




## Research Article

# Wind loads on girder bridges

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## ABSTRACT

Bridges are facilities that are in exploitation outdoor. Often the wind is the leading horizontal force in the transverse direction. Therefore the bridges have received the due attention in the standards for wind loading. Unfortunately, in all available standards for wind load on the bridges, one, summarized value of the aerodynamic coefficient is indicated. It is related to the entire cross-section of the facility. There is no differentiation for the individual longitudinal girders and/or roadway. Information about the specific wind pressure on each of the bridge's element is required for the correct design of their supporting systems, whether they are framed or braced type. To fill this gap, the author has built several models of bridges with longitudinal girders, using a Computational Fluid Dynamics (CFD) analysis. Through them he determined the values of the aerodynamic coefficients for each of the bridge girders under the roadway and the cross-section of the bridge as a whole. Conclusions are summarized and the results clearly show the values of the aerodynamic coefficients for the whole section of the bridge are with 50-60% lower than the ones reported for the windward girder.

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## 1. Introduction

Bridges are facilities that are in exploitation outdoor. Often the wind is the leading horizontal force in the transverse direction. Therefore in the following standards for loading on bridges AS/NZS 1170.2 (2011), BS 5400-2 (2006), EN 1991-1-4 (2005), IRC: 6-2017 (2017), Standards for Design of Road and Railway Bridges and Culverts (SDRRBC) (1989) and CII 35.13330.2011 (2011), the bridges have received due attention for wind impact. To increase the safety, the values of aerodynamic coefficients, specified in these standards, have been increased several times in comparison to those for buildings. However, the presented aerodynamic coefficients in the aforementioned standards are applicable to the entire sections of the bridges only. There is no separation and additional data by elements. Only in standard BS 5400-2 (2006) is written that the aerodynamic coefficient for assembled girders is 2.2, without taking into account any sheltering effect. Information about the wind load on each of the girders is required for the correct design of the supporting systems.

One possible approach is to determine the aerodynamic coefficient for the whole section of the bridge and to use it separately for each of its elements. Another possible solution would be to look for some analogy with known facilities, such as long buildings or walls. But which of these approaches would produce more reliable results? And are they even close to the real wind load on bridges? To answer these questions, the author has built and researched several models of girder bridges, using Computational Fluid Dynamics (CFD) analysis. Based on these models, he determined the values of the aerodynamic coefficients for each one longitudinal girder under the roadway and for the cross-section of the bridge as a whole.

## 2. Model Description

Computational Fluid Dynamics (CFD) analysis is selected as a suitable approach to be used in the present study. Through the graphical interface Workbench of ANSYS (2020) and its module Fluid Flow (CFX) have

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been created two general spatial models of bridge structures. In the first model the girders are with a rectangular cross section, by reinforced concrete. In the second model the girders are made of steel sheets. The height of all beams is 1,000 mm. The reinforced concrete beams are 400 mm wide, the steel ones - as is shown in Fig. 1b. Reinforced concrete slab with a thickness of 200 mm is placed above the girders there, see Fig. 1.

To increase the scope and usefulness of the study, the following sub-models have been created:

- a) the number of beams under the slab  $n = 2, 3$  and  $4$ ;
- b) the distance between the beams  $x = 1, 2, 3, 4$  and  $5$  m.

A spatial analysis is used in this paper. A typical cross-section of the bridge's structure is modelled in 2D and then extruded into a 6 m depth making an overall domain shape of a parallelepiped. Around the bridge structures are created box enclosure, see Fig. 3. The walls of the simulated wind tunnel around each bridge section are located at the following distances from them:

- a) for bridges with two or three girders:
  - fluid inlet - 5 m;
  - fluid outlet - at 20 m, i.e. the body of the bridge is located much closer to the inlet of the wind tunnel, see Fig. 2;

- vertical sidewalls - as the "Symmetry" option is used, there is no distance between the walls and the cross-section of the bridge;

- horizontal walls (bottom and roof) - 10 m.

b) for bridges with four girders:

- fluid inlet - at 8 m;

- fluid outlet - at 32 m;

- vertical sidewalls - as the "Symmetry" option is used, there is no distance between them and the cross-section of the bridge;

- horizontal walls (bottom and roof) - 16 m.

