İSTANBUL UNIVERSITY CERRAHPAŞA

ANNALES

du 21e CONGRÈS de l'ASSOCIATION INTERNATIONALE pour l'HISTOIRE du VERRE

3-7 Septembre 2018, Istanbul

efe glass

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İstanbul 2018

Editor
Orhan Sevindik

Editorial Committee
Erdoğan Köse
Üzlifat Özgümüş
Ergün Laflı
Ömür Bakırer
Ömür Dünya Çakmaklı

İSTANBUL 2021

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in memoriam
YOKO SHINDO

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MODELLING THE EFFECTS OF DAYLIGHT SCATTERING BY WINDOW GLASS: THE CASE OF SIXTH CENTURY HAGIA SOPHIA IN ISTANBUL

1. INTRODUCTION

1.1. Glazing and daylight in Hagia Sophia

The illumination in today's Hagia Sophia is predominantly diffuse, comprising –mostly indirect sun– and skylight admitted by a multitude of windows. Based on illuminance measurements on a day in Spring, Schibille describes this illumination as even and non-directional, characterised by a generally homogeneous illuminance distribution along the axis of the nave, with no significant gradient before and after noon[1].

This finding was called into question by a detailed luminance analysis deploying High Dynamic Range (HDR) photography, showing that, on sunny days, pools of direct light from the windows wander through the interior and accentuate different features of the architecture[2]. These pools are projections of the windows on diffusely reflecting surfaces, and show details such as the grid of shadows cast by the frames if the windows are nearby, e.g., in the galleries or aisles. Even distant windows, in particular the rows of windows of the tympanum walls, cause distinct bright spots of light that are surrounded by less pronounced yet bright areas. Windows and their specular reflections on glossy marble, e.g. on the floors, form regions of high luminance that - other than the pools of direct light on diffuse surfaces - depend on the observer's viewpoint.

The present configuration of windows exhibits deviations from the original design, caused by centuries of modifications and repairs[3]. Based on a detailed architectural sur-

1 SCHIBILLE 2014

2 INANICI 2014

3 MAINSTONE 1988

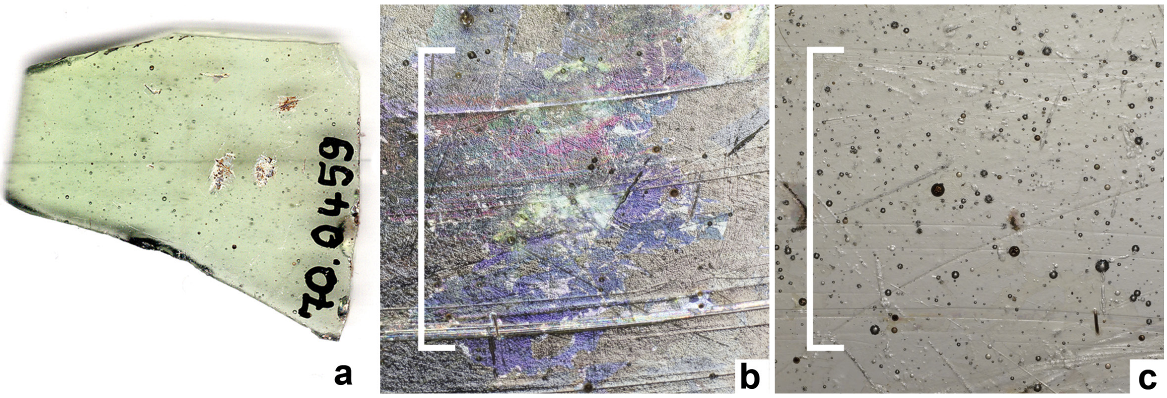

Fig. 1: The measured sample of blown window glass (a). Macro photographs under grazing light emphasizing corrosion and the surface structure (b) and with transmitted light showing the bubbles in the glass volume (c), l =10 mm).

vey[4], an analysis[5], and a reconstruction of the liturgical installations[6], the authors have developed a model of the building in its 6th century state[7]. Lighting simulation employing this model shows that the geometry of the original fenestration admits light into the aisles, causing apperception of the building as a nearly continuous space. However, since no original window glass of the building has been preserved[8], the previous simulation studies could not account for the optical properties of the glazing and its predicted effects, such as a more even illumination[9].

