Title	Deterioration and Preservation of City Wall in Nanjing
Author(s)	Araoka, Wakana; Hokoi, Shuichi; Ogura, Daisuke; Iba, Chiemi; Li, Yonghui; Hu, Shi
Citation	Energy Procedia (2017), 132: 945-950
Issue Date	2017-10
URL	http://hdl.handle.net/2433/234981
Right	© 2017 The Author(s). Published by Elsevier Ltd. Under a Creative Commons license.
Type	Journal Article
Textversion	publisher

Available online at www.sciencedirect.com

ScienceDirect

Energy Procedia 132 (2017) 945–950

Energy Procedia

www.elsevier.com/locate/procedia

11th Nordic Symposium on Building Physics, NSB2017, 11-14 June 2017, Trondheim, Norway

Deterioration and Preservation of City Wall in Nanjing

Wakana Araoka[a], Shuichi Hokoi[b]*, Daisuke Ogura[c], Chiemi Iba[d], Yonghui Li[e], Shi Hu[e]

[a]*Graduate student, Department of Architecture and Architectural Engineering, Graduate School of Engineering, Kyoto University, C2 Kyoto daigaku-katsura, Nishikyo, Kyoto, 615-8540 Japan*
[b]*Professor Emeritus, Kyoto University, Yoshida-honmachi, Sakyo, Kyoto, 606-8501 Japan*
[c]*Associate Professor, Department of Architecture and Architectural Engineering, Graduate School of Engineering, Kyoto University, C2 Kyoto daigaku-katsura, Nishikyo, Kyoto, 615-8540 Japan*
[d]*Assistant Professor, Department of Architecture and Architectural Engineering, Graduate School of Engineering, Kyoto University, C2 Kyoto daigaku-katsura, Nishikyo, Kyoto, 615-8540 Japan*
[e]*Associate Professor, School of Architecture, Southeast University, Nanjing, China*

Abstract

Nanjing City Wall in Nanjing, China, an important cultural heritage of the city, has deteriorated owing to factors such as the presence of microorganisms, salt crystallization, exfoliation, and cracks in the bricks and stones. For this research, the present status regarding the deterioration of the Nanjing City Wall was first surveyed, after which we attempted to identify the factors causing the deterioration. Herein, a simulation model expressing the infiltration of rainwater into the city wall is proposed, and based on the simulation results, the influence of rainwater on the deterioration of the wall is examined. The simulation results showed that the rainwater increases the moisture content of the inside bricks and plaster only very slowly.

Peer-review under responsibility of the organizing committee of the 11th Nordic Symposium on Building Physics.

Keywords: Brick wall; Deterioration; Cultural property; Moisture; Rain

1. Research background and purpose

Nanjing City Wall in Nanjing city, Jiangsu Province, China, was designated an important cultural heritage of the city, and is visited by a multitude of tourists and local citizens. However, microorganisms, such as moss, algae, and lichen, as well as ferns, are growing on the wall, which was constructed around 700 years ago during the Ming Dynasty.

* Corresponding author. +81-(0)75-753-5534; fax: 81-(0)75-753-5534.
E-mail address: hokoi@maia.eonet.ne.jp

Peer-review under responsibility of the organizing committee of the 11th Nordic Symposium on Building Physics
10.1016/j.egypro.2017.09.734

Furthermore, other types of deterioration such as salt crystallization on the wall surface, exfoliation, and cracks in the bricks and stones have been observed.

For this research, the present status regarding the deterioration of the Nanjing City Wall was first surveyed. We then attempted to identify those factors causing the deterioration. Herein, a simulation model that expresses the infiltration of rainwater into the city wall during a period of precipitation is proposed. Using the simulation results, we examined influence of rainwater on the deterioration of the wall.

