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Inspecting the Effects of Moisture Bridge on the Performance of Building and Providing Appropriate Preventive Solutions

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Abstract: Although many studies have investigated the effects of thermal bridges on building energy performance, multidimensional thermal humidity analysis of building coatings remains a challenge due to multiple problems such as complexity of modeling, computer analysis execution time, numerical convergence restraints, and numerous properties related to humidity. The study's main aim is to investigate the effects of moisture bridges on building performance and provide appropriate preventive solutions. In this study, thermal-humidity simulation for evaluating heat and mass transfer in walls of a historic building (building No. 4, Tehran University of Arts, The National Garden Campus) was analyzed using WUFI 2D software. This study evaluated the effectiveness of executive details used in the studied building and compared the performance with recent common details. The obtained results indicate that the information obtained from the moisture and heat audit of the building should be investigated simultaneously and the results lead to a solution to reduce the heat transfer and minimize condensation risks. Appropriate solutions have been studied, according to the conditions of each building element.

Keywords: building envelope; combined heat; humidity transfer analysis; hygrothermal problems; moisture bridge; walls

1 INTRODUCTION

The abundant water on our planet constantly leads to interactions with all living and non-living organisms, driving substances to physicochemical processes. As much as water is essential for all species, it can destroy many natural and man-made building materials and products, such as the blocks used to make building walls that are meant to serve for decades [1-3].

Thus researchers, designers, and building contractors are always trying to reduce tructive role of moisture in buildings to improve human comfort and building durability. This is while the results of this research will cause an annual reduction of billions of tomans in energy consumption. Meanwhile, the main question raised in this research is the effect of moisture transfer on the efficiency of buildings in terms of energy consumption [4, 5].

Saving energy is one of the most important and vital expectations in building and using a building. Some measures for optimizing energy consumption, such as using thermal insulation, reducing air infiltration, limiting ventilation regardless of the function of the building, and the using proper execution details, can cause moisture problems. On the other hand, moisture problems not only increase thermal problems and energy consumption, but also impose huge costs for the destruction and renovation of materials [6-9].

Exterior wall is always exposed to the influx of natural factors such as Humidity. In case of inappropriate design regardless to detailing rules and guidelines, the excessive increase of humidity can have a significant effect on reducing the thermal resistance of the wall. Moisture bridge or in other words, concentrated condensated moisture in the building envelope walls, especially in cold climates, increases heat exchange through the moisture bridge which is most of the time initiated by a thermal bridge, leading to serious damages of the wall materials, when freezing and thawing cycles occur, and causing serious problems in terms of thermal performance and durability of the building. On the other hand, accumulation of moisture in the building wall lead to the growth of fungi and mold, which causes many health problems for residents, including respiratory diseases. Therefore, it is necessary to identify and eliminate the moisture problems of the outer wall of the building, in order to protect national assets, reduce annual energy consumption and increase the useful life of the building [4, 10, 11].

Moisture bridge is a phenomenon occurring due to the condensation of moisture in the building envelope elements, such as double-glazed windows with metal prefixes, corners, thermal bridges, etc., which causes problems and damages more than rainwater infiltration in a cold climate. This phenomenon is considered one of the most essential moisture problems in the building wall, which can significantly affect the performance and durability of the outer wall and cause damage to thermal and humidity insulation. This not only imposes problems for the wall in terms of indoor health conditions (consequences of fungal and mold growth in the wall), but also has a significant negative effect on the thermal performance of the building [7, 8, 12].

Moisture bridge is an example that highlights this problem and causes the destruction of materials and increases the annual energy consumption of a building. The existence of thermal bridge in the building is one of the factors causing this phenomenon in the inner layers of the wall and consequently the formation of moisture bridge changing the heat transfer of the wall from vertical and one-dimensional state to a multidimensional one. Thus, the amount of heat transfer and energy consumption in the building also increases. In this research, by recognizing the types of condensation cases and influencing factors causing moisture bridge in building elements, we try to obtain adequate solutions to prevent condensation risk by eliminating or minimizing moisture bridge. This will lead to a better understanding of their effect on the durability and thermal performance of buildings in cold climate.

The building envelope constantly interacts with changes in indoor and outdoor temperature, pressure and humidity, leading to variable heat and mass (air and humidity) exchange between the indoor and outdoor environment. Building physicists refer to this phenomenon as "heat, air, and moisture transfer" in building materials and components. Building envelope designers and constructors are always trying to provide optimal durable building envelope elements. In this regard, moisture is one of the most influencing factors affecting the energy balance of the building envelope elements.

Moisture bridge is a phenomenon occurring due to deep condensation in thermal bridges of the building envelope elements, such as metal prefixes of windows, structural elements at the junction of the wall with the roof and floor.

