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Icing Effect on Steel Bar Structures

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1. Introduction

Ice action is a kind of load that in many cases is not included by designers, since it concerns a small number of objects. The structures vulnerable to icing effect are i.e. masts, towers, electrical overhead lines, chimneys, tie rods as well as any type of unprotected steel truss structures. They are usually located in open areas and icing is one of important determinants for their dimensioning. Icing is defined as an atmospheric phenomenon that occurs as a result of cooling and condensation. It may arise due to two processes: hoarfrost or precipitation icing, and takes various forms i.e.: soft rime, hard rime, wet snow or glaze. Its density is differentiated and varies from 200 kg/m^3 to 900 kg/m$^{3.}$ Undoubtedly, the key factors in formation of ice include ambient temperature, air humidity, wind velocity and direction as well as atmospheric pressure.

The literature can find references on the effect of ice action on structures, however, there is an insignificant number of works that relate to research in the area of Poland.

In the Polish technical literature there are not too many publications that refer solely to the issues pertaining to ice action. Appropriate adoption of all loads acting on structures as well as determination of load combinations acting on them is of great importance in the design process. Improper determination of loads acting on structures or not taking into consideration some of load types in the design process (i.e. ice action) may lead to failures or construction disasters. The most spectacular construction disasters are the destructions of power systems, since they involve depriving consumers of energy. Such blackouts occurred in recent years in Szczecin (in 2008) and in Kielce (in 2010) (Rawska-Skotniczny 2014). The literature has provided the issue of icing effect on overhead power line cables with a substantially serious concern. Undoubtedly, the effect of icing on design and safety of use of overhead power networks is particularly vital (Qimao et al. 2011). In order to investigate this effect, appropriate calculation models and environmental source data should be adopted (Farzaneh 2008). One of the methods of measuring the icing of power line cables, also under uneven icing distribution, is to determine the ice action based on the final stresses caused by this type of load (McComber et al. 1987). Overhead traction networks, both rail and tram ones are another types of structures exposed to the negative effect of icing. In order to avoid failures caused by ice accumulation on cables, some technical solutions should be applied to monitor traction networks that allow for their continuous and reliable work in long-term operation (Maciołek & Szeląg 2016). It is particularly important to take into account ice action and to adopt this load in load combinations for steel bars as examples of building structures sensitive to this type of action (El-Reedy 2010). Correct value assumption of icing action – as well as its type, methods for measuring and collecting data to determine the effect of icing – is a technique incorporated by many scientists from such countries as: Austria, Bulgaria, Czech Republic, Finland, Germany, Hungary, Norway, Slovakia, Spain, Sweden, Switzerland and the United Kingdom (including data from Russia and Canada). On the basis of this extensive research and interpretation of national standards, the European guidelines have been created. (Fikke et al. 2007).

For many years in Poland there have been a great interest in a fund collecting campaign to treat children and seniors, known as the Great Orchestra of Christmas Charity (Wielka Orkiestra Świątecznej Pomocy). It takes place during winter and numerous steel structures need to be installed in order to perform charity concerts and shows. As this type of construction is particularly exposed to ice action, attention should be paid to the correct design and safety of use of these facilities (Czaplińska 2016).

2. Determination of ice load

For the time being there is no separate European standard – Eurocode on ice action. However, there are standards that designers apply selectively, depending on their requirements. In order to present the issue, the subject of ice action is presented on the basis of the following standards: PN-EN 1993-3-1:2008 Eurocode 3: Design of steel structures Part 3-1: Towers, masts and chimneys – towers and masts, PN-EN 1993-3-2:2008 Eurocode 3: Design of steel structures Part 3-2: Towers, masts and chimneys – chimneys, ISO 12494:2017 Atmospheric Icing of Structures, PN-87/B-02013 Actions on structures. Variable environmental loads. Ice load and Minimum design loads for buildings and other structures and ASCE Standards ASCEISEI 7-05, 2006.

