



Получена: 13.06.2020 г.

Приета: 21.07.2020 г.

STUDY OF THE AIR PERMEABILITY OF DIFFERENT TYPES OF SAFETY NETS FOR FACADE SCAFFOLDS DURING WIND ACTIONS

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Keywords: facade scaffold, safety nets, wind action, wind tunnel

ABSTRACT

Modern trends in the construction practice imply covering of the facade scaffoldings with different types of claddings in the form of safety nets or sheets. The use of claddings, however, is associated with increasing the wind loads on the scaffold structure itself. The paper presents a methodology for evaluation of the air permeability during wind actions of safety nets used for facade scaffold coverings with wind tunnel test. The results of the test of fifteen different types of nets are presented. The obtained results are analysed and specific conclusions are drawn on the effect of the wind pressure on the safety nets as a function of the wind velocity values.

1. Introduction

Facade scaffolds combine two main functions – providing safe access to the facades at the required heights of buildings and facilities, and ensuring comfort and ergonomics during construction and installation works.

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The facade scaffolds belong to the working scaffold category which, according to the definition given in EN 12811-1, comprises temporary structures needed to provide a safe workplace for the construction process, maintenance, repair or demolition of buildings and other structures, as well as the required access for those works [1].

A number of studies in Bulgaria and other countries show that scaffolds are a dangerous source of workplace accidents [2 – 5]. Large part of the safety issues arise due to neglecting the basic requirements for erection and working on facade scaffolds [6]. One of the most common risks is related to the occurrence of physical injuries due to falling objects. For this reason and the aim for cleaner environment with lesser amount of dust, especially in urban areas, according to the requirements of the current norms and regulations, it is recommended and in some cases obligatory to install safety nets on the facade scaffolds [7].

In the structural design of the facade scaffold, the self-weight of the frame structure elements, the service loads and the wind loads should be taken into account [1]. Particular attention should be paid to wind loads, especially for covered scaffolds, which are classified as class “B” according to EN 12810-1 [8]. It is to be noted that the covering of the facade scaffold with different nets or covers leads to an increase in the internal forces in the scaffold elements. For example, when using nets with low wind permeability, the compressive forces in the vertical standards of high-rise facade scaffolds can increase by more than 35% [9]. In the design procedures, the influence of the type of facade cover is taken into account by the aerodynamic force coefficient $c_{f,i}$. For nets, the standard [1] allows the coefficient $c_{f,i}$ to be obtained from a wind tunnel test.

Research on working and facade scaffolding in Bulgaria discusses various aspects of the design and specifics of the facade scaffold structures. Basic principles and rules for design, according to European standards, are presented in [10] and [11]. The specifics of the tubular scaffolds are discussed in details in [12] and [13]. In recent years, the facade scaffolds used in Bulgarian construction practice were also analysed [14], as well as their typical configurations and assembly schemes [15]. The current trends in the use of safety nets are also analysed, including advertising networks and claddings as part of the urban interior [16]. However, there are no specific studies related to the evaluation of wind effects on the facade scaffolds, covered with different types of netting or sheeting.

The assessment of wind loads on the structural behaviour of the temporary structures is a subject of numerous studies in the world construction practice and science. Those employ numerical models [17, 18] as well as in-situ monitored scaffolds installed on real buildings [19].

The influence of the facade scaffold covers is also discussed in many scientific studies. In [20] and [21] a number of summaries of research related to wind impacts on covered facade scaffolds were made. The results of an experimental study of two types of scaffold nets are analysed and discussed in [22]. Both types have different porosity and thickness. The characteristics of wind pressure on the scaffolding for different building opening ratios, scaffolding geometries and wind directions are studied in [23] and [24]. In this researches nonporous scaffold claddings are used.

In summary of the above laid analysis, it can be concluded that wind actions and the presence of cladding on the facade scaffolds have a significant adverse impact on the structural behaviour of the scaffold itself.

On the other hand, a study of the types of safety nets for scaffolds offered on the Bulgarian market showed that manufacturers declare a relatively limited set of product characteristics. In the most common cases, these comprise: self-weight of the netting/sheeting per square meter, UV resistance, shading factor, geometric dimensions, etc., but not permeability characteristics [25]. The lack of specific technical data on the aerodynamic force coefficient for the cladding and the surface porosity or conversely the net area of the specific

cladding pattern, leads to the impossibility to determine correctly the wind load on the scaffolds covered with safety nets or advertising covers.

This necessitates targeted research to determine the permeability of different types of facade scaffold claddings under wind actions, as well as to determine specific relationships between the main characteristics of the facade claddings and their air permeability.

2. Research Methodology

For the realisation of the research the following tasks have been performed: creating an experimental model along with cladding specimens (nets); determining the main characteristics of different types of facade scaffold claddings (nets); experimental study in a wind tunnel of the parameters determining the wind pressure on the different specimens with different characteristics; systematisation of the experimentally obtained data; processing the results using the methods of mathematical analysis; determining specific relations and drawing conclusions on the influence of the characteristics of different types of claddings on their wind permeability.