Despite the lack of directly attributable archaeologic finds, plausible assumptions on the scattering properties of the original glazing of Hagia Sophia can be made. Any window glass that can be denoted as Roman – beginning with the first appearance of glass as a building material in the 1st century[10] until the end of centralized raw glass production in the Levante in the 9th century[11] – features a varying but significant amount of bubbles, inclusions and surface irregularities. These features, which affect the scattering of transmitted and reflected light, and thereby the illumination of attached architectural spaces, can be attributed to a few different manufacturing processes[12]. A pilot study conducted by the authors on modelling the effects of the measured scattering properties of Roman glass samples suggest that classification by manufacturing processes correlates with effects on illumination and visual appearance[13]. The presented research applies this finding to the case of Hagia Sophia, based on a sample that is exemplary for the most probable manufacturing process for window glass in a 6th century church. Consequently, despite being from another province and context, the characteristics of the sample are expected to present a plausible scenario for the fenestration of Hagia Sophia and its impact on illumination.

1.2. Daylight simulation in building history research

The use of physically valid lighting simulation, based on measurements and reconstruction, has been proposed to approxi-

4 NICE 1995
5 MAINSTONE 1988
6 STICHEL 2010; SVENSHON 2010
7 GROBE, HAUCK, and NOBACK 2010
8 SCHIBILLE 2014
9 MAINSTONE 1988, 124 et seqq.
10 BAATZ 1991
11 SAGUÌ 2007
12 KOMP 2009
13 GROBE et al. 2019; NOBACK et al. 2017

mate the visual perception of historic states of buildings[14]. Most efforts to model the optical properties of glazing in the field of predictive rendering of cultural heritage aim to replicate the spectral transmission properties of coloured, clear glass[15]. One exception are the detailed investigations of the effects of light scattering by translucent roof tiles. These, however, rely on simplified measurement and modelling techniques[16].

Advanced measurement and modelling techniques, as employed in the field of engineering to evaluate the distribution of daylight through complex modern fenestration, promise applications in historical and archaeological research[17]. Light scattering as described by the Bidirectional Scattering Distribution Function (BSDF) as a function of incident and outgoing directions[18] can be measured by gonio-photometers[19]. Parametric and data-driven models replicate these measurements in simulations, and thereby predict the admission and distribution of daylight through windows with a high accuracy[20].

1.3. Objectives

Extending preliminary research on Roman window glass, we present the exemplary application of advanced measurement and modelling techniques to reconstruct the illumination of late antique Hagia Sophia. The light scattering properties of an exemplary sample of Roman window glass shall be

- characterised by gonio-photometric measurements of its BSDF,
- replicated by a physically plausible transmission and reflection model, and
- evaluated with regard to their effect on the illumination of Hagia Sophia.

The analysis of the building's illumination covers both the distribution of admitted daylight over the building plan in terms of horizontal illuminance (E_h), and the glazing's effects on the visual perception of the illuminated interior surfaces by the analysis of imagery in terms of luminance (L).

The presented method opens a new access to the important role of window glass as a determinant for the perception of buildings in the past, and provides a basis for future cross-disciplinary research.

2. CHARACTERISING ROMAN WINDOW GLASS

2.1. A sample of blown window glass

While the 6th century window glass of Hagia Sophia seems to be entirely lost[21], finds from this time are documented in Istanbul[22] and other sites in the late antique Roman empire[23]. Since the end of the 2nd century, flat window panes are predominantly produced by cutting and flattening of blown cylinders[24]. This manufacturing technique has been common in different places in the Roman empire and bears window panes of great similarity: only a few millimetres thick, they feature two smooth surfaces and an often significant amount of bubbles[25]. While such panes are a plausib lechoice for Hagia Sophia, crown glass and flat glass formed on

14 DEVLIN 2012; EARL et al. 2013; PAPADOPOULOS and EARL 2014; HAPPA et al. 2012
15 CERISE et al. 2012; THANIKACHALAM et al. 2016
16 PATAY-HORVÁTH 2016
17 NOBACK forthcoming
18 STOVER 2012
19 APIAN-BENNEWITZ 2014
20 WARD, KURT, and BONNEEL 2014

21 SCHIBILLE 2014
22 CANAV ÖZGÜMÜŞ 2009; HARRISON and GILL 1986
23 SCHIBILLE, MARIL, and REHREN 2008; KOMP 2009; ARLETTI et al. 2010
24 KOMP 2009, 69; ARLETTI et al. 2010
25 KOMP 2009, 73 et seqq.

a surface – although less probable – cannot be entirely ruled out and would cause stronger scattering.