The determining of the above-written distances between the walls of the virtual wind tunnel and bridge is based on the principle that airflow adjacent to the bridge should not be affected, see Rusev et al. (2012a). Accepted distances are bigger than requirements of Tominaga et al. (2008), as follow:

- the top / bottom boundary should be set  $5H$  or more away the obstacle, where  $H$  is the height of the bridge section in the current research ( $H = d = 1,200$  mm, see Fig. 1);

- the outflow boundary should be set at least  $10H$  behind the obstacle.

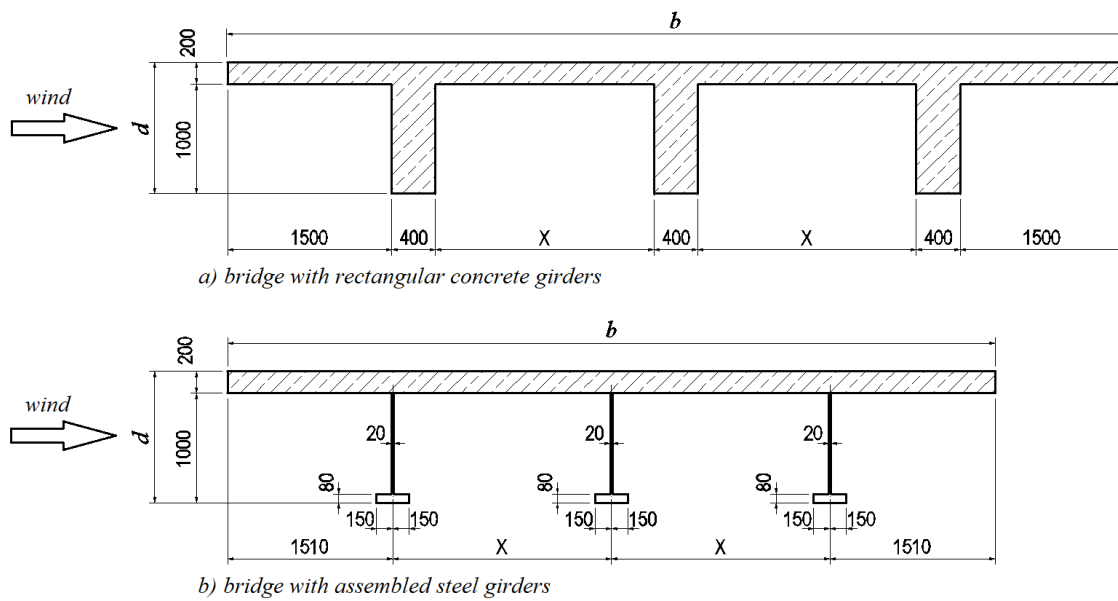


Fig. 1. Cross-sections of the researched bridges.

