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Article

Investigation of Moisture Condensation on the Surface of the Bottom Chord of a Steel Truss of a Historical Building

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Abstract: This paper investigates the conditions under which moisture condensation occurs on the surface of the bottom chord of a steel truss at the ceiling level of the attic hall of a historical building in Poltava, Ukraine. Moisture condensation on steel structural elements leads to steel corrosion and a decrease in the thickness of structural elements. As a result, the load-bearing capacity of both individual elements and the entire structure can be reduced. This paper describes how different parameters affect the process of condensate formation on the surface of steel bottom chord angles of the truss. Three parameters are investigated: the filling of the gap between the angles and precast reinforced concrete elements resting on the lower flange of the angles with thermal insulation; the filling of the gap between the two angles of the bottom chord of the truss with thermal insulation; and the possibility of detachment of the different sizes of finishing layer from the bottom flange surface of the angles. Verification calculations of the possibility of condensation forming on the metal surfaces of the bottom chord of trusses were also performed for the developed design solutions for restoration.

Keywords: steel corrosion; moisture condensation; temperature and humidity fields

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1. Introduction

There are cases of hidden load-bearing steel elements in the body of enclosing structures. In such structures, moisture condensation on the surface of steel elements is possible, leading to corrosion processes. These corrosion processes are dangerous for two reasons: they reduce the load-bearing capacity of the steel structures, and the corrosion products destroy the concrete and mortar covering the steel elements. The second process is particularly dangerous for historical buildings, as it leads to the destruction of the finishing layer (which can be the basis for historical paintings, frescoes, stuccoes, etc., which are the subject of cultural heritage protection).

This problem was identified during the restoration of the building described in this paper. Therefore, the authors set out to design an algorithm for assessing the possibility of moisture condensation on the steel elements inside the ceiling/covering structure to prevent the destruction of the finishing layer and the steel structure in time.

The general value of performed investigation is a proposed and proven algorithm for assessing the possibility of corrosion in hidden steel load-bearing elements. The proposed algorithm can prevent the reduction of the load-bearing capacity of the structures. In the case of historical buildings, it could prevent the destruction of the finish layer too, which may have cultural heritage value. An integrated approach to assessing the technical condition of building structures, which considers various factors of the work of structures and makes it possible to predict the state of structures under specific temperature and humidity influences, determines the article's novelty. The results of the study can be used by engineers and scientists when inspecting similar structures and identifying hidden defects that may appear after prolonged periods of service. The results are typical for unheated attics of buildings that lack or have insufficient protective properties of the thermal insulation of the attic floor structure.

The restoration of historical buildings is a complex matter. However, unlike listed buildings, it is subject to stricter legislation regarding the energy efficiency of buildings. Rigid application of legislation and standard requirements can do more harm than good in the case of historical buildings. The presented study of the preservation of the low-carbon steel roof trusses of the historical hall of the museum in Poltava confirms that excessive thickness of thermal insulation causes thermal bridges [1] and their detrimental effects on the supporting structure. In justified cases such as this, it is better to accept higher heat losses and, therefore, higher heating costs, than to unnecessarily compromise the supporting structure's functionality. A uniformly 'worse' envelope suppresses thermal bridges, albeit at the cost of higher heat losses (Figure 1) [2]. As far as the building authorities are concerned, this strategy must be thoroughly justified, and the designer must use all available technical knowledge and resources. The present study describes the reasoning and calculation procedures used in the restoration of the historical museum hall in Poltava. It also offers an insight into design practice in the Ukraine that foreign investors and construction companies may find helpful in the anticipated restoration of the country.

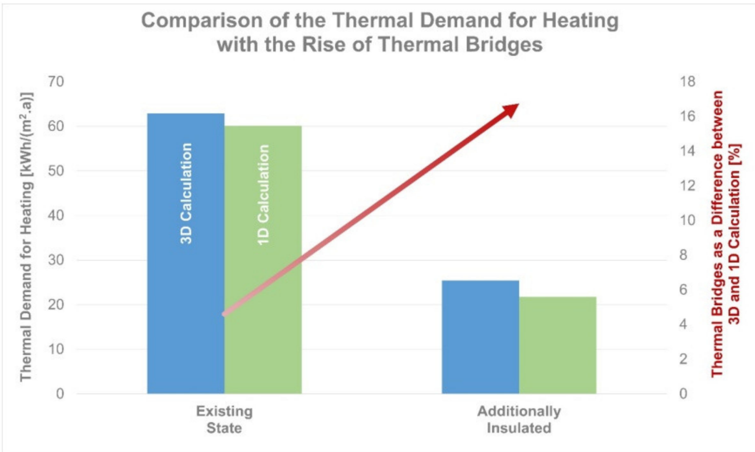


Figure 1. Comparison of heating demand with the increase in thermal bridges (Adapted from Ref. [2]). The proportion of thermal bridges is defined as the difference between 3D and 1D calculation of the heating demand. The calculations were performed for the existing, non-insulated facade and retrofitted (i.e., additionally insulated facade of an apartment building).

During the restoration of the hall of a historical building in the city of Poltava (Ukraine), the question of determining the actual technical condition of the steel trusses of the roof arose. The building (Figure 2) was built in 1902–1908 in the style of Ukrainian architectural modernism [3–5] and is an architectural monument of national importance. After a fire in 1943, the building was restored in the 1950s and 1960s. In the current restoration project, the designers plan to restore the interior decoration of the building's historical halls. The thermal insulation of the attic floor is also being improved.

The designers assigned the authors the task of determining the actual technical condition of the steel trusses of the roof. The authors surveyed the load-bearing and enclosing structures of a part of the attic space of the historical building [6]. The steel structures of the attic space consist of different types of trusses spaced at 1.55–2.15 m. The steel trusses have a triangular contour of the top chord and a radially elevated bottom chord

(Figure 3). Deformations and damage to the steel truss elements that occurred during the fire in 1943 were identified. During the restoration in the 1950s and 1960s, the steel truss elements were reinforced. The designers and authors assumed that the steel trusses are made of low-carbon steel, which imposes certain limitations on their operation (the temperature in the attic space should not be lower than −15 °C). Determination of the mechanical properties of trusses' steel is not relevant to the topic of the article. The steel trusses have been used for a long time; truss elements have been strengthened or modified many times in 1924, 1945, 1978, and 2001, including after fire actions. The top chord of steel trusses is supported on the brick walls (Figure 4d). Along the bottom chord of F1 and F2 type trusses (1), there are precast reinforced concrete elements (2) with a span of 1.55–2.15 m and a cross-section of 240 × 100 (h) mm (Figure 4b). Precast reinforced concrete elements (2) are supported on the bottom chord of the steel truss (3) and form the vault of the hall (Figure 4a,c). They are made of concrete with coarse aggregate in the form of broken bricks or stones. The thermal insulation is made of mineral wool with a thickness of 50–400 mm, contaminated.

Figure 2. General view of the building (source: authors).

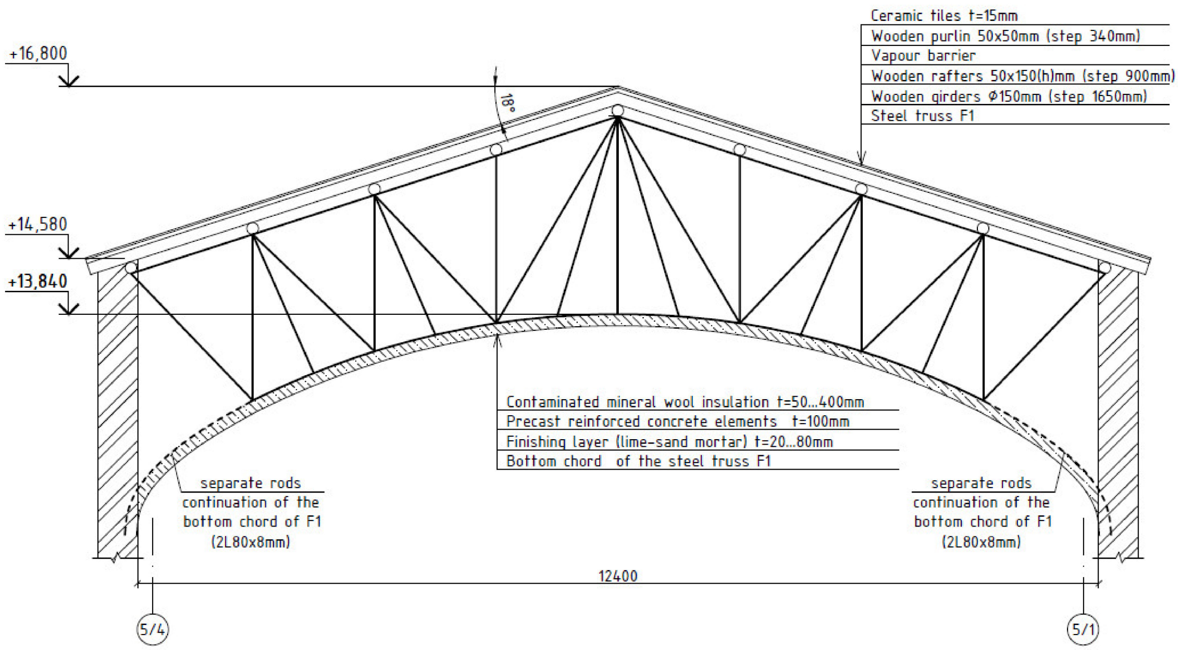


Figure 3. Schematic drawing of the truss.