Nomenclature

c: specific heat [J/(kgK)]
g: acceleration of gravity [m/s^2]
n: unit vector directed toward the downward vertical direction
r: phase change heat for evaporation [J/kg]
t: time [s]
T: temperature [K]
λ: thermal conductivity [W/mK]
μ: water chemical potential [J/kg]
ρ: density [kg/m^3]
φ: volumetric moisture content [-]
λ'_T: moisture conductivity due to temperature gradient [kg/msK]
λ'_μ: moisture conductivity owing to the gradient of the water chemical potential [kg/ms(J/kg)]
subscript w: liquid water, and g: gaseous phase

2. Outline of Nanjing city wall and present measures for its preservation and maintenance

2.1. Outline of Nanjing city wall [1, 2, 3]

Nanjing City Wall was constructed during a 21-year period during the Ming Dynasty, from 1368 to 1644 (Fig. 1). Although the City Wall is currently separated into five sections, more than two-thirds of the originally constructed wall, i.e., 25,091 km, still remains. The City Wall is made of bricks and stones. The bricks are of different sizes and materials (ingredients) because they were produced at various places throughout China. Plaster and soil were used as masonry joints. The wall structure is roughly categorized into two types. One is a self-bearing type, which is not in contact with any large masses of soil on the rear face, and where both sides of the wall are made of bricks. The other one is a covering type, whose rear side is large mass of soil, where the wall is constructed such that it surrounds the soil mass (Fig. 2). The inside of a self-bearing type wall is either soil or only bricks.

Fig. 1 Overview of City Wall

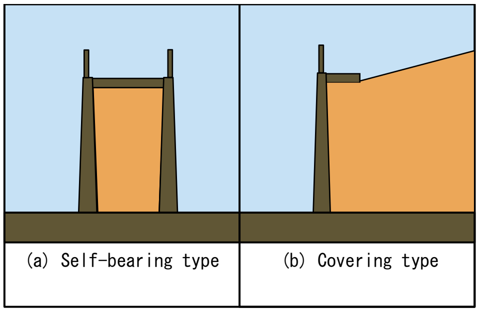

Fig. 2 Types of wall structures

Fig. 3 Sidewalk on top of wall under rain

2.2. Present measures for city wall preservation and maintenance [2]

Nanjing city has issued city bylaws regarding the preservation of the City Wall seven times since Nanjing was first designated as a historical and cultural city in 1982. In the “Bylaw on the preservation of the historical and cultural Nanjing City Wall,” issued in 2010, areas within 30 m from the City Wall and other related remains have been designated as preservation areas where new buildings are prohibited from being constructed.

The sidewalk on top of the Nanjing City Wall is slightly sloped from its center toward both sides, and thus the rainwater flows to the side drainage ditches (Fig. 3). The water gathered in the ditches is drained to the outside of the wall through drainpipes installed beneath the handrails. When the amount of rain is not too significant, most of the rainwater is absorbed into the bricks or joints along the way to the ditches, and thus sufficient drainage cannot be expected. In the case of heavy rain, the drainage system works, although a large amount of rainwater still seems to be absorbed by the sidewalk surface. The plants growing on the side faces of the wall are periodically removed, and restoration work has been conducted to replace any deteriorated bricks with new ones.

3. Deterioration of city wall

On the 27th and 29th of September 2015, a visual inspection survey was carried out near Teijun-mon and Kaiho-mon gates. The wall near Teijun-mon is a covering type 5 m in width and 12 m in height, and residential buildings and shops have been built within its neighborhood. Parks and a promenade have also been constructed and the neighborhood has become an area for citizens. The wall near Kaiho-mon is a self-bearing type 12 m in width and 22 m in height. There are temples and restaurants near the gate, and the area has become a tourist attraction.

Regarding the deterioration of the brick surfaces, many types of deterioration such as perforated holes, hollows at the center of the bricks, bricks whose centers remain with their surrounding parts depressed, cracks running through the entire brick, and brick surfaces cut back smoothly have been found. The reasons for such deterioration may be salt weathering, freeze thawing, expansion and shrinkage from changes in temperature or humidity, acid rain, and other factors.

On the side face of the wall, as shown in Fig. 4, a number of plants are growing, and an exfoliation or extrusion of bricks from the forces caused by tree roots or trunks can be seen. In contrast, the side faces of the wall in front of tall trees, as shown in Fig. 5, are in relatively good condition despite being covered by algae or moss. This is probably because of the protection from solar radiation and precipitation by the trees, and because of the evapotranspiration by the plants and microorganisms. The plants around the wall and on its side faces are thus closely related to the deterioration of the wall. In addition, solar radiation has a significant influence on the plant growth around the city wall. Therefore, the plants, microorganisms, and orientation of the wall have a drastic influence on its deterioration.

Because a portion of the rain falling on the wall is stored inside the wall, thereby causing internal pressure, extruding bricks can be seen (Fig. 6). As the worst case, a large-scale destruction of the wall has occurred (Fig. 7).