2.1. Experimental Model. Measuring Equipment and Apparatus

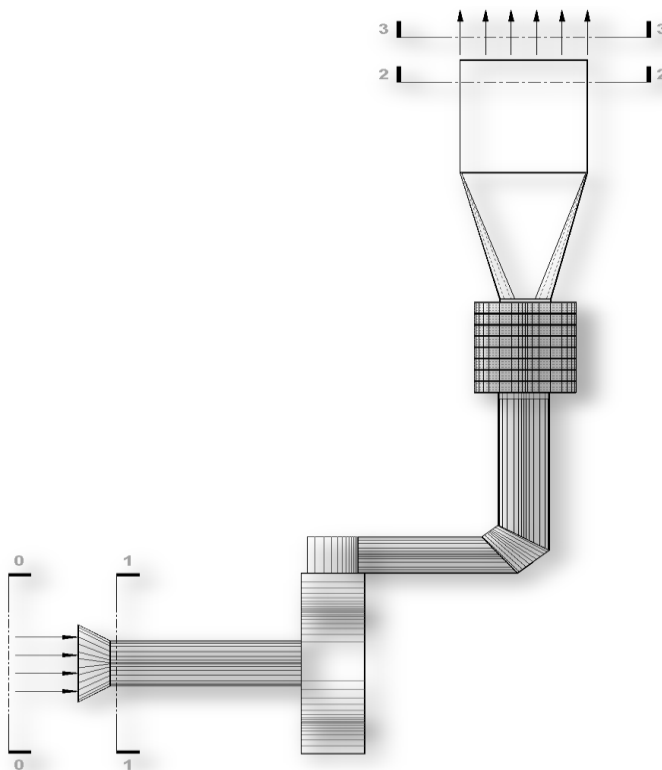


Figure 1. Principal scheme of the wind tunnel



Figure 2. Installed cladding specimen prior to testing

The test was conducted with the use of a wind tunnel in the laboratory of the Department of Hydroaerodynamics and Hydraulic Machines at the Technical University – Sofia. The tunnel principal scheme is shown in Fig. 1, whereas photo with an installed test specimen prepared for testing is given in Fig. 2. Detailed information regarding the wind tunnel structure and its technical characteristics are given in [25].

The cladding specimens are placed in a square supporting frame – a lightweight structure of small aluminium box sections, which was installed at the outlet section of wind tunnel via bolts with wingnuts and clamps to secure the corners in place. The airtightness between the supporting frame and the wind tunnel outlet was ensured by means of peripheral seals – see Fig. 2 for reference. Thus all of the wind flow is restricted to go through the examined specimen, providing accurate results.

The specialised measuring equipment used includes: aneroid barometer, differential electronic micromanometer MS351 (Fig. 3), which measures the pressure after the conical nozzle, which is used to calculate the flow rate; an electronic micromanometer FCO12 (Fig. 4), which measures the static pressure before the test cladding specimen; digital thermometer.



Figure 3. Electronic micromanometer MS 351



Figure 4. Electronic micromanometer FCO 12

2.2. Monitored Factors and Considered Parameters

An independent parameter in the study is the volumetric flow rate through the inlet end of wind tunnel Q_1 . It is used to control the speed of the wind flow through the tested cladding specimen V .

The input parameters that are measured directly are: atmospheric pressure ($B = P_{s,0} = P_{s,3}$), inlet air temperature (T_0), outlet air temperature (T_3), the difference between the static pressure in section 1 and the pressure in the laboratory (ΔP_1), the difference between the static

pressure before the netting/sheeting and the pressure in the laboratory (ΔP_2). Based on the pressure and temperature data, the air density at the inlet and outlet of the wind tunnel is calculated using the ideal gas law.

The air flow rate Q_1 is determined at the inlet of the suction end, at section 1-1 (Fig. 1), meeting the requirements of BS848-Part 1: 1980. Static air pressure before the netting $P_{s,2}$ is measured as the difference between the static pressure at section 2-2 (Fig. 1) and the pressure in the laboratory (atmospheric pressure), using an electronic micromanometer FCO12. Additional calculations also yield the equivalent wind speed V_e corresponding to the wind action at the measured air density. The theoretical justification of the relationship between the considered parameters is presented in section 2.3.

2.3. Theoretical Foundations of the Research

The theoretical basis of the experimental setup includes a reference to Bernoulli's principle regarding an established flow of an ideal fluid inside a pipe.

In the experimental setup thus developed, the wind speed after the cladding specimen is equal to the wind speed immediately before the cladding specimen (and through it), see Fig. 5. The air temperature before and after the test frame which holds the cladding specimen in place is the same. Due to the resistance of the netting, the static air pressure before the specimen (P_s , 2) is higher than the air pressure in the laboratory ($P_{s,3} = B$) and thus the air density before and after the supporting frame is different. This leads to different dynamic pressures at both sides of the test specimen. The total pressure in the wind tunnel immediately before the netting barrier is equal to the dynamic pressure created by the wind under normalized real conditions.