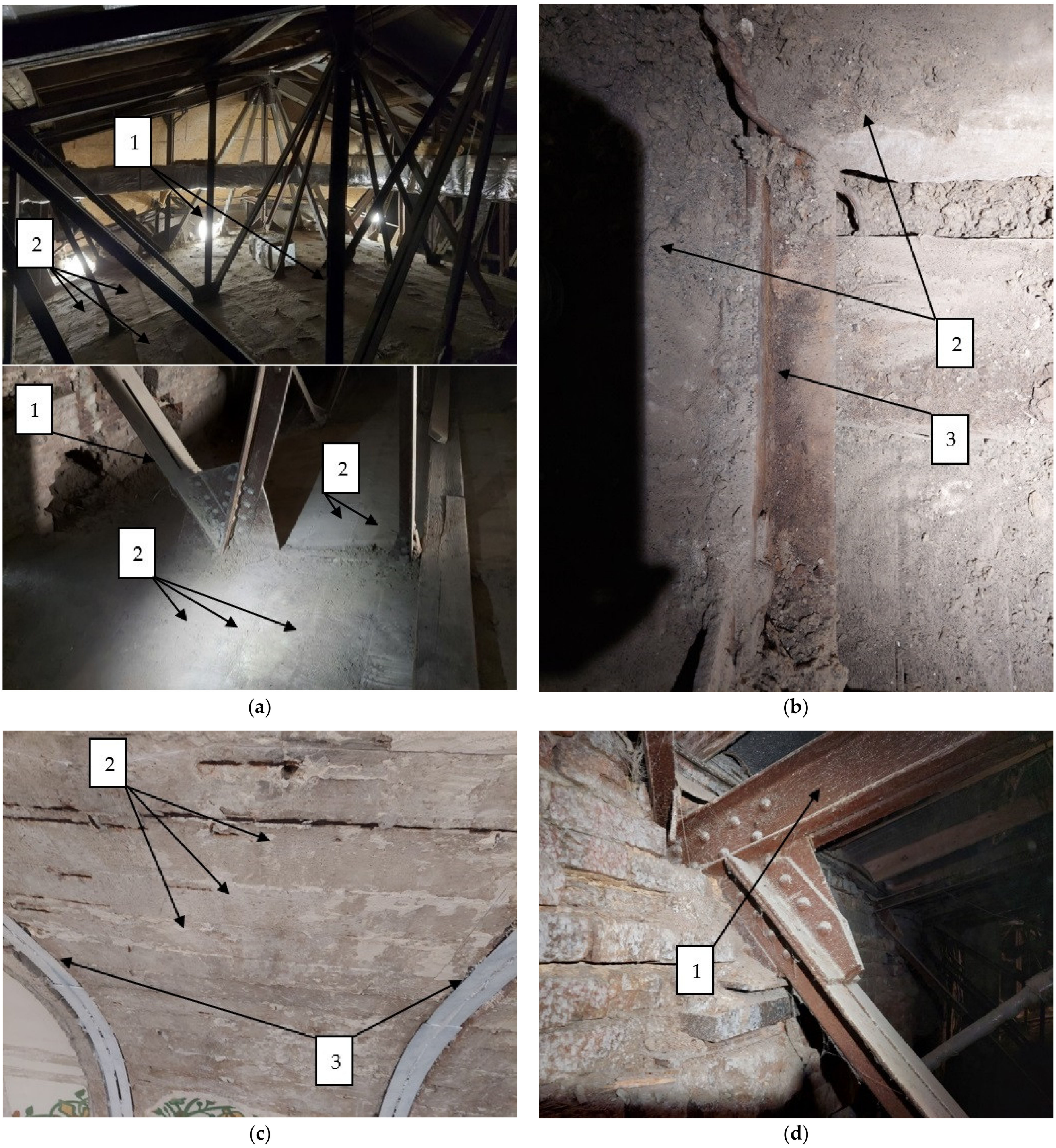


Figure 4. Construction of the attic ceiling: (**a**) general view of the steel roof trusses (1) and precast reinforced concrete elements (2) after cleaning the thermal insulation; (**b**) the bottom chord of the truss (3) which supports the precast reinforced concrete elements (2); (**c**) general view of the cover construction from below—precast reinforced concrete elements (2) are supported on the bottom chord of the steel truss (3) and form the vault of the hall; (**d**) the top chord of steel trusses is supported on the brick walls (source: authors).

On the inside of the room, a finishing layer of cement/lime-sand plaster of variable thickness of 20–80 mm was applied to the slabs to level the curvature of the ceiling. In part of the hall, the finishing is executed as a false ceiling. In this part, during the inspection of the attic space, several precast reinforced concrete elements (2) were dismantled to survey the bottom chord (3) of the steel truss (Figure 4b). Significant corrosion damage was found on the inner surface of the angles supporting the precast reinforced concrete elements. During further restoration work on the hall of the historical building, the bottom chords of the trusses, which support the precast reinforced concrete elements, were opened and examined from the hall. Significant corrosion damage was found to the elements of the bottom chord of the trusses (Figure 5)—two angles 65 × 6 mm in truss F1 and two angles 100 × 8 mm and an overlay strip with a cross-section of 12 × 210 mm in the middle section of truss F2.

(**a**) (**b**)

Figure 5. Technical condition of the bottom chord of the steel trusses: general view of the bottom chord of the steel trusses in different places (**a**) the finishing layer had no adhesion to the surface of the bottom chord; (**b**) the finishing layer had good adhesion to the surface of the bottom chord.

During the survey, the technical condition of the thermal insulation and the finishing layer of the bottom chord of the steel trusses was found to be varied. In the nodes, where the bottom chord of the truss supports the precast reinforced concrete elements, it was found that the gap between the reinforced concrete element and the steel angles of the truss was sometimes filled with bulk thermal insulation, at other times it was empty (Figure 5b). It was also found that on some trusses, the finishing layer had good adhesion to the surface of the bottom chord (Figure 5b), although this was not found on most trusses (Figure 5a). In the authors' opinion, this may affect condensation conditions on the surface of the metal elements of the truss. Moisture condensation on steel structural elements leads to steel corrosion and a decrease in the thickness of structural elements. As a result, it can lead to a loss of load-bearing capacity of both, individual parts, and the entire structure. The significant corrosion of the bottom chord elements of the attic ceiling trusses and the different conditions for their operation presented the authors with a challenge, namely to investigate the conditions under which moisture condensation occurs on their surface by modelling the temperature and humidity conditions of the structures.

Paper [7] provides an analysis of the corrosion of steel elements of facade systems and describes the various types of corrosion of steel facade systems and methods of their prevention. However, this thorough analysis was carried out for facade systems, while this paper assesses the conditions for the appearance of condensation and further corrosion of steel elements in the ceiling structure. In papers [8,9], the effect of moisture condensation on the internal elements of the coating—wooden beams and OSB boards—was assessed. It was demonstrated that moisture condensation on the surface of wooden elements worsens the performance of the structures, as in the case under consideration.

Studies of moisture condensation on interior building surfaces [10] and building glazing surfaces [11–13] were carried out both by experimental and numerical methods. In [14], experimental studies of the hygrothermal operating conditions of a historical building were carried out, and a computational analysis of the risks of moisture condensation on the inner surface of the partitions was performed. However, such studies concerned the open surfaces of structures, while the work investigated the conditions of condensation on the surface of structures located in the attic ceiling. Features of the humidity regime in the enclosing structures of the building were studied in [15–17], and in [18], a numerical study of moisture condensation in the enclosing structures of the building was performed using the Glaser diagram method. Studies of the temperature and humidity regime and the possibility of mold formation with various design solutions, materials and thermal insulation of enclosing structures were carried out [19,20]. Numerical modelling of the performance of waterproofing materials in building structures and their influence on temperature and humidity conditions were carried out in [21].

In [22,23], monitoring of changes in temperature and humidity, their distribution in the attic and the impact on the building's roof structures were carried out. The temperature and humidity regime of attic spaces was studied in [24,25] when developing recommendations for the repair and restoration of building roofing. The impact of air exchange on the temperature and humidity regime of attic spaces was studied in [26–28]. In [29], it was determined that most roof damages are caused by precipitation or moisture inside the room, which requires attention to the design of the temperature and humidity conditions of the structures.

The restoration of historical buildings requires a balanced approach; energy conservation in historical buildings is often achieved by partial thermal insulation of the enclosing structures. The use of internal thermal insulation can cause a risk of condensation, deterioration of temperature and humidity conditions and, as a result, damage to the enclosing structures. The works [30–35] deal with the modernization of historical buildings and the impact on the temperature and humidity conditions of the enclosing structures of such buildings. A detailed review of the problems and methods of energy retrofitting of historical and traditional buildings is given in [36]. The energy retrofitting of historical buildings from a legislative and regulatory point of view has been highlighted in [37].

2. Materials and Methods

The studies were carried out using calculations of flat temperature and humidity fields [38]. The calculations assumed that the attic air temperature is from $t_{attic} = -15$ °C and higher up to the temperature at which water vapor does not condense on the metal surfaces of the bottom chord of the trusses. The indoor temperature is assumed to be $t_{internal} = 20$ °C (for a public building) [39].