Owing to the significant influence of precipitation and solar radiation seem to have a significant influence on the deterioration of the wall, an analysis of the movement of rainwater inside the wall when taking into consideration the presence of solar radiation is a main focus of the present study.

Fig. 4 Plant growing on south side of wall

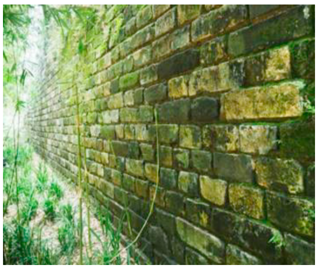

Fig. 5 Side face shaded from sunshine

Fig. 6 Extrusion of bricks

Fig. 7 Severe destruction of wall

4. Simulation of water and heat transfer inside the wall

4.1. Fundamental equations for analysis [4]

An analysis of the movement of moisture and heat inside the wall was carried out using the following equations (1) and (2), respectively, whose validity have been confirmed in previous papers [4, 5].

Moisture balance:

$$\rho_w \frac{\partial \varphi}{\partial \mu}\frac{\partial \mu}{\partial t} = \frac{\partial}{\partial x}[\lambda'_{\mu}(\frac{\partial \mu}{\partial x} - n_x g) + \lambda'_T \frac{\partial T}{\partial x}] \quad (1)$$

Heat balance:

$$c\rho \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}[(\lambda + r\lambda'_{Tg})\frac{\partial T}{\partial x} + r\lambda'_{\mu g}(\frac{\partial \mu}{\partial x} - n_x g)] \quad (2)$$

4.2. Modelling of wall

A self-bearing type portion of the wall near Kaiho-mon was analyzed. The inside of the wall is assumed to have been filled with bricks and plaster, excluding air voids or soil. This portion of the wall was modeled as a two-dimensional rectangle with a height of 21.93 m and a width of 11.85 m. The end of the brick is a rectangle 15.0 cm by 9.0 cm in size, and the bricks are connected to each other by plaster with a thickness of 3 cm. The way of laying bricks was a type of header bond, as shown in Fig. 10. This section of the modeled wall and the manner in which the bricks were laid are shown in Figure 8.

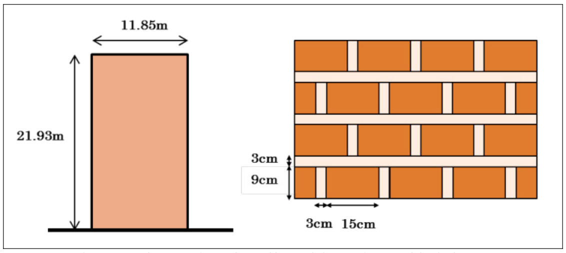

Fig. 8 Schematic of wall and layering of bricks

4.3. Calculation conditions [6, 7]

During the simulation, it was assumed that the upper surface of the wall is saturated with rainwater, and the water chemical potential at the upper surface was set at μ＝－0.000001 [J/kg]. The water chemical potential and the temperature at the bottom of the wall were assumed to be μ＝－1000 [J/kg] and 20.6°C, respectively, the latter of which is the average yearly temperature in Nanjing. The initial conditions were set the same as those at the bottom.

The physical properties of the wall are listed in Table 1, and the equilibrium moisture content of each material used is shown in Fig. 9 [11, 12]. Because the bricks and plaster comprising the present City Wall are considered more brittle and rougher than standard, the moisture transfer coefficients of the bricks and plaster were set to 10-times and a million-times greater than the standard values (Fig. 10), respectively [11, 12].

The analyzed model was discretized into small elements by control volume method, and the representative point of the element is assumed to be located at the center of the element. Using thermal and moisture resistances, the heat and moisture fluxes of all materials including the boundary air layer were expressed as common forms of discretized equations. Time and special increments were set as 150s and 0.03m considering numerical stability and convergence.