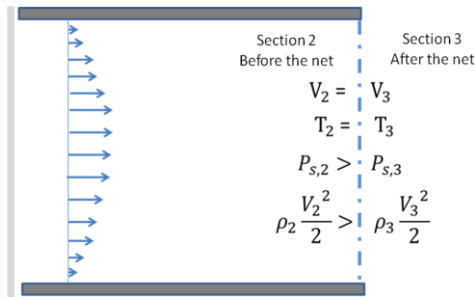


Figure 5. Measured parameters at section 2-2 of the wind tunnel

The difference in static pressures before and after the netting is measured directly

$$\Delta P_2 = P_{s,2} - B. \quad (1)$$

The wind speed through the test specimen is calculated from the flow rate continuity condition:

$$V = V_3 = \frac{\rho_0}{\rho_3} \frac{Q_1}{A_3} = \frac{T_3}{T_0} \frac{Q_1}{A_3}. \quad (2)$$

The total pressure immediately before the netting (section 2-2) is calculated from the Bernoulli equation:

$$P_{t,2} = P_{s,2} + \rho_2 \frac{V_2^2}{2} = (B + \Delta P_2) + \frac{(B + \Delta P_2) V_3^2}{RT_2} \frac{V_2^2}{2}. \quad (3)$$

The force exerted by the wind on the cladding in real conditions is equal to the force exerted by the air flow during the measurement:

$$(P_{t,2} - P_{s,2}) A_2 = A_2 \frac{(B + \Delta P_2) V_3^2}{RT_2} \frac{V_2^2}{2} = A_2 \rho_e \frac{V_e^2}{2} = A_2 \frac{B_e V_e^2}{RT_e} \frac{V_e^2}{2}. \quad (4)$$

The equivalent wind speed, under standardized conditions, is calculated from equation (4) by eliminating the test specimen surface area:

$$\frac{(B + \Delta P_2) V_3^2}{RT_2} \frac{V_2^2}{2} = \frac{B_e V_e^2}{RT_e} \frac{V_e^2}{2}. \quad (5)$$

2.4. Test Specimens

For the needs of the experimental study, 15 types of different covering nets were chosen (see Fig. 6 to Fig. 21). They are representative for the market availability in Bulgaria. All come in masses ranging from 40 g/m² to 220 g/m². The set of test specimens includes claddings made by fabric-knit technology of polyethylene monofilaments or monofibers, woven polyethylene fabric or glued structures of polyvinyl chloride (PVC).

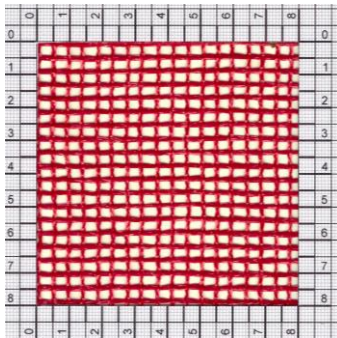


Figure 6. Net type "A"

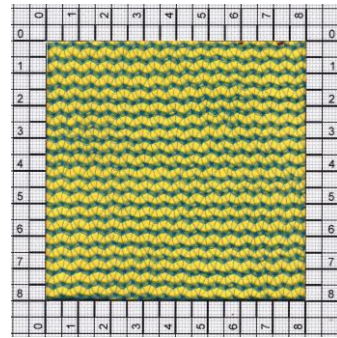


Figure 7. Net type "B"

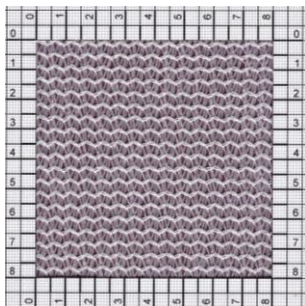


Figure 8. Net type "C"

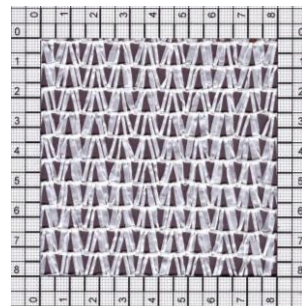


Figure 9. Net type "D"

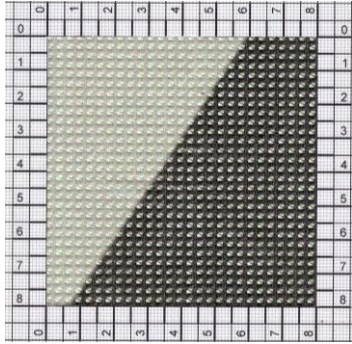


Figure 10. Net type "E"

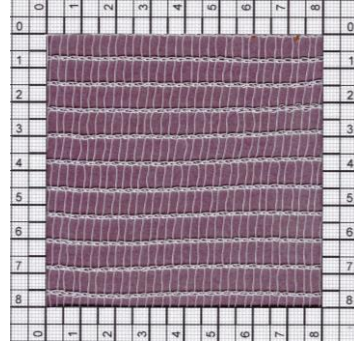


Figure 11. Net type "F"

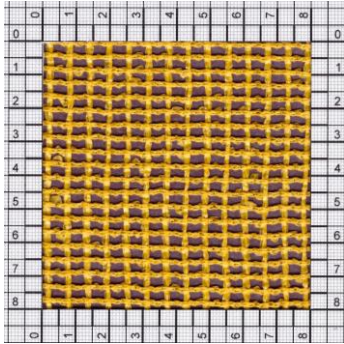


Figure 12. Net type "G"

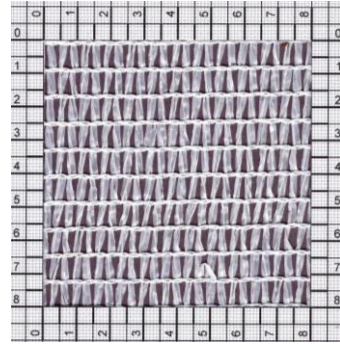


Figure 13. Net type "H"