The ceiling structure is shown in Figure 6. The characteristics of the layers of the buildings enclosing structures are shown in Table 1.

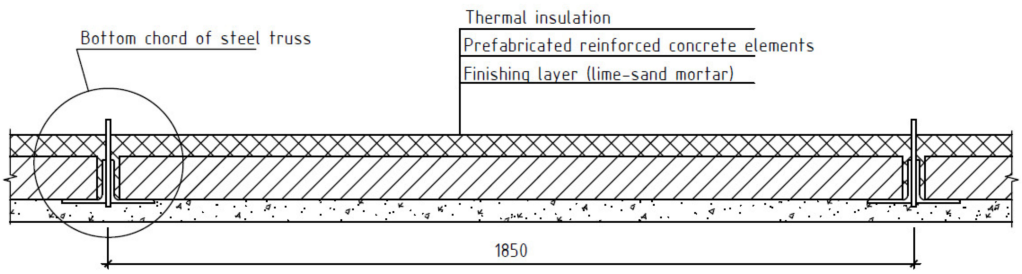


Figure 6. Construction of the existing attic ceiling (unit: mm).

Table 1. Characteristics of the layers of the buildings enclosing structures.

Name of the Layer	Thickness, m	Thermal Conductivity, W/(m·K)	Vapor Permeability Coefficient, mg/(m·h·Pa)
Finishing layer (lime-sand mortar)	0.05	0.81	0.12
Precast reinforced concrete elements	0.1	2.04	0.03
Thermal insulation contaminated with debris	0.05	0.26	0.22
Metal		58	0

The study area (Figure 7) was surveyed along the axes of symmetry of the attic ceiling structure, where the direction of the heat flow passing through the structure does not deviate from these axes. The axes of symmetry pass through the midpoint between the truss chords and the midpoint between the truss angles. The beginning of the area of water vapor condensation on the surfaces of metal structures of the bottom chord of the truss was taken in the middle of the bottom surface of the gusset plate (calculated model with a gusset plate) and on the edge of the angles (calculated model without a gusset plate). The surfaces of the metal structures of the truss's bottom chord, where the possibility of condensate formation was investigated, are shown in Figure 7.

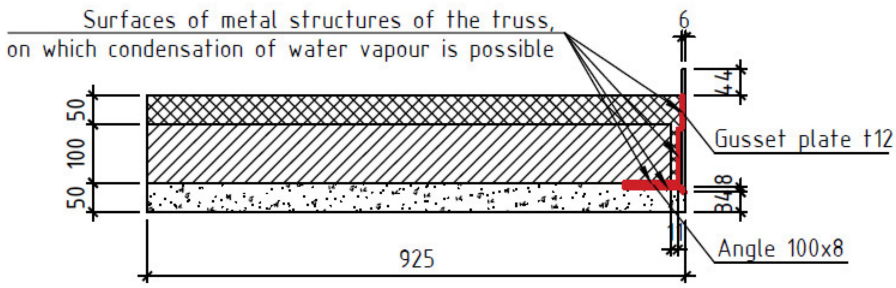


Figure 7. Surfaces of the metal elements of the truss's bottom chord, where condensation of water vapor is possible (units: mm).

The heat transfer coefficient on the inner surface of the attic ceiling $\alpha_{\text{inner}} = 8.7\ \text{W}/\left(\text{m}^2{\cdot}\text{K}\right)$, on the outer surface $\alpha_{\text{outer}} = 6\ \text{W}/\left(\text{m}^2{\cdot}\text{K}\right)$, were taken from Appendix B [40]. Moisture exchange resistance on the inner surface $R_{e.\text{inner}} = 0.027\ (\text{m}{\cdot}\text{h}{\cdot}\text{Pa})/\text{mg}$, on the outer surface $R_{e.\text{outer}} = 0.013\ (\text{m}{\cdot}\text{h}{\cdot}\text{Pa})/\text{mg}$.

Condensation of water vapor occurs on the surfaces of metal structures of the bottom chord of the truss, connected to layers of plaster, reinforced concrete, and thermal insulation. Condensation does not occur on the surfaces of metal structures that are connected to the attic air since the temperature of these surfaces is higher than the temperature of the attic.

The damage found during the survey (Figure 5) was modeled as follows:

- The presence of thermal insulation (Figure 5b) was modelled with different options for filling the gap between the reinforced concrete element and the angles of the truss with thermal insulation for the area with a gusset plate connecting the two angles and for the area without a gusset plate.
- The finishing layer detachment from angles of the truss (Figure 5a) was modelled in the form of a gap of various sizes.

The numerical modeling method will be demonstrated for a calculation scheme with a gusset plate. The gaps between the angles and precast reinforced concrete elements are filled with thermal insulation.

The calculation scheme is shown in Figure 8. The temperature in the attic is assumed to be −15 °C, relative humidity is 70%. The resulting temperature field and the field of partial pressure of water vapor are shown in Figure 9 (calculated by the software package «ELCUT», education version).

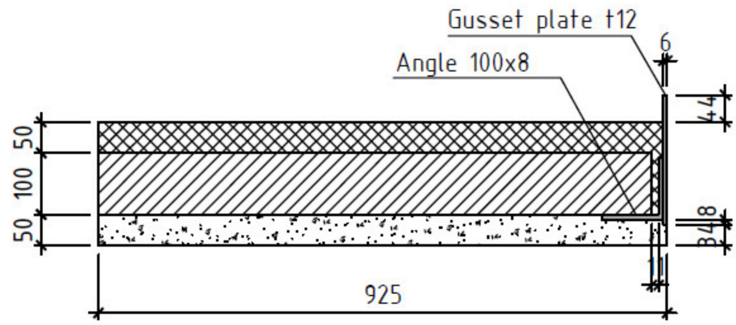
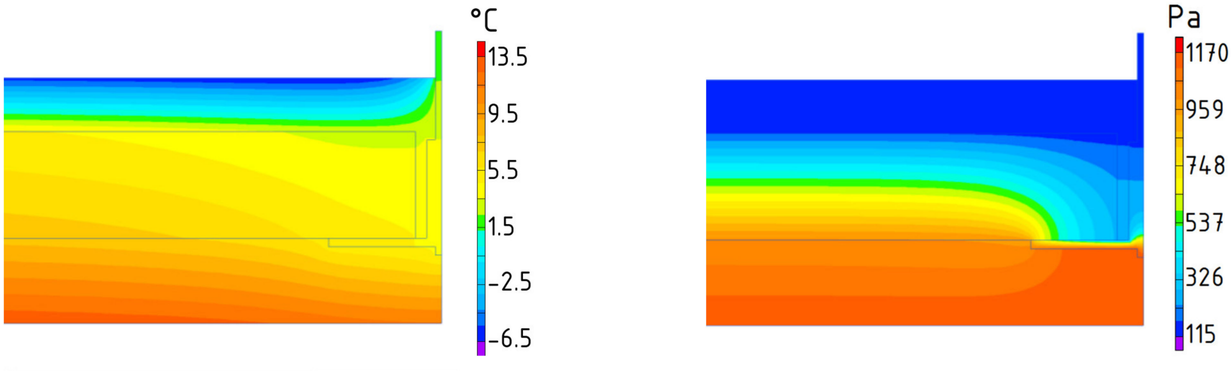


Figure 8. Calculation scheme with a gusset plate. The gaps between the angles and precast reinforced concrete elements are filled with thermal insulation (units: mm).

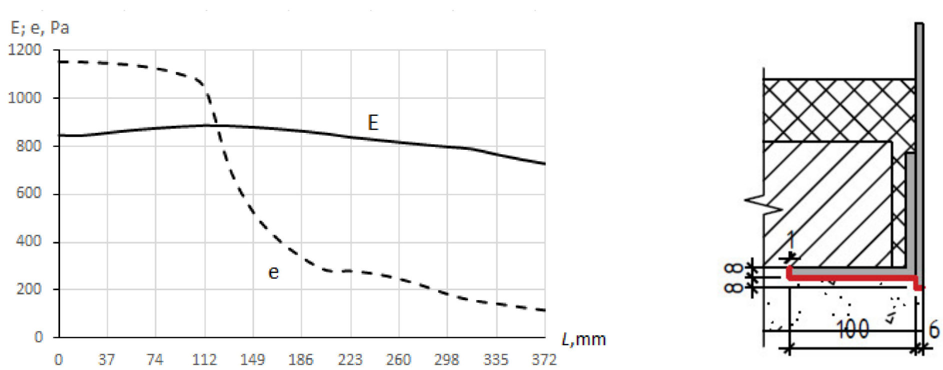


(**a**) (**b**)

Figure 9. Fields: (**a**) temperature; (**b**) partial pressure of water vapor.

The possibility of condensate formation was determined in the areas of the metal structures of the bottom chord of the truss that did not come into contact with the attic air. Areas that come into contact with the attic air were not considered. Condensation of water vapor from the attic air is impossible on these areas since the attic air temperature is higher than the surface temperature of these elements.

Figure 10a shows graphs of changes in the partial pressure of water vapor e and partial pressure of saturated water vapor E in the area of metal structures that do not come into contact with the attic air.



