure plays a very important role in the presented algorithm because of reviewing all values that can be different in the nearest zones. Fourth, in case of open space over the arena the general form of the coefficient curves and polynomial functions are the same. Some differences appear in case of a half-rolled tent, more valuable – while the

tent is fully stretched. Such analysis shows that the tent area could be divided by finite elements more precisely because of its important influence. To say once more about an important feature – differences between experimental selection and polynomial curves are valuable in a case of the biggest absolute values of aerodynamic coefficients important for a transversal direction of the wind (across the arch and nearly along the commented highest frame). On the top of the facility near the arch the coefficient values are evaluated from -0.6 to -1.1 enough slowly, whereas on the external edge the process takes place quickly: -0.6 for wind direction 0° , -1.6 for 45° and -2.6 for 90° .

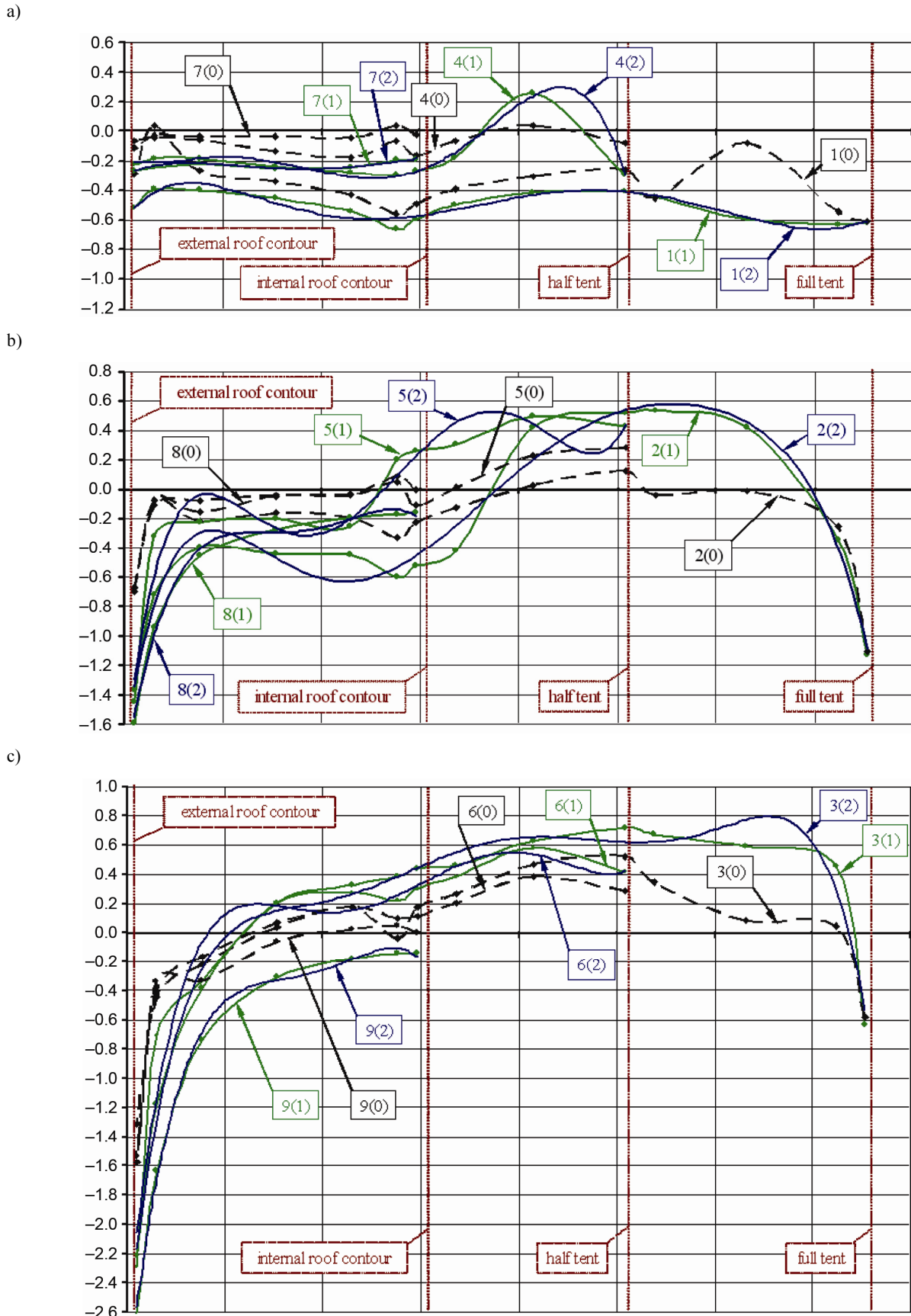


Fig. 7. The distribution of aerodynamic coefficients (on the ordinate) along the highest transversal frame line on the roof and tent (sheets (a), (b) and (c) respectively 0°, 36° and 90° angles): 1, 2, 3 – the tent is stretched completely; 4, 5, 6 – the tent is half-stretched; 7, 8, 9 – without the tent. Curves: (0) – experimental; (1) – during selection; (2) – polynomial

Table 6. Relative (to average) load values of the roof

No.	Roof relative load values, while curve No. (Fig. 7)					
	1	2	3	4	5	7
1	-0.949	-2.289	-4.475	-0.377	-2.417	-0.500
2	-0.687	-1.132	-1.950	-0.365	-0.270	-0.407
3	-0.673	-0.748	-0.665	-0.327	-0.208	-0.398
4	-0.726	-0.645	0.076	-0.317	-0.445	-0.409
5	-0.789	-0.662	0.491	-0.336	-0.605	-0.420
6	-0.841	-0.719	0.713	-0.370	-0.628	-0.422
7	-0.877	-0.777	0.823	-0.407	-0.549	-0.416
8	-0.897	-0.822	0.868	-0.440	-0.417	-0.403
9	-0.902	-0.850	0.875	-0.464	-0.239	-0.380
10	-0.893	-0.854	0.859	-0.474	-0.046	-0.351
11	-0.873	-0.832	0.832	-0.464	0.108	-0.321
12	-0.848	-0.793	0.805	-0.439	0.222	-0.295
13	-0.822	-0.746	0.781	-0.404	0.302	-0.272
14	-0.795	-0.692	0.762	-0.363	0.359	-0.253
15	-1.296	-0.319	1.217	0.139	1.109	-
16	-1.142	0.930	1.617	-0.071	1.250	-
17	-1.319	1.388	1.945	-	-	-
18	-1.587	-0.116	1.071	-	-	-

The presented algorithm shows a good agreement on the area of the roof over spectators' stands. Therefore, the tent area should be more exactly investigated.

Some individual elective results of wind load distribution along the highest frame axis (Fig. 8) show that the tent surface is more valuable in comparison with the surface of the whole façade. It is important that the tent area is acted by more strong wind. On the other hand, the strongest wind effect is available in winter when using the tent is not allowed according to operation require-

ments for the building. Moreover, tent maintenance during windless time is strongly recommended. Generally, the process of using the tent is manually managed, thus it can be artificially regulated. In case of such assumptions, the above described simulation of the wind action seems correct.

The sequence of calculations shows (Fig. 9) that the proposed algorithm is complicated enough because of a huge volume of data and many different steps that cannot be logically eliminated.