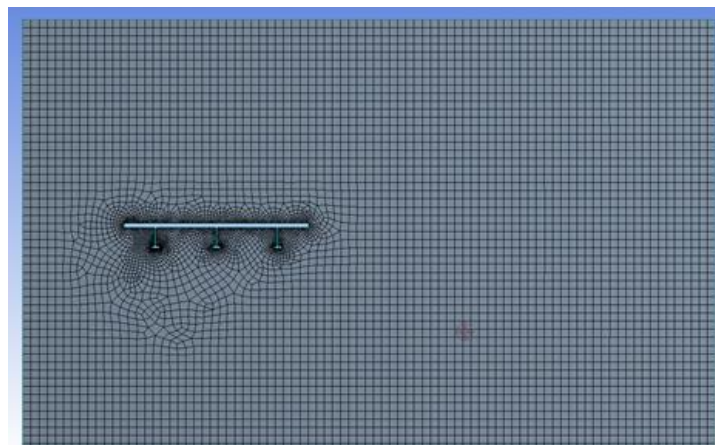
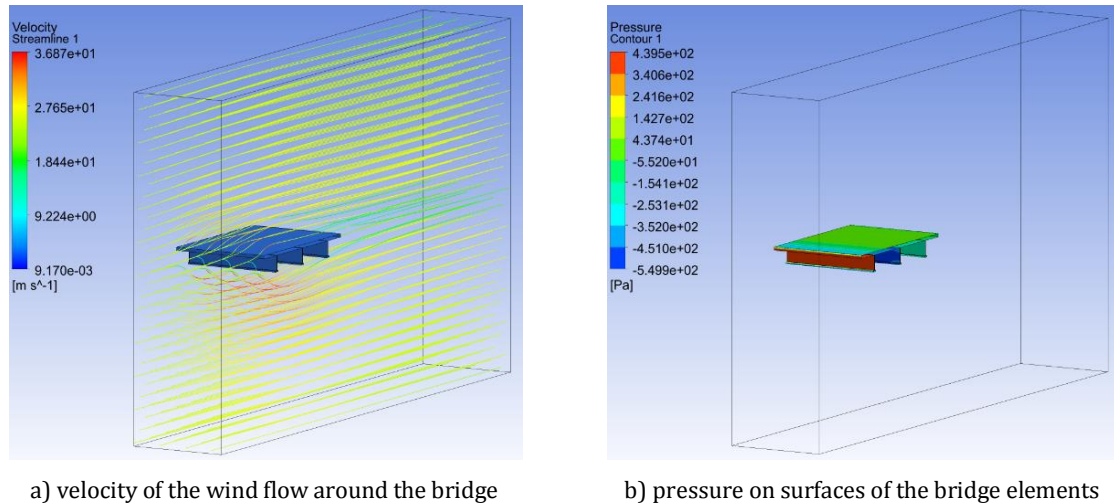


Fig. 2. Mesh refinement of the elements around the bridge.



**Fig. 3.** Wind flow around the bridge and the resulting pressure on the elements.

At the same time, to avoid heavy computer solutions and save computational time, the maximum number of finite elements is maintained into reasonable limits. To optimize their mesh, it is significantly refined in the area around the bridge, see Fig. 2, and is sparse to the periphery, as is done in Rusev et al. (2012b). The maximum size of the finite elements of the air is limited to:

- elements in direct contact with the slab and girders - 50 mm;
- all other elements - 400 mm.

Another model with a denser mesh is created to check the sufficiency of the accepted mesh sizes. The maximum sizes of the finite elements there are twice as small as is written above – 25 mm for elements in direct contact and 200 mm for all other elements. The differences in resulting forces  $F_{x,i}$  in the girders and the total aerodynamic coefficients  $C_{cp,x}$  are less than 6%, i.e. accepted mesh has a good density.

When creating the mesh of finite elements, the “Quadratic” option is used, as a result of which the nodes in the middle of their sides are preserved. This type of element is characterized by its nonlinear deformation behaviour.

Steady state analysis type is used in a Fluid flow (CFX) module. K- $\epsilon$  model, part of Reynolds-averaged Navier Stokes (RANS) family, is used to simulate the turbulent flow of the fluid around the bridges. These RANS equations are an adequate representation of the wind tunnel's reality, Baklanov et al. (2007). Accepted turbulence has a medium (5%) intensity. No combustion and thermal radiation. The used fluid is an air ideal gas with a temperature of 25 °C. Its speed at the inlet domain of the tunnel is constant in height and has a value of  $v = 25$  m/s. Flow regimes in outlet and opening domains are subsonic, with a relative pressure 0 Pa. Flow direction is normal to boundary conditions. Bridge section domain is no slip rough wall.

Unlike of the research of Mei Yu et al. (2011), there main wind flow is horizontal, i.e. the angle of attack is 0°. The direction of the approaching wind is perpendicular to the longitudinal axes of the bridge girders and deck.

The models of the bridge with rectangular reinforced concrete beams, see Fig. 1a, have roughness with a high of 0.5 mm on all surfaces. Models with steel girders, see

Fig. 1b, have roughness with a height of 0.1 mm on all surfaces. The surface of the terrain under the bridge is perfectly smooth.