(**a**) (**b**)

Figure 10. Graphs of changes in partial pressure of water vapor e and partial pressure of saturated water vapor E in the area of metal structures that do not come into contact with the attic air (**a**); the condensation area along the perimeter of the section of the bottom chord of the truss (units: mm) (**b**).

As seen from the graphs in Figure 10a, water vapor condenses and corrosion of metal structures is possible. The length of the condensation area along the perimeter of the section of the bottom chord of the truss is 123 mm (Figure 10b). The beginning of the condensation area ($\ell = 0$ mm) is located in the middle of the bottom surface of the gusset plate between the angles. It extends along the bottom surface of the angles.

Similar studies were performed at relative air humidity in the attic of 50% and 30%. The attic air temperature at which the calculations of temperature and humidity fields were performed was −15 °C, −10 °C, −5 °C, and −4 °C. The last temperature, −4 °C is the temperature at which condensation does not occur.

Graphs of changes in partial pressures at a relative humidity of 70% in the attic are shown in Figure 11, at 50% in Figure 12, and at 30% in Figure 13.

Table 2 shows the length of the condensation area along the perimeter of the section of the bottom chord of the truss, depending on the temperature and relative humidity of the air in the attic.

Table 2. The length of the condensation area along the perimeter of the section of the bottom chord of the truss, depending on the temperature and relative humidity of the air in the attic (calculation scheme with a gusset plate: the gaps between the angles and precast reinforced concrete elements are filled with thermal insulation).

Air Temperature in the Attic, °C	The Length of the Condensation Area along the Perimeter of the Section of the Bottom Chord of the Truss, mm at Relative Air Humidity in the Attic, %		
	70	50	30
−15	123	123	123
−10	115	114	113
−5	31	29	27
−4	0	0	0

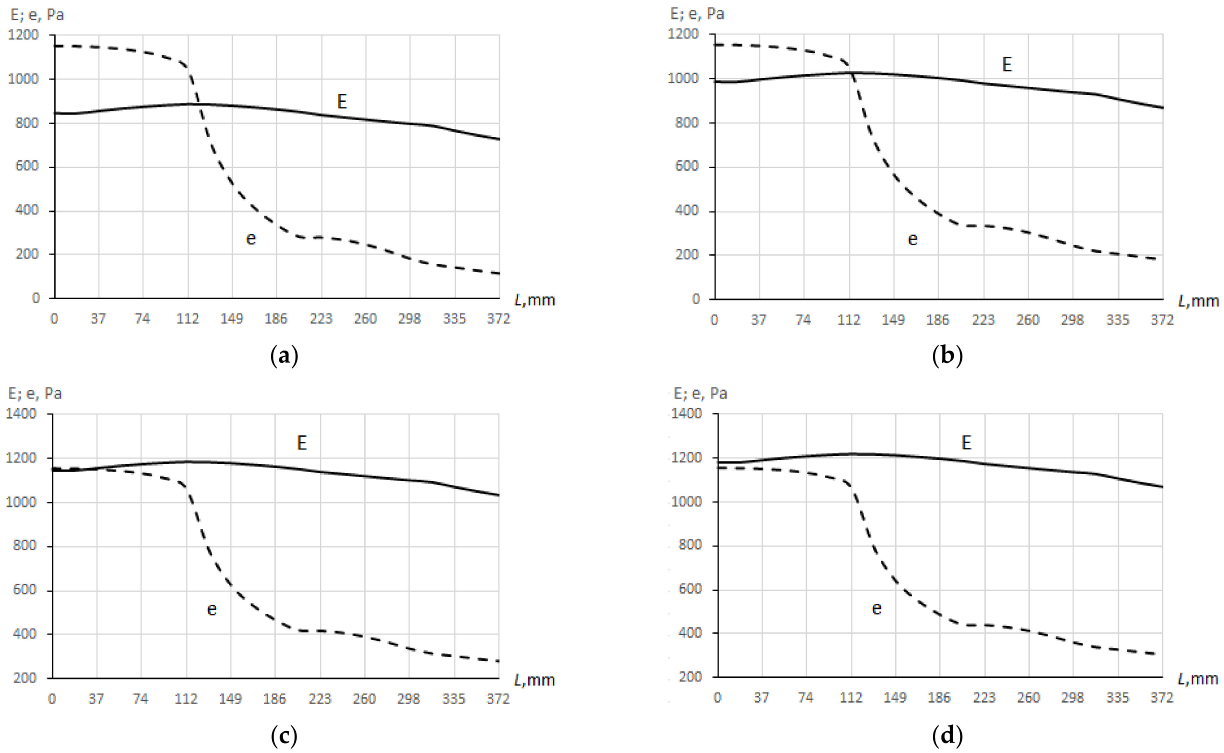


Figure 11. Graphs of changes in the partial pressure of water vapor e and partial pressure of saturated water vapor E in the area of metal structures that are not in contact with the attic air at a relative humidity in the attic of 70% and its temperature: (**a**) −15 °C; (**b**) −10 °C; (**c**) −5 °C; and (**d**) −4 °C.

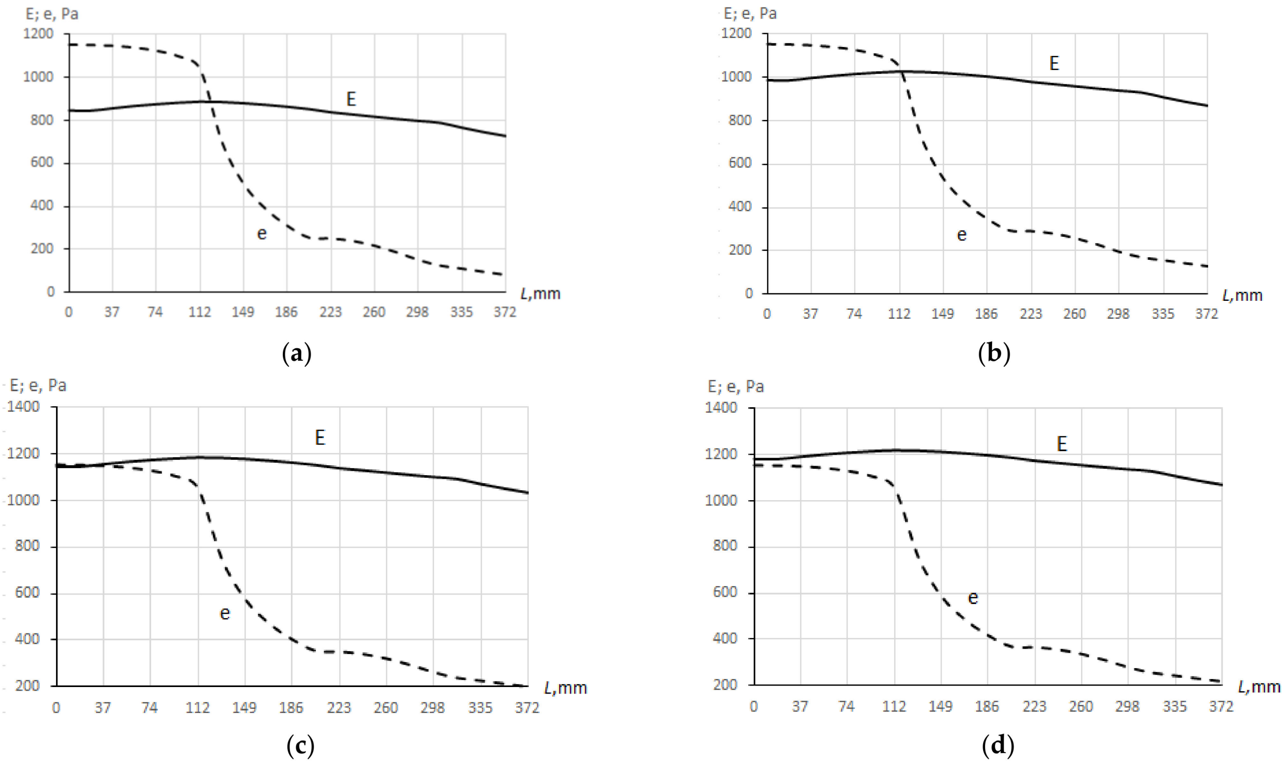


Figure 12. Graphs of changes in the partial pressure of water vapor e and partial pressure of saturated water vapor E in the area of metal structures that are not in contact with the attic air at a relative humidity in the attic of 50% and its temperature: (**a**) −15 °C; (**b**) −10 °C; (**c**) −5 °C; and (**d**) −4 °C.