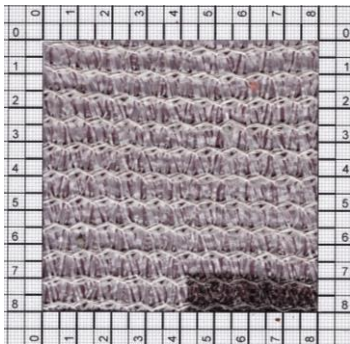


Figure 14. Net type "I"

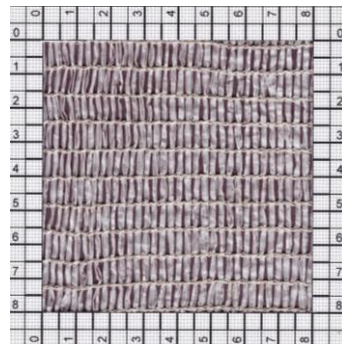


Figure 15. Net type "J"

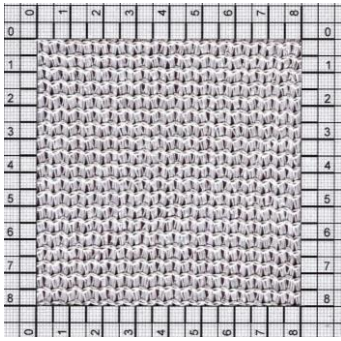


Figure 16. Net type “K”

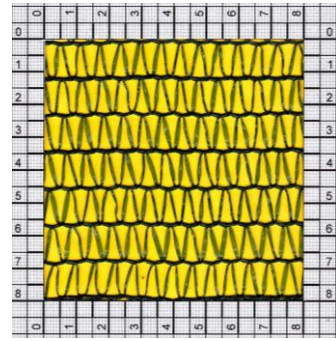


Figure 17. Net type “L”

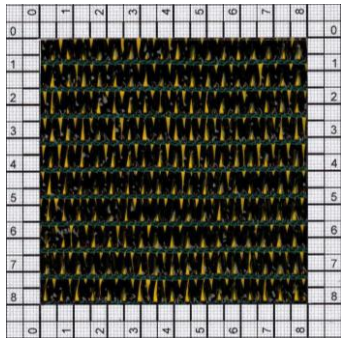


Figure 18. Net type “M”

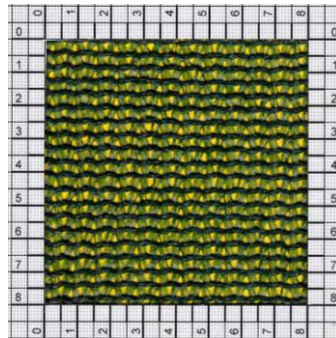


Figure 19. Net type “N”

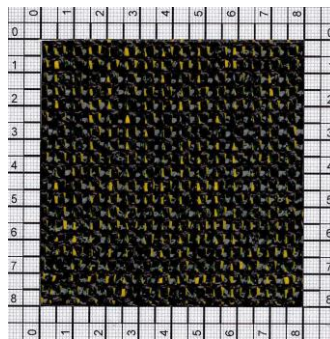


Figure 20. Net type “O”

3. Results and Analysis of the Experimental Study of the Wind Pressure on Facade Scaffold Covers Depending on the Equivalent Wind Speed

After the completion of a preliminary test in order to calibrate the experimental model, a series of fifteen facade scaffold nets specimens was tested. The experiment focus was to determine the pressure exerted on the nets.

At the initial processing of the results, a relation was found in terms of increasing the pressure on the different types of nets with increasing the equivalent wind speed.

For this reason, in order to determine more accurately the relationship between the pressure on the claddings (nets) and the wind parameters (mainly the equivalent wind speed), additional processing and analysis of the results were performed using regression analysis. The goal of regression analysis is to find the relationship between one dependent variable/outcome variable (wind pressure on the network) and one or many independent variables/predictors (equivalent wind speed). The relationship is expressed by a regression equation whose coefficients are determined such that the sum of the squares of the deviations along the ordinate axis (OY) is minimal.

In the current study, based on the data obtained from the experimental test on the equivalent wind speed and pressure on the facade scaffold nets, the regression equations are derived and the coefficient of determination R^2 is determined. The coefficient of determination R^2 represents the deviation of the experimentally measured values from the predicted trend according to the regression model (regression equation). It is one of the criteria for assessing the adequacy of the regression model. When using the coefficient of determination in relation to the correlation coefficient, a correlation between 0,7 and 0,9 is interpreted as high, whereas above 0,9 is considered as very high [26].

The relations, regression equations and coefficients of determination R^2 presented below were determined on the basis of the obtained data for the equivalent wind speed and exerted pressure on the nets for all 15 specimens (nets) used in the experiment. The graphics showing the regression equations and the coefficients of determination are presented in Fig. 21 to Fig. 35. In the figures, the equivalent wind speeds measured in the experiment are plotted up to a speed of 40 m/s. This limitation is in accordance with the basic wind velocities given in BDS EN 1991-1-4/NA [27] for the different regions in Bulgaria, showing a maximum value of 35,8 m/s for the town of Sliven.