During its movement, the wind flows around the bridge, see Fig. 3a, which leads to the appearance of pressure on its elements, see Fig. 3b. As a result, generated in the bridge girders forces could be accounted for. Knowing the value of forces and area of the girders, the value of the total (whole) wind pressure on the girders can be determined by the formula:

$$q_{cp,x} = \frac{F_{x,i}}{A_g} \quad (1)$$

where  $q_{cp,x}$  is the total (whole) pressure on the  $i$ -th bridge girder. It is equal to the sum of the conditionally positive (compression) and negative (suction) pressure on the girder;  $F_{x,i}$  - the value of the accounted force on the  $i$ -th girder in the direction of the horizontal wind flow;  $A_g$  - the area of the  $i$ -th girder, transverse to the wind flow.

Reference mean (basic) velocity pressure  $q_b$  could be determined by the written in EN 1991-1-4 (2005) formula:

$$q_b = \frac{1}{2} \rho v_b^2 = \frac{1}{2} \cdot 1.25 \cdot 25^2 = 390 \text{ N/mm}^2 \quad (2)$$

where  $\rho = 1.25$  kg/m<sup>3</sup> is the air density;  $v_b = 25$  m/s – accepted wind speed in the current research.

The ratio of the total pressure  $q_{cp,x}$  on the girders and the reference mean pressure  $q_b$  give us information about the value of the total aerodynamic coefficient  $C_{cp,x}$  of the girders, i.e.:

$$C_{cp,x} = \frac{q_{cp,x}}{q_b} \quad (3)$$

### 3. Results

The values of the aerodynamic coefficients  $C_{cp,x}$  for wind load in the horizontal plane, obtained by equations (1-3) are shown in:

- Tables 1-3 for a bridge with rectangular reinforced concrete girders;
- Tables 4-6 for a bridge with assembled steel girders.

**Table 1.** Total aerodynamic coefficient  $C_{cp,x}$  for wind pressure on the elements of a bridge with two rectangular reinforced concrete beams.

$x, m$	1	2	3	4	5
$b, m$	4.8	5.8	6.8	7.8	8.8
$b/d$	4.0	4.833	5.667	6.5	7.333
$C_{cp,x,L}$	1.615	1.606	1.673	1.708	1.713
$C_{cp,x,R}$	-0.237	-0.309	-0.49	-0.65	-0.578
$C_{cp,x,tot}$	1.321	1.261	1.164	1.054	1.106

$x$  - "clear" distance between the rectangular girders, see Fig. 1a  
 $b$  - entire width of the bridge section  
 $d = 1.2 m$  - the entire height of the cross-section of the bridge  
 $C_{cp,x,L}$  - total aerodynamic coefficient for the windward (left in this case) girder  
 $C_{cp,x,R}$  - total aerodynamic coefficient for the leeward (right here) girder  
 $C_{cp,x,tot}$  - total aerodynamic coefficient for the whole section of the bridge

**Table 2.** Total aerodynamic coefficient  $C_{cp,x}$  for wind pressure on the elements of a bridge with three rectangular reinforced concrete beams.

$x, m$	1	2	3	4	5
$b, m$	6.2	8.2	10.2	12.2	14.2
$b/d$	5.167	6.833	8.5	10.167	11.833
$C_{cp,x,L}$	1.676	1.785	1.793	1.705	1.676
$C_{cp,x,m}$	-0.1573	-0.346	-0.482	-0.478	-0.533
$C_{cp,x,R}$	-0.205	-0.374	-0.340	-0.1209	0.1491
$C_{cp,x,tot}$	1.274	1.06	0.975	1.067	1.248

$C_{cp,x,m}$  - total aerodynamic coefficient for the middle girder

**Table 3.** Total aerodynamic coefficient  $C_{cp,x}$  for wind pressure on the elements of a bridge with four rectangular reinforced concrete beams.

