Journal of Cultural Heritage 15 (2014) 621–627

Available online at
ScienceDirect
www.sciencedirect.com

Elsevier Masson France
EM|consulte
www.em-consulte.com/en

Original article

Quantitative modeling of blistering zones by active thermography for deterioration evaluation of stone monuments

Young Hoon Jo, Chan Hee Lee*

Department of Cultural Heritage Conservation Sciences, Kongju National University, 314-701 Gongju, Republic of Korea

ARTICLE INFO

Article history:
Received 8 October 2013
Accepted 12 December 2013
Available online 22 January 2014

Keywords:
Graduated heating thermography
Stone monuments
Blistering
Quantitative modeling
Deterioration map

ABSTRACT

Infrared thermography for stone monuments to date has primarily focused on qualitative analysis to judge the location of defect zones using relative temperature differences, but there are difficulties in mapping a blistering zone and quantitatively calculating its area. Therefore, this study used quantitative modeling to map blistering zones with graduated heating thermography. To achieve this goal, the following steps were performed: acquisition of thermographic images by passive and active methods, construction of a temperature distribution curve, establishment of the critical temperature and transitional zone, classification of the relative deterioration grades of the blistering zone, monochrome processing, vectorization, and deterioration evaluation of the blistering zone. After evaluating the blistering degree of the specimen through modeling, the total areas and rates were calculated as 359.3 cm^2 and 80.1%, respectively. This study was very useful for identifying the location, area, and relative degree of deterioration of blistering zones that were not easily detectable with the naked eye. In the future, if quantitative modeling of blistering zones is actively applied to deterioration maps, the reliability of deterioration evaluation for stone monuments will be improved, and additional deterioration, such as scaling, may be prevented.

1. Introduction

Most stone monuments have suffered from multiple types of weathering and damage, such as cracking, blistering, scaling, bursting, disintegration, discoloration and biological colonization, due to their exposure to the outdoor environment after construction [1–5]. Among these deterioration categories, blistering is defined as creation of separated, air-filled and raised hemispherical elevations on the face of stone resulting from the detachment of an outer stone layer [6]. In contrast to other deterioration categories, this detachment is not easily detected with the naked eye, especially its location and range, because it usually occurs at the stone's subsurface layers (Figs. 1a–1d). Therefore, a state-of-the-art technique should be employed to accurately diagnose the blistering zone. One recently developed non-destructive method for blistering detection in stone monuments is infrared thermography analysis.

This method is like a real-time imaging technique and creates a thermal map that depicts the surface temperature distribution with a visible temperature scale by recording infrared radiant energy emitted from a target object. The thermal map has different temperature information, and such temperature characteristics enable quantitative discrimination between fresh and blistering zones and seem to allow dimensional characterization of the blistering zone. In addition, the thermography analysis is able to measure a broad temperature range which depends upon the actual system used and can non-destructively and quickly investigate wide scope with few people in the field, so the method is favorable for the non-destructive survey of large structures such as buildings, bridges, stone monuments, murals, and frescoes. Accordingly, infrared thermography has been widely used to detect invisible defects [7], monitor structures [8], inspect damped zones [9–11], assess conservation treatment [12], characterize subsurface cracks [13,14] and investigate hidden internal walls [15] for various structures and civil engineering.

However, infrared thermography analysis of stone monuments has many restrictions due to the features of cultural heritage, and the method to date has been primarily focused on qualitative analysis to judge the location of defect zones using relative temperature differences [16]. Qualitative analysis for the detection of defect zones will not be an issue in the field of modern structures, which permits active replacement and reinforcement of component materials. In contrast, the quantitative identification of a location and range of defect zones using infrared thermography and the illustration of these zones on a deterioration map are very important in the field of cultural heritage. Cultural heritage assets must be preserved through monitoring, conservation treatment and management, except in unavoidable circumstances such as

* Corresponding author. Tel.: +82 41 850 8543; fax: +82 41 850 8540.
E-mail addresses: joyh@kongju.ac.kr (Y.H. Jo), chanlee@kongju.ac.kr (C.H. Lee).

1296-2074/$ – see front matter © 2013 Elsevier Masson SAS. All rights reserved.
http://dx.doi.org/10.1016/j.culher.2013.12.002