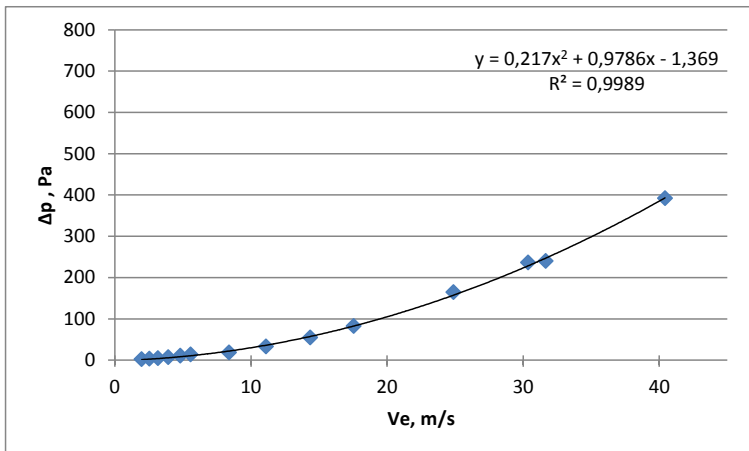


Figure 21. Relationship between equivalent wind speed and wind pressure on net type “A”

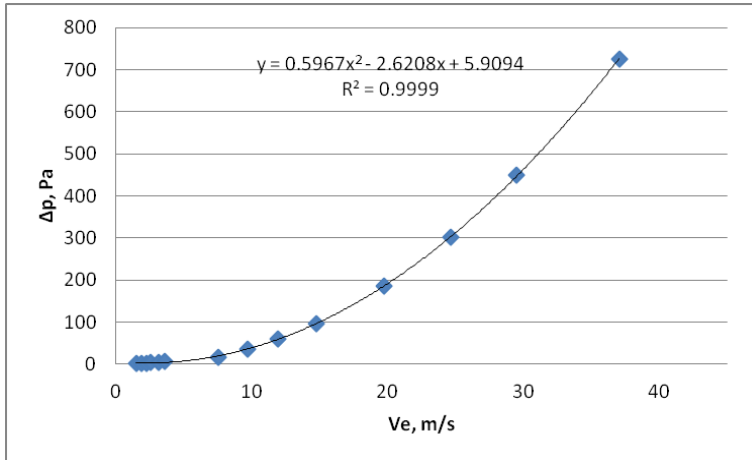


Figure 22. Relationship between equivalent wind speed and wind pressure on net type "B"

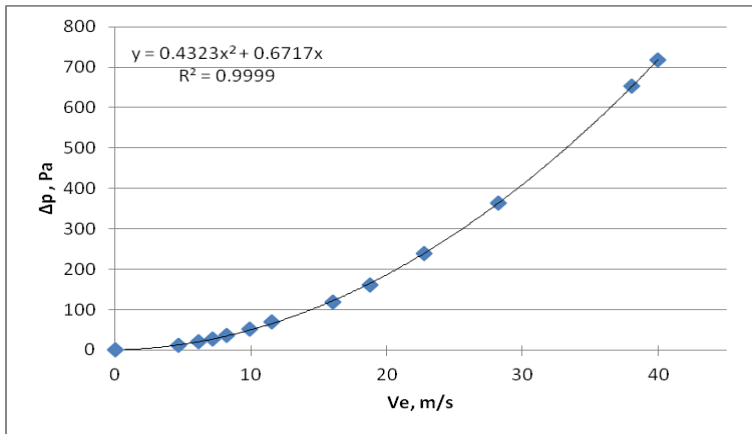


Figure 23. Relationship between equivalent wind speed and wind pressure on net type "C"

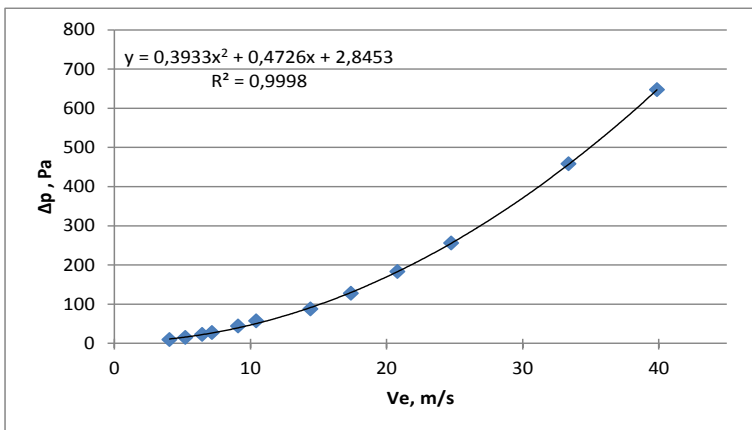


Figure 24. Relationship between equivalent wind speed and wind pressure on net type "D"

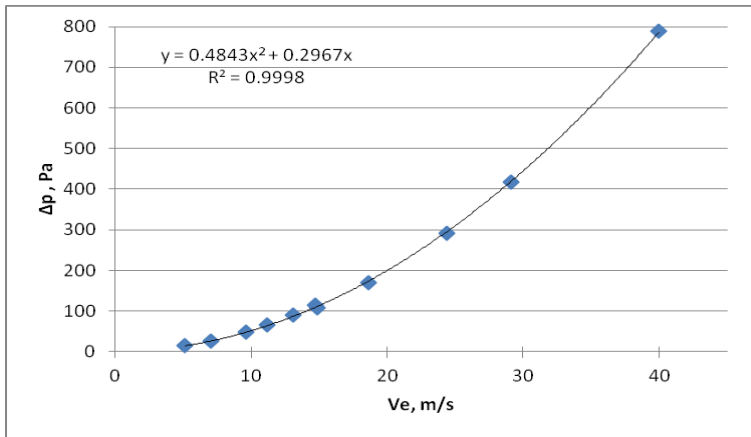


Figure 25. Relationship between equivalent wind speed and wind pressure on net type "E"