The chosen sample of 1.9 mm to 2.9 mm thickness and greenish colour (Fig. 1a) is typical for blown window glass and preserved in good overall condition. It originates from a castrum near Bonn, and is dated between the 1st and the 5th century. The surfaces feature fine, curved ridges (Fig. 1b), regions of iridescent corrosion, and are partly chipped. Brownish regions covering agglomerations of inclusions are affected by strongercorrosion. The glass volume comprises plenty of small, spherical air bubbles (Fig. 1c). These are expected to be the primary cause for light scattering, since their interfaces with the glass deflect incident light by refraction. By contrast, light passing between the bubbles is only deflected by surface irregularities.

2.2. Instrumentation and measurement method

To characterise the light scattering properties of the glass sample, its BSDF is measured, i.e. the directional distribution of reflected and transmitted light is sampled for a set of incident directions. A scanning gonio-photometer is employed that comprises (Fig. 2)

- an illuminator, collimating the light emitted by a halogen lamp into a beam aimed toward
- a sample mount that can be rotated over two axes to change the incident light's direction θ_i, f_i, and
- a set of detectors installed on a robotic arm, scanning the distribution of transmitted and reflected light over outgoing directions θ_s, f_s at high resolution.

The illuminator can be configured according to the specific requirements of a given sample. The beam is focused on the glass fragment, shaping a small, circular illuminated area at normal incidence. This area extends to an ellipse at oblique incident directions, and exceeds the width of the sample when θ_i is greater than 60°– thereby limiting the range of incident directions covered by the measurement.

Prior to any measurement, the unobstructed beam is characterised by a scan informing about the illuminance E_i incident on the sample, as well as the instrument signature defining the maximum resolution and the lowest measurable BSDF. Since all subsequent measurements are relative to this beam characterisation, no particular calibration of the stabilised illuminator or detector is required.

The scan path of the detectors is configured so that its density adapts to the properties of the sample. In a first pass, the entire transmission and reflection hemispheres are sampled at moderate resolution, covering all diffuse light scattering. Within this coarse measurement, peaks caused by directional reflection and transmission are detected. In a second pass, outgoing directions adjacent to these peaks are refined. The measurement sequence assumes that transmission and reflection distributions for any incident direction comprise

- one distinct transmission peak, due to regular transmission between the bubbles;
- one distinct reflection peak, due to regular, mirror-like reflection on the smooth surface; and

- a diffuse background, due to surface structures and contamination, and due to scattering in the glass volume by bubbles and inclusions.

Since the underlying scattering mechanisms remain constant, these distributions are expected to change only gradually with varying incident directions. This allows the efficient characterisation of the scattering properties by an asymmetric measurement, pairing few, regularly spaced incident directions with a dense and locally refined set of outgoing directions.

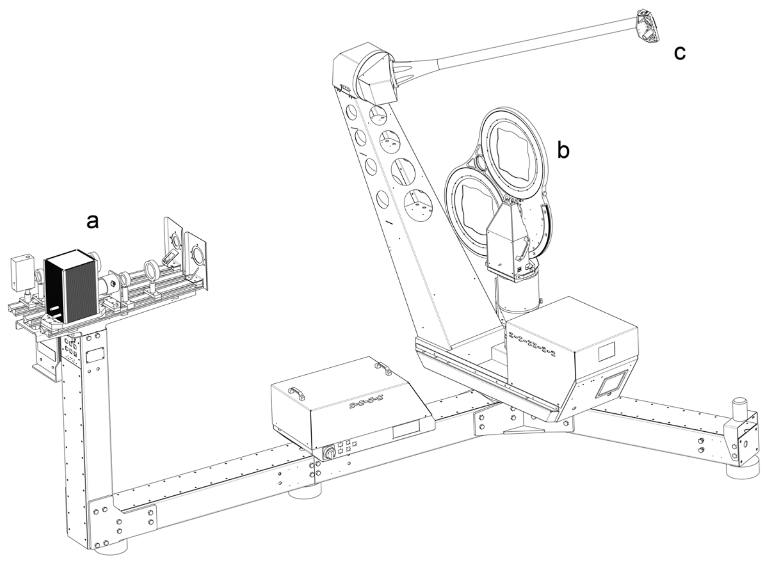

Fig. 2: Gonio-photometer comprising illuminator (a), sample mounts (b) and detectors on robotic arm (c). Image courtesy pab advanced technologies Ltd.