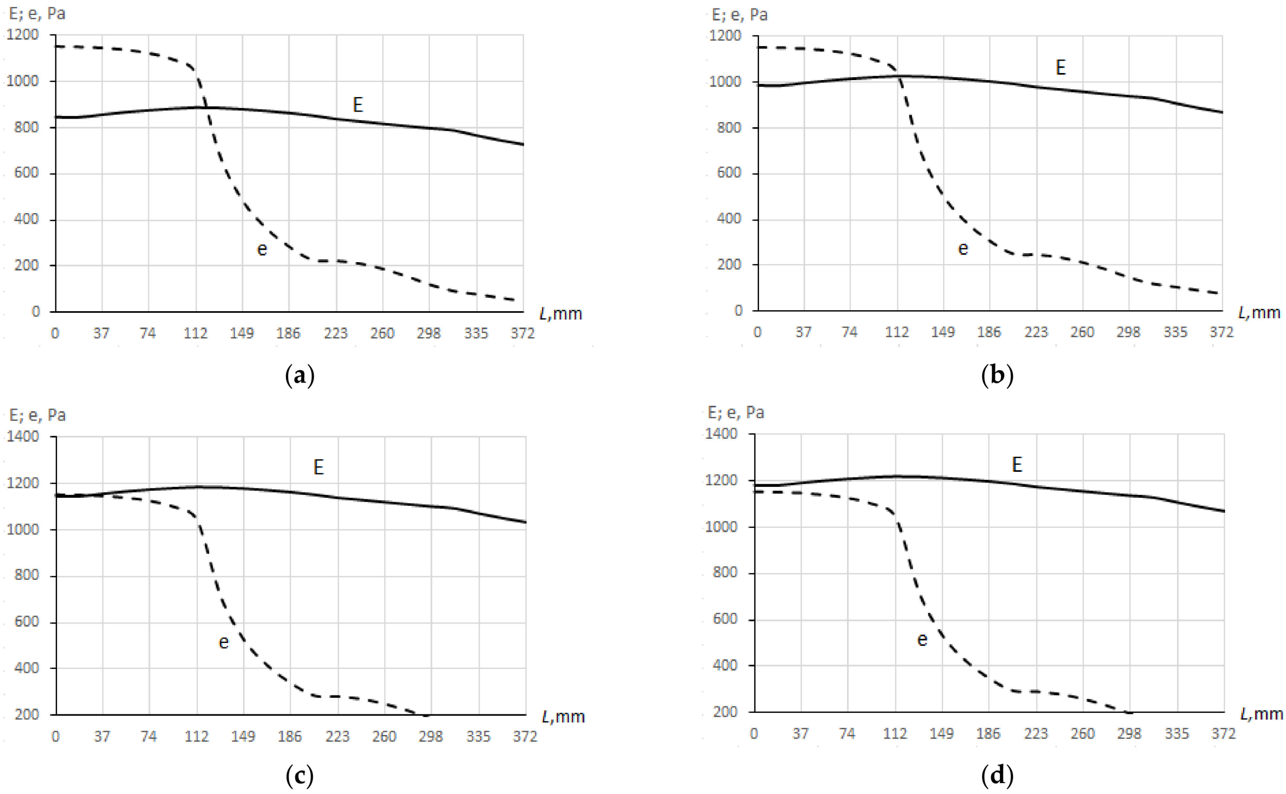


Figure 13. Graphs of changes in the partial pressure of water vapor e and partial pressure of saturated water vapor E in the area of metal structures that are not in contact with the attic air at a relative humidity in the attic of 30% and its temperature: (**a**) −15 °C; (**b**) −10 °C; (**c**) −5 °C; and (**d**) −4 °C.

Based on the values obtained (Table 2), graphs were plotted for the length of the condensation area along the perimeter of the section of the bottom chord of the truss depending on the temperature and relative humidity of the attic air (Figure 14). As can be seen from the results in Table 2 and the plotted graph (Figure 14), relative air humidity in the attic has virtually no effect on the size of the condensation area. Since the longest condensation area along the perimeter of the section of the bottom chord of the truss is observed at a relative humidity in the attic of 70%, and the value of the relative humidity slightly affects its value, further studies were carried out only with relative humidity in the attic of 70%.

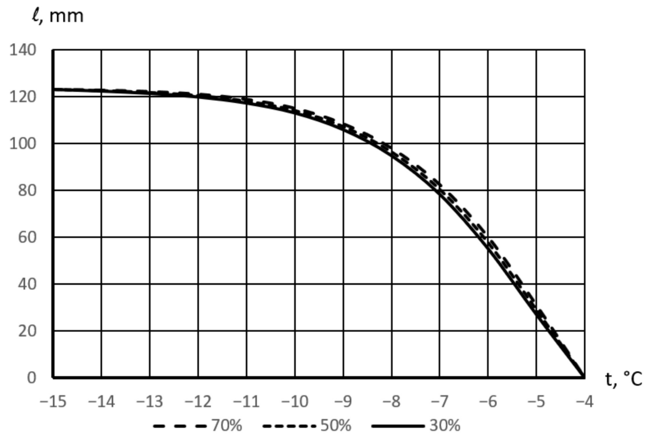


Figure 14. Graphs of the length of the condensation area along the perimeter of the section of the bottom chord of the truss depending on the temperature and relative humidity of the air in the attic.

The performed studies have shown that when the gaps between the angles and precast reinforced concrete elements are filled with thermal insulation, water vapor condensation on the surfaces of the bottom chord of the metal truss occurs when the air temperature in the attic is below −4 °C. When the air temperature in the attic drops, the size of the condensation area increases. Most moisture condenses on the bottom surface of the gusset plate.

3. Results

3.1. Calculation Scheme with a Gusset Plate: The Gaps between the Angles and Precast Reinforced Concrete Elements Are Not Filled with Thermal Insulation

The calculation scheme is shown in Figure 15. The temperature field and the field of partial pressure of water vapor, graphs of changes in the partial pressure of water vapor e and partial pressure of saturated water vapor E at a relative humidity in the attic of 70% and its temperature −15 °C, −10 °C, −5 °C, 0 °C, and 4 °C were constructed. Table 3 shows the length of the condensation area along the perimeter of the section of the bottom chord of the truss depending on the air temperature and relative humidity in the attic.

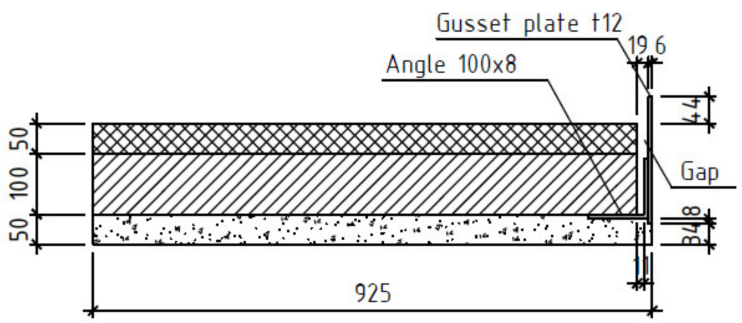


Figure 15. Calculation scheme with a gusset plate. The gaps between the angles and precast reinforced concrete elements are not filled with thermal insulation (units: mm).

Table 3. The length of the condensation area along the perimeter of the section of the bottom chord of the truss, depending on the temperature and relative humidity of the air in the attic (calculation scheme with a gusset plate: the gaps between the angles and precast reinforced concrete elements are not filled with thermal insulation).

Air Temperature in the Attic, °C	The Length of the Condensation Area along the Perimeter of the Section of the Bottom Chord of the Truss, mm at Relative Air Humidity in the Attic 70%
−15	143
−10	133
−5	126
0	116
4	0

After analyzing the obtained results, the following conclusion can be drawn: if there is an air gap between the thermal insulation and the bottom chord structures of the metal truss, then when the air temperature in the attic is below 4 °C, water vapor condensation occurs on the surface of the bottom chord of the truss, resulting in possible corrosion of these elements.

3.2. Calculation Scheme with a Gusset Plate: Detachment of the Finishing Layer from the Elements of the Bottom Chord of the Truss

The calculation scheme is shown in Figure 16. The studies were carried out with detachment sizes of 5 mm, 10 mm, 15 mm (air gap sizes). The temperature field and the field of partial pressure of water vapor, graphs of changes in the partial pressure of water vapor e and partial pressure of saturated water vapor E at a relative humidity in the attic of 70% and its temperature −15 °C, −10 °C, −5 °C, −3 °C were constructed. Table 4 shows the length of the condensation area along the perimeter of the section of the bottom chord of the truss depending on the air temperature in the attic and air gap sizes.

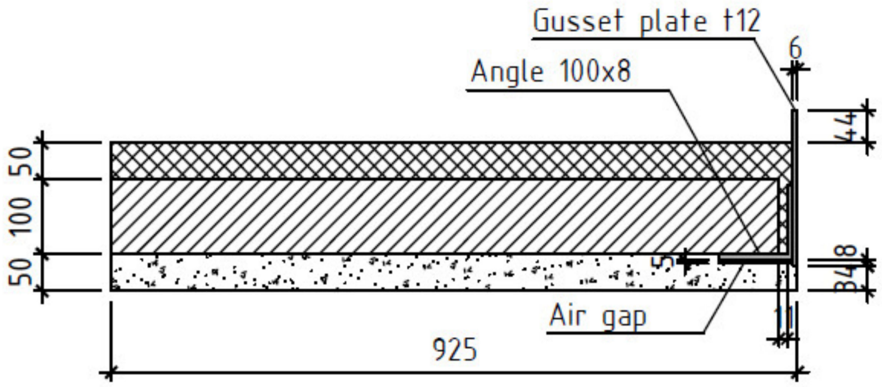


Figure 16. Calculation scheme with a gusset plate. Detachment of the finishing layer from the elements of the bottom chord of the truss (units: mm).