Currently, the most appropriate to use is Annex C to PN-EN 1993-3-1:2008 (PN-EN 1993-3-1:2008 Eurocode 3: Design of steel structures Part 3-1: Towers, masts and chimneys – towers and masts) since it provides rules for determining ice load as well as ice and wind load combined. The code PN-EN 1993-3-2:2008 (PN-EN 1993-3-2:2008 Eurocode 3: Design of steel structures Part 3-2: Towers, masts and chimneys – chimneys) refers to the same annex, although it additionally refers to ISO 12494:2017 (ISO 12494:2017 Atmospheric Icing of Structures), which is an English international standard not planned to be used directly by designers but by standardisation committees. The Polish annex for those two codes PN-EN 1993-3-1:2008 and PN-EN 1993-3-2:2008 allows for applying the standard PN-87/B-02013 (PN-87/B-02013 Actions on structures. Variable environmental loads. Ice load and Minimum design loads for buildings and other structures), which restores the necessity of using PN standards, previously withdrawn as the consequence of adopting Eurocodes.

According to the code PN-EN 1993-3-1:2008 the constant thickness of ice for design purposes is adopted around the periphery of elements, which allows computation of both weight and aerodynamic drag. The method is justified for calculating elements subject to icing in the form of glaze or wet snow. The below Fig. 1 demonstrates the constant (symmetrical) thickness of ice.

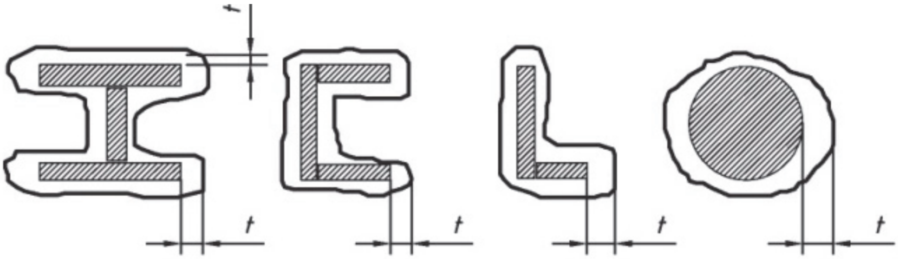

Fig. 1. Glaze thickness on structural elements according to ISO 12494:2017 (ISO 12494:2017 Atmospheric Icing of Structures), where:
t – ice thickness (depending on the location of the object)
Rys. 1. Grubość oblodzenia szkliwem elementów konstrukcyjnych wg normy ISO 12494:2017 (ISO 12494:2017 Atmospheric Icing of Structures), gdzie:
t – grubość warstwy oblodzenia (w zależności od lokalizacji obiektu)

The icing in the form of rime is deposited on structural elements in a completely different way; it is uneven. Consequently, when designing, the same constant ice thickness is assumed, however this value is appropriately overstated as much as the largest thickness of rime.

Fig. 2 shows the model of glaze growth on structural elements, with its asymmetrical location. It should be added that the models shown in Figure 2 are adequate for profiles with a height of $w \leq 300$ mm.

It should be examined individually, which form of ice load, symmetrical or asymmetrical, is the most unfavourable for a designed structural element.

Ice thickness for structures located in Poland can be calculated on the basis of PN-87/B-02013. Characteristic values for ice load should be calculated per unit length of a given structural element. Load acting on the element with a circular cross-section e.g. a pipe, rope or rod can be calculated with the use of the following formula:

$$g_k = \pi \cdot \gamma \cdot s \cdot (d + s) \tag{1}$$

where:
g_k – characteristic value for icing [kN/m],
γ – ice density [kN/m^3]'
s – effective thickness of ice [m],
d – diameter of element with a circular cross-section [m].