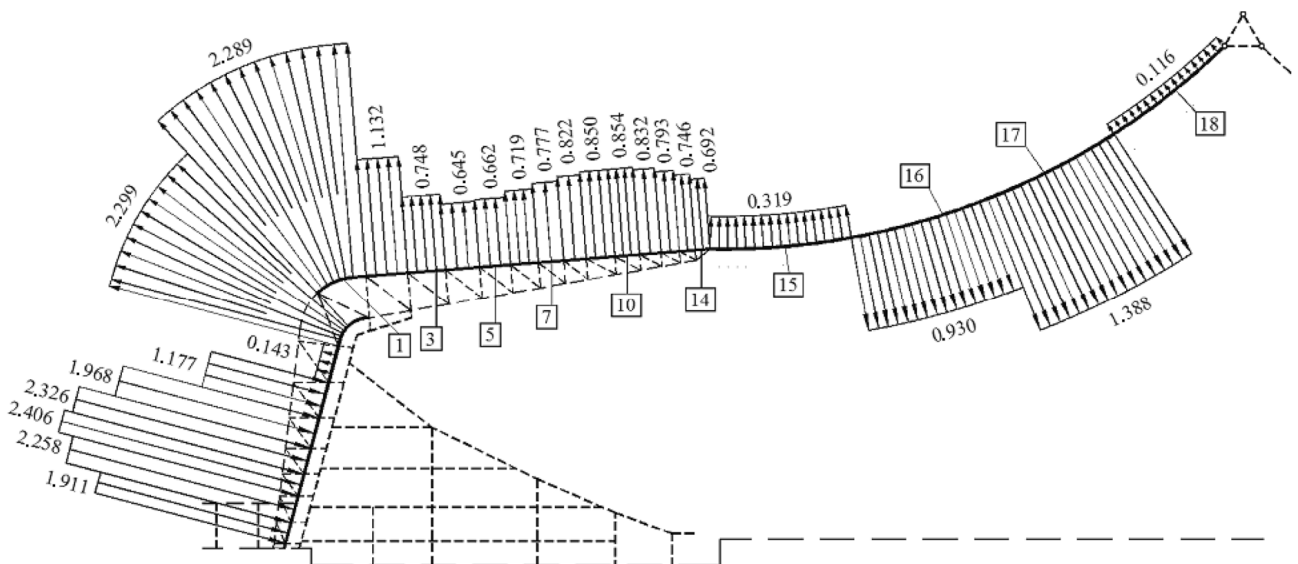


Fig. 8. The final distribution of relative wind load along the axis of the highest frame of the facility when the tent is stretched completely at the wind direction angle of 36°