If there is a detachment of the finishing layer from the metal structures of the truss, then when the air temperature in the attic is below −3 °C, water vapor condensation occurs on the surface of the bottom chord of the truss, resulting in possible corrosion of these elements. As the thickness of the detachment increases, the length of the condensation area along the perimeter of the section of the bottom chord of the truss increases.

Table 4. The length of the condensation area along the perimeter of the section of the bottom chord of the truss, depending on the temperature and relative humidity of the air in the attic (calculation scheme with a gusset plate: detachment of the finishing layer from the elements of the bottom chord of the truss).

Air Temperature in the Attic, °C	The Length of the Condensation Area along the Perimeter of the Section of the Bottom Chord of the Truss, mm at Relative Air Humidity in the Attic 70% At Air Gap Sizes, mm		
	5	**10**	**15**
−15	125	126	126
−10	121	122	123
−5	76	90	99
−3	0	0	0

3.3. Calculation Scheme with a Gusset Plate: Partial Filling of the Gap with Thermal Insulation between Precast Concrete Elements and Metal Structures

The calculation scheme is shown in Figure 17. The temperature field and the field of partial pressure of water vapor, graphs of changes in the partial pressure of water vapor e and partial pressure of saturated water vapor E at a relative humidity in the attic of 70% and its temperature −15 °C, −10 °C, −5 °C, −4 °C were constructed. Table 5 shows the length of the condensation area along the perimeter of the section of the bottom chord of the truss depending on the air temperature and relative humidity in the attic.

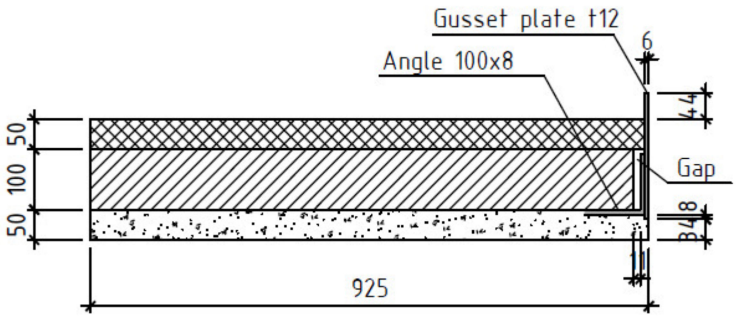


Figure 17. Calculation scheme with a gusset plate. Partial filling of the gap with thermal insulation between precast concrete elements and metal structures (units: mm).

Table 5. The length of the condensation area along the perimeter of the section of the bottom chord of the truss, depending on the temperature and relative humidity of the air in the attic (calculation scheme with a gusset plate: partial filling of the gap with thermal insulation between precast concrete elements and metal structures).

Air Temperature in the Attic, °C	the Length of the Condensation Area along the Perimeter of the Section of the Bottom Chord of the Truss, mm at Relative Air Humidity in the Attic 70%
−15	123
−10	114
−5	31
−4	0

When the thermal insulation gap between the precast concrete elements and the metal structures is partially filled, when the air temperature in the attic is below −4 °C, water vapor condenses on the surfaces of the bottom chord of the truss, resulting in possible corrosion of these elements.

3.4. Calculation Scheme without a Gusset Plate: The Gaps between the Angles and Precast Reinforced Concrete Elements Are Filled with Thermal Insulation

The calculation scheme is shown in Figure 18. The temperature field and the field of partial pressure of water vapor, graphs of changes in the partial pressure of water vapor e and partial pressure of saturated water vapor E, were constructed. Table 6 shows the length of the condensation area along the perimeter of the section of the bottom chord of the truss depending on the air temperature and relative humidity in the attic.

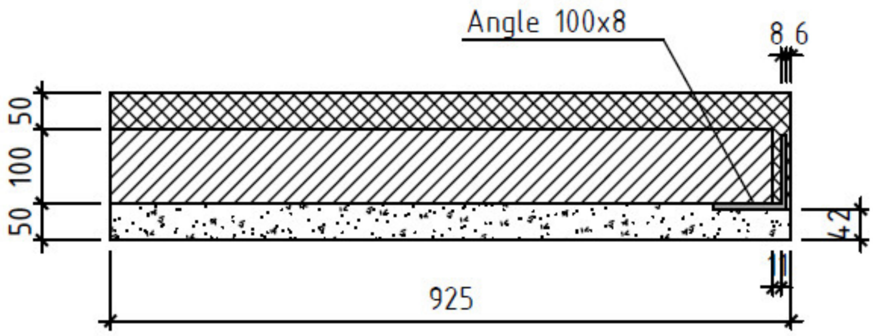


Figure 18. Calculation scheme without a gusset plate. The gaps between the angles and precast reinforced concrete elements are filled with thermal insulation (units: mm).

Table 6. The length of the condensation area along the perimeter of the section of the bottom chord of the truss, depending on the temperature and relative humidity of the air in the attic (calculation scheme without a gusset plate: the gaps between the angles and precast reinforced concrete elements are filled with thermal insulation).

Air Temperature in the Attic, °C	The Length of the Condensation Area along the Perimeter of the Section of the Bottom Chord of the Truss, mm at Relative Air Humidity in the Attic 70%
−15	60
−14	0

In the section without a gusset plate, when completely filled with thermal insulation, condensation on the surfaces of the bottom chord of the metal truss occurs when the temperature in the attic is below −14 °C. This is explained by the fact that if there is a layer of thermal insulation between the angles of the bottom chord of the truss and the attic air, the surface temperature of the angles increases. The partial pressure of saturated water vapor on these surfaces also increases, which improves the humidity condition.

3.5. Calculation Scheme without a Gusset Plate: The Gaps between the Angles and Precast Reinforced Concrete Elements Are Not Filled with Thermal Insulation

The calculation scheme is shown in Figure 19. The temperature field and the field of partial pressure of water vapor, graphs of changes in the partial pressure of water vapor e and partial pressure of saturated water vapor E at a relative humidity in the attic of 70% and its temperature −15 °C, −10 °C, −5 °C, 0 °C, 1 °C were constructed. Table 7 shows the length of the condensation area along the perimeter of the section of the bottom chord of the truss depending on the air temperature and relative humidity in the attic.

In the area without a gusset plate, in the absence of thermal insulation between the angles and the precast reinforced concrete elements, condensation occurs when the temperature in the attic is below 1 °C.

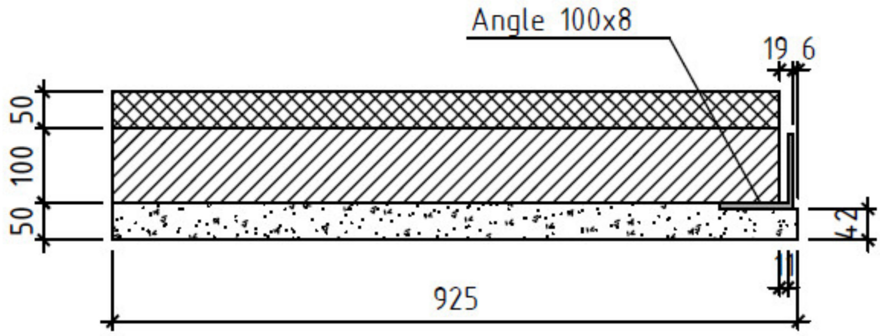


Figure 19. Calculation scheme without a gusset plate. The gaps between the angles and precast reinforced concrete elements are not filled with thermal insulation (units: mm).

Table 7. The length of the condensation area along the perimeter of the section of the bottom chord of the truss, depending on the temperature and relative humidity of the air in the attic (calculation scheme without a gusset plate: the gaps between the angles and precast reinforced concrete elements are not filled with thermal insulation).

Air Temperature in the Attic, °C	The Length of the Condensation Area along the Perimeter of the Section of the Bottom Chord of the Truss, mm at Relative Air Humidity in the Attic 70%
−15	122
−10	108
−5	93
0	45
1	0

3.6. Verification Calculations of the Possibility of Condensate Formation on the Metal Surfaces of the Bottom Chord of Trusses

Since the truss is made of low-carbon steel, its brittle fracture is possible at −20 °C and below. In addition, when the attic temperature is below 0 °C, snow and ice on the roof of the building will stop melting, thus increasing the load on the truss. Therefore, it is necessary to keep the attic temperature above 0 °C when developing solutions for the restoration of the ceiling above the hall of the historical building. This is achieved by air entering the attic from the ventilation ducts and sufficient heat flow through the attic ceiling. A minimum thickness of thermal insulation was determined (a layer of mineral wool with a density of 200 kg/m^3 and a thickness of 100 mm) to prevent condensation on the bottom chord of the steel trusses. At the same time, the resistance to heat transfer of the attic ceiling will be less than the norm [39].

In order to verify the possibility of condensate formation on the metal surfaces of the bottom chord of the trusses, two calculation schemes, with and without a gusset plate, were considered in the developed design solutions.

3.6.1. Calculation Scheme with a Gusset Plate: Thermal Insulation—Mineral Wool with a Density of 200 kg/m^3 and a Thickness of 100 mm

The calculation scheme is shown in Figure 20. The air temperature in the attic is assumed to be −15 °C. Figure 21 shows graphs of changes in the partial pressure of water vapor e and partial pressure of saturated water vapor E in the area of metal structures that are not in contact with the attic air.