3. MODELLING THE LIGHT SCATTERING CHARACTERISTICS OF ROMAN WINDOW GLASS

3.1. Fitting a transmission model to the measured BSDF

The daylight simulation suite RADIANCE was chosen due to its physical accuracy and the thorough validation work confirming its capabilities, and its support for data-driven as well as parametric models to describe light scattering by translucent glass. Since the data-driven model, compiled from measured BSDF, is incapable to extrapolate beyond the range of incident directions contained in the measurement, the parametric *trans* model was chosen and fitted to the acquired distributions. This model extends the Ward reflection model and applies it to transmission, which it describes as the combination of a constant diffuse background with a Gaussian specular peak[26]. Based on an initial evaluation of the measurements, the isotropic formulation of the model was chosen. This reduces the peak model to a function of the incident off-normal angle θ_i , outgoing direction θ_s, f_s, and constant values for surface roughness α, diffuse reflection in three colour channels *RGB* and specularity r_s.

The trans model is parametrised by seven arguments *a1 . . . a7* (Table 1) in RADIANCE. Fitting the model to a slice of the measured BSDF in the scattering plane (φ = 0°), employing the implementation of the nonlinear least-squares Marquardt-Levenberg algorithm in Gnuplot[27], revealed the set of parameters listed in Table 1. Since the shapes of the measured peaks vary significantly with changing incident directions, but the formulation of the model assumes invariant roughness α (parameter *a5*), the model

26 WARD 2004; GROBE, GEISLER-MORODER, and WITTKOPF 2010
27 WILLIAMS and KELLEY 2018

Table 1: Parameters of the trans model with constraints and result of fitting.

parameter	description	min	max	fit
$a_1 \ldots a_3$	non-absorbed fraction of incident light	0.0	1.0	0.964
a_4	specular fraction of $a_1 \ldots a_3$	0.0	1.0	0.229
a_5	surface roughness	0.0	0.2	0.046
a_6	transmitted fraction of $a_1 \ldots a_3 - a_4$	0.0	1.0	0.972
a_7	transmitted fraction of a_4	0.0	1.0	0.955

$$f(\theta_i, \theta_s) = \frac{\exp\left(\left(2 \cdot (\vec{i} \cdot \vec{t}) - 2\right) / \alpha^2\right)}{\pi \cdot \alpha^2 \cdot \sqrt{\cos(\theta_i) \cdot (-\cos(\theta_s))}}$$

Equation 1

was fitted to only one measured distribution for $\theta_i = 20°$. To enforce plausible results, the range of the parameters was constrained in the fitting process as shown in Table 1. A comparison between the parametrised model and the measurements for the corresponding incident directions is shown in Figure 3.

3.2. Application of the glass model in daylight simulation

To explore the impact of the scattering characteristics of the historic window glass, the transmission model of the sample was applied to the window panes of a model of the reconstructed interior of Hagia Sophia in the 6th century[28].

This geometric model, prepared in particular for lighting simulation, comprises all the interior surfaces of the building as well as important exterior obstructions. The reflection properties of the interior surfaces were set based on calibrated photographs (in particular the colours of the marble lining), laboratory measurements on similar samples (e.g. tesserae of gold mosaic and reflectance of marble), and values taken from literature (e.g. silver surfaces). The illumination is provided by a synthetic sky model, reflecting sunny sky conditions at Easter three hours after sunrise[29].

The characteristic complexity of reflection properties and building geometry imposes a challenge to the backward ray-tracing algorithm in RADIANCE. To accurately replicate light propagation through the windows, and by many specular and diffuse inter-reflections on the interior surfaces, the implementation of the bi-directional photon mapping algorithm in RADIANCE was applied[30]. This algorithm comprises a forward pass, modelling light propagation as a particle transport mechanism, and a backward ray-tracing pass reduced to one reflection. The forward pass ensures that diffuse reflection accounts for complex light paths. The backward pass accounts for specular reflections and the visibility of light sources, and reduces the effects of noise.

The distribution of horizontal illuminance (E_h [lx]) on the floor was evaluated as an indicator of the daylight distribution in the building. The illuminance values were mapped to colours and visualised as an overlay on the building plan.