$x, m$	1	2	3	4	5
$b, m$	7.6	10.6	13.6	16.6	19.6
$b/d$	6.333	8.833	11.333	13.833	16.333
$C_{cp,x,L}$	1.547	1.675	1.603	1.570	1.501
$C_{cp,x,m,L}$	-0.076	-0.241	-0.268	-0.729	-0.498
$C_{cp,x,m,R}$	-0.174	-0.389	-0.455	-0.001	-0.013
$C_{cp,x,R}$	-0.174	-0.129	0.076	0.244	0.302
$C_{cp,x,tot}$	1.099	0.921	0.950	1.069	1.251

$C_{cp,x,m,L}$  - total aerodynamic coefficient for the left internal girder, in the direction of the wind flow  
 $C_{cp,x,m,R}$  - total aerodynamic coefficient for the right internal girder

**Table 4.** Total aerodynamic coefficient  $C_{cp,x}$  for wind pressure on the elements of a bridge with two steel girders.

$x, m$	1	2	3	4	5
$b, m$	4.02	5.02	6.02	7.02	8.02
$b/d$	3.350	4.183	5.017	5.850	6.683
$C_{cp,x,L}$	1.610	1.664	1.773	1.803	1.798
$C_{cp,x,R}$	-0.086	-0.226	-0.560	-0.667	-0.683
$C_{cp,x,tot}$	1.422	1.372	1.160	1.078	1.090

$x$  - axial distance between the steel girders, see Fig. 1b

**Table 5.** Total aerodynamic coefficient  $C_{cp,x}$  for wind pressure on the elements of a bridge with three steel girders.

$x, m$	1	2	3	4	5
$b, m$	5.02	7.02	9.02	11.02	13.02
$b/d$	4.183	5.850	7.517	9.183	10.850
$C_{cp,x,L}$	1.632	1.832	1.929	1.844	1.795
$C_{cp,x,m}$	-0.041	-0.274	-0.672	-0.565	-0.512
$C_{cp,x,R}$	-0.133	-0.325	-0.308	-0.211	0.026
$C_{cp,x,tot}$	1.387	1.201	0.953	1.054	1.257

**Table 6.** Total aerodynamic coefficient  $C_{cp,x}$  for wind pressure on the elements of a bridge with four steel girders.

$x, m$	1	2	3	4	5
$b, m$	6.02	9.02	12.02	15.02	18.02
$b/d$	5.017	7.517	10.017	12.517	15.017
$C_{cp,x,L}$	1.573	1.729	1.749	1.648	1.572
$C_{cp,x,m,L}$	-0.066	-0.153	-0.645	-0.623	-0.412
$C_{cp,x,m,R}$	-0.109	-0.266	-0.224	-0.103	-0.147
$C_{cp,x,R}$	-0.156	-0.293	0.077	0.194	0.262
$C_{cp,x,tot}$	1.189	1.002	0.953	1.089	1.230

When the value of the aerodynamic coefficient  $C_{cp,x}$  is positive, it means that the equivalent force  $F_{x,i}$  on the corresponding girder has the same direction of action as the wind flow. When  $C_{cp,x}$  has a negative value, it means that the equivalent force  $F_{x,i}$  has a direction of action opposite to the wind flow.

The change in the values of the aerodynamic coefficients  $C_{cp,x}$ , depending on the ratio  $b/d$ , is graphically shown in Fig. 4. Here it is noticeable that the equal force on the windward girders (left in these models) always has a direction coinciding with that of the wind flow. As a result, only positive values of the aerodynamic coefficient were accounted for, which are in the range  $C_{cp,x,L} = 1.5-1.93$ . They are smaller than the value of the coefficient  $C_{cp,x} = 2.2$ , specified in BS 5400-2 (2006), but bigger than the shown by Wassef (2016) value  $C_{cp,x} = 1.3$ .

The equivalent force on the leeward girders (right in this case) can have a direction that is the same or oppo-

site to that of the wind flow. The accounted values of the aerodynamic coefficient are in the range  $C_{cp,x,R} = -0.68 \div 0.3$ .

The forces on the inner girders are always in the opposite direction to the wind flow. The reported values of the aerodynamic coefficient are  $C_{cp,x,m} = -0.73-0$ .