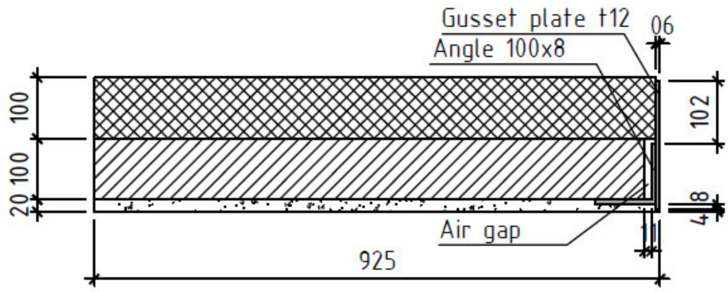


Figure 20. Calculation scheme with a gusset plate (units: mm). Thermal insulation—mineral wool with a density of 200 kg/m^3 and a thickness of 100 mm.

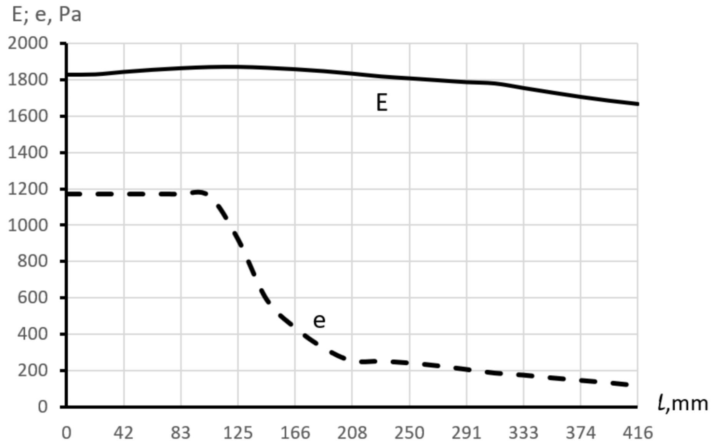


Figure 21. Graphs of changes in the partial pressure of water vapor e and partial pressure of saturated water vapor E in the area of metal structures that are not in contact with the attic air for calculation scheme with a gusset plate (thermal insulation—mineral wool with a density of 200 kg/m^3 and a thickness of 100 mm).

As seen from the graphs in Figure 21, condensation does not occur.

3.6.2. Calculation Scheme without a Gusset Plate: Thermal Insulation—Mineral Wool with a Density of 200 kg/m^3 and a Thickness of 100 mm

The calculation scheme is shown in Figure 22. The air temperature in the attic is assumed to be −15 °C. Figure 23 shows graphs of changes in the partial pressure of water vapor e and partial pressure of saturated water vapor E in the area of metal structures that are not in contact with the attic air.

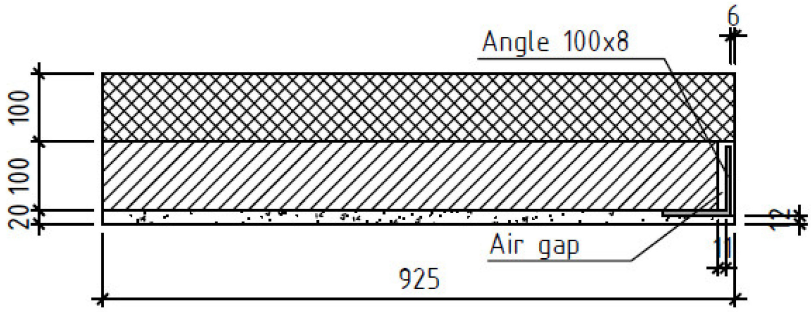


Figure 22. Calculation scheme without a gusset plate (units: mm). Thermal insulation—mineral wool with a density of 200 kg/m^3 and a thickness of 100 mm.

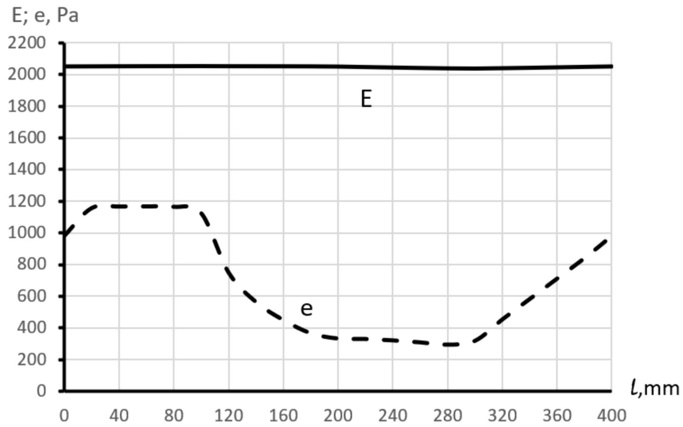


Figure 23. Graphs of changes in the partial pressure of water vapor e and partial pressure of saturated water vapor E in the area of metal structures that are not in contact with the attic air for calculation scheme without a gusset plate (thermal insulation—mineral wool with a density of 200 kg/m^3 and a thickness of 100 mm).

As seen from the graphs in Figure 23, condensation does not occur.

4. Discussion

In the existing structure of the attic ceiling of the hall of the historical building, water vapor condensation on the metal surfaces of the bottom chord of trusses, and, as a result, their corrosion occurs in the area where the metal gusset plate is located between the paired angles. This is explained by the fact that the metal gusset plate cuts through the thermal insulation and partially mixes with the attic air. This leads to a decrease in the temperature of the metal structures. This results in a decrease in the partial pressure of saturated water vapor on them and condensation. Condensation occurs when the air temperature in the attic is below 4 °C to −4 °C with various options for incomplete filling of gaps between angles and angles and precast reinforced concrete elements with thermal insulation.

In the areas of the bottom chord of the trusses without a gusset plate between the angles, the moisture condition process is smaller. So, when filling the gaps between angles and angles and precast reinforced concrete elements with thermal insulation, condensation occurs if the air temperature in the attic is below −14 °C. This is explained by the fact that there is thermal insulation between the angles and the attic air. As a result, the surface temperature of the angles increases. The partial pressure of saturated water vapor on these surfaces also increases, which improves the moisture condition. If these gaps are not completely filled with thermal insulation, condensation occurs when the air temperature in the attic is below 1 °C.

After analyzing the graphs of the changes in the partial pressure of water vapor e and partial pressure of saturated water vapor E in the area of metal structures that are not in contact with the attic air at an air temperature in the attic of −15 °C, −10 °C, −5 °C, −4 °C, and the relative humidity in the attic of 70%, 50%, 30% (Table 2), we can conclude that the relative humidity of the air in the attic does not affect the length of the condensation area along the perimeter of the section of the bottom chord of the truss.

The minimum thickness of thermal insulation (a layer of mineral wool with a density of 200 kg/m^3 and a thickness of 100 mm) at which moisture does not condense on the bottom chord of the steel trusses was determined. Verification studies of the proposed design solution using mineral wool thermal insulation with a density of 200 kg/m^3 and a thickness of 100 mm indicate that the proposed design solution prevents the formation of condensation by increasing the heat transfer resistance of the attic ceiling area between the metal structures and the attic air. The thermal insulation covers the connecting gusset plate, resulting in an increase in the temperature of the metal structures. The partial pressure of saturated water vapor on the metal surfaces of the bottom chord of the trusses increases.

This prevents the formation of condensation in the range of possible temperatures in the attic.

5. Conclusions

The case considered in the article may prove to be typical for historical buildings with a long service life. Massive steel structures were used quite frequently in the construction of reinforced concrete or brick ceilings/coverings. At the same time, the issue of safety of the steel elements from corrosion damage in the middle of the overlap structure was scarcely addressed.

The results are typical for unheated attics of buildings that lack or have insufficient protective properties of the thermal insulation of the attic floor structure. The study made it possible to determine the influence of the following parameters on the possibility of condensation forming on the surface of steel structures: filling the gap between the angles and precast reinforced concrete elements resting on the lower flange of the angles with thermal insulation; filling the gap between the two angles of the bottom chord of the truss with thermal insulation; the possibility of detachment of the different sizes of finishing layer from the surface of the bottom flange of the angles. The temperature and humidity parameters at which moisture condensation occurs on the surface of metal structures of the bottom chord of steel trusses for the covering of the historical building were determined. Based on the design features of the coating of the historical building, the minimum thickness of the thermal insulation of the attic floor of the building was determined to prevent moisture condensation on the surfaces of the bottom chord of the steel trusses.

The performed investigation is a proposed and proven algorithm for assessing the possibility of corrosion in hidden steel load-bearing elements. The proposed algorithm can prevent the reduction or loss of the load-bearing capacity of the structures. In the case of historical buildings, it could prevent the destruction of the finish layer too (which may have cultural heritage value).