To reconstruct the visual perception of the building, HDR imagery was generat-

28 GROBE, HAUCK, and NOBACK 2010

29 CIE 1996

30 SCHREGLE, GROBE and WITTKOPF 2016

ed with pixel values corresponding to luminance (L [cd m^{-2}]). Since the results of the simulation are typically displayed on devices of limited dynamic range, a model of human visual perception as implemented in the RADIANCE program *pcond* was applied to these photometric data-sets, anticipating aspects of vision such as contrast reduction and glare by bright light sources[31]. The generated images therefore provide a visualisation of the building interior by combining optical and perceptual mechanisms.

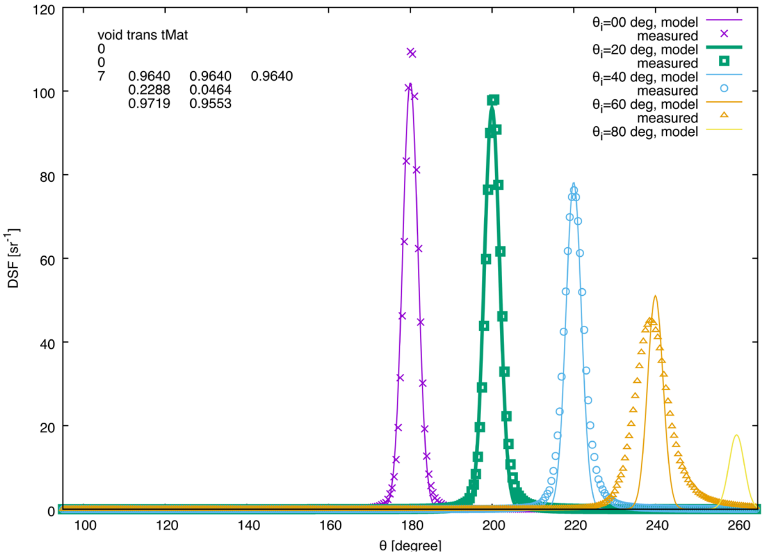

Fig. 3: Model parametrized for $\theta_i = 20°$ and measurements ($\varphi = 0°$).

For comparison, the simulation was repeated with two models representing clear and diffusing glass.

4. RESULTS AND DISCUSSION

4.1. Effects of window glass on the illuminance distribution

Figure 4 shows the distribution of E_h. It is characterised by a gradual increase from the dim illumination in the West of the nave and the aisles (≈ 150 lx) to the brightly illuminated apsis (≈ 400 lx), and can be attributed to indirect illumination by inter-reflected sunlight and diffuse skylight. The simulation reveals a distinct directionality in terms of E_h and does not correlate with Schibille's observations in the building in its present state[32].

The gradual increase of E_h is locally interrupted by directly illuminated regions, where it reaches values of up to 20 000 lx in the East, and 500 lx in the dim West of the nave. Set into relation with the surrounding, diffuse and indirect illumination, the illuminance ratios between diffuse background and directly illuminated regions evaluate to around 50:1 in the East, and around 3: 1 in the West of the nave. This correlates with the observation of "light pools" in the building in its present state[33].

Directional scattering by window glass, as already indicated by the measurements, is reflected by the brightly illuminated regions. In the East, where the distance between the scattering window pane and the receiving floor is short, transmitted sunlight causes perceptible projections of the windows' shapes as blurred grids of shadows. With increasing distance between window and receiving floor toward the West, the edges of the shadows get smoother. The "pools", e.g. in front of the entrance as illuminated by the windows in the Eastern semi-dome, gradually blend into each other.

Since the optical properties of the particular window glass that was once used in