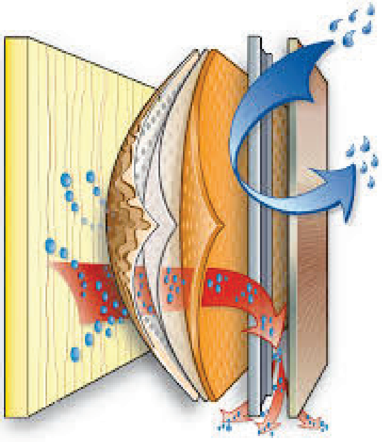


Figure 1 Simultaneous transfer of moisture and heat from the moisture bridge in the building

The formation of a moisture bridge changes the heat transfer of the wall from vertical and one-dimensional state to multidimensional state. Hence, the rate of heat transfer and consequently energy consumption in the building also increases [3]. It is very important to note that in these points, moisture and heat transfer takes place simultaneously (Fig. 1). Generally, the factors affecting moisture problems such as moisture bridge, can be mentioned as follows:

- Hgrothermal (hyumidity and thermal) properties of wall materials
- Climate and hgrothermal conditioning of the interior spaces (with HVAC systems), acting as driving forces on either side of the wall
- Thermal properties of outer and inner surfaces of the wall
- Design of executive details of the wall and its thermal insulation
- Locating the interior spaces of a building (building architecture) [4]

In cold climates, the main moisture concerns are originated from rainwater infiltration, groundwater, deep condensation (condensation in building components), and inner space fungus and mold, which are often associated with high levels of inner humidity.

In this research, after the identification of moisture damage, such as moisture bridge, calculations are formulated, in order to provide appropriate solutions to reduce the above-mentioned damages and improve the humidity-thermal behavior of the external wall of the building.

2 LITERATURE REVIEW

In order to analyze the effects of thermal bridges on building energy performance, some researchers in the 1990s - such as Hagentoft and Claesson [2], Anderson [1], Karti and Blomberg [12] - considered heat loss to the ground, and the effect of peripheral insulation on conventional slab foundations on degree, but no moisture transfer was considered. Narowski et al. [10] described a simple method that enables the modeling of conduction transfer functions for conventional thermal bridges. The aim of the present study is to improve the building energy calculation results obtained from dynamic simulations by combining thermal bridge correction factors in building simulation codes. Al-Sanea and Zadan [11] used a computer model based on the finite volume method in order to quantify the effects of mortar joint height on the thermal performance of building walls under stable two-dimensional periodic conditions. Also Blomberg [12] conducted a study on moisture bridge in the outer wall in 2014. In this study, the location of thermal insulation in different layers has been optimized according to the moisture status of the wall. In the results, the best place for insulation of the inner part of the wall is obtained, while it has many problems in terms of moisture. In order to solve this problem, they suggested the use of silica aerogel in the outer layers, without suggestions related to the durability problems of this gel. In 2012, Häkkinen [6] conducted a study on how to renovate and improve the exterior walls of buildings in Europe and provided a comprehensive solution according to meeting expectations such as modern European standards, annual energy savings, increasing the life span of the building, economic justification of investment payback time. This approach, which is called SUSREF (Sustainable Renovation), ultimately leads to the provision of executive details and suitable materials for a wall that is validated by humidity-thermal simulation [6].

However, there is only a few studies on the effects of humidity on thermal bridges. Therefore, mass transfer in porous media is assumed to be unsaturated and solved using the matrix algorithm MultiTriDiagonal; problems related to numerical instability are avoided by introducing a strong coupling between the energy and mass conservation equations. In the results section, the multidimensional transfer effect in the lower hot-humidity stairs consisting of soil, wall and floor is shown and analyzed in terms of temperature and relative humidity profiles and steam and heat flux in the floor for different foot configurations. For the upper corner, the effects of concrete beams on temperature and relative humidity profiles are presented.

3 METHODOLOGY

The Research prerequisites have been met through field and library studies, using existing databases, as well as observation, photography, and computer simulations. According to the criteria obtained in the theoretical framework, identification of the moisture cases and problems and provision of solutions in various areas are performed; Afterwards, the technical evaluation and validation of best solutions are made by WUFI 2D software, using descriptive statistical methods and logical reasoning.

According to the computational method used in this software, all modes of moisture transfer, including the transfer in gas and liquid phases are investigated. Also, temperature conditions and thermal resistance are simultaneously calculated in each detailed layer of the wall. Due to fluctuations in relative humidity and the ambient temperature inside and outside the building elements, humidity may be long-lasting and vary depending on the type of materials used and their physical characteristics.

Another effective feature of this software is to the possibility of evaluating the moisture storage capacity, by taking into consideration the capillary property of various used materials. Moisture transfer speed is much less than heat transfer time; therefore, the occurrence of condensation at high partial vapor pressure is associated with an increase in ambient temperature and humidity levels. In WUFI software, the boundary conditions on both sides of the wall can be considered dynamic; in another term, the daily and seasonal temperature and humidity fluctuations can be taken into account as dynamic driving forces. For this purpose, in the computational model, building elements are divided into finer layers (meshing). In this case, the nonlinear distribution of temperature and humidity in different layers of a building element can be investigated more precisely. The computational algorithm of this software is briefly described in the Fig. 2.