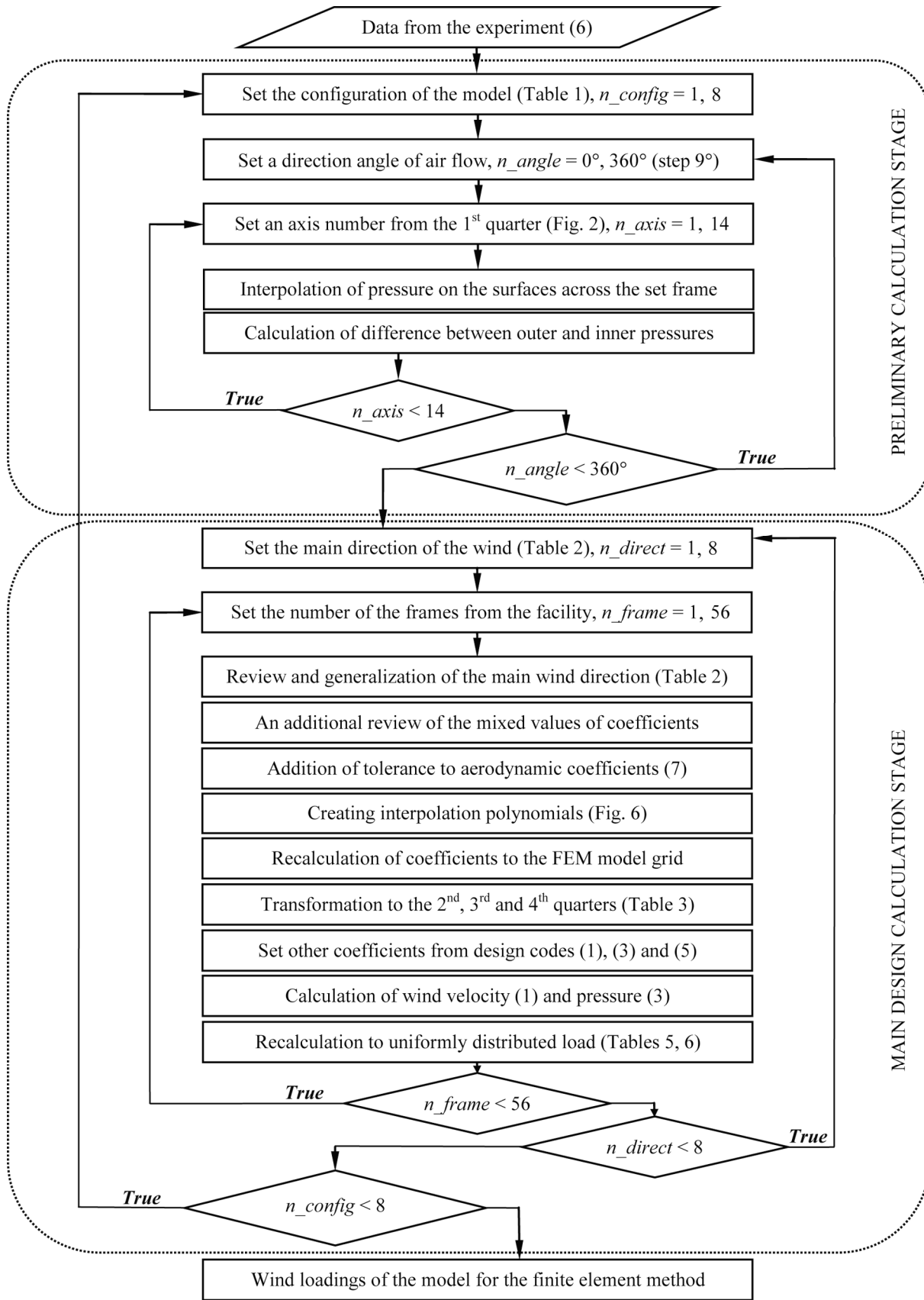


Fig. 9. A general algorithm for recalculating experimental data to wind design loadings for the FEM model

5. Final conclusions and recommendations

During the transformation of experimental data on the facility from the aerodynamic tunnel to the loadings of the finite element model, the following conclusions are made:

1. The investigated facility is of an untypical shape, thus, the presented algorithm, engineering assumptions and experience in the analysis of results should be taken into account while designing other buildings of original shapes.

2. For facilities of untypical shapes, an original designing sequence based on aerodynamic investigations (STR 2.05.04 2003; Simiu and Scanlan 1986; Барштейн 1978) is recommended.

3. Extreme zones on the roof and tent edges should be more exactly investigated because of the functional “jumps” of aerodynamic coefficient distribution. Similar features can put some additions to the presented algorithm.

4. Dividing selection sectors is based only on engineering assumptions. This question should be additionally analysed using some reviewed steps of coefficient distribution through the whole effected surface.

5. Working towards a solution to a complex engineering problem, scientific support provided by technical universities, scientific organizations and well known competent design institutions should be used. Such kind of experience is successfully applied abroad (ДБН В.1.2–5 2007; МРДС 02–08 2008).

6. Creating a new algorithm does not completely exclude an alternative solution. Therefore, it is necessary to improve management in designing providing for alternative simulation employing other methodology (ДБН В.2.2–24 2009), for example, virtual aerodynamic modelling.

7. The distribution of real wind load on the surfaces of huge volume and light facilities is a very important factor for bridge stress/strain state (Grigorjeva et al. 2010) and for solutions to structural optimization when elastic and plastic deformation (Jankovski and Atkočiūnas 2010, 2011) could be analyzed.

Acknowledgement

The authors appreciate help and assistance provided by Vilnius municipality administration and specialists who participated in designing the given opportunity to familiarize the engineers of Lithuania and other countries with scientific principles of this research.