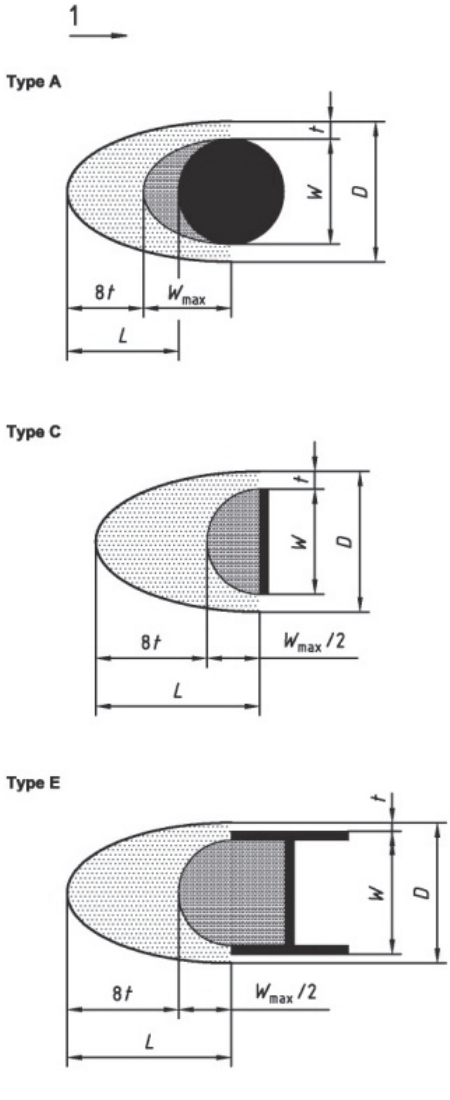

Fig. 2. Glaze thickness on structural elements according to ISO 12494:2017 (ISO 12494:2017 Atmospheric Icing of Structures)
Rys. 2. Grubość oblodzenia sadzią elementów konstrukcyjnych wg normy ISO 12494:2017 (ISO 12494:2017 Atmospheric Icing of Structures)

where:
A, B, C, D, E, F – different types of rime icing depending on shapes and dimensions of profiles and their position relative to the wind direction,

1 – wind direction,
t – ice thickness (depending on the location of the object),
w – width of object (excluding ice) perpendicular to wind direction,
L – length of ice vane measured in windward direction,
D – diameter of accreted ice or total width of object including ice.

gdzie:
A, B, C, D, E, F – różne typy oblodzenia sadzią w zależności od kształtu i wymiarów profili oraz ułożenia względem kierunku wiatru,
1 – kierunek wiatru,
t – grubość lodu (w zależności od lokalizacji obiektu),
w – szerokość kształtownika (bez lodu) prostopadle do kierunku wiatru,
L – długość nawisu lodowego mierzona po stronie nawietrznej,
D – średnica oblodzonego kształtownika lub jego szerokość (w tym lodu).

To calculate load acting on structural elements with different cross-sections, the following formula should be used:

$$g_k = \gamma \cdot s \cdot u \tag{2}$$

where:
u – circumference of the outer element contour that is measured in half of the effective ice thickness [m].

The effective thickness of ice is presented with the formula below:

$$s = b \cdot \mu \cdot \xi \tag{3}$$

where:
b – characteristic value for ice thickness [m],
μ – shape coefficient,
ξ – height above terrain coefficient.

The calculated value of load is determined from the correlation:

$$g = g_k \cdot \gamma_f \tag{4}$$

where:
γ_f – load coefficient, for icing $\gamma_f = 1.5$.

Comparing the code PN-87/B-02013 to ISO 12494:2017 and ASCEISEI 7-05, 2006 (ASCE Standards ASCEISEI 7-05, 2006), results in noticing the following differences and similarities. According to PN-87/B-02013, the density of ice should be 700 kg/m^3, while ISO 12494:2017 and ASCEISEI 7-05, 2006 designate that value as 900 kg/m$^{3.}$ Characteristic values for ice thickness b should be adopted for particular areas in Poland separately. The map of Poland with division into load zones is included in the code PN-87/B-02013. There is no possibility of using a different standard in this matter, since the codes ISO 12494:2017 and ASCEISEI 7-05, 2006 do not cover the area of Poland. ISO 12494:2017 contains a division into ice classes for both rime and glaze, but it does not relate this data to the location of objects. On the other hand, the code ASCEISEI 7-05, 2006 provides design guidance for all actions affecting structures, yet it covers only the territory of the United States of America.

The shape coefficient μ is precisely provided in the code PN-87/B-02013. Its value depends on a cross-section shape, i.e. there are given values for sections (μ = 0,5), closed profiles, box profiles (μ = 0,7) and profiles with a circular cross-section according to their diameter (when d ≤ 0,007 m then μ = 1,1, when 0,007 m < d ≤ 0,16 m then $\mu = \frac{1}{\sqrt[4]{100 \cdot d}}$ and when d > 0,16 m then μ = 0,5). The code PN-87/B-02013 designates the height above terrain coefficient as ξ, the code ISO 12494:2017 as K_h, while the code ASCEISEI 7-05, 2006 as $f_{z.}$

The code PN-87/B-02013 determines the coefficient ξ with the use of the following formula:

$$\xi = (\frac{h}{10})^{0.3} \tag{5}$$

where:
h – height above terrain of a structural element.