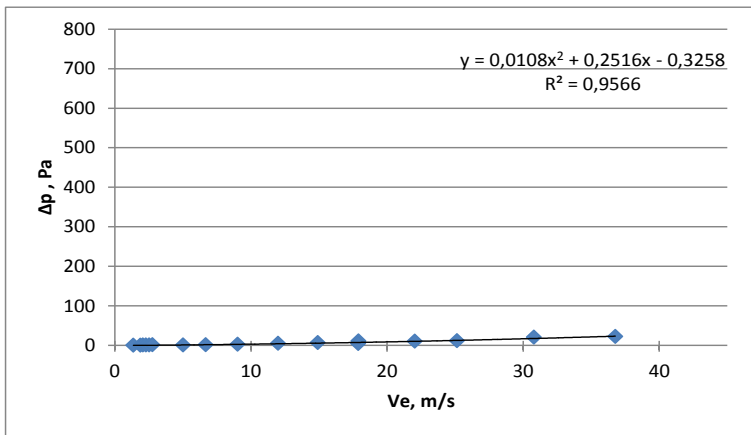


Figure 26. Relationship between equivalent wind speed and wind pressure on net type "F"

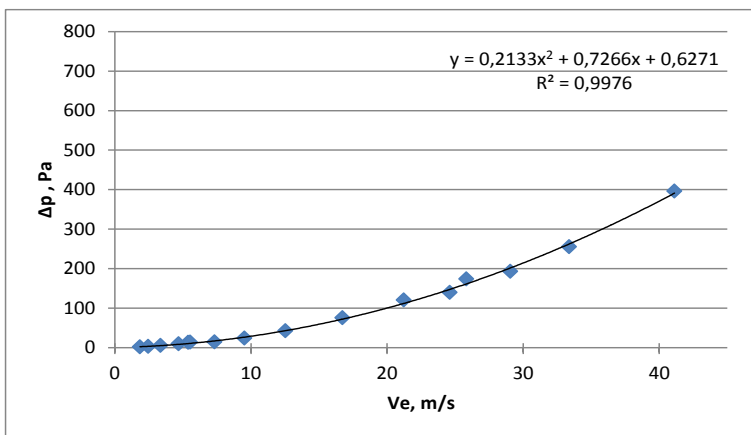


Figure 27. Relationship between equivalent wind speed and wind pressure on net type "G"

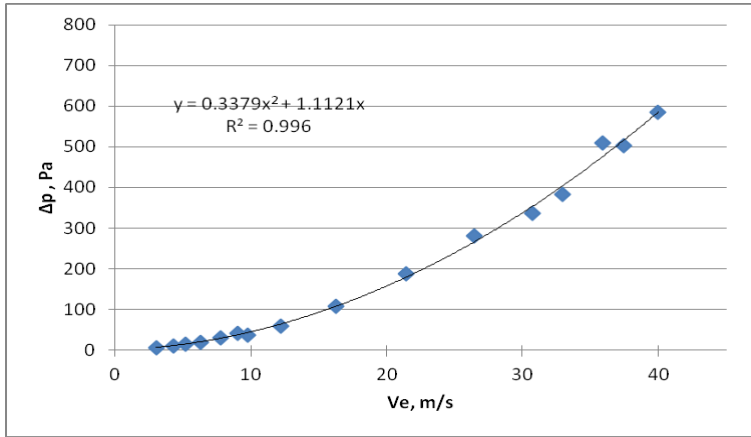


Figure 28. Relationship between equivalent wind speed and wind pressure on net type "H"

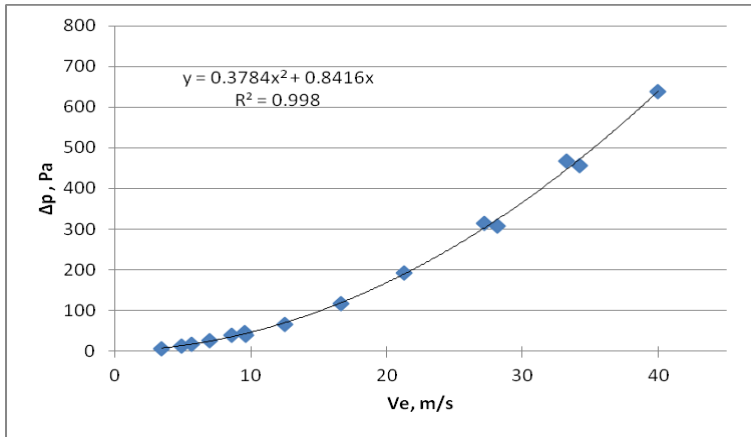


Figure 29. Relationship between equivalent wind speed and wind pressure on net type "I"