The accounted values of the aerodynamic coefficient for the whole section of the bridge are only positive and are in the range  $C_{cp,x,tot} = 0.92-1.4$ , i.e. they are smaller than the accounted for the windward girders.

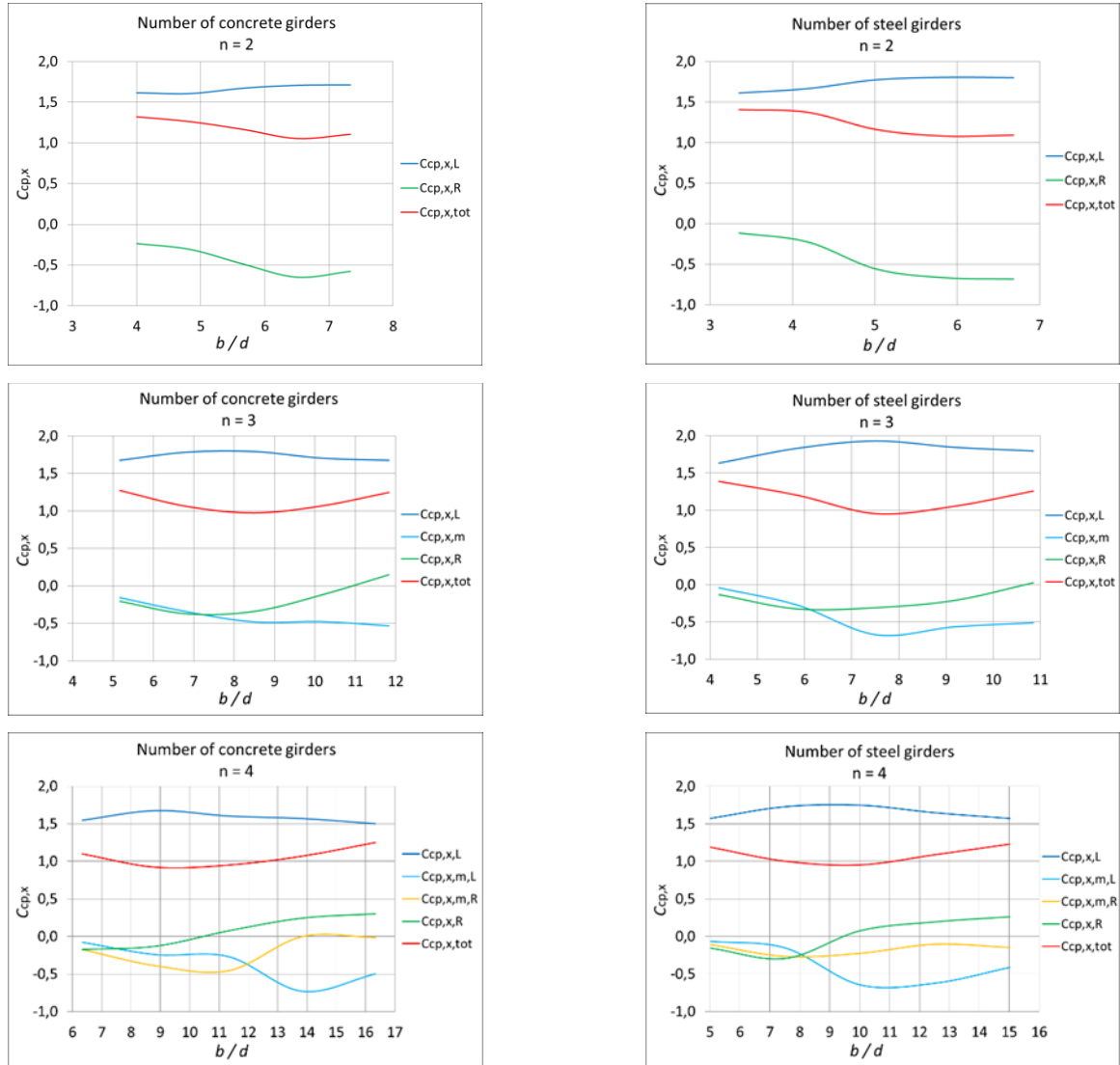
The vertical force  $F_{z,tot}$ , which acts on the entire section of the bridge, was also taken into account in the study. Using the formulas (1-3), adapted for the vertical projection of the bridge, are determined the values of the generalized aerodynamic coefficients  $C_{cp,z,tot}$  for the wind load in the vertical plane. They are shown in:

- a) Tables 7-9 for a bridge with rectangular reinforced concrete beams;
- b) Tables 10-12 for a bridge with assembled steel beams.