31 WARD LARSON, RUSHMEIER, and PIATKO 1997
32 SCHIBILLE 2014
33 INANICI 2014

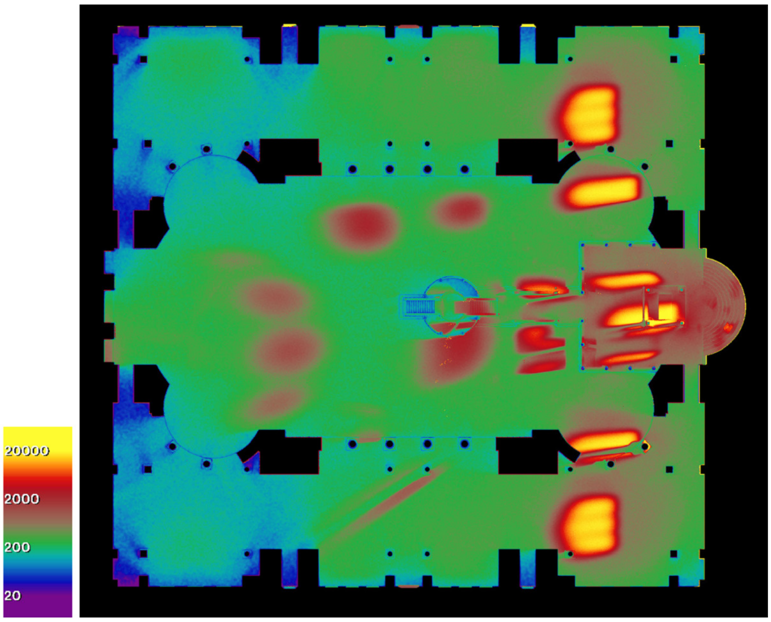

Fig. 4: Distribution of horizontal illuminance on the floor. A continuous increase from West toward East characterises nave and aisles. This gradual increase is interrupted by regions of high illuminance, due to sunlight that is directly transmitted through the windows. In the East, these regions form perceptible projections of the windows.

Fig. 5: View toward the entrance wall in the West, brightly illuminated by light transmitted through the windows of the cupola.

Hagia Sophia may differ from the measured sample, the exact gradient and resulting boundaries of these illuminated regions are not known. Nevertheless, the simulation reveals fundamental effects by any glass exhibiting directional scattering, and can be considered an important constituent of Hagia Sophia's historical illumination.

4.2. Effects on visual perception

Figure 5 shows the view towards the West wall with the ceremonial "Emperor's Door" with the ambo in the foreground. The image was adjusted to reflect effects of human perception, and illustrates the visual impact of the illumination and the effects of the directional scattering of sunlight by the historic window panes.

The entrance wall is brightly illuminated by sunlight originating from the windows of the dome. Scattering by the window glass widens and effectively distributes the contribution of the individual windows, and blends them into one directional but continuous and non-distracting illuminated area. The illumination augments the polychromy, and the fine profiled architectural details of the marble decoration. It thereby emphasises the architectural staging of the entrance of the emperor and the patriarch on important holidays. The liturgical furnishings, e.g. ambo and sanctuary – outside the field of view of the image – and architectural elements such as the porphyry columns of the Southern colonnades show similar accents. The volume and form of these elements is pronounced by the soft but distinct half-tones that are caused by the directional but scattered illumination.

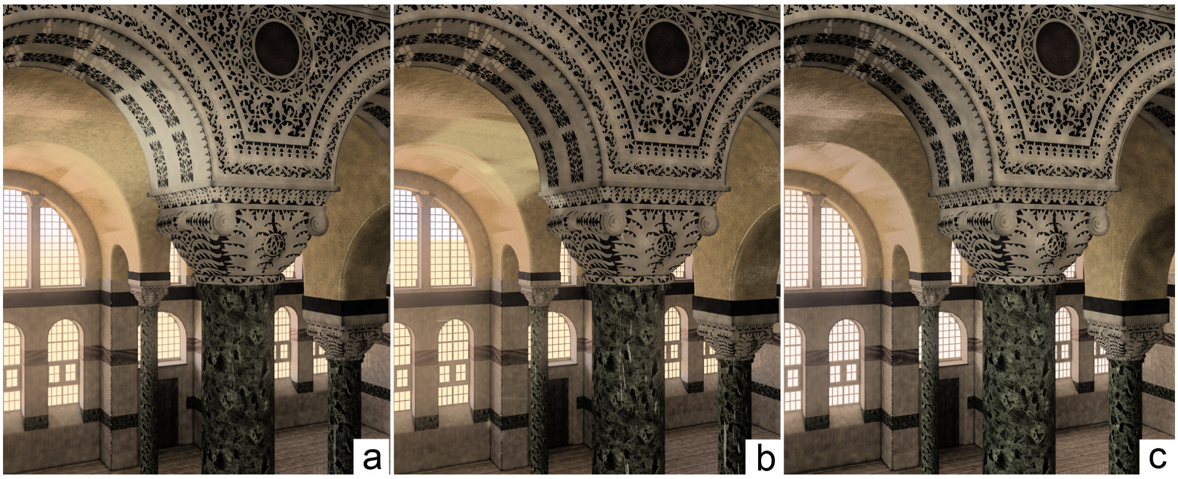

Fig. 6: Effect of light scattering Roman window glass (a), modern glass (b) and diffuse (frosted) glass (c) on the illumination of architectural elements.