References

- Grigorjeva, T.; Juozapaitis, A.; Kamaitis, Z. 2010. Static analysis and simplified design of suspension bridges having various rigidity of cables, *Journal of Civil Engineering and Management* 16(3): 363–371. doi:10.3846/jcem.2010.41
- Holmes, J. D. 2007. *Wind Loading of Structures*. 2nd ed. Spon Press. 379 p.
- Jankovski, V.; Atkočiūnas, J. 2010. SAOSYS Toolbox as MATLAB implementation in the elastic-plastic analysis and optimal design of steel frame structures, *Journal of Civil Engineering and Management* 16(1): 103–121. doi:10.3846/jcem.2010.10
- Jankovski, V.; Atkočiūnas, J. 2011. Biparametric shakedown design of steel frame structures, *Mechanika* 17(1): 5–12.
- LST EN 1990. *Eurokodas. Konstrukcijų projektavimo pagrindai* [Eurocode. Basis of Structural Design]. Vilnius, 2004. 71 p.
- LST EN 1991. *Eurokodas I. Poveikiai konstrukcijoms* [Eurocode 1. Actions on Structures]. Vilnius, 2005. 34 p.
- Nasvytis, A.; Krištapavičius, R.; Stasėnas, R. ir kt. 2007. *Lietuvos vardo tūkstantmečio Nacionalinis stadionas Vilniuje. Techninio projekto architektūrinė dalis* [National Stadium in Vilnius Named after One Thousand Years of Lithuania. Basic Design. Architectural Chapter]. Vilnius: Viltakta. 135 p.
- RSN 156–94. *Statybinė klimatologija* [Climatology for Civil Engineering]. Vilnius, 1995. 136 p.
- Samofalov, M.; Cvirka, V. 2010. Mechanical state analysis and an original sequence of calculations of a huge bay arch under static and dynamic actions, in *Proc. of the 10th International Conference MBMST*, Vilnius, Lithuania, 19–21 May, 2010. Vilnius: Technika, 2: 1045–1054.
- Samofalov, M.; Pavlovsky, R. M.; Popov, V.; Lebedich, I. M. 2008. Experimental aerodynamic investigation of shape properties of National stadium in Vilnius, in *Proc. of the 13th International Conference “Mechanika 2008”*, Kaunas, Lithuania, 3–4 April, 2008. Kaunas: Technologija, 456–461.
- STR 2.05.03. *Statybinių konstrukcijų projektavimo pagrindai* [Basis of Structural Design]. Vilnius, 2003.
- STR 2.05.04. *Poveikiai ir apkrovos* [Actions and Loads]. Vilnius, 2003.
- Simiu, E.; Scanlan, R. H. 1986. *Wind Effects on Structures: An Introduction to Wind Engineering*. 2nd ed. John Wiley & Sons. 598 p.
- Simiu, E.; Scanlan, R. H. 1996. *Wind Effects on Structures: Fundamentals and Applications to Design*. 3rd ed. John Wiley & Sons. 688 p.
- Барштейн, М. Ф. 1978. *Руководство по расчёту зданий и сооружений на действие ветра* [Barshtein, M. Ph. Manual of Building and Facility Calculation on Wind Action]. Москва: Стройиздат. 216 с.
- Горлин, С. М.; Слезингер, И. И. 1969. *Аэромеханические измерения. Методы и инструменты* [Gorlin, S. M.; Slezinger, I. I. Aeromechanical Measurements. Methods and Instruments]. Москва: Наука. 720 с.
- ГОСТ 8.207–76. *Прямые измерения с многократными наблюдениями. Методы обработки результатов наблюдений. Основные положения* [Direct Measurements with Multiple Observations. Methods of Processing the Results of Observations. Basic principles]. Москва: ИПК Издательство стандартов, 1976. 7 с.