Table 1. Physical properties of materials [8, 9, 10]

	Brick	**Plaster**	**Water**
Density [kg/m^3]	1800	1300	998
Specific Heat [J/(kgK)]	920	840	4200
Thermal Conductivity [W/(mK)]	1.1	0.7	-
Vapor Conductivity [kg/(msPa)]	2.6x10^{-11}	8.14x10^{-13}	-

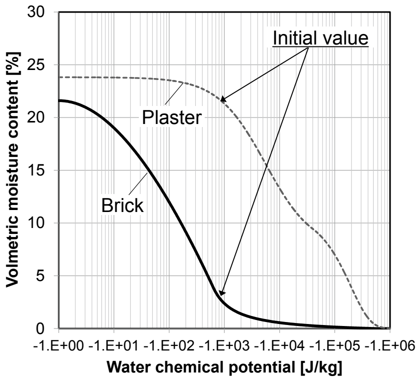

Fig. 9 Equilibrium moisture content of brick and plaster [11,12]

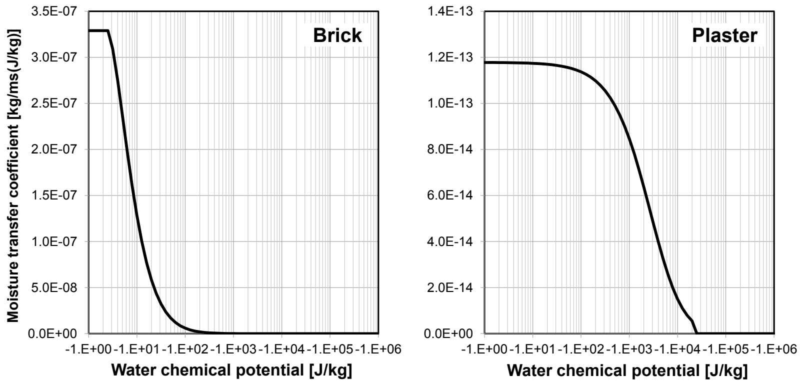

Fig. 10 Moisture transfer coefficients of brick (left) and plaster (right) under standard conditions [11, 12]

4.4. Calculated results

Heat and moisture transfer inside the wall when the upper surface is saturated with rainwater was calculated for a full year. Figures 11 and 12 show the water chemical potential and temperature after half a year and one year, respectively. Because the wall is symmetric to the centerline, only the results of the left half are shown.

The water chemical potential increases particularly at the upper part of the wall owing to the penetration of rainwater. Because the increased region of the potential extends wider after one year than after half a year, it can be stated that the moisture content inside the wall increases over time. From the detailed results of the moisture transfer within the region 1.65 m from the upper surface (corresponding to 14 layers of bricks) after one year, it can be understood that the moisture moved mainly through the plaster layers (figure omitted here), which resulted from setting the value of the moisture transfer coefficients of the plaster to larger than that of the brick.

The temperature increases slightly in the center region of the wall (by less than 0.0002℃). The temperature increase after one year is less than that after half a year because the moisture content increases with the water chemical potential, which causes a temperature increase owing to the heat of condensation. In addition, the temperature drops near the side face of the wall because the water evaporates there.

Next, we calculated a situation in which the rain continues for a full week and dry conditions continue for three days. The moisture chemical potential of the upper surface under dry conditions was set at $\mu = -39194$ [J/kg]

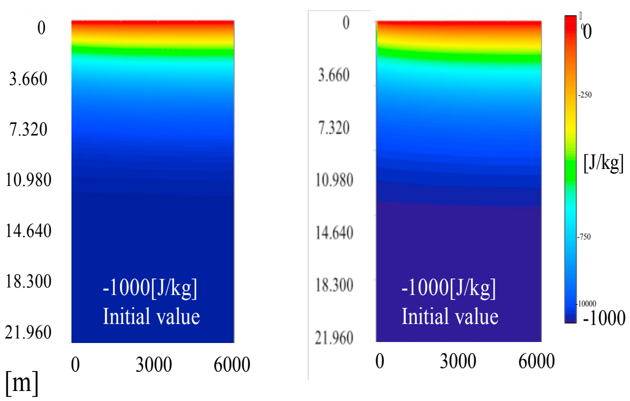

Fig. 11 Water chemical potential after half a year (left) and one year (right)

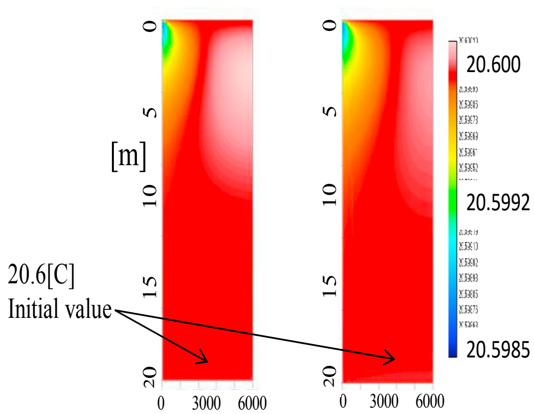

Fig. 12. Temperature after half a year (left) and one year (right)

because the average annual relative humidity in Nanjing is 74.9%. Figure 13 shows the temperature and water chemical potential after three months (90 days). This figure only shows the results at the upper 4.8 m region (corresponding to 40 layers of brick), where the change can be clearly seen.