**Table 7.** Total aerodynamic coefficient  $C_{cp,z,tot}$  for wind pressure on the elements of a bridge with two rectangular reinforced concrete girders.

$x, m$	1	2	3	4	5
$b, m$	4.8	5.8	6.8	7.8	8.8
$b/d$	4.0	4.833	5.667	6.50	7.333
$F_{z,tot}, kN$	8.033	5.991	2.910	-1.085	-4.681
$C_{cp,z,tot}$	0.715	0.441	0.183	-0.059	-0.227

$F_{z,tot}$  - vertical force, generated by the wind flow acting on the whole section of the bridge;  
 $C_{cp,z,tot}$  - total aerodynamic coefficient in the vertical plane for the whole section of the bridge



a) for rectangular concrete girders

b) for steel girders

**Fig. 4.** Values of the coefficient  $C_{cp,x}$  in relation with the ratio  $b/d$ .

**Table 8.** Total aerodynamic coefficient  $C_{cp,z,tot}$  for wind pressure on the elements of a bridge with three rectangular reinforced concrete girders.

$x, m$	1	2	3	4	5
$x, m$	1	2	3	4	5
$b, m$	6.20	8.20	10.20	12.20	14.20
$b/d$	5.167	6.833	8.5	10.167	11.833
$F_{z,tot}, kN$	5.873	-0.514	-5.717	-7.117	-5.609

**Table 9.** Total aerodynamic coefficient  $C_{cp,z,tot}$  for wind pressure on the elements of a bridge with four rectangular reinforced concrete girders.

$x, m$	1	2	3	4	5
$b, m$	7.6	10.6	13.6	16.6	19.6
$b/d$	6.333	8.833	11.333	13.833	16.333
$F_{z,tot}, kN$	3.332	-3.846	-5.413	-1.873	-1.775
$C_{cp,z,tot}$	0.187	-0.155	-0.170	-0.048	-0.039

**Table 10.** Total aerodynamic coefficient  $C_{cp,z,tot}$  for wind pressure on the elements of a bridge with two steel girders.

$x, m$	1	2	3	4	5
$b, m$	4.02	5.02	6.02	7.02	8.02
$b/d$	3.350	4.183	5.017	5.850	6.683
$F_{z,tot}, kN$	9.702	7.472	3.170	-0.089	-4.455
$C_{cp,z,tot}$	1.031	0.636	0.225	-0.005	-0.237

**Table 11.** Total aerodynamic coefficient  $C_{cp,z,tot}$  for wind pressure on the elements of a bridge with three steel girders.

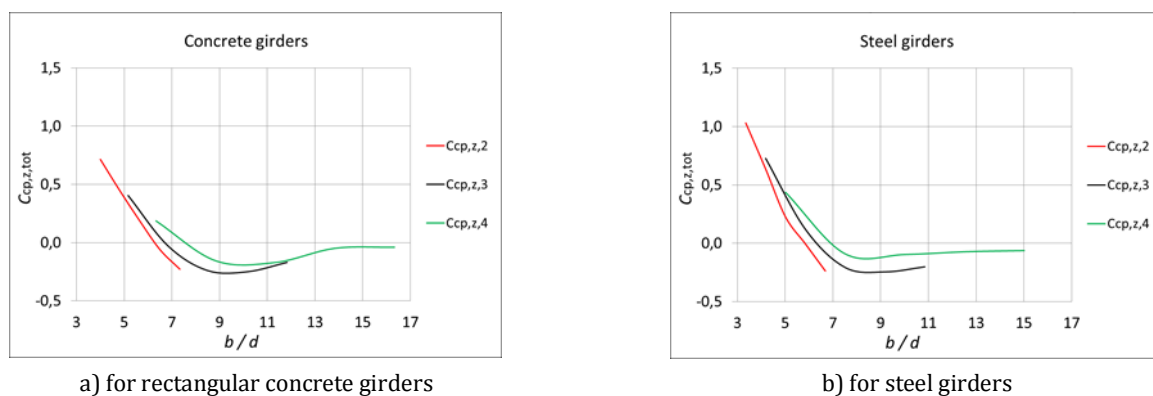
$x, m$	1	2	3	4	5
$b, m$	5.02	7.02	9.02	11.02	13.02
$b/d$	4.183	5.850	7.517	9.183	10.850
$F_{z,tot}, kN$	8.545	1.960	-4.381	-6.321	-6.129
$C_{cp,z,tot}$	0.727	0.119	-0.208	-0.245	-0.201