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References

1. Heindl, W.; Krec, K.; Panzhauser, E.; Sigmund, A. *Wärmebrücken*; Springer: Wien, Austria, 1987. (In German)
2. Panzhauser, E.; Rabenseifer, R. Die bauökologische Belastung der umgebenden Außenwelt durch sanierte und nichtsanierte Plattenwohnhäuser anhand eines Beispiels aus Bratislava. In Proceedings of the 1996 International Symposium of CIB Working Commission 67-Energy and Mass Flow in the Life Cycle of Buildings, Vienna, Austria, 4–10 August 1996; pp. 361–366. (In German).
3. Skibitska, T.; Shuleshko, I. Decorative decoration of Poltava buildings in the 1900–1910s. *Res. Fine Arts* **2016**, *2*, 65–72. (In Ukrainian)
4. Pavlovsky, V. *The Live and Work of Vasyl H. Krychevsky*; The Ukrainian Academy of Arts and Sciences in the U.S., Inc.: New York, NY, USA, 1974. (In Ukrainian)

5. Chepelyk, V. *Ukrainian Architectural Modern*; KNUBA: Kyiv, Ukraine, 2000. (In Ukrainian)
6. Semko, O.; Filonenko, O.; Hasenko, L.; Mahas, N.; Rudenko, V. Temperature-humidity regime in the operation of the roofs of historic buildings. *Acad. J. Ind. Mach. Build. Civ. Eng.* **2021**, *2*, 47–52.
7. Soufeiani, L.; Foliente, G.; Nguyen, K.; San Nicolas, R. Corrosion protection of steel elements in façade systems—A review. *J. Build. Eng.* **2020**, *32*, 101759. [CrossRef]
8. Martín-Garín, A.; Millán-García, J.A.; Terés-Zubiaga, J.; Oregi, X.; Rodríguez-Vidal, I.; Baïri, A. Improving Energy Performance of Historic Buildings through Hygrothermal Assessment of the Envelope. *Buildings* **2021**, *11*, 410. [CrossRef]
9. Graham, L.; Scott, M.; Pappas, A. Natatorium Building Enclosure Deterioration Due to Moisture Migration. *Buildings* **2012**, *2*, 534–541. [CrossRef]
10. You, S.; Li, W.; Ye, T.; Hu, F.; Zheng, W. Study on moisture condensation on the interior surface of buildings in high humidity climate. *Build. Environ.* **2017**, *125*, 39–48. [CrossRef]
11. Nguyen, C.K.; Teodosiu, C.; Kuznik, F.; David, D.; Teodosiu, R.; Rusaouën, G. A full-scale experimental study concerning the moisture condensation on building glazing surface. *Build. Environ.* **2019**, *156*, 215–224. [CrossRef]
12. Nguyen, C.K.; Teodosiu, C.; Kuznik, F.; David, D.; Rusaouën, G. Full-scale experimental study of moisture condensation on the glazing surface: Condensation rate characterization. *IOP Conf. Ser. Mater. Sci. Eng.* **2019**, *609*, 032035. [CrossRef]
13. Hong, G.; Kim, D.D.; Kim, B.S. Experimental Investigation of Thermal Behaviors in Window Systems by Monitoring of Surface Condensation Using Full-Scale Measurements and Simulation Tools. *Energies* **2016**, *9*, 979. [CrossRef]
14. Nawalany, G.; Sokołowski, P.; Michalik, M. Experimental Study of Thermal and Humidity Conditions in a Historic Wooden Building in Southern Poland. *Buildings* **2020**, *10*, 118. [CrossRef]
15. Yurin, O.; Mahas, N.; Zyhun, A.; Musiienko, O. Aspects of calculation of resistance vapor penetration of enclosing structures. *Acad. J. Ind. Mach. Build. Civ. Eng.* **2020**, *2*, 96–101.
16. Yurin, O.; Mammadov, N.; Semko, P.; Mahas, N. Analysis of the Humidity Condition of Wall Enclosing Structures of Cooling Warehouses and Possible Ways to Improve It. *Lect. Notes Civ. Eng.* **2022**, *181*, 439–448. [CrossRef]
17. Colinart, T.; Glouannec, P.; Pierre, T.; Chauvelon, P.; Magueresse, A. Experimental Study on the Hygrothermal Behavior of a Coated Sprayed Hemp Concrete Wall. *Buildings* **2013**, *3*, 79–99. [CrossRef]
18. Biserni, C.; Imbiombato, A.N. Numerical analysis on building envelope moisture condensation: A case study using the glaser diagram method. *AIP Conf. Proc.* **2019**, *2191*, 020023. [CrossRef]
19. Kon, O.; Caner, İ. The Effect of External Wall Insulation on Mold and Moisture on the Buildings. *Buildings* **2022**, *12*, 521. [CrossRef]
20. Ingebretsen, S.B.; Andenæs, E.; Gullbrekken, L.; Kvande, T. Microclimate and Mould Growth Potential of Air Cavities in Ventilated Wooden Façade and Roof Systems—Case Studies from Norway. *Buildings* **2022**, *12*, 1739. [CrossRef]
21. Ksit, B.; Szymczak-Graczyk, A.; Pilch, R. Numerical Simulation of the Impact of Water Vapour and Moisture Blockers in Energy Diagnostics of Ventilated Partitions. *Materials* **2022**, *15*, 8257. [CrossRef]
22. Korenkova, R.; Krusinsky, P.; Pisca, P. Analysis of the Impact of Microclimate in a Roof Space on a Gothic Truss. *Constr. Commun. Sci. Lett. Univ. Zilina* **2013**, *15*, 27–31. [CrossRef]
23. Kysela, P.; Ponechal, R.; Krušinský, P.; Korenková, R. Pilot monitoring of the internal temperature and humidity in the historic building attic space. *Transp. Res. Procedia* **2021**, *55*, 1214–1220. [CrossRef]
24. Spišáková, M.; Mokrenko, D. Renovation of roof structure of historical building–case study. *Czech J. Civ. Eng.* **2021**, *6*, 71–78. [CrossRef]
25. Semko, O.V.; Yurin, O.I.; Filonenko, O.I.; Mahas, N.M. Investigation of the Temperature–Humidity State of a Tent-Covered Attic. *Lect. Notes Civ. Eng.* **2020**, *73*, 245–252. [CrossRef]
26. Richter, J.; Staněk, K.; Tywoniak, J.; Kopecký, P. Moisture-Safe Cold Attics in Humid Climates of Europe and North America. *Energies* **2020**, *13*, 3856. [CrossRef]
27. Kvist Hansen, T. Danish Dwellings with Cold Attics—Ventilation Rates and Air Exchange between Attic and Dwelling. *Buildings* **2021**, *11*, 64. [CrossRef]
28. Rupp, S.H.; McNeil, S.; Plagmann, M.; Overton, G. Hygrothermal Characteristics of Cold Roof Cavities in New Zealand. *Buildings* **2021**, *11*, 334. [CrossRef]
29. Gullbrekken, L.; Kvande, T.; Jelle, B.P.; Time, B. Norwegian Pitched Roof Defects. *Buildings* **2016**, *6*, 24. [CrossRef]
30. Lisitano, I.M.; Laggiard, D.; Fantucci, S.; Serra, V.; Fenoglio, E. Evaluating the Impact of Indoor Insulation on Historic Buildings: A Multilevel Approach Involving Heat and Moisture Simulations. *Appl. Sci.* **2021**, *11*, 7944. [CrossRef]
31. Negro, E.; Cardinale, T.; Cardinale, N.; Rospi, G. Italian Guidelines for Energy Performance of Cultural Heritage and Historical Buildings: The Case Study of the Sassi of Matera. *Energy Procedia* **2016**, *97*, 7–14. [CrossRef]
32. Curto, D.; Franzitta, V.; Guercio, A.; Panno, D. Energy Retrofit. A Case Study—Santi Romano Dormitory on the Palermo University. *Sustainability* **2021**, *13*, 13524. [CrossRef]
33. Harrestrup, M.; Svendsen, S. Full-scale test of an old heritage multi-storey building undergoing energy retrofitting with focus on internal insulation and moisture. *Build. Environ.* **2015**, *85*, 123–133. [CrossRef]
34. Todorović, M.S.; Ećim-Đurić, O.; Nikolić, S.; Ristić, S.; Polić-Radovanović, S. Historic building's holistic and sustainable deep energy refurbishment via BPS, energy efficiency and renewable energy—A case study. *Energy Build.* **2015**, *95*, 130–137. [CrossRef]
35. Ameen, A.; Bahrami, A.; El Tayara, K. Energy Performance Evaluation of Historical Building. *Buildings* **2022**, *12*, 1667. [CrossRef]

36. Webb, A.L. Energy retrofits in historic and traditional buildings: A review of problems and methods. *Renew. Sustain. Energy Rev.* **2017**, *77*, 748–759. [CrossRef]
37. Mazzarella, L. Energy retrofit of historic and existing buildings. The legislative and regulatory point of view. *Energy Build.* **2015**, *95*, 23–31. [CrossRef]
38. *DSTU ISO 10211-1:2005*; Thermal Bridges in Building Construction—Calculation of Heat Flows and Surface Temperatures—Part 1: General Methods (ISO 10211-1:1995, IDT). Derzhspozhyvstandart of Ukraine: Kyiv, Ukraine, 2008; Valid in Ukraine from 2008 to present.
39. *DBN V.2.6-31: 2021*; Thermal Insulation and Energy Efficiency of Buildings. Minregion of Ukraine: Kyiv, Ukraine, 2022; Valid in Ukraine from 2022 to present.
40. *DSTU-N B V.2.6-189: 2013*; Methods for Choosing Heat-Insulating Material for Building Insulation. Minregion of Ukraine: Kyiv, Ukraine, 2014; Valid in Ukraine from 2014 to present.