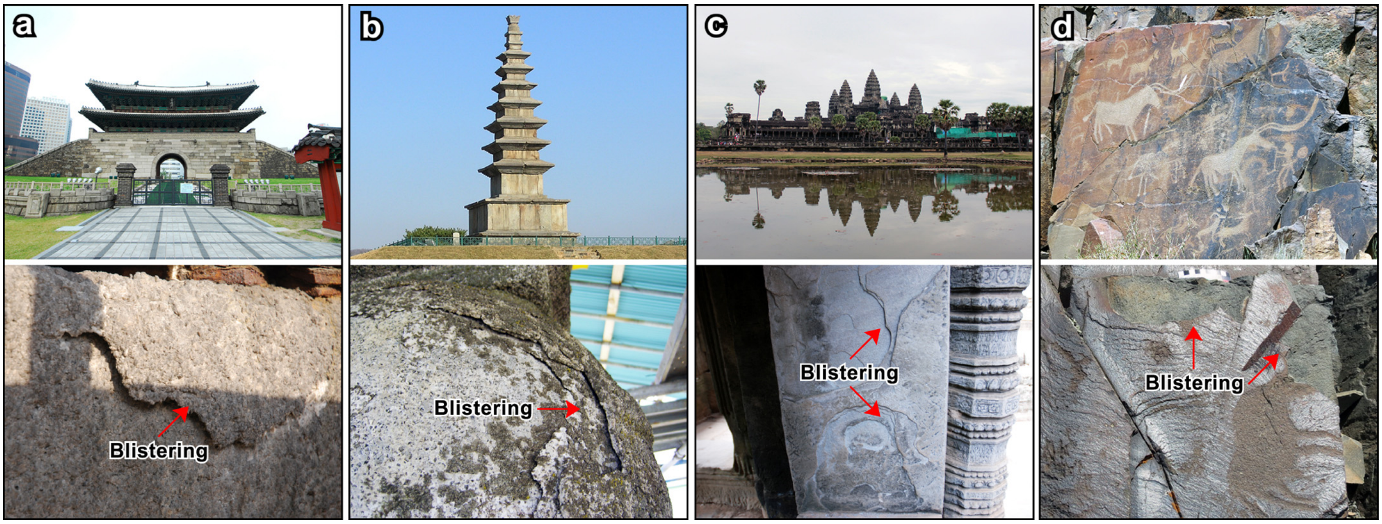

Fig. 1. Images from the field, showing blistering on stone monuments: a: Sungnyemun gate, Republic of Korea; b: seven-storied Jungwon Tappyeongri stone pagoda, Republic of Korea; c: Angkor monuments, Cambodia; d: petroglyphs in the archaeological landscape of Tamgaly, Kazakhstan.

destruction by war, natural disasters and high degrees of deterioration.

This study detected blistering zones occurring at stone subsurface layers from rock samples with similar blistering shapes as those of stone monuments using infrared thermography and quantitatively analyzed the temperature characteristics of detected blistering. In addition, the relative deterioration grade at the blistering zone, according to the temperature and rate of temperature change, was classified to assess the degree of blistering. Lastly, quantitative modeling for mapping of the blistering zone was conducted using a temperature distribution curve and monochrome process by the relative deterioration grade.

2. Methodology

Infrared thermography uses variations in infrared radiant energy to detect fresh and blistering zones based on optical, thermal (heat conduction, specific heat, and thermal diffusivity) and physical characteristics (porosity, density, and water content) [12,16]. If infrared radiant energy emitted from fresh and blistering zones is analyzed using an infrared thermography camera, then the location, shape and size of blistering zones at the subsurface layer of the stone monument can be expressed as quantitative temperature distributions.

To perform the relative deterioration evaluation and quantitative modeling of blistering zones, a rock sample (310 × 185 mm) with similar blistering shapes as a stone monument were collected from Gongju (gneiss) (Fig. 2a). The specimen showed noticeable gaps due to blistering (Figs. 2b and 2c). The thermography camera used in the study was ThermaCAM SC660 produced by FLIR Systems (Sweden), which was also used in safety diagnoses for buildings and stone cultural heritage monuments by Moropoulou *et al.* [13]. This thermography camera performs remarkably well in terms of thermal sensitivity (0.045°C) and measurable temperature range (-40 to 1500°C). Furthermore, the camera has a spectral range of 7.5 to 13 μm and an IR resolution of 640 (horizontal) × 480 (vertical) pixels. Its thermal sensitivity (noise equivalent temperature difference) is under 30 mK.

In general, methods of infrared thermography analysis can be divided into two categories: passive and active. The passive method uses infrared energy naturally radiated from an object and natural temperature differences without artificial heating and cooling. However, the active method is based on the thermal excitation of the specimen to obtain significant temperature differences indicative of the presence of subsurface defects [7], so an artificial external stimulus is applied to the object. Depending on the artificial external stimulus, there are many possible thermography methods, such as pulse thermography (PT), lock-in thermography (LT), pulsed phase thermography (PPT), square phase thermography (SPT), and graduated heating thermography (GT) [17–23]. This study acquired thermographic images of the blistering sample via graduated heating thermography using an infrared heater (2,000 W) with a halogen lamp (Philips, 15021Z) (Fig. 2d).

In graduated heating thermography, the artificial thermal source is applied to the blistering sample using the principle that the blistering zone reacts more sensitively to external temperatures; furthermore, its surface temperature should increase more rapidly due to its decreased thermal conductivity and density as well as reduced volumetric heat capacity when constant heat is supplied to the blistering sample [24]. This method is favorable for acquiring clear images of blistering zones because it promotes the sensitivity of thermographic images regardless of the surroundings and is applicable in any location or time. In addition, the temperature characteristics of the acquired thermographic images were analyzed using the ThermaCAM Researcher 2.9 software provided by FLIR Systems. The mapping of blistering zones was completed using AutoCAD2012 and vector transformation software.

3. Results

3.1. Acquisition of thermographic images

Prior to the thermographic screening of the specimen, it was first visually examined, photographed and tapped with a metal instrument. As a result, the specimen showed diverse blistering layer thicknesses (2.0–8.0 mm) and blistering crack widths (0.5–5.0 mm). The specimen had also deteriorated from the blistering that occupied 60% of its total area, according to the percussion method (Fig. 3a). To perform quantitative modeling of the blistering zone, a thermographic image was obtained through the passive method using the natural temperature difference without artificial heating and cooling. Consequently, the location and range of the blistering zone was not detected by the passive method, relative