- ДБН В.1.2–5:2007. *Науково-технічний супровід будівельних об'єктів* [Scientific–Technical Support for Civil Engineering Buildings]. Київ: Мінрегіонбуд України, 2007. 16 с.
- ДБН В.2.2–24:2009. *Проектування висотних житлових і громадських будинків* [Designing of High-rise Residential Buildings of Public Buildings]. Київ: Мінрегіонбуд України, 2009. 133 с.

- Египко, В. М.; Зинченко, В. П.; Белоусов, Б. Н.; Горин, Ф. Н. 1992. Системы автоматизации экспериментальных исследований в аэродинамических трубах [Egipko, V. M. *et al.* Automation Systems for Experimental Investigations in Aerodynamic Tunnels]. Киев: Наукова Думка. 264 с.
- Кузнецов, С. Г. 2009. Испытание высотных зданий в аэродинамической трубе с атмосферным приземным пограничным слоем [Kuznecov, S. G. High-rise building testing in the wind tunnel with an atmospheric surface boundary], *Металлические конструкции* [Metal designs] 15(1): 85–91.
- Кузнецов, С. Г.; Назаров, Г. А.; Лозинский, Э. А. 2010. Изменения статических ветровых нагрузок на здания под воздействием ветровых волн [Kuznecov, S. G. *et al.* Changes of static wind loadings on buildings under the influence of wind waves], *Современное промышленное и гражданское строительство* [Modern industrial and civil building] 6(1): 51–59.
- Лебедич, И. Н.; Павловский, Р. Н.; Жданов, А. И. 2007. Исследование аэродинамических особенностей навеса над зрительскими трибунами стадиона ФК ДНЕПР в городе Днепропетровске [Lebedich, I. N. *et al.* Analysis of aerodynamic features of the over-stand roof in Dnepropetrovsk FC “Dnipro” stadium], *Металлические конструкции* [Metal designs] 13(2): 65–78.
- МРДС 02–08. *Пособие по научно-техническому сопровождению и мониторингу строящихся зданий и сооружений, в том числе большепролетных, высотных и уникальных* [Handbook of Scientific–Technical Support and Monitoring of Buildings and Facilities Including Big-span, Big-height and Unique Buildings]. Москва: Госстрой, 2008. 121 p.
- Новицкий, П. В.; Зорграф, И. А. 1991. Оценка погрешностей результатов измерений [Novickij, P. V.; Zorgraph, I. A. Estimation of Errors of the Measurements Results]. 2-е изд. Ленинград: Энергоатомиздат. 304 с.
- Павловский, Р. Н. и др. 2007. *Комплексные аэродинамические исследования влияния ветра и аэрационного режима на модели Национального стадиона в г. Вильнюсе. Литовская Республика. Технический отчет* [Pavlovskij, R. N. *et al.* Complex Aerodynamic Investigation of Wind Influence and Aero-regime on the Model of National Stadium in Vilnius. Lithuanian Republic. Technical Report]. Киев: Лаборатория аэродин. исп. НАУ. 58 p.
- Павловский, Р. Н.; Кузнецов, С. Г. 2009. Моделирование приземного пограничного слоя атмосферы в аэродинамических трубах с короткой рабочей частью [Pavlovskij, R. N.; Kuznecov, S. G. Modelling of atmospheric ground boundary layer in short air dynamic tubes wind tunnels], *Современное промышленное и гражданское строительство* [Modern industrial and civil building] 5(1): 15–22.
- СНУП 2.01.07–85. *Нагрузки и воздействия* [Loads and Actions]. Москва: ЦИТП Госстроя СССР, 1987. 36 с.