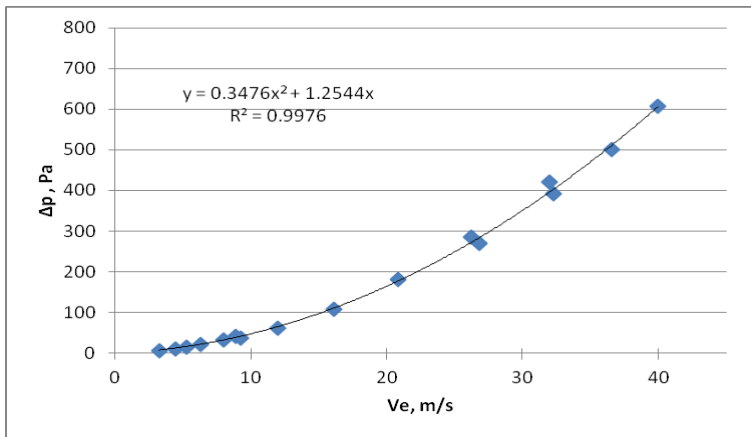


Figure 30. Relationship between equivalent wind speed and wind pressure on net type "J"

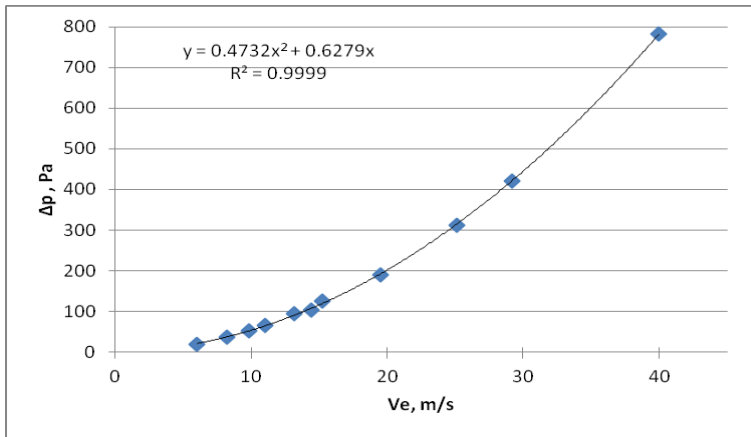


Figure 31. Relationship between equivalent wind speed and wind pressure on net type "K"

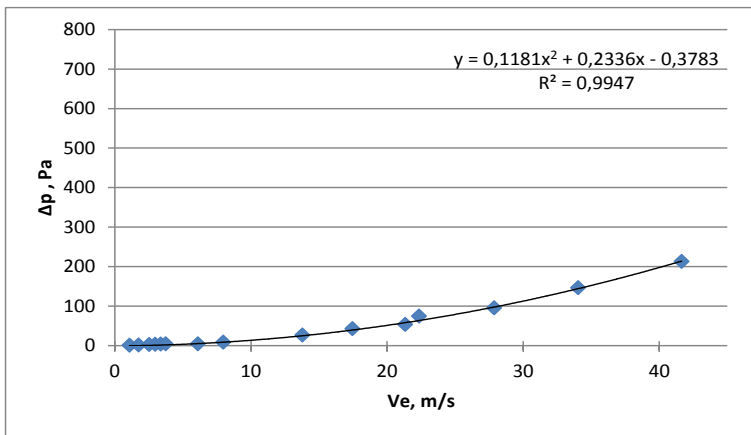


Figure 32. Relationship between equivalent wind speed and wind pressure on net type "L"

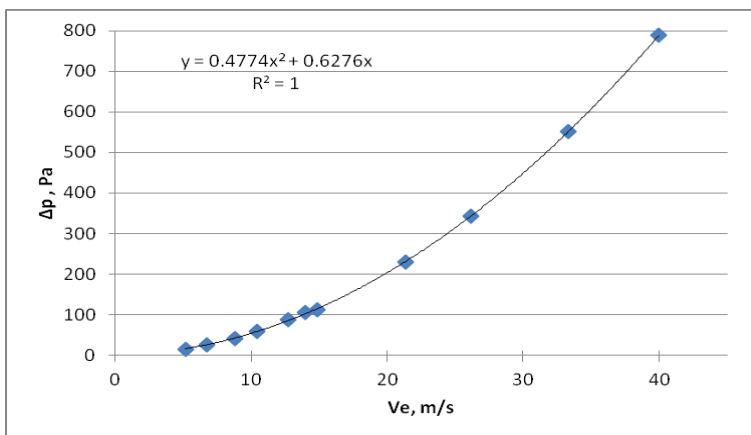


Figure 33. Relationship between equivalent wind speed and wind pressure on net type "M"

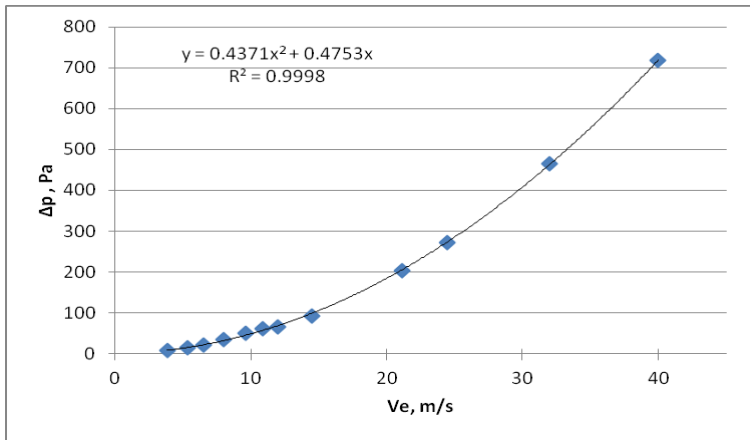


Figure 34. Relationship between equivalent wind speed and wind pressure on net type “N”