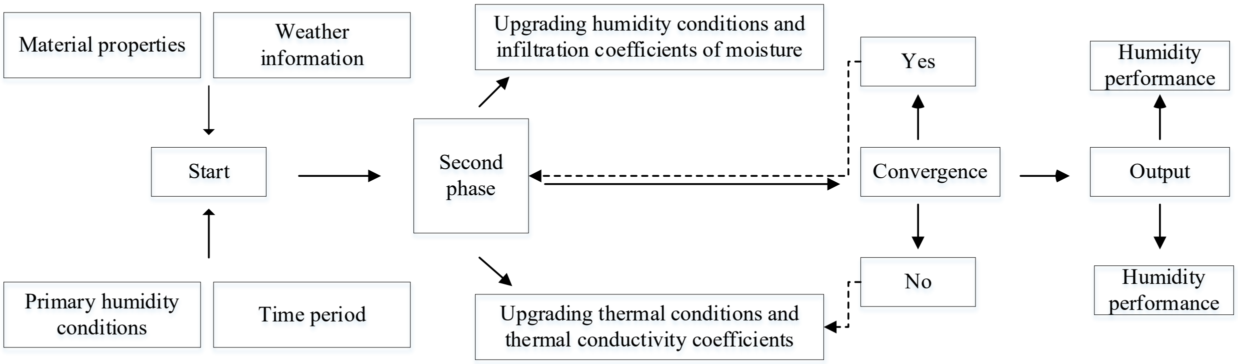
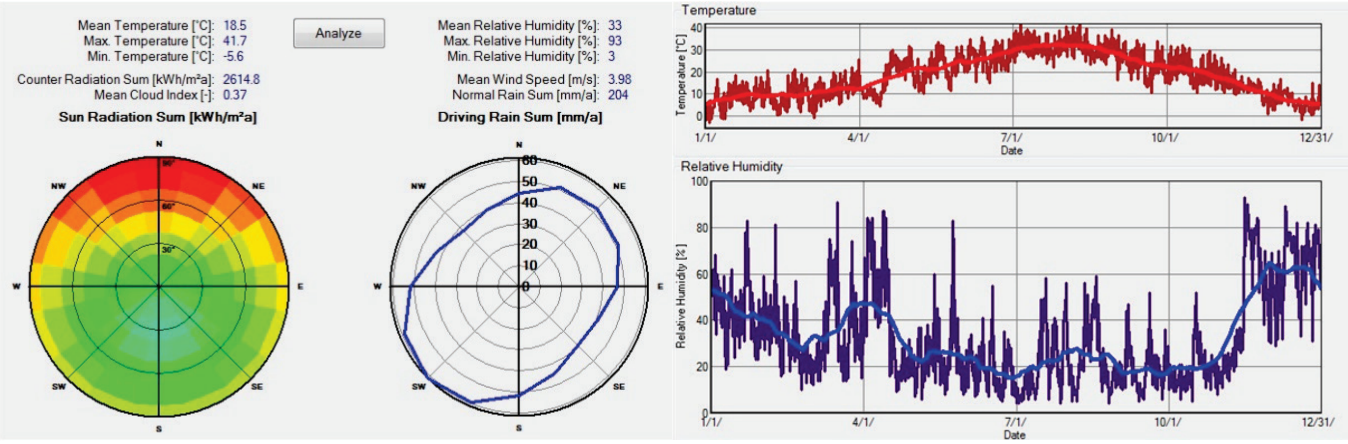


Figure 2 Computational algorithm of WUFI software [13]

To provide appropriate solutions to prevent humidity bridges, Tehran climatic conditions are taken into consideration. Due to the lack of rainfall information in the weather data file of this city, Las Vegas, NV in North America was substituted by similitude to Tehran, in terms of latitude, altitude, temperature, humidity, and annual rainfall information (Fig. 3).


Mean Temperature [°C]: 18.5
Max. Temperature [°C]: 41.7
Min. Temperature [°C]: -5.6
Counter Radiation Sum [kWh/m²a]: 2614.8
Mean Cloud Index [-]: 0.37

Mean Relative Humidity [%]: 33
Max. Relative Humidity [%]: 93
Min. Relative Humidity [%]: 3
Mean Wind Speed [m/s]: 3.98
Normal Rain Sum [mm/a]: 204

Figure 3 Climate information of Las Vegas, NV [13]

3.1 Data Analysis

Data of the walls of an educational building in Tehran has been analyzed based on the following equations. Given the higher temperature fluctuations in the south-oriented facades, this orientation will contain the most critical humidity-thermal hazards; For this reason, south-oriented walls have been simulated. The internal thermal humidity is considered in accordance with the previous cases and EN15026 standard. Which include:

Outer boundary conditions simulated in WUFI software: surface thermal conductivity coefficient = 17 W/(m^{2}K), short-wavelength radiation absorption coefficient and long-wavelength radiation emission coefficient based on outer materials, rain adhesion coefficient to surfaces 0.7.

Internal boundary conditions simulated in WUFI software: Surface thermal conductivity coefficient = W/(m^{2}K).

Internal temperature and humidity conditions: Internal conditions in all models are considered according to EN15026 standard with humidity and thermal information according to the following figure (Fig. 4).