Principles included in the code ASCEISEI 7-05, 2006 describe the height above terrain coefficient with the following formula:

$$f_z = (\frac{z}{10})^{0.1} \tag{6}$$

where:
z – height above terrain of a structural element within 0 m < z ≤ 275 m.

The code ISO 12494:2017 describes the height above terrain coefficient with the following formula:

$$K_h = e^{0.01H} \tag{7}$$

where:
H – height above terrain of a structural element.

The comparison of height above terrain coefficient values on the basis of the referred formulas is included in the calculation example set out in the following part of the article.

Scientific expertise proves that a structure is never subject to just one load. In case of ice load what might be of crucial importance is a combination of various loads, including wind action. The maximum load may cause an increase in the aerodynamic drag due to icing of an element, even at a lower wind velocity value than the maximum one. The code PN-EN 1993-3-1:2008 presents a calculation algorithm for the aerodynamic drag of a structure subject to icing, taking into account an increase in the width of elements at glazed icing. The code PN-EN 1993-3-1:2008 provides combinations of ice load and wind load, which should be followed, taking into consideration the class of icing i.e. whether it is symmetrical or asymmetrical. There are two combinations to be considered:

– ice load is dominant, while wind load is accompanying, which is presented as the following correlation:

$$\gamma_G \cdot G_k + \gamma_{ice} \cdot Q_{k,ice} + \gamma_w \cdot \Psi_w \cdot k \cdot Q_{k,w} \tag{8}$$

where:
γ_G – partial coefficient for constant loads,
γ_{ice} – partial coefficient for ice load,
γ_w – partial coefficient for wind load,
G_k – characteristic value for constant loads,
$Q_{k\ ice}$ – characteristic value for ice load,
$Q_{k,w}$ – characteristic value for wind load,
Ψ_w – factor of combination for wind load,
k – factor for velocity pressure from wind action.

– wind load is dominant, while ice load is an accompanying phenomena, which is presented as the following correlation:

$$\gamma_G \cdot G_k + \gamma_w \cdot k \cdot Q_{k,w} + \gamma_{ice} \cdot \Psi_{ice} \cdot Q_{k,ice} \tag{9}$$

where:
Ψ_{ice} – combination factor for ice load.

The given formulas also include the coefficient k described in the code PN-EN 1993-3-1:2008. It concerns a characteristic wind pressure and is used to decrease a wind pressure value. Its value depends on the class of icing, which – in line with the recommendation contained in PN-EN 1993-3-1:2008 – should be determined according to the code ISO 12494:2017. However, the recommendation is completely unworkable for Polish designers, since the code ISO 12494:2017 does not include Poland within its territorial scope. Another incoherence is the value of a combination factor, as the code PN-87/B-02013 determines ice load on structures but does not specify the value of a combination factor. In such a case, it is recommended to refer to the code PN-EN 1993-3-1:2008 where there are given combination values adopted for the Polish territory. These are $\Psi_w = 0.5$ and $\Psi_{ice} = 0.5$, respectively. Summing up the above overview of standards, the current legal status in respect of ice action considerations can be regarded as unsatisfactory and ambiguous for designers.

3. Calculation example

To demonstrate the effect of ice load there were carried out calculations for a steel bar with the diameter of 25 mm. It is a bracing element of the platform in the object directly exposed to atmospheric conditions, located 20 m above terrain in Poznań.

– weight of bar Ø 25 mm is m = 3.85 kg/m,
– ice thickness according to PN-87/B-02013 is b = 0.012 m,
– shape coefficient for elements with a circular cross-section, if 0.007 m ≤ d ≤ 0.16 m, acc. to PN-87/B-02013 is:

$$\mu = \frac{1}{\sqrt[4]{100 \cdot d}} = \frac{1}{\sqrt[4]{100 \cdot 0.025}} = 0.795$$

The height over terrain coefficient calculated according to the referred formulas (5-7) is summarized in a tabular form. Table 1 additionally presents the value of effective ice thickness according to the code PN-87/B-02013 taking into consideration various height over terrain coefficients. There are also summarized the values of characteristic load per unit length having regard to the fact that according to the code PN-87/B-02013 the density of ice is 700 kg/m^3, while according to the codes ISO 12494:2017 and ASCEISEI 7-05, 2006 the value adopted is 900 kg/m^3. To summarise calculations, Table 1 presents ice mass for particular calculations as well as there is given a percentage increase in weight of the bar including the ratio of self-weight of ice to self-weight of the bar.