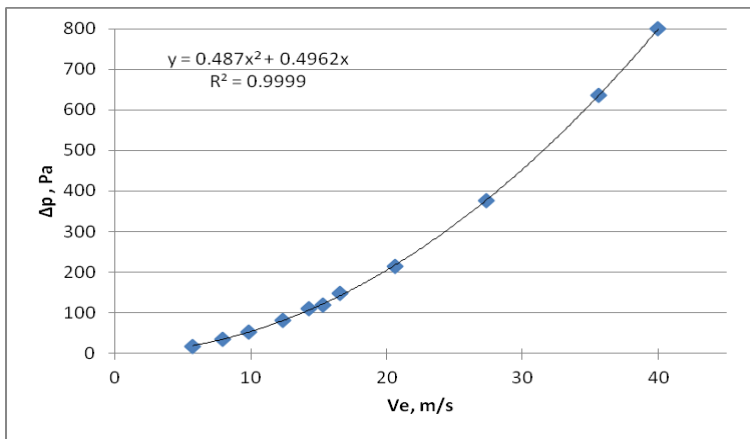


Figure 35. Relationship between equivalent wind speed and wind pressure on net type “O”

The obtained results show that the highest values of the pressure on the nets due to the simulated wind action are obtained for specimens type “E”, type “K”, type “M” and type “O”. The values of the pressure on those nets are of the order of 780 – 800 Pa at a wind speed of 40 m/s. The lowest values of the pressure on the nets are obtained for specimens type “B”, type “F” and type “L”. Those specimens represent the nets with the highest permeability. Their maximum values of the wind pressure at the given wind speed of 40 m/s reach up to about 80 Pa. The following important clarification should be made – nets type “B” and type “F”, according to the manufacturer’s product description, are facade scaffold nets meant to provide protection against falling objects. Nets type “K”, type “M” and type “O”, according to manufacturer’s product description (or DOP for some of them, declaration of performance), are not specifically designed to cover scaffolds, but in the construction practice examples of their use as such exist. Net type “E” is made of polyvinyl chloride (PVC) and is used mainly as a cover providing advertising space, enabling high quality of the prints. This type of advertising sheetings finds broader application in the recent years in the Bulgarian and world construction practice.

Analysing the graphically presented results, the high values of the coefficient of determination are to be noted R^2 . Its values are predominantly around 0,99 which allows the obtained correlation between the parameters: equivalent wind speed and pressure on the nets, to be evaluated as very high.

The distribution of the regression curves shows that different pressure values were measured at different nets at the same equivalent wind speed. Studying the images presented in Fig. 6 to Fig. 20 draws the conclusion that the different nets have different patterns achieved via various manufacturing processes, thus implying different nets porosity. This requires further research to establish the relationship between the porosity of the nets and the wind pressure on them.

4. Conclusion

This paper presents a methodology for assessing the air permeability of different facade scaffold nets, subjected to wind action, with testing in a wind tunnel.

As a result of the performed tests several main conclusions can be formulated. Different types of facade scaffold nets are characterized with different permeability which leads to different values of wind pressure on them. The obtained correlation between the parameters: equivalent wind speed and pressure on the cladding nets can be evaluated as very high.

The highest experimentally determined values of the pressure on the nets were found to be around 780 – 800 Pa at a wind speed of 40 m/s. The lowest values of the pressure observed on the nets were about 80 Pa. When testing polyvinyl chloride (PVC) nets made for advertising purposes, the pressure on the cladding surface was found to be significant and among the highest observed on the test specimens – about 790 Pa at a wind speed of 40 m/s. The determined values of the wind pressure at the relevant wind speeds for the different types of nets could be used to determine the wind loads in the design of facade scaffolds.

Given that the different porosity of the safety nets leads to different values of the wind pressure on them, it is necessary to conduct additional research in order to establish the relationship between the porosity of the nets and the wind pressure on them.

Acknowledgements

The current research development under contract D-114/2018 is financially supported by the Centre for Research and Design at UACEG.

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ИЗСЛЕДВАНЕ НА ПРОПУСКЛИВОСТТА НА РАЗЛИЧНИ ТИПОВЕ МРЕЖИ ЗА ФАСАДНО СКЕЛЕ ПРИ ВЕТРОВИ ВЪЗДЕЙСТВИЯ

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Ключови думи: фасадно скеле, предпазни мрежи, ветрови въздействия, аеродинамичен тунел

РЕЗЮМЕ

Съвременните тенденции в изпълнението на строителството са свързани с покриването на фасадните скелета с различни типове покрития във вид на предпазни мрежи или платнища. Използването им води до повишаване на ветровите натоварвания върху конструкцията на самите скелета. В статията е представена методика за оценяване на пропускливостта на предпазни мрежи за покриване на фасадни скелета при ветрови въздействия с изпитване във ветрови тунел. Получените резултати са анализирани, като са формулирани конкретни изводи за влиянието на налягането върху предпазните мрежи в зависимост от стойностите на скоростта на вятъра.

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