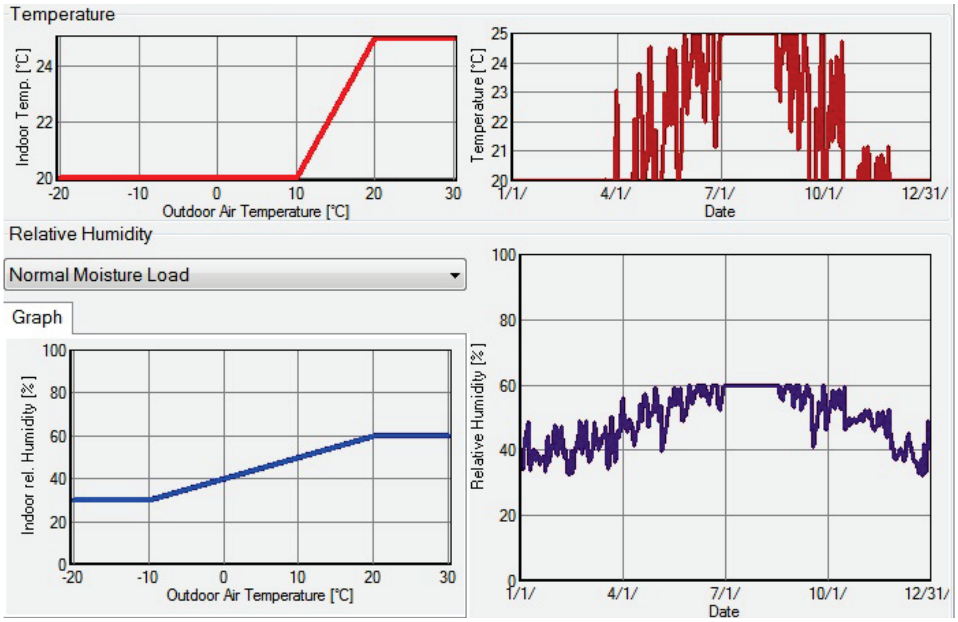


Figure 4 Upper right, internal temperature conditions based on time - upper left, internal temperature conditions based on outside temperature - lower right, relative internal humidity conditions based on date - lower left, internal humidity conditions based on outside temperature [13]

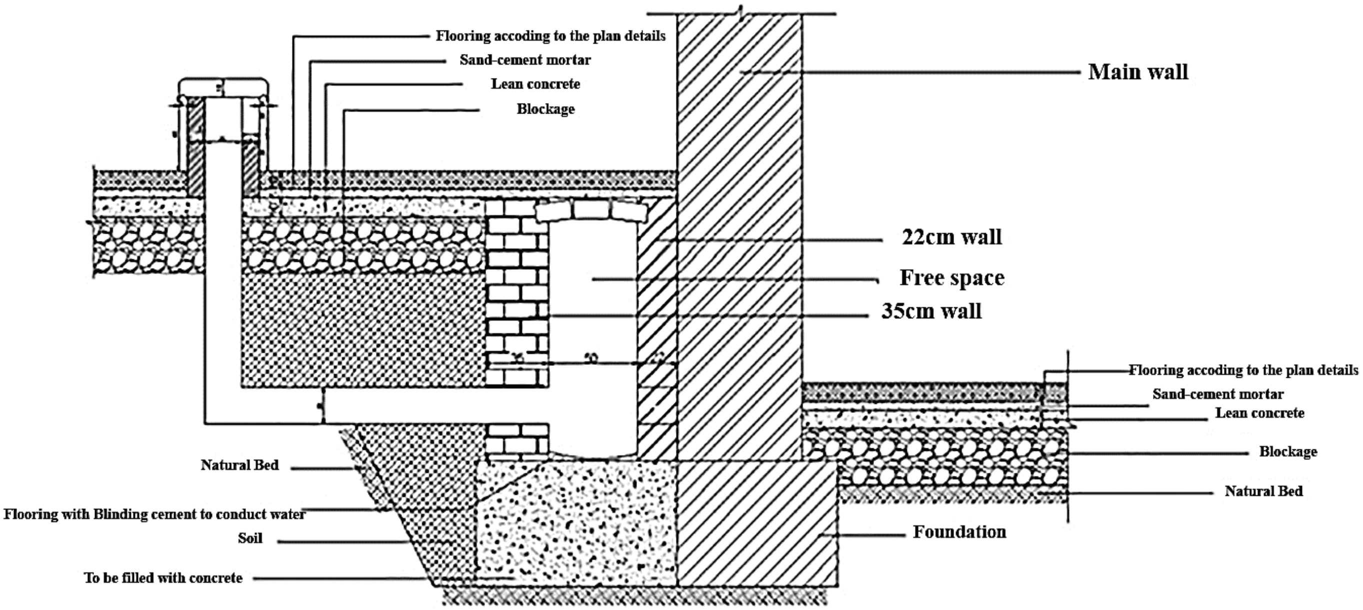


Figure 5 Executive details of the building No. 4, University of Arts, Garden Campus (Technical Department and Supervision of Development Plans of the University of Arts)

The executive details of the basement wall of building No. 4, University of Arts, National Garden Campus are as follows (Fig. 5).

According to the current situation, the drainage channel has not been fully implemented. The following images show the current status (Fig. 6).

According to the current situation, the simulation was performed in two configurations. In the first mode, the drainage channel was simulated in accordance with the current situation (Fig. 6), contiguous to the wall; In the second configuration, the outer channel was modeled, in full compliance with the executive details of the plan approved by the University of Arts.

Figure 6 Images of the construction of building No. 4, University of Arts, National garden Campus, Source: (Technical Department and Supervision of Development Plans of the University of Arts) 1400

3.2 First Configuration

As shown in Fig. 7, the wall layers consist of 350 mm brick (1), 500 mm non-ventilated air layer (2), 220 mm brick (3), 700 mm brick wall (4), and floor layers, respectively, 20 mm of stone (1), 50 mm of sand-cement mortar (2), 100 mm lean concrete (3), 300 mm blockage (4 and 5) and rammed earth (5), outer floor layers respectively, floor bricks 100 mm (a), cement-sand mortar 50 mm (b), lean concrete 100 mm (c) 400 mm blockage (d), rammed earth, concrete under humidity absorbent layer (f), grass table (g).