**Table 12.** Total aerodynamic coefficient  $C_{cp,z,tot}$  for wind pressure on the elements of a bridge with four steel girders.

$x, m$	1	2	3	4	5
$b, m$	6.02	9.02	12.02	15.02	18.02
$b/d$	5.017	7.517	10.017	12.517	15.017
$F_{z,tot}, kN$	6.148	-1.920	-2.698	-2.547	-2.623
$C_{cp,z,tot}$	0.4364	-0.0910	-0.0959	-0.0725	-0.0622

When the value of the aerodynamic coefficient  $C_{cp,z,tot}$  is positive, it means that the equivalent force  $F_{z,tot}$  on the bridge has a bottom-up direction. When  $C_{cp,z,tot}$  has a negative value, it means that the equivalent force  $F_{z,tot}$  has a top-down direction, i.e. coinciding with the gravity.

The change in the values of the aerodynamic coefficients  $C_{cp,z,tot}$ , depending on the ratio  $b/d$ , is graphically shown in Fig. 5 where  $C_{cp,z,2}$ ,  $C_{cp,z,3}$ ,  $C_{cp,z,4}$ , are the total coefficients for pressure when the number of girders under the plate is  $n = 2, 3$  and  $4$  pcs.



**Fig. 5.** Values of the coefficient  $C_{cp,z,tot}$  in relation with the ratio  $b/d$

It is noteworthy here that at small values of the ratio  $b/d$ , the equivalent vertical force  $F_{z,tot}$  acts from the bottom-up direction. The maximum value of the total aerodynamic coefficient accounted here is  $C_{cp,z,tot} = 1.1$ . At higher values of the ratio  $b/d$ , the equal vertical force  $F_{z,tot}$  acts from top to bottom, i.e. wind loads have the same direction as gravitational ones. Values of the total aerodynamic coefficient accounted here are of the order of  $C_{cp,z,tot} = -0.24$ . It can be seen that there is a difference

with the value of  $C_{cp,z,tot} = \pm 0.9$ , recommended in EN 1991-1-4 (2005).

#### 4. Conclusions

In widespread standards for loading on bridges does not exist information about wind loading on the individual elements. For their determination, through the graphical interface Workbench of ANSYS (2020) and its

module for computational fluid dynamics Fluid Flow (CFX) are researched several typical bridge sections with longitudinal girders. From the conducted study the following conclusions could be drawn:

- The windward beams are the heaviest loaded by the wind flow;
- The total load on the leeward girders may have a direction that coincides with or is opposite to that of the wind flow. The reference aerodynamic coefficients are two to three times smaller than those for the windward girders;
- The total load on the internal girders is always in the opposite direction to the wind flow;
- The reported values of the aerodynamic coefficient for the whole section of the bridges are only positive and are with 50-60% lower than the ones reported for the windward girders. And if they are used for measurement of the stabilizing elements of the girders, it would be in the direction of uncertainty;
- In addition to forces in their plane, horizontal wind flows also cause forces in the vertical direction. Which forces in narrow bridges are unloading, but in wide ones, they are superimposed with gravitational loads.

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### Conflict of Interest

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this manuscript.

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