After a cyclic repetition of rain and a drying period, the water accumulated in between 2 to 4 layers of brick from the upper surface, although the upper part of the bricks remained dry. Furthermore, the repetition of temperature increases and decreases with increases and decreases in moisture content created a characteristic temperature distribution.

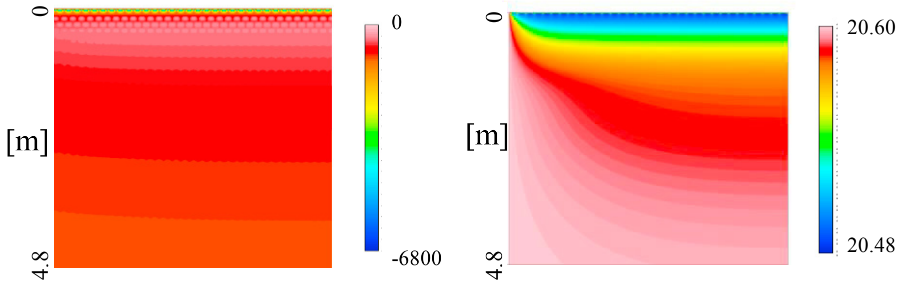

Fig. 13 Distributions of temperature and water chemical potential after two months

5. Conclusion

Aiming at the proposal of preservation methods for the Nanjing City Wall as our final goal, we surveyed the present state of deterioration of the wall, subsequently attempted to identify the causes for such deterioration, and further simulated the moisture behaviors inside the wall.

•The main factors causing the deterioration of the brick surface were weathering from salt crystallization, freezing and thawing, and expansion and contraction owing to changes in temperature. The plants around the wall and on its side faces were shown to have a significant influence on the deterioration of the wall.

•Simulation results showed that the rainwater increases the moisture content of the inside bricks and plaster very slowly, and that a temperature drop occurs on the side face of the wall owing to moisture evaporation.

Acknowledgements

This research was partially supported by the Ministry of Education, Science, Sports, and Culture Grant-in-Aid for Scientific Research (B), 26289203, 2014.

References

[1] Nagoya Sister Cities Association HP, http://nsca.gr.jp/sistercities/nanjing/index.html 2016.
[2] W. Chengkang, A. Deguchi, E. Minoura, and T. Sakai, Transformation and classification of city wall spaces in Nanjing, China, J. Archit. Plann., AIJ, 77 No. 672, 2012, PP.385-391.
[3] 穆保岗：南京城墙的承载机理初探王成康
[4] M. Matsumoto, A Series of Modern Architecture, 10 Architectural Environmental Engineering, (Shokokusha, 1984)
[5] S. Hokoi, M.K. Kumaran, Experimental and Analytical Investigations of Simultaneous Heat and Moisture Transport through Glass Fiber Insulation, Journal of Thermal Insulation and Building Envelope, Vol. 16, PP. 263-292, 1993.
[6] Y. Yoshida, "Degradation of a big Buddha in Sukhothai ruins," Master Thesis, Kyoto University, 2011.
[7] China Meteorological Administration, National Weather Information Center, 2014-01-01
[8] Architectural Institute of Japan, "Heat, air, and moisture properties of building materials," 2001.
[9] M.K. Kumaran, Thermal and Moisture Transport Property Databases for Common Building and Insulating Materials, Final Report from ASHRAE Research Project 1018-RP, 2002.
[10] Japan Society of Thermophysical Properties, "Handbook of thermal properties," 2000.
[11] C. Iba, "Freeze-thawing processes of water in porous building materials," Master Thesis, Kyoto University, 2002.
[12] E. Mizutani, D. Ogura, T. Ishizaki, M. Abuku, and T. Sasaki, Influence of Infiltration of Rain Water on Degradation of Wall Painting in Hagia Sophia, J. Archi. Plann., AIJ, Vol.80, No.716, PP.1001-1011, 2015.