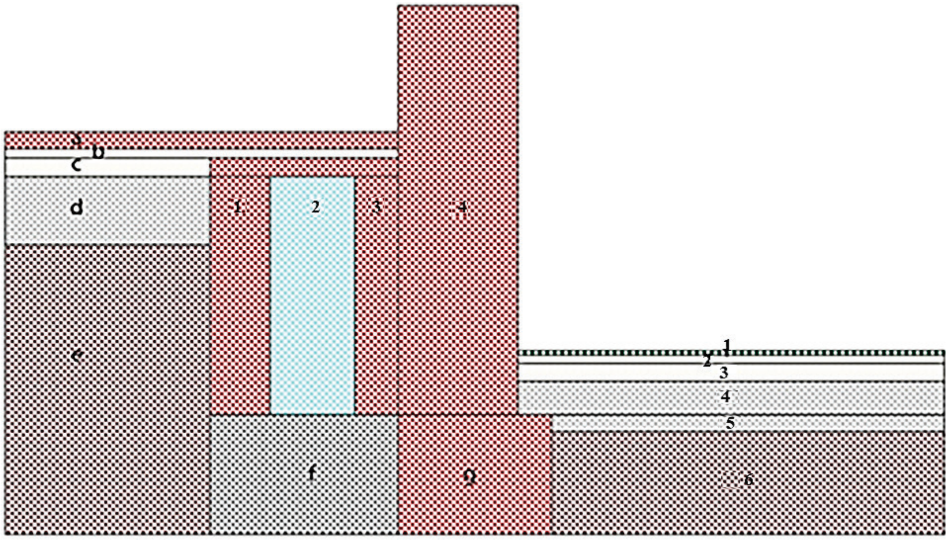


Figure 7 Simulated Executive Details Mode 1, University of the Arts, National Garden Campus, Building No. 4, Current Status (Author)

The above executive details have been simulated for a year in the conditions mentioned earlier. The most critical point during the design year is at 2 o'clock in the morning on April 2, for which surface and internal temperature and humidity (water content) of the wall layers are proof investigated.

Fig. 8 shows the temperature of the different layers of the intersection of the inside and outside floor with the basement wall. All levels at the beginning and end of each layer are numbered according to the executive details. According to the selected time and the outside air temperature, integrated temperature conditions are observed. The obtained results indicate that due to the high thermal inertia, the executive details of the above temperature fluctuations are low in day and night and the temperature of each layer is not much different from the other layers. It was observed that during the one-year simulation period, due to the proximity to the soil at a depth lower than the freezing point, temperature fluctuations below the floor on the soil are neglectable. Considering that the executive details are related to the construction period of the building, thermal insulation has not been used in the renovation of this building. Although this indicates an increase in energy consumption at first glance, the simulations show that due to the excessive thickness of the wall and the use of an air layer, heat transfer through the wall is greatly reduced (Fig. 9).

According to the temperature study of the surfaces in the previous diagram, it is quite clear that the relative humidity at levels 2 and 3 of the inner floor, b and c of the outer floor and all wall surfaces is at its highest. The layer under the drainage channel (layer f) has a high relative humidity during construction due to the water in the concrete. The high moisture content of this layer increases the relative humidity in the wall layers. Layer No. 2 of the inner floor (cement-sand mortar) is also causing similar problem in the inner part.

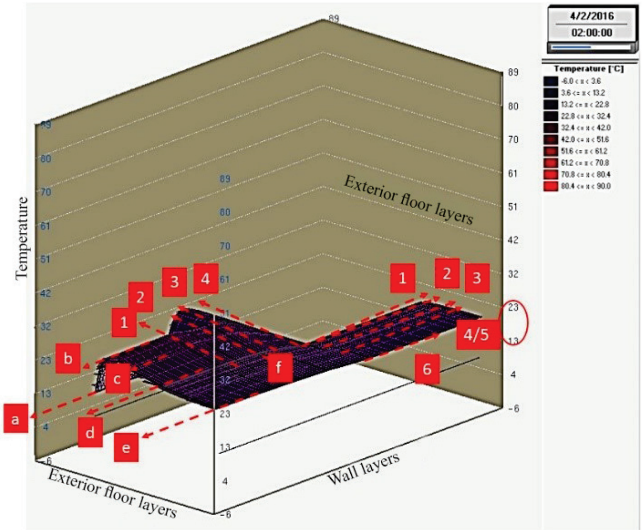


Figure 8 Temperature of floor and wall layers at 2 o'clock in the morning, April 2, Mode 1, University of Arts, National Garden Campus, Building No. 4, Current status (Author)

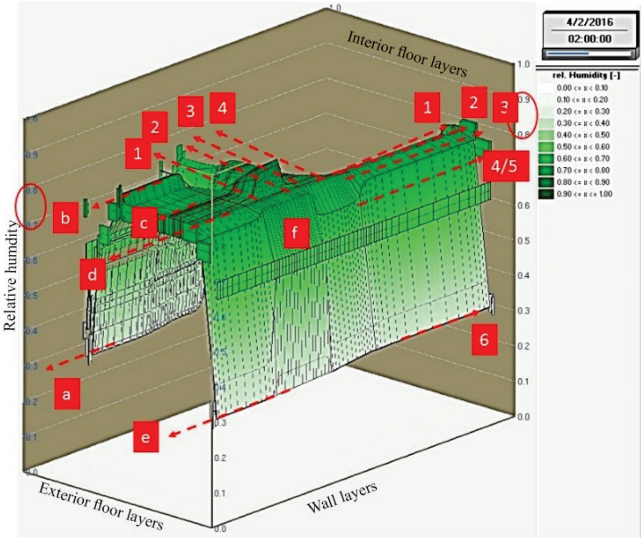


Figure 9 Relative humidity of floor and wall at 2 o'clock in the morning, April 2, Mode 1, University of Arts, National Garden Campus, Building No. 4, Current status (Author)