AERODINAMINIO BANDYMO DUOMENŲ PERSKAIČIAVIMO Į VĖJO POVEIKIO APKROVŲ ATMAINAS ALGORITMO ESMĖ

M. Samofalov, A. Kazakov, R. M. Pavlovsky

Santrauka

Straipsnyje nagrinėjamas laboratorinio bandymo rezultatų apdorojimo algoritmas, kai aerodinaminiam tunelyje gauti eksperimentiniai duomenys apie oro slėgio pasiskirstymą ant pastato maketo paviršių perskaičiuojami į vėjo apkrovas, reikalingas baigtinių elementų metodo virtualiajam modeliui skaičiuoti. Duomenų perkėlimo uždavinys yra aktualus, nes laboratorinių tyrimų metodika ir priemonės iš esmės skiriasi nuo skaitinio modeliavimo baigtiniais elementais eigos ir principų, kai atsižvelgiama į realiai projektuojamo statinio vietovės klimatologines sąlygas ir galiojančių projektavimo normų reikalavimus. Straipsnyje apžvelgta eksperimento duomenų apdorojimo problematika, nagrinėjama konkretaus statinio konstrukcijų skaičiavimo situacija, aptarti pagrindiniai laboratorinio aerodinaminio bandymo principai, paaiškintas duomenų perkėlimo inžinerinis algoritmas bei esminės prielaidos, pasirinktinai pateikti rezultatai uždavinio sprendimui vaizduoti. Baigiamosios išvados ir siūlymai padės rasti tinkamiausią sprendinį kuriant panašaus pobūdžio algoritmus.

Reikšminiai žodžiai: perskaičiavimo algoritmas, vėjo inžinerija, sudėtingas statinys, aerodinaminiai bandymai, baigtinių elementų metodas.

Michail SAMOFALOV. A lecturer at the Department of Strength of Materials, Vilnius Gediminas Technical University (VGTU), Lithuania. BSc in civil engineering, 1995. MSc in informatics, 1997. PhD in mechanics, 2002 at VGTU. A certificated structural designer and expert in civil, industry and bridge engineering of Lithuanian Ministry of Environment. Research interests: structural designing of complex buildings, numerical simulation, non-linear structural analysis, management and examination of design solutions.

Artur KAZAKOV. BSc in civil engineering, 2005. MSc in civil engineering, 2007. PhD student of civil engineering at Vilnius Gediminas Technical University, Lithuania. Research interests: inspection of building sites, aerodynamic tests, numerical simulation on airflow.

Roman M. PAVLOVSKY. Assoc. Prof., PhD. A scientific researcher at Ukrainian National Aviation University, Aero-Cosmic Institute, Laboratory of Aerodynamic Investigations, Ukraine. Research interests: general and local aerodynamics, aerodynamic tests in airplane and car engineering, civil engineering.