Table 1. Comparison of values according to: ISO 12494:2017, PN-87/B-02013and ASCEISEI 7-05, 2006
Tabela 1. Porównanie wartości wg norm: ISO 12494:2017, PN-87/B-02013 i ASCEISEI 7-05, 2006

standards applied for calculations	height above terrain coefficient	effective ice thickness [m]	characteristic load per unit length [kN/m]	ice mass [kg/m]	percentage increase in weight of the bar due to icing [%]
ISO 12494:2017	1.22	0.012	0.0123	1.23	32
PN-87/B-02013	1.23	0.012	0.0096	0.96	25
ASCEISEI 7-05, 2006	1.07	0.010	0.0097	0.97	25

4. Conclusion

On the basis of theoretical considerations and the above calculation example it can be determined that ice load has a significant effect on structural elements. It should be added that it concerns a small number of structures, primarily closed profiles with small cross sections for which additional weight of ice constitute a large percentage of weight relative to their self-weight. However, this is not the reason for the ambiguity of standards. By analysing Table 1, it can be stated that Polish designers should design structures taking into account ice action on structures according to ISO 12494:2017. Subsequently, there is obtained the most unfavourable ice load for a given element for calculation purposes in which the most important is to know the ice class that depends on location. Unfortunately, the codes ISO 12494:2017 and ASCEISEI 7-05, 2006 are excluded from being applied in Poland, since they do not include data in regard to the Polish territory. Undoubtedly, it is very important to take into account ice load together with other loads acting on structures, with the most important ones i.e. wind action and temperature load. For the reason that currently there is no separate standard relating to calculation of ice load, designers find it difficult and confusing to include this action in their calculations. As a consequence, it often leads to adopting underestimated values, as exemplified in the Table 1.

Evidently, the normalisation of ice load can benefit from the experience of the electricity industry, for it is an economy branch with great potential that uses global standards for design, construction and operation of overhead lines.

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Oddziaływanie oblodzeniem na stalowe konstrukcje prętowe

Streszczenie

Postępujące zmiany klimatyczne przyczyniają się do występowania ponad normatywnych obciążeń środowiskowych działających na konstrukcje budowlane. Obciążenia te są często przyczyną występujących na świecie katastrof budowlanych. Dlatego bardzo ważne jest właściwe określanie działających na obiekt budowlany obciążeń jak również przyjęcia najbardziej niekorzystnej kombinacji działających oddziaływań. Oddziaływanie oblodzeniem jest zaliczane do obciążeń zmiennych środowiskowych. Jest ono nie precyzyjnie określone w polskich przepisach normowych dotyczących projektowania konstrukcji. W pracy odniesiono się do norm polskich: PN-87/B-02013 Obciążenie budowli. Obciążenia zmienne środowiskowe. Obciążenie oblodzeniem, PN-EN 1993-3-1:2008 Eurokod 3: Projektowanie konstrukcji stalowych Część 1-1: Wieże, maszty i kominy. Wieże i maszty, PN-EN 1993-3-2:2008 Eurokod 3: Projektowanie konstrukcji stalowych Część 3-2: Wieże, maszty i kominy – kominy oraz norm międzynarodowych: ISO 12494:2017 Atmospheric Icing of Structures i Minimum design loads for buildings and other structures, ASCE Standards ASCEISEI 7-05, 2006. Ponieważ na dzień dzisiejszy nie istnieje oddzielny Eurokod dotyczący oddziaływania oblodzeniem, zaproponowano zasady określania tego oddziaływania podczas projektowania konstrukcji stosując wymienione normy. Trudność stosowania norm międzynarodowych wiąże się z barierą językową projektantów lub po prostu brakiem szczegółowych danych dla Polski. Ustawa z dnia 12 września 2002 r. o normalizacji zniosła obligatoryjność stosowania norm przy projektowaniu obiektów budowlanych, przyczyniając się do dobrowolności ich stosowania. Zatem decyzji projektanta pozostawiono, według których norm wykonuje projekt lub czy w ogóle z nich skorzysta. Konstrukcje stalowe, szczególnie prętowe i o niewielkich polach przekroju, narażone na wpływy atmosferyczne podlegają oddziaływaniu oblodzeniem. Również stalowe konstrukcje hydrotechniczne narażone są na szereg oddziaływań, w tym także na obciążenie oblodzeniem. Oddziaływaniem towarzyszącym oblodzeniu jest oddziaływanie wiatrem. W pracy pokazano kombinacje oddziaływań atmosferycznych dotyczące obciążeń wiatrem i oblodzeniem. Wskazano, że dla konstrukcji wrażliwych na oblodzenie warto korzystać z doświadczeń przemysłu elektroenergetycznego. W napowietrznych liniach elektroenergetycznych jak również sieciach trakcyjnych można stosować pewne rozwiązania techniczne umożliwiające monitoring ich stanu w niekorzystnych warunkach atmosferycznych. W artykule zamieszczono przykład obliczeniowy obrazujący wpływ oddziaływania oblodzeniem dla stalowego elementu prętowego. Porównano między innymi procentowy przyrost ciężaru pręta z oblodzeniem w stosunku do ciężaru własnego pręta. Analizę wykonano dla następujących norm: ISO 12494:2017, PN-87/B-02013 i ASCEISEI 7-05, 2006.