As shown in Fig. 10, layers 3 and 4 of the wall, layers 1 and 2 of the inner floor and layer f are in critical moisture conditions. The high water content in layer 3 and 4 of the wall is about 29 kg / m3 and also in layer 1 and 2 of the floor due to the water used in the mortar in layer 2 and the high water absorption of (about 42 kg/m^3), layer f (Concrete) with 94 kg/m^{3}will not have the possibility to dry due to the adjacent layers being high. In addition, the trapped air layer, due to lack of proper ventilation, cannot have the expected functionality and drain the moisture trapped in this layer. For this reason, the water content of layer f diffuses through the wall layers. Due to the high water content of layer 2 of the inner floor (cement-sand mortar), dry floor technics instead of wet methods are more appropriate.

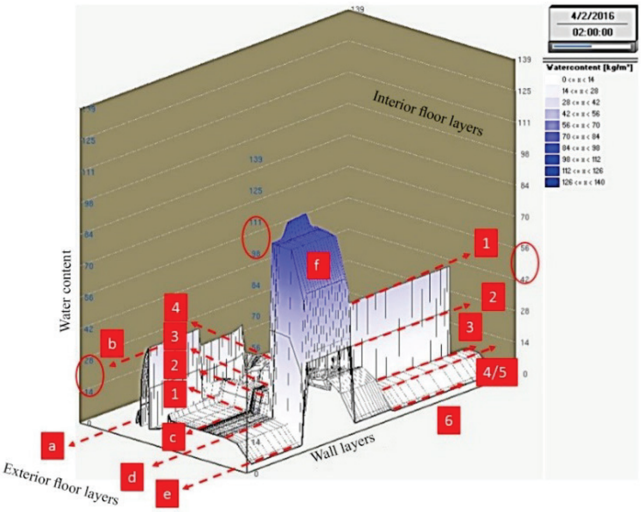


Figure 10 Floor and wall water content at 2 am, April 2, Mode 1, University of Arts, National Garden Campus, Building No. 4, Current status (Author)

3.3 Second Mode

As shown in Fig. 11, the wall layers consist of 350 mm brick (1), 500 mm non-ventilated air layer (2), 220 mm brick (3), 700 mm brick wall (4), and floor layers, respectively, 20 mm of stone (1), 50 mm of sand-cement mortar (2), 100 mm lean concrete (3), 300 mm blockage (4 and 5) and rammed earth (5); The outer floor layers consist of floor bricks 100 mm (a), cement-sand mortar 50 mm (b), lean concrete 100 mm (c) 400 mm blockage (d), rammed earth, concrete under humidity absorbent layer (f), grass table (g). It is also modeled for humidity absorbent output the same as executive details of the stone cap.

The above executive details have been simulated for a year in the conditions mentioned earlier. The most critical point during the year occurs at 2:00 AM on April 2. The ambient temperature and relative humidity, the temperature and water content of the wall layers are investigated. It should be noted that all simulation conditions are in accordance with mode 1.

Fig. 12 shows the temperature of the different layers of the intersection of the inside and outside floor with the basement wall. All levels at the beginning and end of each layer are numbered in accordance with the executive details. According to the selected time and the outside air temperature, integrated temperature conditions are observed. The obtained results show that due to the high thermal inertia, the executive details of the daily temperature fluctuations are low and the temperature of each layer is not much different from the other layers. It was observed that during the one-year simulation period, due to the proximity to the soil at a depth lower than the glacier, temperature fluctuations below the floor on the soil are minimized. The state of the layers is very similar to the previous mode. During some cold winter hours, the draining channel was observed to be colder than mode 1, which did not affect the temperature of the inner layers.

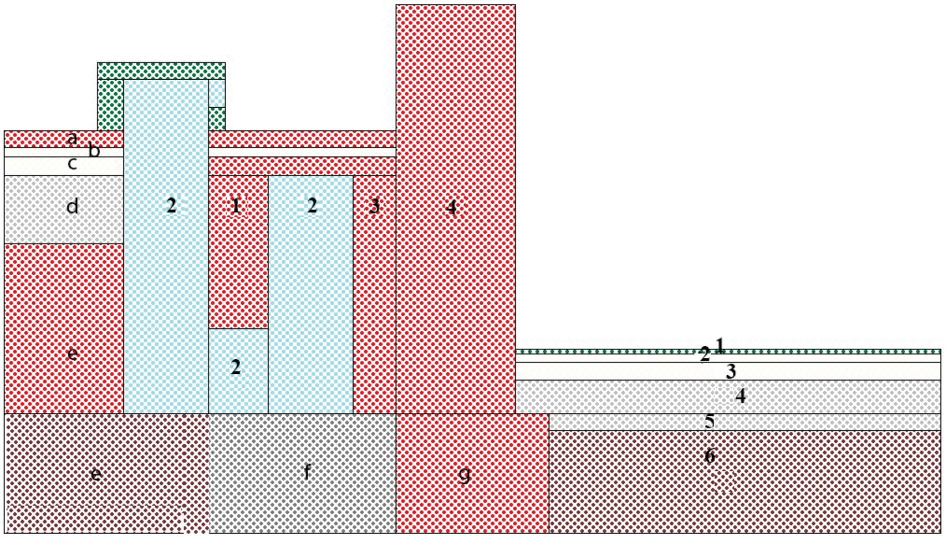


Figure 11 Simulated Executive Details of Mode 2, University of the Arts, National Garden Campus, Building No. 4, Approved Design (Author)