The visual impression is amplified by the sparkling reflections of the gold mosaics covering the vaults, and by the bright appearance of the windows. The entire scene is characterised by the interplay of the dramatic illumination with the splendid decor of the building's interior.

Figure 6 shows the effect of the window glass on the illumination of the particularly rich decorations of the arcades and a capital above the Southern colonnades. The windows of the South aisle are located below these architectural elements. Yet, the reliefs of capitals as well as the arcs are illuminated (a), since the widened beam of sunlight transmitted by the Roman window glass is partially scattered upward. This effect is absent under the assumption of the properties of clear glass (b). The capital and the arc appear dark, the rich decoration and reliefs appear flat. If diffuse scattering eliminates the directionality of the illumination, the resulting overall appearance is flat, the interior is evenly brightened up, and all accentuation of relief and volume of the capital is eliminated (c).

5. CONCLUSIONS

The impact of Roman window glass on the distribution of daylight within Hagia Sophia, and thereby the perception of its interior, could be demonstrated in an exemplary simulation. The observation of the local accentuation by regions of high illuminance in the building's current state, as reported in literature, could be replicated in the reconstruction[34]. The stated lack of directionality[35], on the other hand, is contradicted both by the illuminance distribution and the wide luminance range even within a single field of view - at least for the chosen sky condition.

Given the fact that, to the knowledge of the authors, no other attempts to systematically characterise the light scattering properties of ancient window glass have been made so far, our knowledge is selective and not sufficient for quantitative statements on the range of optical properties achieved by Roman glass-making techniques. Our knowledge is further limited by the unexplored relation of surface deterioration by aging and light scattering. Yet, the measured strong for-

34 INANICI 2014
35 SCHIBILLE 2014

ward scattering due to surface irregularities, bubbles and inclusions is at least partially the inherent result of the manufacturing process of, and thereby typical for, cylinder-blown window glass.

Even if no finds of window glass directly attributable to the 6th century Hagia Sophia are known, the model offers a plausible scenario of the daytime illumination of the building, and the perception of its interior, for qualitative interpretation. Furthermore, the light scattering properties of Roman window glass had a major impact on the perception of any Roman building featuring glazing, which was very different from our experience of natural illumination through modern, clear float glass. Consequently, we consider the scattering properties of windows glass as a worthwhile new field of glass research with implications on the understanding of the functional and stylistic development of architecture. Daylight simulation, and the accurate modelling of glazing in particular, are indispensable for such research.

The *trans* model in RADIANCE lends itself as a general means to inter- and extrapolate light scattering of translucent glazing based on BSDF measurements within a limited directional range. It is, however, limited by attributing scattering exclusively to constant surface roughness. It therefore achieves good alignment with the measurements for a limited range of incident directions only, and does not account for volume scattering by bubbles and inclusions in the glass. Other models may achieve better alignment over a wider range of directions, but are not implemented in RADIANCE and therefore hard to employ in daylight simulation.

6. FUTURE RESEARCH

The prominence of moderately scattered sunlight in the building calls for a systematic assessment of the dynamic, temporal accentuating of building features. Climate-Based Daylight Modelling (CBDM) lends itself to such research, offering an efficient simulation technique to account for any sun position over the course of the day and the year.

The evaluated glass find is not truly representative. Systematic research is needed to understand the range of variation of optical properties of Roman window glass. Such research needs to distinguish the inherent glazing properties at the time of production, and the effects of aging that are present in any measurement on archaeological finds. The reconstruction of the glazing properties emerges as an important challenge for the accurate modelling of daylight in buildings in historical research.

Seemingly contradictory statements about the characteristics of illumination in Hagia Sophia in literature, e.g. in terms of illuminance, luminance and directionality, are strong indicators for the need of a consistent methodology when disciplinary boundaries between art history, archaeology, natural and engineering sciences are crossed. In this context, the authors are planning to further develop their approach of daylight simulation as an experimental platform within building history to complement knowledge from the studies of written records and historic building surveys.

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