Praca stanowi wstęp do dalszych szerszych rozważań nad uwzględnieniem oddziaływania oblodzeniem dla konstrukcji szczególnie narażonych takich jak kratownice wiat, słupy elektroenergetyczne, prętowe konstrukcje stężeń i inne konstrukcje obiektów nieosłoniętych, które podczas użytkowania narażone są na bezpośredni wpływ warunków atmosferycznych. W pracy zwrócono uwagę na problem niejednoznaczności przepisów prawnych dotyczących oddziaływania oblodzeniem podczas projektowania konstrukcji.

Abstract

Progressive changes in climate have been substantially contributing to the occurrence of abnormal environmental loads acting on building structures. These loads are often the cause of construction disasters occurring in the world. Therefore, it is of crucial importance to properly determine loads acting on the exposed structures and to include the most unfavourable combination of actions. Ice load is classified as an environmental variable. It is imprecisely defined in the Polish standards for structural design. The paper refers to the Polish standards: PN-87/B-02013 Loads on structures. Variable environmental loads. Ice load, PN-EN 1993-3-1:2008 Eurocode 3: Design of steel structures Part 1-1: Towers, masts and chimneys. Towers and masts, PN-EN 1993-3-2:2008 Eurocode 3: Design of steel structures 3-2: Towers, masts and chimneys – chimneys as well as international standards: ISO 12494:2017 Atmospheric Icing of Structures and Minimum design loads for buildings and other structures, ASCE

Standards ASCEISEI 7-05, 2006. Since there is no separate Eurocode for ice action at present, it has been proposed to follow the rules for determining the action when designing a structure compliant with the standards listed above. The general difficulty in applying international regulations lies in the language barrier affecting some of designers or simply in the lack of detailed data for Poland. The Act of 12 September 2002 on normalisation abolished the obligatory application of standards in building design, contributing to their voluntary use. Therefore, it is the designer who decides whether or not to implement a given standard. Steel structures, particularly bars and structures with small cross-sections exposed to atmospheric conditions are affected by icing. Hydraulic steel structures are also exposed to a number of actions, including icing. Ice load is dominant, while wind load is an accompanying phenomena. The paper presents the combinations of atmospheric interactions describing wind and ice loads. It also points out that for structures sensitive to ice action, it is highly recommended to learn from the experience of the electricity industry. Overhead power lines, as well as traction lines, may use certain technical solutions to monitor their operation under adverse atmospheric conditions. In support of the arguments put forward, the article contains a calculation example illustrating the effect of icing on a steel bar element. The authors compared a percentage increase in weight of the bar with icing in the ratio to self-weight of the bar. The analysis was conducted in compliance with the following standards: ISO 12494, N-87/B-02013 and ASCEISEI 7-05, 2006.

The paper is an introduction to further broader reflections on the effect of icing on particularly vulnerable structures such as truss systems, power poles, steel bracings and other unprotected engineering elements, which during use are exposed to direct impact of weather conditions. Additionally, it draws attention to the problem of ambiguity of legal provisions regarding the icing effect that are to be applied in structural design.

Słowa kluczowe:
oddziaływanie oblodzeniem, kombinacje obciążeń, stalowy element prętowy, zasuwa płaska, norma polska, norma europejska

Keywords:
ice action, load combinations, steel bar, flat valve, Polish Standard, European Standard