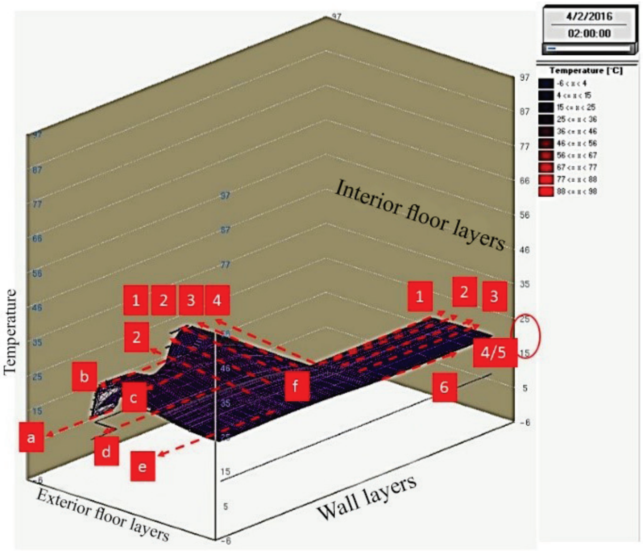


Figure 12 Temperature of studied floor and wall layers at 2 o'clock in the morning, April 2 (Author)

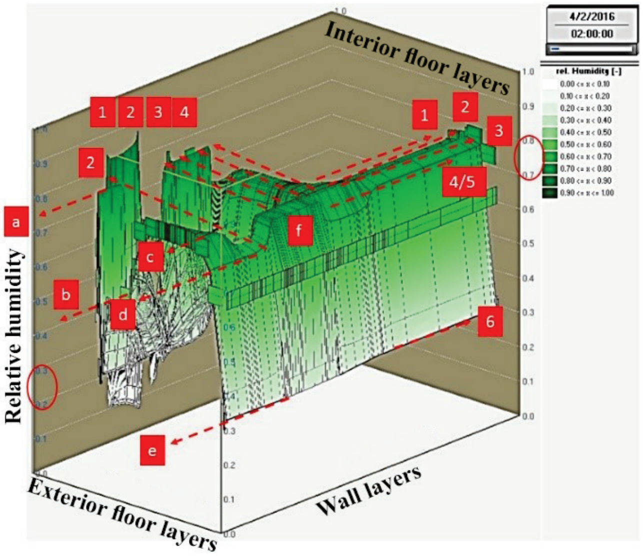


Figure 13 Relative humidity of floor and wall at 2 o'clock in the morning, April 2, Mode 2, (Author)

According to the above (Fig. 13), there is a significant decrease in relative humidity in the wall layers compared to the previous mode. This phenomenon is due to the connection of the draining channel with the outside air and the establishment of ventilation. In mode 1, the air layer adjacent to the basement wall is unventilated and trapped, which prevents moisture from draining and consequently diffuses to the inner layers. In this mode, with the ventilation of the air layer, not only the relative humidity in layers 3 and 4 of the wall is reduced, but also the relative humidity of layer f (humidity absorbent floor) is dimmed. Also, similar to mode number 1, the use of cement-sand plaster in the interior has increased the relative humidity in the interior flooring layers.

As shown in Fig. 14, there is a decrease in water content in layers 1, 2, 3 and 4 of the wall, layers 1 and 2 of the inner floor and layer f. As illustrated above, the water content in layer 3 and 4 of the wall is about 12 kg/m^3 and also in layers 1 and 2 of the floor due to the water used in the mortar in layer 2 and due to the high absorption of moisture by the stone is about Is 39 kg/m^3, both of which are reduced compared to mode 1, layer f (concrete) with 84 kg of water per cubic meter, the water content is also reduced by 10 kg per cubic meter compared to the previous mode, this phenomenon is due to the connection of the humidity absorbent with the air layer adjacent to the wall. Given the high water content in layer 2 of the inner floor (cement-sand mortar), it is recommended to use dry floor execution technics instead of the current wet method. It also seems that there are more suitable concrete options for the draining channel flooring material.

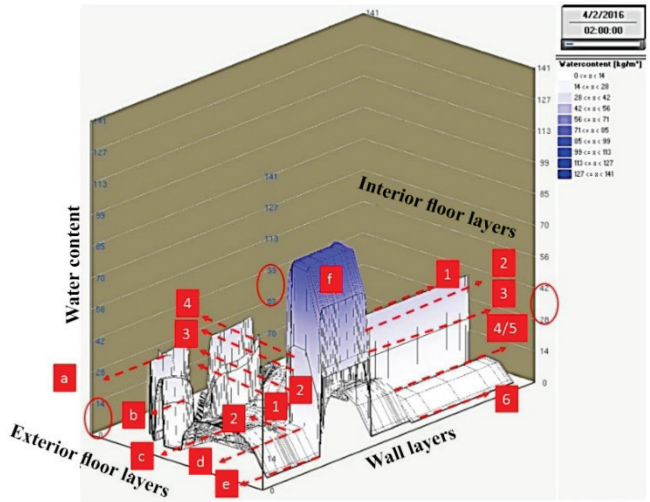


Figure 14 Floor and wall water content at 2 am, April 2, mode 2, (Author)

In the following step of this research, we will examine the chart of relative humidity and water content in the fifth year after execution. In order to achieve this information, the simulation was performed with previous information and in accordance with the approved executive details for 5 consecutive years, and comparative information at the same time and day is provided below.

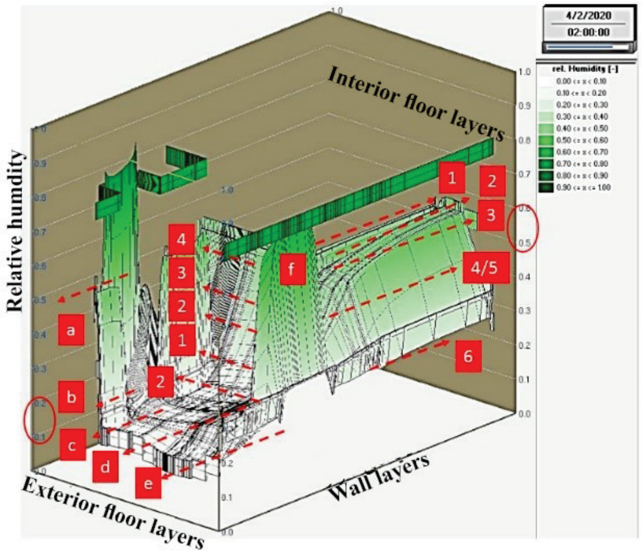


Figure 15 Relative humidity of floor and wall at 2 am, April 2, Mode 3 (Author)

3.4 Third Mode (Fifth Year after Execution)

As shown in Fig. 15, the decrease in relative humidity of all wall layers and draining channel floor layer (f) is remarkable; Relative humidity has been reduced by up to 20% in the inner floor layers and up to 30% in the wall layers. This result indicates the proper functioning of the draining channel.

According to Fig. 16, there is a decrease in water content in layers 1, 2, 3 and 4 of the wall, layers 1 and 2 of the inner floor and layer f. The water content in layer 3 and 4 of the wall is about 3 kg/m^3 and also in layer 1 and 2 of the floor due to the water used in the mortar in layer 2 and due to the high absorption of moisture by the stone is about 30 kg/m^3; Compared to mode number 1, remarkable decrease is observed in wall and layer f (concrete) with 75 kg of water per cubic meter is also reduced in water content by 9 kg per cubic meter compared to the previous mode. This phenomenon is due to the proper functioning of the draining channel and the proper ventilation of the humidity absorbent channel.

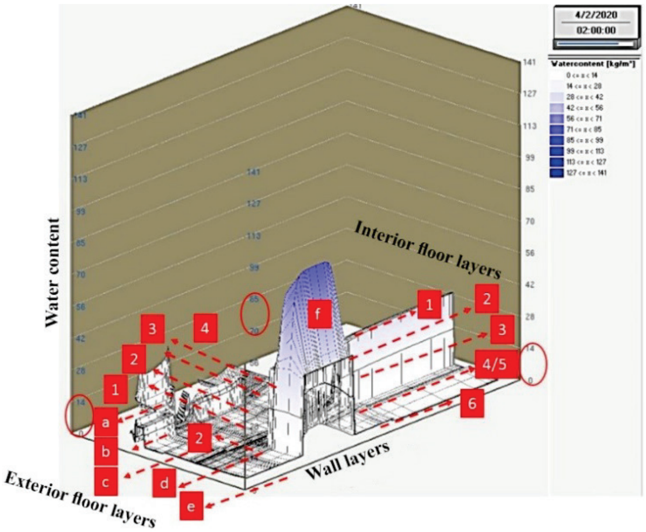


Figure 16 Water content of floor and wall at 2 am, April 2, Mode 3 (Author)

4 CONCLUSION

In this study, thermal-humidity simulations for evaluating heat and mass transfer in walls of a historic building were analyzed using WUFI software. This study was conducted to evaluate the effectiveness of executive details used the studied building and to compare the performance with recent standard details.

After simulating each detail, the problematic cases and critical points were identified, and finally, the thermal-humidity audit was performed according to the principles and logic of executive details. The simulation results related to configurations before and after the audit are compared. The most appropriate executive detail is selected based on simulation results for a general wall section (from the roof to the foundation). Appropriate solutions have been studied according to the conditions of each building element. Based on the results, the following general results can be formulated:

- Regardless of humidity conditions, thermal audit not only does not reduce the problems of the building but can also lead to humidity problems.
- The information obtained from the humidity and thermal audit of the building should be checked simultaneously and the results will lead to a solution to improve the thermal and humidity conditions.
- Proper and ventilated air gap is always effective in reducing the relative humidity of the wall and floor on the ground.

- Dry execution technics will always dim the condensation risks, compared to the situation with wet execution, due to the reduction of the water content of materials.
- The presence of proper thermal insulation is effective in reducing moisture problems when adequate executive details are used. Also, thermal bridges always play a role in increasing humidity problems and lead to the formation of moisture bridges.
- The presence of moisture bridges in the building causes internal cold surfaces during the cold period and increases heat transfer.
- The hydrophobic layer added on the outer side of the building envelope element has a positive effect in reducing moisture problems.
- The presence of the vapor barrier layer in the right place reduces the moisture problems of the building and protects the thermal insulation.

In the executive details related to the intersection of an intermediate floor with the external wall, the use of external insulation is always suggested. This will reduce the thermal bridge and limit the thermal-humidity problems of the building.

Finally, the existing case study of the basement wall of this historic building has shown that the study of moisture problems, before making decisions related to renovation can minimize eventual problems that can occur when existing draining technics, such as ventilated canals are eliminated by mistake.

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